EPA/600/X-99/XXX
December 1999

Guidance Manual for Integrated Wet Weather Flow (WWF) Collection and Treatment Systems for Newly Urbanized Areas (New WWF Systems)

Final Project Report

by

Robert Pitt and Melissa Lilburn
Department of Civil and Environmental Engineering
The University of Alabama at Birmingham
Birmingham, Alabama

S. Rocky Durrans, and Steve Burian
Department of Civil and Environmental Engineering
The University of Alabama
Tuscaloosa, Alabama

Stephan Nix
College of Engineering and Technology
Northern Arizona University
Flagstaff, Arizona

John Voorhees and Jeff Martinson
Engineering Programming Consultants
Madison, Wisconsin

Project Officer

Chi-Yuan Fan
Urban Watershed Management Branch
Wet Weather Flow Program
U.S. Environmental Protection Agency
Edison, New Jersey 08837

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Notice

(draft only, report not reviewed yet)

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under cooperative agreement no. CX 824933-01-0 for the University of Alabama at Birmingham. Although it has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document, it does not necessarily reflect the views of the Agency and no official endorsement should be inferred. Also, the mention of trade names or commercial products does not imply endorsement by the United States government.

Foreword

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts and search for solutions.

The National Risk Management Research Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensive engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and user community. The purpose of this report is to prepare a guidance manual integrating wet weather flow (WWF) collection and treatment systems for newly urbanized areas (New WWF Systems). It presents an extensive literature survey and discussion on changes in the design methods for urban wet weather runoff collection systems. It also integrates two computer models that can be easily used by designers and planners to comprehensively consider both drainage and water quality objectives in collection system designs.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

This research project develop and demonstrated a methodology to guide design engineers in developing appropriate wet weather flow (WWF) drainage systems. Specific aspects of this guidance document address the historically mutually conflicting objectives of providing drainage services at the same time as decreasing stormwater pollutant discharges. Numerous drainage design procedures have been used for more than 100 years in the western world. However, major changes have occurred frequently over this period of time in response to specific problems encountered. Unfortunately, current drainage design procedures, while providing adequate levels of service if correctly implemented, commonly conflict with attempts to reduce stormwater pollutant discharges and associated receiving water problems. Water quality aspects of wet weather flow discharges and associated receiving water problems have only been studied for a relatively short period (a few decades), compared to conventional drainage designs (a few centuries), and few large-scale drainage systems adequately address both of these suitable objectives.

This report presents a methodology that incorporates procedures that can be applied to the broad range of conditions that are likely to be encountered in the U.S. to address both drainage and water quality objectives. The methodology builds upon past experiences in drainage design (including some currently not being used in the U.S.) and uses current design tools that are readily available. As an example, it may be appropriate to consider the use of combined sewers and WWF discharge treatment in heavily urbanized areas. Source area controls, especially biofiltration practices that can be easily implemented with simple grading, may be appropriate in newly developing areas. In addition, critical source areas (such as vehicle service facilities) may require more extensive on-site treatment strategies. In-line storage with large diameter sewerage may also be appropriately utilized in some areas, depending on land costs and availability.

Other design strategies addressed in this report include the conventional concept of design storms that have worked reasonably well for drainage objectives. Unfortunately, single design storms have been found to be generally inadequate in water quality evaluations of WWFs. Quasi-continuous evaluations over long periods of time may be more appropriate for these combinations of objectives. The use of inexpensive computers enables more comprehensive design evaluations to be rapidly and cost-effectively made.

The use of computers has become common in many aspects of engineering practice, including drainage design and water quality evaluations. No currently available model adequately integrates these multiple objectives into a single system. This research activity therefore developed a methodology that includes the integration of two currently used computer models (SWMM for drainage design and CSO evaluations, plus SLAMM for source area runoff volume and pollutant reduction evaluations). Both of these programs are freely available and their use will not require the purchase of software. This research included the preparation of software utilities that makes the integrated use of these programs as seamless as possible. In addition, this project includes selected enhancements to both of these models to incorporate recent research results and innovations. Four of the investigators of this project were responsible for the design and programming of these models.

Contents

List of Tables

List of Figures

Section 1
Introduction and Overall Design Approach

This objectives of this project were to review historical developments in urban drainage practices, examine current practices, and produce useful tools for drainage design in the future. Therefore, this report has a strong historical basis, both in its extensive literature reviews and in the analysis of substantial amounts of available data. The historical information was necessary in order to understand how we arrived at the current state of the art in drainage design, what choices have been historically made based on poor information and should be re-examined, and what data gaps currently exist in our knowledge. This information was necessary to formulate and substantiate our design approach for the future. The data analyses were conducted to illustrate common misconceptions and misuse of available stormwater models that are used for design.

SLAMM, the Source Loading and Management Model, was developed in the late 1970s to better consider small and moderate storms of most interest in water quality evaluations. Typical stormwater models used for drainage design have numerous assumptions appropriate for these larger events that are not appropriate for these smaller events. SLAMM has been continuously improved and is capable of examining many source area and outfall controls and development practices. During this project, SLAMM was integrated with EPA's SWMM, the Storm Water Management Model, probably the most used urban drainage model, which had also been continuously updated since its initial development in the 1970s. The integration of these models replaces SWMM's RUNOFF block with SLAMM. This combination will result in much greater flexibility in the evaluation of stormwater quality controls, it eliminates many of the faulty assumptions inherent in RUNOFF, and utilizes the comprehensive drainage sewerage evaluation tools inherent in SWMM's EXTRAN, TRANSPORT, and STORAGE/TREATMENT blocks.

This report has 5 main sections and 5 appendices, as follows:

Section 1. Introduction and Overall Design Approach
Section 2. The Beneficial Uses of Stormwater in Urban Areas and the Need for Change in Urban Water Management
Section 3. Historical Review of Wet Weather Flow Management and Designs for the Future
Section 4. Current and Future Design Practices
Section 5. The Integration of SWMM and SLAMM

Appendix A. The Integration of Water Quality and Drainage Design Objectives
Appendix B. U.S. EPA Urban Rainfall-Runoff Quality Data, U.S. EPA/USGS NURP Data, and Ontario's TAWMS Data Plots
Appendix C. Using SLAMM
Appendix D. Stormwater Quality Controls in SLAMM
Appendix E. SLAMM Source Code

Design Methodology Issues

Precipitation falling over an urban watershed passes through an extremely complex hydrologic and hydraulic system. As it moves through this system, it is concentrated into larger and larger flow streams and picks up a suite of pollutants in the process. An urbanized area is, by definition, an area of concentrated human activity. With this activity comes an increase in runoff volumes and flow rates due to the covering of much of the surface with impervious materials (concrete, asphalt, etc.) In addition, such a system can only be maintained by a large influx of a great variety of materials. Subsequently, there is a high concentration and diversity of waste materials. Some of this waste is transported from the urban area by wet weather flows to receiving waters. This transport process is very efficient since urban areas generally have elaborate drainage systems to remove runoff quickly. Essentially, an urban area produces larger, more diverse, waste discharges and no longer has the physical, biological, and chemical "buffers" it had in its natural state.

The engineering community's view of urban wet weather flows have changed and evolved over the years. In earlier times, the concern was for flood control and removing runoff as expeditiously as possible. In more recent times, the cross purposes of efficiently removing runoff from streets and parking lots, and yet not overwhelming receiving waters, led to more comprehensive management techniques. Presently, engineers and planners are faced not only with the control and management of runoff quantity, but the maintenance of water quality as well.

Urban wet weather quantity problems remain a high priority in most localities. However, interest in urban wet weather quality has swelled as a result of the 1987 Water Quality Act. This act, which amended the 1972 Clean Water Act, outlines a permitting system to regulate stormwater discharges from medium and large municipal storm sewer systems, current holders of NPDES (National Pollutant Discharge Elimination System) permits, and a host of industrial activities. The EPA published regulations in November, 1990 to flesh out the permitting system (Federal Register, 40CFR, 1990). The result is that a good portion of the urban wet weather discharges in the United States are to be handled, from a regulatory perspective, as "point" sources of pollution.

Urban Wet Weather Quantity Problems

Precipitation falling on an urban watershed will strike either a pervious surface or an impervious surface. On pervious surfaces most of the rainfall infiltrates to the subsurface -- a small part remains as surface runoff. A portion of the infiltrated water may take a relatively slow subterranean path to a surface stream. On impervious surfaces, nearly all rainfall becomes surface runoff. Surface runoff from both surfaces finds its way to channels and streams. Urban drainage systems speed this process along.

Urban watersheds are, of course, characterized by impervious surfaces and efficient drainage systems. The increased volumes and flow rates of runoff produced under these conditions have a number of harmful impacts, including the following (Nix 1994):

- *Flooding*. Developed areas and their drainage systems are usually very good at discharging runoff -- so much so that they transfer the problem to downstream locations that may not be as hydraulically efficient. On the other hand, older or inadequately designed drainage systems can themselves be overwhelmed by runoff from increased urbanization.

- *Stream Erosion.* The increased runoff accompanying urban development increases the bed load, or sediment-carrying, capacity of a stream. This diminishes the integrity of the stream bed and stream banks. In addition, the sediment load carried by the stream can accumulate at downstream points where the flow characteristics (e.g., velocity) are such that the bed load capacity is reduced.

- *Habitat Destruction*. A stream ecosystem is a delicate balance between all of its biological and chemical components. It is also in a precarious equilibrium with the physical environment. Increased runoff to a stream changes this balance and can threaten the established ecosystem. Increased thermal loads normally associated with urban runoff can also disrupt sensitive ecosystems.

Urban Wet Weather Pollution

As rainfall moves through the atmosphere, it washes out air pollutants and carries them to the ground surface. Rain drops striking the surface will dislodge some particles (mostly soil on pervious surfaces; a wide variety of dust and debris on impervious surfaces) and dissolve other materials. Surface runoff carries the particles dislodged by the initial precipitation impact, other particles dislodged by the movement of the runoff itself, and a variety of dissolved materials to drainage systems and watercourses. In some cases, the infiltrated water will threaten aquifers with a variety of pollutants.

The range and variety of sources of wet weather pollution is extensive. The pollutants carried from the watershed surface come from a number of sources, such as (Nix 1994):

- Transportation
- Industrial activities
- Decaying vegetation
- Soil erosion
- Animals
- Fertilizer/pesticide application
- Deicing agents
- Dryfall
- General litter

Pollutants may also be contributed by the watershed's drainage system. Such a system may contain natural or manmade channels as well as sewerage. In natural channels, erosion can produce significant amounts of pollutants. Some manmade systems may be designed exclusively for stormwater flows, in which case they are known as separate sewer systems. These systems are sometimes victimized by illegal sanitary connections or direct disposals. Some drainage systems are designed to carry both stormwater and sanitary sewage flows, in which case they are known as combined sewer system. The major contributor of pollutants in combined sewer systems is obviously sanitary and industrial sewage.

Other, less obvious, opportunities for urban wet weather pollution are plentiful. Examples include:

- Leaking sanitary sewers
- Poorly operating septic systems
- Accidental spills
- Leaking underground storage tanks
- Leachate from landfills
- Leakage from hazardous waste sites

Stormwater Problems and Selection of Control Programs

Before stormwater control programs can be selected and evaluated, it is necessary to understand the stormwater problems in local receiving waters. The lists below give typical receiving water problems, associated with the long-term accumulation of pollutants, and by short-term (event-related) problems.

Long-term problems associated with accumulations of pollutants in waterbodies include:

- Sedimentation in stormwater conveyance systems and in receiving waters.
- Nuisance algal growths from nutrient discharges.
- Inedible fish, undrinkable water, and shifts to less sensitive aquatic organisms caused by toxic heavy metals and organics.

Short-term problems associated with high pollutant concentrations or frequent high flows (event related) include:

- Swimming beach closures from pathogenic microorganisms.
- Water quality violations, especially for bacteria and heavy metals.
- Property damage from increased flooding and drainage system failures.
- Habitat destruction caused by frequent high flow rates (bed scour, bank erosion, flushing of organisms downstream, etc.).

Many of these problems have been commonly found in urban receiving waters in many areas of the U.S. (as summarized by Pitt 1995, for example). Because these problems are so diverse, a wide variety of individual stormwater controls must usually be used together to form a comprehensive wet weather management strategy. Unfortunately, combinations of controls are difficult to analyze using conventional stormwater models, or directly from the results of monitoring activities. These difficulties will require new modeling techniques that will enable an effective evaluation of a wide variety of control practices and land uses that may affect the entire suite of receiving water problems, at the same time as meeting the over-riding storm drainage objective of flood control.

Wet Weather Flow Management in Newly Urbanizing Areas

Unfortunately, wet weather flow management in the United States has been fragmented and mostly ineffective. This is a direct result of at least three factors. First, individual property rights are among the most cherished of U.S. values. Many wet weather flow management techniques infringe on those rights. Second, the U.S. governmental system is a multi-level web of competing interests. It is not unusual for several governmental entities to be involved in wet weather management for a given area. Third, we understand little about wet weather flows, the pollutants they carry, and the impact of those flows and pollutants -- and what we do know has not been well communicated to mainstream America. Americans have traditionally viewed wet weather flow as “clean” water. Thus, when some more seemingly catastrophic environmental problem comes along, wet weather flow takes a back seat. It is not very surprising that so little has been accomplished to solve wet weather flow problems -- the social and political will is generally lacking.

It is also clear that the technical community is slow to adopt new methods and strategies. Why is this so? A simplistic answer is probably dangerous. Nevertheless, it is probably fair to say that most stormwater management projects are designed by small local firms for fairly small developments. Good business practice probably requires the use of simple, “time-tested” (at least in the mind of the users!), narrowly focused design methodologies, not the use of a flexible, comprehensive methodology requiring higher levels of engineering expertise and judgment.

These factors will not change significantly in the foreseeable future. Wet weather flow management will not occur by large coordinated efforts backed by significant public concern and funds, nor will sweeping changes occur in the technical community. While it is true that there have been some wet-weather management successes, most of these have occurred in “upscale areas” with disposal public income and/or the political clout to attract state and federal funds. These are uncommon situations not readily adapted to most locales.

So how is the problem solved? Much of the urban growth in America is relatively uncontrolled and much of it occurs in areas far more interested in economic growth than environmental quality. Existing urban areas will, for the most part, not lead the effort. “Retrofitting” for comprehensive wet weather flow control is an expensive luxury that few urban areas can afford. However, one extraordinary opportunity exists. The incorporation of control measures in newly urbanizing areas is probably fairly painless, especially if the marginal costs above and beyond the normal drainage functions are low. Many U.S. cities have grown 50% and more over the last 20 years. The inescapable truth is that if measures had been incorporated in these areas as they were constructed, the wet weather problem would have already been reduced at a cost that would almost certainly be less than an “equivalent” amount of retrofitting. Starting now to incorporate control measures in expanding urban areas will help to avoid continuing this situation 20 years from now.

Wet Weather Management Objective

Wet weather management involves the prevention, transport, and treatment of excess runoff flows and pollutant loads. Prevention is often the technique of first choice since the control of flashy, dynamic flows and loads is expensive and difficult. Upland controls, “best” management practices, and good “housekeeping” prevent pollutants from being carried along with storm flows or entering the drainage system. Preventative measures, such as detention basins, infiltration basins, and porous surfaces, can all be used to replace the natural storage lost through development. Runoff flows and pollutant loads not captured by upland controls enter a drainage or transport system. Here there are opportunities for controls as well, with in-line storage or other hydraulic measures leading the list. Treatment of “end-of-the-pipe” flows can be accomplished by a variety of storage-treatment systems, perhaps integrated with dry weather treatment facilities. Regardless of the actual technology used, the objective of wet weather management is to control runoff flows and pollutant loads to acceptable levels in a cost-effective manner. Ideally, wet weather controls are implemented in concert with an overall urban wastewater management scheme.

Design Methodology Framework

The literature is replete with design methodologies and planning strategies for wet weather flow management. Few have gained wide practice. Some of this is due to the lack of pressure to solve the problem. Equally at fault is the fact that most are not geared toward the practicing engineer. We feel that a good, well-accepted design methodology will:

- be focused on micro-development (the tens of acres level),
- be robust and flexible,
- be cognizant of the expense of data collection and management,
- be reproducible and consistent,
- use the power of the computer found on nearly every engineer's desk,
- use widely accepted models to simulate wet weather flow system,
- use the levels of spatial and temporal discretization appropriate to the task,
- account for uncertainty in the real and modeled systems,
- have a common-sense feel,
- have a rationale easily conveyed to lay persons,
- be relatively inexpensive to implement, and
- produce results that are economically, politically, and socially acceptable in the average urban setting.

With these points in mind, a possible framework, or flowchart, for a workable, effective design methodology is presented in Figure 1-1. This proposed methodology is based on three premises:

1. *The selection of control technologies must be strongly influenced by actual performance data and the applicability of each control technology to given watershed conditions and receiving water problems.* There are a wide variety of well-documented control methods with fairly ample performance data collected under wet weather conditions. Appendix D reviews some that are incorporated in SLAMM. In addition, it will be clear from that appendix that different technologies have different weaknesses and strengths that must be matched with their suitability for each watershed and the water quality objectives of the associated receiving water. A matrix approach is anticipated in which the characteristics and capabilities of each control technology are arrayed against a range of scenarios.

2. *The analysis of the overall control strategies must be based on long-term simulation.* For many decades the approach to wet weather management has been through the use of the design rainstorm. The problems associated with design rainstorms are many and discussions can be found in a number of publications (McPherson 1978; Nix 1982; Voorhees and Wenzel 1982; Niemczynowicz 1984; Adams and Howard 1985; Huber and Dickinson 1988; Nix 1994). The main problem is that the frequency characteristics of a given rainfall event rarely, if ever, coincide with the frequency characteristics of the corresponding runoff event. The "10 year" rainstorm may well produce a "1-year" runoff event if the watershed is dry, or a "25-year" runoff event if the watershed is saturated. The use of design rainstorms is also problematic when trying to evaluate water quality problems associated with stormwater. Receiving water problems are typically caused by a variety of different causative factors, as noted previously. Therefore, no clear "design" condition can be met to guarantee acceptable receiving water quality conditions. Continuous simulation can overcome these deficiencies by driving a model of the urban watershed (and any control technologies) with many decades of rainfall data and analyzing the frequency characteristics of the runoff quantity and quality themselves. A hybrid of two currently available and popular models (SLAMM and SWMM) will be used to accomplish this.

3. *Marginal cost analysis should be used to conduct an evaluation of the economic efficiency of potential integrated control strategies.* Wet weather control strategies are often very complicated and require more than

the traditional method of evaluating discrete alternatives. A method capable of evaluating a interconnected network of controls will be used. Such a method is discussed below.

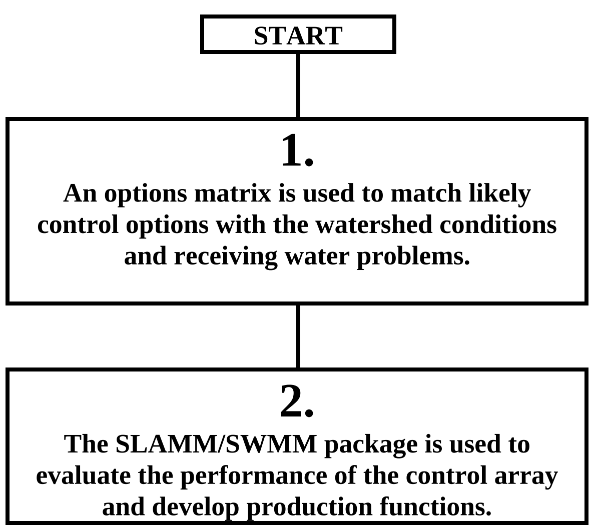
The scheme shown in Figure 1-1 is obviously oversimplified. Among other details, it is missing the many feedback loops that are a part of any design methodology. However, the steps shown illustrate the desired components.

Economic Evaluations of Alternative Control Programs

A number of studies have investigated the response of wet-weather management systems (including Howard 1976; Heaney, Huber and Nix 1976; Heaney and Nix 1977; DiToro and Small 1979; Hydroscience, Inc. 1979; Nix 1982; Nix and Heaney 1988; Segarra and Loganathan 1994; among others). The fundamental basis of most of this work is that many stormwater control measures can be viewed as a storage/treatment system with one of the two general configurations shown in Figure 1-2. These two arrangements differ in the placement of storage. In the on-line system, all wet-weather flows pass through storage. In the off-line system, only a portion of the wet-weather flow is diverted to storage as the treatment facility reaches capacity. It should be noted that the terms “storage” and “treatment” are not always clear. For example, there may be no actual “treatment” facility, but pollutant removal (“treatment”) may occur in storage. Or, there may be pollutant removal occurring in both treatment and storage. The term “storage” can apply to a storage tank in the conventional sense, or to storage distributed over an area (rooftops, in-system storage, catchbasins, natural depressions, parking lots, etc.).

The long-term performance of a storage/treatment system can be summarized as shown in Figure 1-3. This “production function,” as it is known in economic theory, summarizes the behavior of the system, in this case wet-weather pollution control. The production function can be most created by simulation or statistical analysis (as can be seen in the references cited above).The optimization of wet-weather storage/treatment systems has also received considerable attention over the last two decades (Heaney, Huber, and Nix 1976; Heaney and Nix 1977; Heaney, *et al*. 1977; Nix 1982; Nix and Heaney 1988; Segarra-Garcia and El Basha-Rivera 1996). Economic information can be used with production theory to optimize the system as shown in Figure 1-4 (Nix and Heaney 1988) to produce an “expansion path” of optimal combinations of storage and treatment. From this expansion path, a curve showing cost versus long-term pollution control can be constructed (as shown in Figure 1-5). With this information, the decision maker can make a rational choice for the level of pollution control. The general procedure can be expanded to address integrated control systems (see Heaney and Nix 1977), like the one shown in Figure 1-6.

Other recent presentations on optimization of control practices are shown on Figures 1-7 and 1-8 (Field, *et al.* 1994). Figure 1-7 shows how the most suitable rain intensity can be selected for various desired control levels. This shows that in Atlanta, a storage-treatment system capable of controlling a 1-month, 1-hour storm is required for a 90% level of control. Figure 1-8 shows another example where the most cost-effective solution for storage-treatment is likely at some mid-point requiring a combination of both practices.



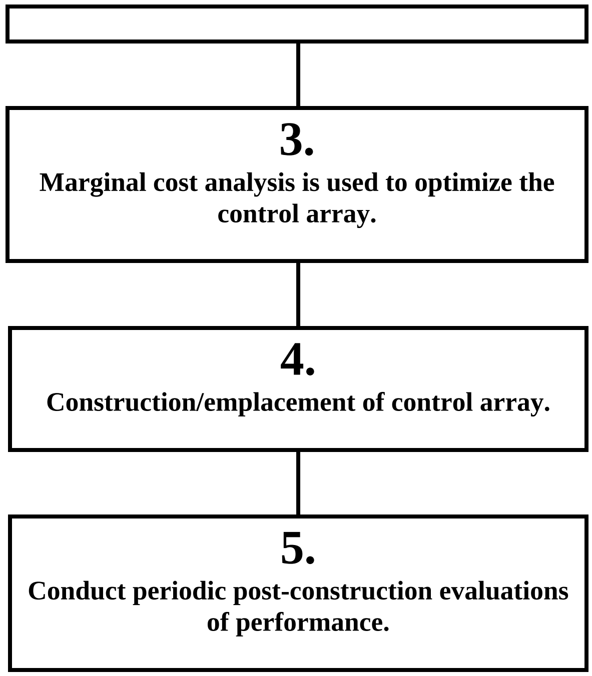
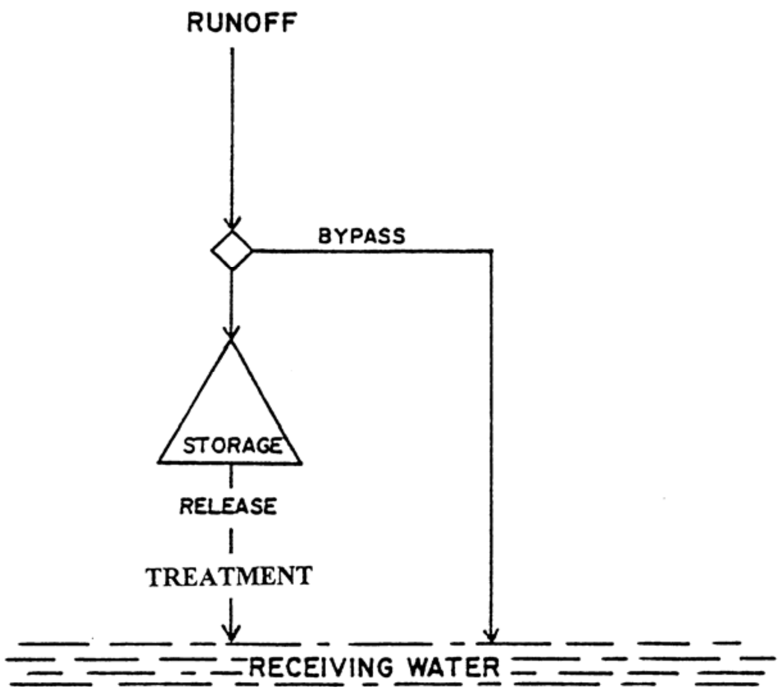
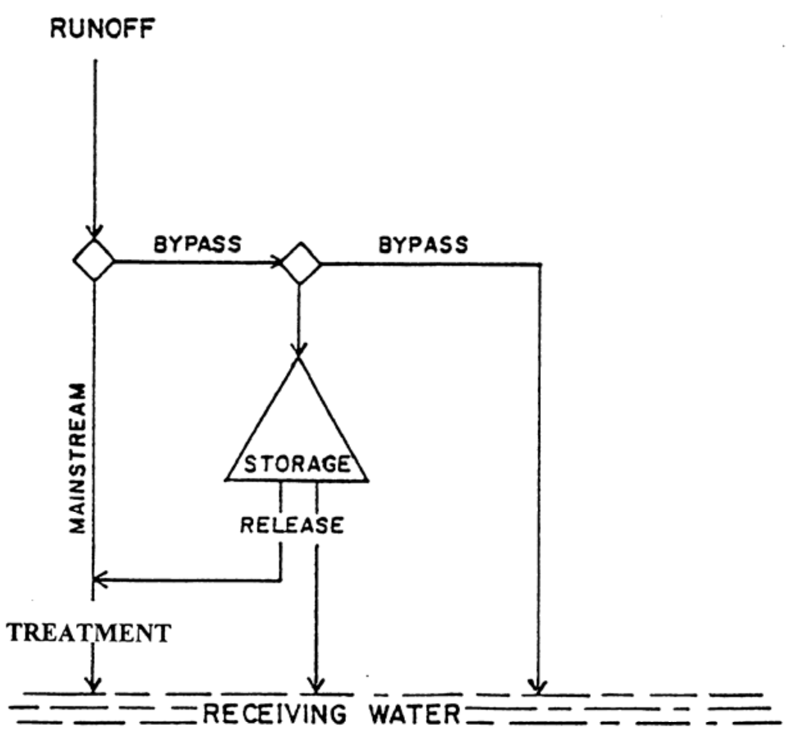


Figure 1-1. Flowchart of outline of design methodology.



(a) In-Line System



(b) Off-Line System

Figure 1-2. Basic storage/treatment system configurations.

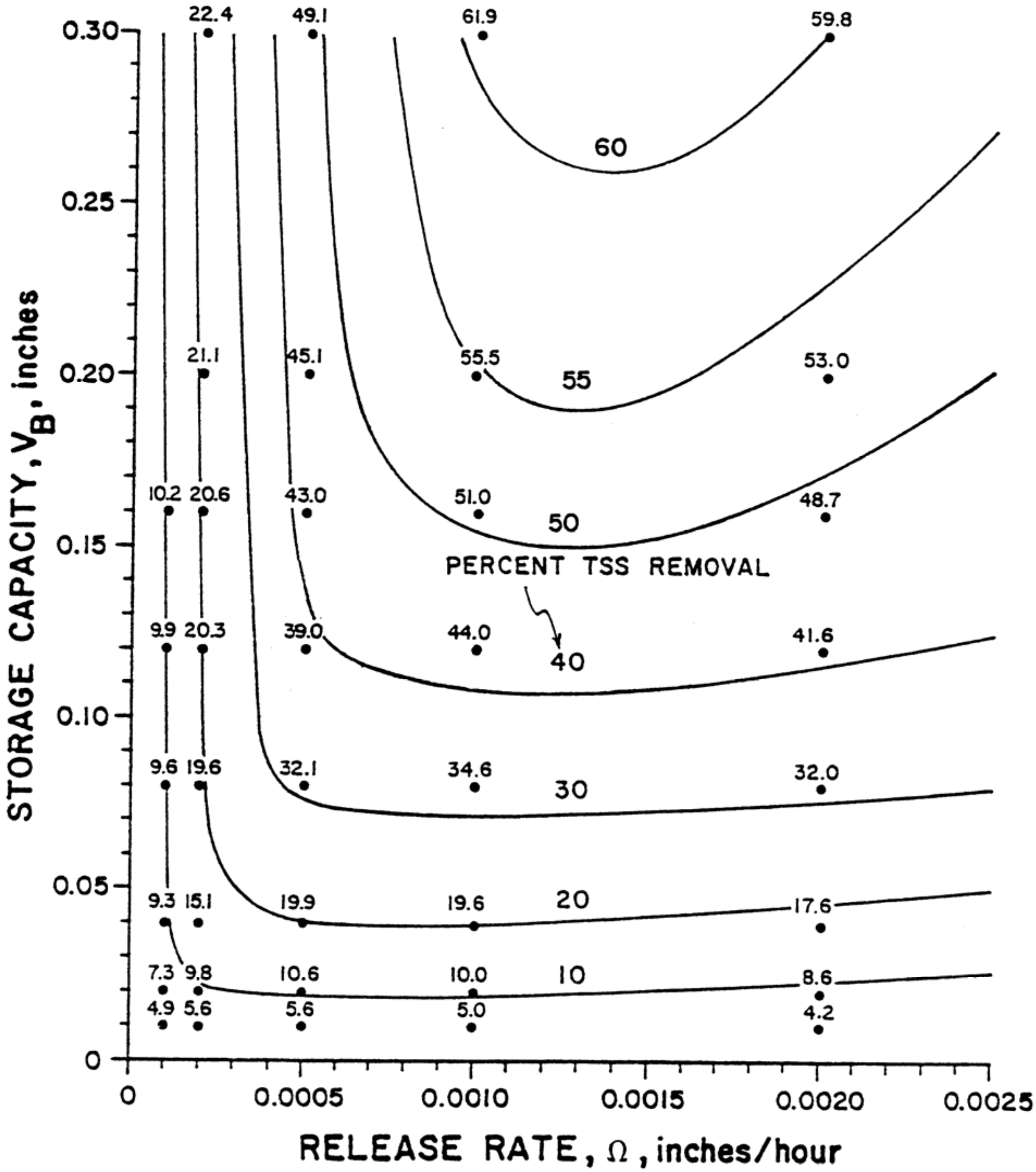


Figure 1-3. Percent TSS removal production function, results of S/T block simulation.

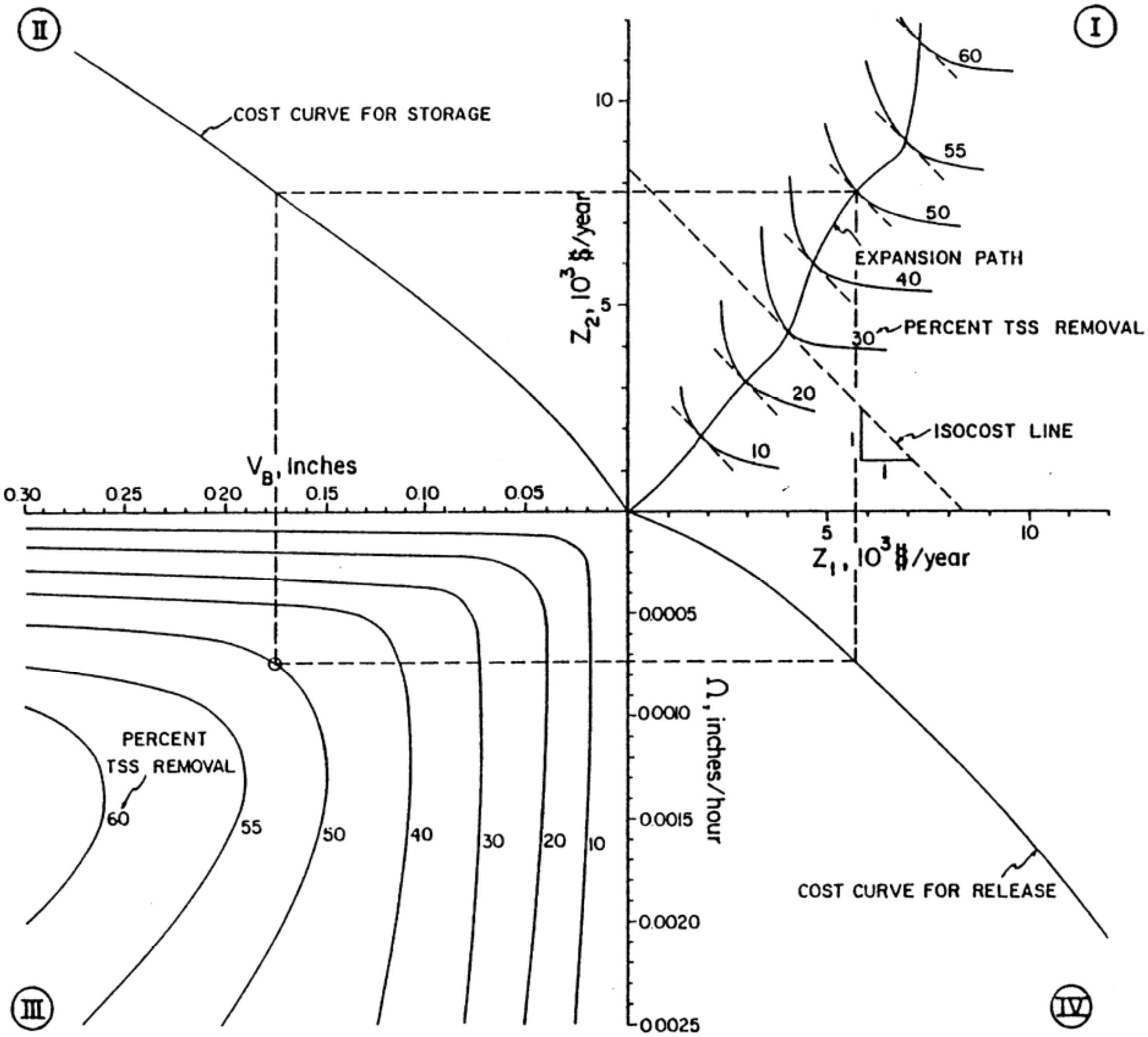


Figure 1-4. Application of storage/treatment optimization procedure (Nix and Heaney 1988).

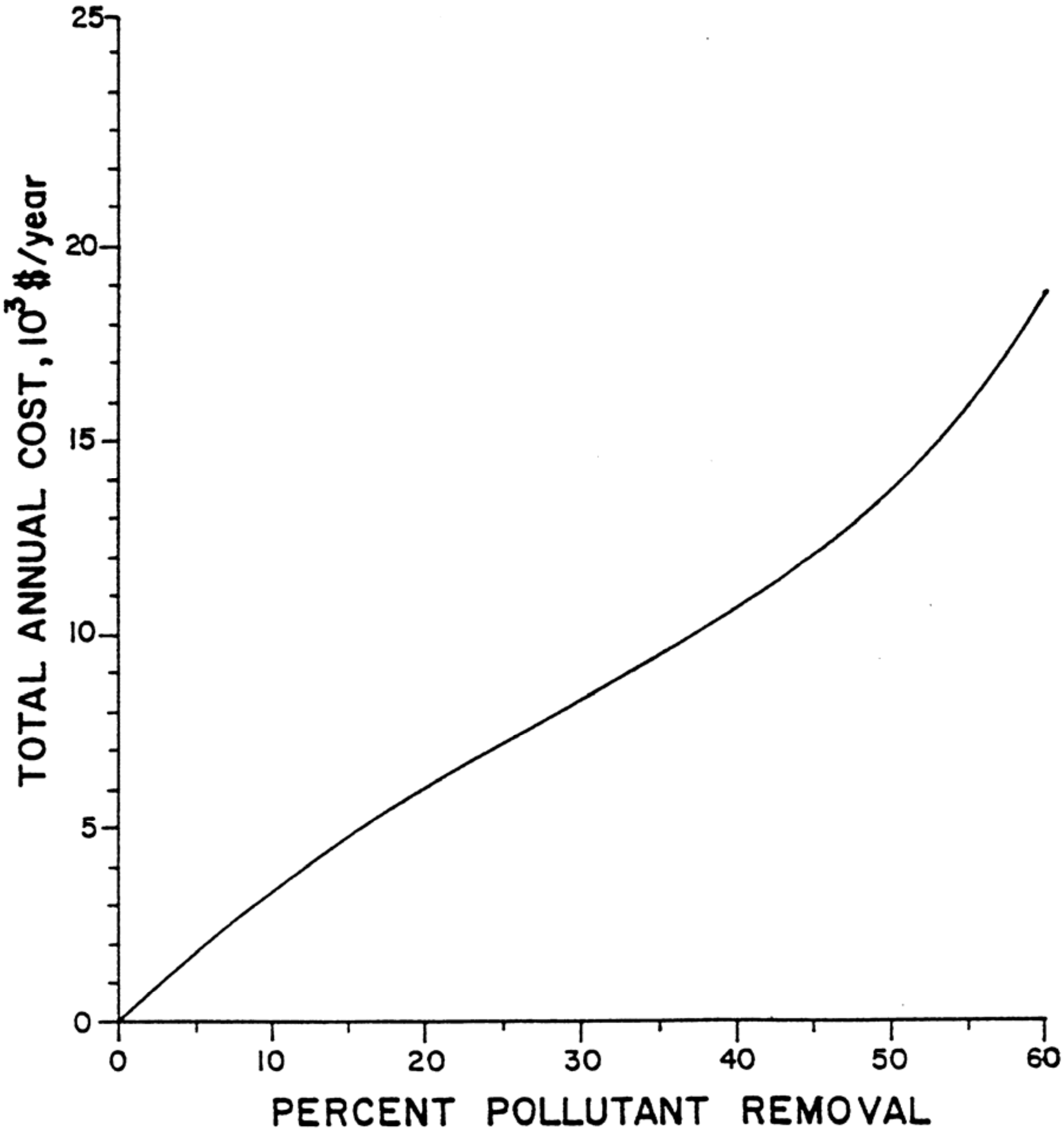


Figure 1-5. Final cost curve.

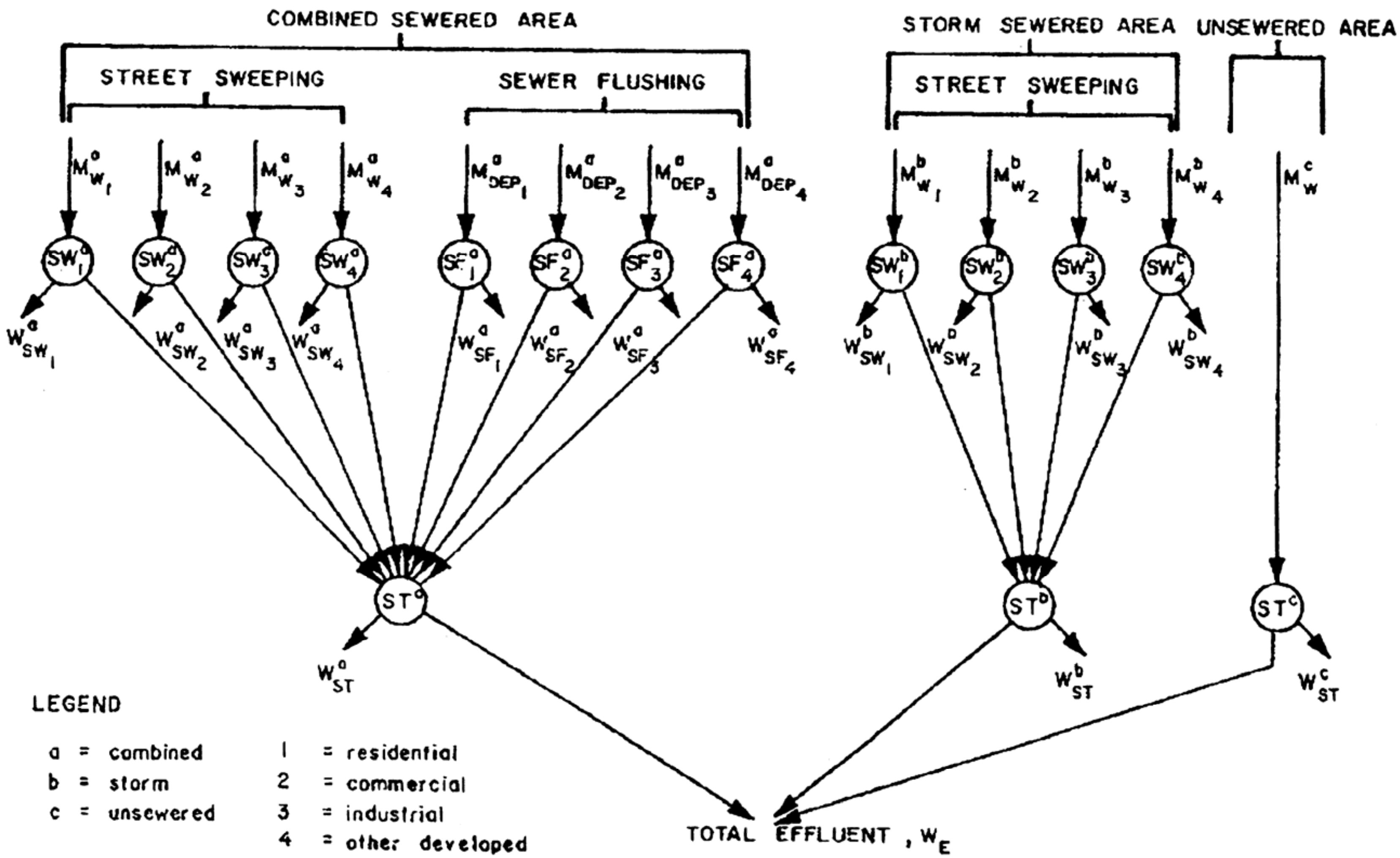


Figure 1-6. Stormwater pollution control network for Anytown, U.S.A. (Heaney and Nix 1977).

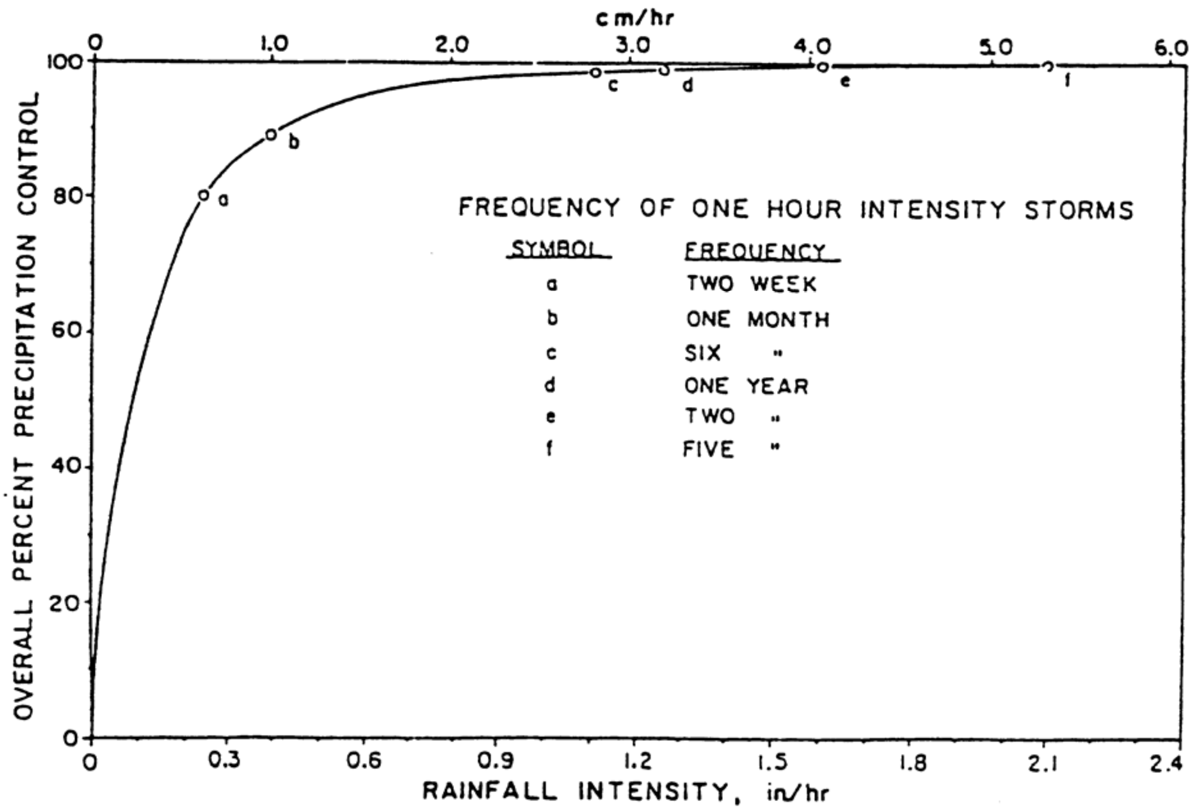


Figure 1-7. Overall percent precipitation control vs. rainfall intensity - Atlanta, Georgia (1948-1972) (Heaney, *et al.* 1977).

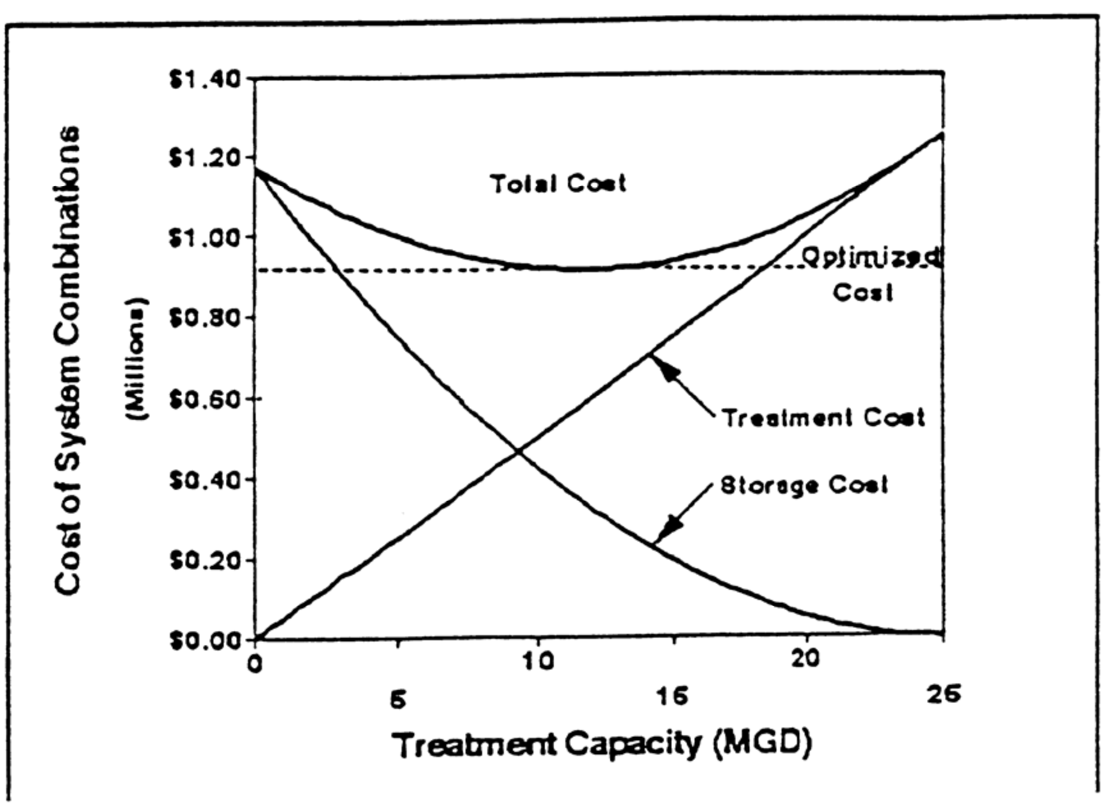


Figure 1-8. Storage/Treatment example – Cost for all combinations (Field, *et al*. 1994).

Much can be done to improve the current state of storage/treatment evaluation methodologies, including:

- improvement of the models used to simulate control technologies,
- better numerical or analytical methods to carry out the optimization process summarized in Figure 1-4, and
- creating an updated compendium of cost information for control technologies.

System Modeling Methodology

The system model to be used in the proposed methodology will be a hybrid of two existing, popular software packages. The best attributes of each will be retained to create a more suitable analytical tool.

The U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) is a large, complex software package capable of simulating the movement of precipitation and pollutants from the ground surface, through pipe/channel networks and storage/treatment facilities, and finally to receiving waters (Huber and Dickinson 1988; Nix 1994). SWMM has been in existence since the early 1970s and is probably the most popular of all urban runoff models. The model uses well-known hydrologic and hydraulic concepts to simulate the urban drainage system and can be used to simulate the behavior of the urban stormwater system over a single event or a long, continuous period. Its reputation for sophistication (and difficulty) derives more from the numerical algorithms necessary to solve the rather straightforward governing equations that are trying to simulate a complex system (i.e., the urban stormwater system) driven by a highly dynamic input (i.e., precipitation). There is an extensive body of literature describing SWMM's capabilities, as summarized by Huber, *et al.* (1985). This large body of experience is an advantage that SWMM probably enjoys over all other urban runoff models.

SWMM is divided into several "blocks". The major blocks, i.e., RUNOFF, TRANSPORT, STORAGE/TREATMENT, and EXTRAN, are *computational blocks* responsible for the hydrologic, pollutant generation and transport, and hydraulic calculations. The RUNOFF Block is responsible for generating runoff flows and pollutant loads. The routines used to simulate runoff flows are well-accepted and work very well (Huber 1986). On the other hand, the pollutant load generation routines are based on build-up and washoff relationships that have not been well proven and require considerable effort to validate for a given application. The TRANSPORT and EXTRAN Blocks route flows and pollutants through the drainage system, with the EXTRAN Block being more sophisticated in the way that surcharges and other hydraulic problems are modeled. The STORAGE/TREATMENT Block simulates control technologies within the drainage system and at the "end of the pipe." Other blocks, *i.e.*, EXECUTIVE, STATISTICAL, RAIN, TEMP, GRAPH, and COMBINE, perform various auxiliary functions, and are known as *service blocks.* While not very user friendly, SWMM is not overly difficult to manage and use. A few "preprocessing" packages are available to help prepare the input data.

SLAMM was originally developed to better understand the relationships between sources of urban runoff pollutants and runoff quality (Pitt and Voorhees 1996). It has been continually expanded since the late 1970s and now includes a wide variety of source area and outfall control practices (infiltration practices, wet detention ponds, porous pavement, street cleaning, catchbasin cleaning, and grass swales). SLAMM is strongly based on actual field observations, with minimal reliance on theoretical processes that have not been adequately documented or confirmed in the field. SLAMM is mostly used as a planning tool, to better understand sources of urban runoff pollutants and their control. Special emphasis has been placed on small storm hydrology and particulate washoff in SLAMM. Many currently available urban runoff models have their roots in drainage design where the emphasis is with very large and rare rains. In contrast, many stormwater quality problems are mostly associated with common and relatively small rains. The assumptions and simplifications that are legitimately used with drainage design models are not appropriate for water quality models. SLAMM therefore incorporates unique process descriptions to more accurately predict the sources of runoff pollutants and flows for the storms of most interest in stormwater quality analyses. However, SLAMM can be effectively used in conjunction with hydraulic models (such as SWMM in this project) to incorporate the mutual benefits of water quality controls and drainage design. SLAMM has been used in many areas of North America and has been shown to accurately predict stormwater flows and pollutant characteristics for a broad range of rains, development characteristics, and control practices.

SLAMM is unique in many aspects. One of the most important aspects is its ability to consider many stormwater controls (affecting source areas, drainage systems, and outfalls) together, for a long series of rains. Another is its ability to accurately describe a drainage area in sufficient detail for water quality investigations, but without requiring a great deal of superfluous information that field studies have shown to be of little value in accurately predicting discharge results. SLAMM also applies stochastic analysis procedures to more accurately represent actual uncertainty in model input parameters in order to better predict the actual range of outfall conditions (especially pollutant concentrations). However, the main reason SLAMM was developed was because of errors contained in many existing urban runoff models. These errors were obvious when comparing actual field measurements to the solutions obtained from model algorithms.

This project will basically substitute the RUNOFF Block in SWMM with SLAMM in order to better account for small storm processes and for its greater flexibility in evaluating source area flow and pollutant controls. The SWMM EXTRAN and TRANSPORT blocks will be used to simulate the performance of the drainage system. The resulting model will enable more efficient and effective evaluations than either alone.

Summary

This project developed an improved methodology to design wet weather flow drainage systems that considers both water quality and drainage benefits. A review of past, present, and emerging control technologies was conducted to present suitable combinations of practices that may be most suitable for many different conditions. An important aspect of this methodology was the integration of two available computer models to assist designers, SWMM and SLAMM. A marginal cost algorithm was also formulated to optimize control option strategies.

We have developed a methodology aimed at the practicing engineer and the kind of development occurring in the average urban setting. It was stated earlier that large-scale, coordinated and integrated control programs are and will be difficult to achieve. We are not proposing that such efforts be abandoned. In recognizing the difficulty and in attempt to not miss an opportunity, we *are* proposing that good sense, practical management measures be designed and implemented for type of development occurring in most of the U.S. -- relatively unplanned, uncontrolled urbanization proceeding a few acres at time.

References

Adams, B.J. and C.D.D. Howard. *The Pathology of Design Storms.* Publication 85-03, University of Toronto, Department of Civil Engineering, Toronto, Ontario, 1985.

DiToro, D.M. and M.J. Small. “Stormwater interception and storage.” *Journal of the Environmental Engineering Division*, ASCE, 105(1):43-54, 1979.

Federal Register, NPDES Permit Application Regulation for Stormwater Discharges, 40CFR, part 122-124, 55FR477990, November 16, 1990.

Field, R., T. O’Conner, and R. Pitt. “Optimization of CSO storage and treatment systems.” *Proceedings of Water Environment Federations Specialty Conference on Reducing CSOs, Balancing Technologies, Costs and Water Quality*, Louisville, Kentucky, pp. 11-33, 1994.

Heaney, J.P., W.C. Huber, and S.J. Nix. *Storm Water Management Model, level 1, preliminary screening procedures*. EPA-600/2-76-275, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1976.

Heaney, J.P. and S.J. Nix. *Stormwater Management Model, Level 1, Comparative Evaluation of Storage-Treatment and Other Management Practices*. EPA-600/2-77-083, NTIS No. PB 265671, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.

Heaney, J.P., W.C. Huber, M.A. Medina, Jr., M.P. Murphy, S.J. Nix, and S.M. Hasan. *Nationwide Evaluation of Combined Sewer Overflows and Urban Storm Water Discharges, Volume 2, Cost Assessments and Impacts*. EPA-600/2-77-064b, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.

Howard, C.D.D. “Theory of storage and treatment-plant overflows.” *Journal of the Environmental Engineering Division*, ASCE, 105(1), 709-722, 1976.

Huber, W.C., J.P. Heaney, and B.A. Cunningham. *Storm Water Management Model (SWMM) Bibliography*. EPA-600/3-85-077, U.S. Environmental Protection Agency, Athens, Georgia, 1985.

Huber, W.C. “Deterministic modeling of urban runoff quality.” In: *Urban Runoff Pollution*, Edited by H.C. Torno, J. Marsalek, and M. Desbordes, NATO ASI Series, Series G: Ecological Sciences, Vol. 10, Springer-Verlag, Berlin, pp. 166-242, 1986.

Huber, W.C. and R.E. Dickinson. *Storm Water Management Model, Version 4, User's Manual*. EPA-600/3-88-001a, U.S. Environmental Protection Agency, Athens, Georgia, 1988.

Hydroscience, Inc. *A Statistical Method for the Assessment of Urban Storm Water*. EPA-440/3-79-023, U.S. Environmental Protection Agency, Washington, D.C., 1979.

McPherson, M.B. *Urban Runoff Control Planning*. EPA-600/9-78-035, U.S. Environmental Protection Agency, Washington, D.C., 1978.

Niemczynowicz, J. “Can the rainfall input be modified so that frequencies of rainfall-input and runoff-output will be similar?” *Water Science and Technology*, 16:251-254, 1984

Nix, S.J. Analysis of storage/release systems in urban stormwater quality management. Ph.D. dissertation, University of Florida, Gainesville, Florida, 1982.

Nix, S.J. *Urban Stormwater Modeling and Simulation*, Lewis Publishers, Boca Raton, Florida, 1994.

Nix, S.J. and J.P. Heaney. "Optimization of storm water storage-release strategies." *Water Resources Research*, 24(11):1831-1838, 1988.

Pitt, R. “Effects of urban runoff on aquatic biota.” In: *Handbook of Ecotoxicology*, Edited by D. Hoffman *et al.*, Lewis Publishers, Boca Raton, Florida, pp. 609-630, 1995.

Pitt, R. and J. Voorhees. *SLAMM, Version 6.4, Source Loading and Management Model for Stormwater Control*, 1996.

Segarra, R.I. and G.V. Loganathan. “A stochastic pollutant load model for the design of stormwater detention facilities.” *Water Science and Technology*, 29(1-2):327-335, 1994.

Segarra-Garcia, R. and M. El Basha-Rivera. “Optimal estimation of storage-release alternatives for storm-water detention systems.” *Journal of Water Resources Planning and Management*, ASCE, 122(6):428-436, 1996.

Voorhees, M.L. and H.G. Wenzel. “Sensitivity and reliability of design storm frequency.” *Proceedings of the Second Conference on Urban Storm Drainage*, Urbana, Illinois, pp. 374-383, 1982.

Section 2
The Beneficial Uses of Stormwater in Urban Areas and the Need for Change in Urban Water Management

Stormwater has classically been considered a nuisance, requiring rapid and complete drainage from areas of habitation. Unfortunately, this approach has caused severe alterations in the hydrological cycle in urban areas, with attendant changes in receiving water conditions and uses. This historical approach of "water as a common enemy" has radically affected how urban dwellers relate to water. For example, most residents are not willing to accept standing water near their homes for significant periods of time after rain has stopped. However, there are now many examples where landscape architects have very successfully integrated water in the urban landscape. In many cases, water has been used as a focal point in revitalizing downtown areas. Similarly, many arid areas are looking at stormwater as a potentially valuable resource, with stormwater being used for beneficial uses on-site, instead of being discharged as a waste. One of the earliest efforts investigating positive attributes of stormwater was a report prepared for the Storm and Combined Sewer Program of the U.S. Environmental Protection Agency by Hittman Associates in 1968. Only recently has additional literature appeared exploring beneficial uses of stormwater. This section discusses some of these progressive ideas.

Stormwater as an Aesthetic Element in Urban Areas

Dreiseitl (1998) states that "stormwater is a valuable resource and opportunity to provide an aesthetic experience for the city dweller while furthering environmental awareness and citizen interest and involvement." He found that water flow patterns observed in nature can be duplicated in the urban environment to provide healthy water systems of potentially great beauty. Without reducing safety, urban drainage elements can utilize waters refractive characteristics and natural flow patterns to create very pleasing urban areas. Successful stormwater management is best achieved by using several measures together. Small open drainage channels placed across streets have been constructed of cobbles. These collect and direct the runoff, plus slow automobile traffic and provide dividing lines for diverse urban landscaping elements. The use of rooftop retention and evaporation reduce peak flows. Infiltration and retention ponds can also be used to great advantage by providing a visible and enjoyable design element in urban landscapes.

Dreiseitl (1998) described the use of stormwater as an important component of the Potsdamer Platz in the center of Berlin (expected to be completed by the end of 1998). Roof runoff will be stored in large underground cisterns, with some filtered and used for toilet flushing and irrigation. The rest of the roof runoff will flow into a 1.4 ha (3.8 acre) concrete lined lake in the center of the project area. The small lake provides an important natural element in the center of this massive development and regulates the stormwater discharge rate to the receiving water (Landwehrkanal). The project is also characterized by numerous fountains, including some located in underground parking garages.

Göransson (1998) also describes the aesthetic use of stormwater in Swedish urban areas. The main emphasis for this study was to retain the stormwater in surface drainages instead of rapidly diverting the stormwater to underground conveyances. Small, sculpturally formed rainwater channels are used to convey roof runoff downspouts to the drainage system. Some of these channels are spiral in form and provide much visual interest in areas dominated by the typically harsh urban environment. Some of these spirals are also formed in infiltration areas and are barely noticeable during dry weather. During rains, increasing water depths extenuate the patterns. Glazed tile, small channels having perforated covers, and geometrically placed bricks with large gaps to provide water passage slightly below the surface help urban dwellers better appreciate the beauty of flowing water.

Tokyo has instituted major efforts to restore historical urban rivers that have been badly polluted, buried or have had all of their flows diverted. Fujita (1998) describes how Tokyo residents place great value on surface waterways: "waterfront areas provide urban citizens with comfort and joy as a place to observe nature and to enjoy the landscape." Unfortunately, the extensive urbanization that has taken place in Tokyo over the past several decades has resulted in severe stream degradation and disappearance of streams altogether. However, there has recently been a growing demand for the restoration of polluted urban watercourses in Tokyo. This has been accomplished in many areas by improved treatment of sanitary sewage, reductions in combined sewer overflows and by infiltration of stormwater.

The Meguro and Kitazawa streams have been recovered by adding sanitary wastewater (receiving secondary treatment, plus sand filtration and UV disinfection, with activated carbon filtration and ozone treatment to provide further odor control) to previously dry channels. The treated wastewater is being pumped 17 km from the treatment facilities to the upstream discharge location in Meguro Stream. The Nogawa Stream has been restored by adding springwater produced from stormwater infiltration. Increased firefly activity has been noted along the Nogawa Stream and the adjacent promenade, providing adequate justification for these projects to the local citizens.

The quality of the treated wastewater entering Meguro Stream (at 0.35 m^3/s) since 1995 is as follows: total BOD_5: 6 mg/L; carbonaceous BOD_5: 2 mg/L; suspended solids: 0.5 mg/L; and ammonia-nitrogen: 7 mg/L. The total coliform bacteria concentrations were initially high (5,000 MPN/100 mL), and UV disinfection was therefore later installed at the outlets of the treated wastewater to the stream. The receiving water biological uses (carp and crustaceans) require the following conditions: total BOD_5: <8 mg/L; a water depth of at least 10 cm, and a stream velocity of at least 0.1 m/s. The BOD_5 goals are being met and the Meguro Stream has a 20 cm depth and a velocity of about 0.3 m/s. When storm events occur, remote valves are operated to decrease the discharge of the treated wastewater into the stream. However, the physical habitat of the stream is currently severely degraded, being concrete lined. The local residents are appreciative of the small flow in the stream, and the Tokyo Metropolitan Government (TMG) plans to modify the stream walls to facilitate groundwater recharge of the stream, to create rapids and pools for fish, and to plant trees along its banks, to further enhance the value of the stream to the local population.

Kitazawa Stream is another example of a severely degraded urban stream in Tokyo that has undergone extensive modification. The stream watershed is 10.5 km^2 and has a population of about 150,000 people. The rapid urbanization in Tokyo since the 1950s has resulted in a severe decrease in groundwater infiltration during rains. This has caused decreased groundwater levels and decreased the associated natural recharge into urban streams. By the 1960s, there was almost no natural flow in Kitazawa Stream during dry weather. The only flows present in the stream was wastewater from homes. The stream was therefore of extremely poor quality, creating an unsafe and nuisance condition. In addition, the increased development caused frequent flooding. The TMG therefore diverted the stream into an underground culvert. The aboveground area was converted into a promenade with extensive plantings. Recently however, local residents have requested the addition of a steam along the promenade. A very small flow (0.02 m^3/s) of treated wastewater has been pumped from 11 km away to create this new stream (a "two-storied watercourse"). Figure 2-1 (Fujita 1998) shows the changes that Kitazawa Stream has undergone as the watershed has developed. This new steam, however small, has created a very important element in the lives of the residents of this heavily urbanized city. Special community organizations have been established to plan and manage the area.

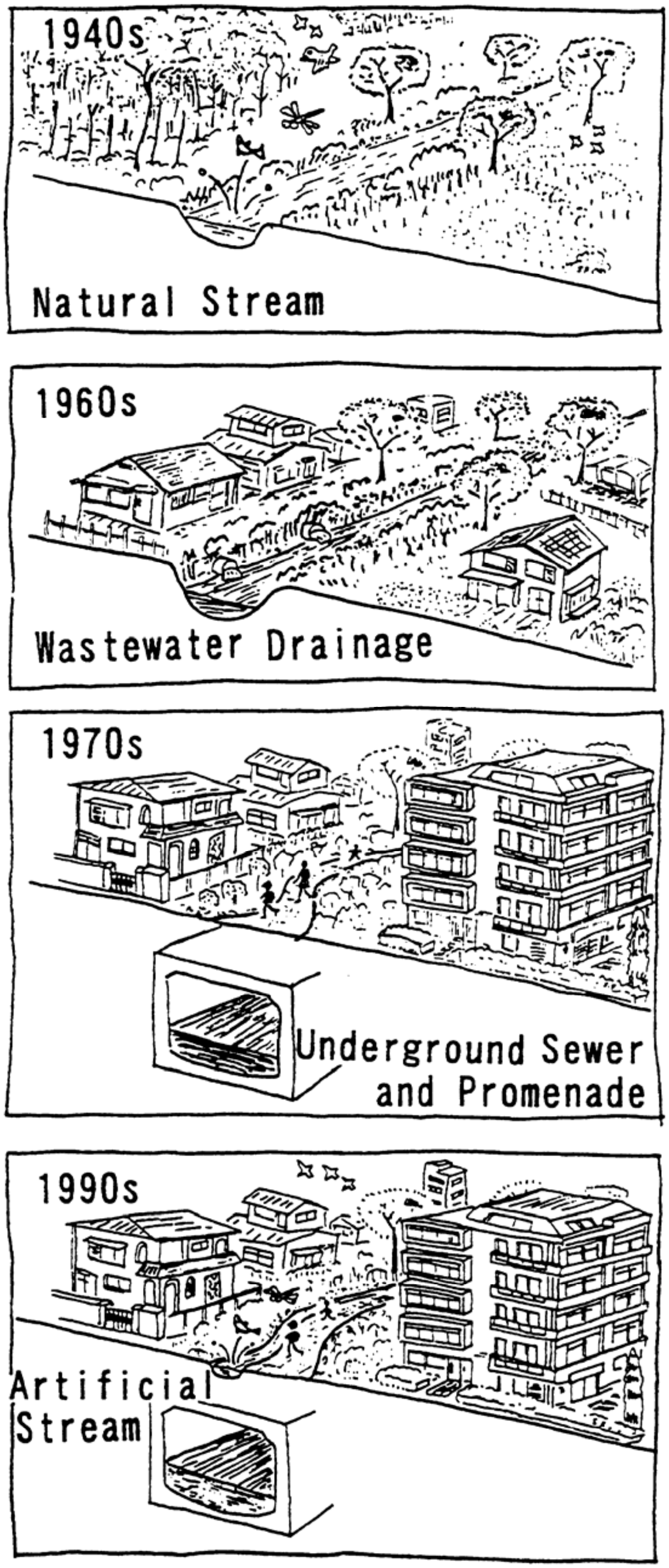


Figure 2-1. The history of Kitazawa Stream (Fujita 1998).

Another Tokyo example of urban stream rehabilitation has occurred in the Nogawa Stream watershed. The watershed is about 70 km^2 in area and has a population of about 700,000 people. Urbanization in this area also dramatically decreased the natural groundwater recharge to the stream. With development, household graywater, some sanitary wastewater, and stormwater were infiltrated into the ground and recharged the stream. When the sanitary wastewater collection and treatment system was improved in the 1980s, the stream flow was severely diminished, as a major source of groundwater recharge was eliminated. The headwater springs in the Nogawa area were of special importance to the local residents and they requested that TMG restore the dried springs. Artificial groundwater recharge, using stormwater, has been successfully used to restore the springs. Many private homes have installed stormwater infiltration devices in the area. In an example in Mitaka City, 4,000 infiltration "soakaways" were constructed during the three years from 1992 to 1995, allowing about 240,000 m^3/yr of stormwater to be infiltrated to revitalize the spring at Maruike. Koganei City residents installed more than 26,000 soakaways and 10.4 km of infiltration trenches at 5,700 homes (about 25% of all of the homes in the area). Other cities in the area have also helped residents install several thousand additional infiltration facilities. Spring flows have increased, although quantitative estimates are not yet available.

Fujita (1998) repeatedly states the great importance that the Japanese place on nature, especially flowing water and the associated landscaping and attracted animals. They are therefore willing to perform what seems to be extraordinary efforts in urban stream recovery programs in the world's largest city. The stream recovery program is but one element of the TMG's efforts to provide a reasonably balanced urban water program. Water reuse and conservation are important elements in their efforts. Stormwater infiltration to recharge groundwaters and the use of treated wastewaters for beneficial uses (including the above described stream restoration, plus landscaping irrigation, train washing, sewer flushing, fire fighting, etc.) are all important elements of these efforts, although this reuse currently only amounts to about 7% of the total annual water use in Tokyo.

Guidelines for the Reuse of Stormwater in Urban Areas

An obviously important consideration when examining the reuse of stormwater is the different quality requirements for the different reuse activities. Reuse guidelines are relatively rare, but Table 2-1 presents some guidance from Japan (Fujita 1998). The most serious restrictions relate to ensuring the safety of the water during inadvertent human contact. The prevention of nuisance conditions is also of concern.

Table 2-1. Quality Standards for the Reuse of Treated Wastewater in Japan (Fujita 1998)[1]

	Toilet Flushing	Fire Sprinklers	Landscape Irrigation	Recreation Use
Total Coliforms (MPN/100 mL)	<1,000	<50	<1,000	<50
Residual Chlorine (mg/L)	present	>0.4		
Color (Pt units)	No unpleasant appearance	No unpleasant appearance	<40	<10
Turbidity (NTU)	No unpleasant appearance	No unpleasant appearance	<10	<5
BOD_5 (mg/L)	<20	<20	<10	<3
Odor	Not unpleasant	Not unpleasant	Not unpleasant	Not unpleasant
pH	5.8 – 8.6	5.8 – 8.6	5.8 – 8.6	5.8 – 8.6

[1]In addition, the objectives for carp and crustaceans in urban streams include the following: total BOD_5: <8 mg/L; a water depth of at least 10 cm, and a stream velocity of at least 0.1 m/s.

Table 2-2 shows Maryland's reuse guidelines, along with acceptable use categories and per capita requirements (Mallory 1973). Only a small fraction (<10%) of the total residential water use requirements need to be of the highest quality water. Class AA water meets all U.S. Public Health Service Drinking Water Standards, class A water is very similar, except for taste and odor considerations, class B water has less restrictions, especially with respect to suspended solids, and class C water only has minimum requirements pertaining to corrosivity. All of these waters require disinfection by the state of Maryland. It is not likely that stormwater would be used for class AA uses without conventional water treatment, but lower levels of use may be feasible. Table 2-3 shows the specific maximum concentrations allowed for each reuse category, as determined by the state of Maryland, in addition to typical residential area stormwater quality. Average stormwater concentrations are presented, as needed storage would provide equalization of concentrations over short periods of time.

Table 2-2. Distribution of Maryland Residential Water Use and Required Quality (Mallory 1973)

Class	Use	Rate of Use (gal/person/day)	Percentage of Total Water Use
AA	Consumption by humans, food preparation, general kitchen use	6.5	7
A	Bathing, laundering, auto washing	31.0	36
B	Lawn irrigation	518 gal/day/acre	29
C	Toilet flushing	24.0	28

Table 2-3. Maximum Concentrations Allowed by Maryland for Different Reuse Categories, Compared to Typical Residential Stormwater Runoff (Mallory 1973)

Constituent (mg/L)	AA	A	B	C	Typical average residential stormwater quality and highest use without treatment (various references)
Total solids	150	500	500	1500	250 (A)
Suspended solids	-	-	10	30	50 (none)
Turbidity (NTU)	0-3	3-8	8-15	15-20	25 (none)
Color (color units)	15	20	30	30	25 (B)
pH (pH units)	7	6	6	6	6 to 9 (AA)
Oxygen, dissolved (minimum)	5	5	4	4	Near saturation (AA)
Total coliform bacteria (MPN/100 mL)	1	70	240	240	>10,000 (none)
Ammonia (as NH_3)	0.5	0.5	0.5	0.5	<0.1 (AA)
Nitrate (as NO_3)	45	50	50	50	1 (AA)
Phosphates	1	1	1	1	0.5 (AA)
Calcium	0.5	75	75	75	10 (A)
Chloride	50	250	250	250	<50 (AA)
Fluoride	1.5	3	3	3	0.03 (AA)
Iron	0.1	0.3	0.3	0.3	
Magnesium	0.5	150	150	150	1 (A)
Manganese	0.05	0.1	0.5	0.5	
Sulfate	50	200	400	400	10 (AA)
Arsenic	0.01	0.05	0.05	0.05	<0.05 (A)
Chromium (+6)	0.05	0.05	0.05	0.05	<0.05 (AA)
Copper	1.0	1	1.5	1.5	0.05 (AA)
Cyanide	0.01	0.2	0.2	0.2	0.05 (A)
Lead	0.05	0.1	0.1	0.1	0.05 (AA)
Zinc	5	15	15	15	0.5 (AA)

As shown on these tables, residential area stormwater can be used to meet at least class A water needs, except for suspended solids, turbidity, color, and coliform bacteria. The solids, turbidity and color levels are likely to be adequately reduced through storage and associated settling, plus possible post-settling filtration. The most serious impediment for the reuse of stormwater in residential areas are the bacteria levels. Unfortunately, stormwater is known to contain pathogens that can cause illness through various exposure mechanisms. However, it must be remembered that stormwater currently comes in contact with many people during rains and runoff from roofs and paved areas are encouraged to drain to landscaped areas to reduce runoff quantities. These practices are not considered hazardous and have not shown detrimental effects. Never-the-less, total coliform bacteria levels in stormwater can be very large, much greater than 10,000 MPM/100 mL and greatly exceed reuse criteria. The criteria for reuse shown on Table 2-3 requires a maximum total coliform level of 240 MPM/100 mL for class B and C water, and a level of 70 MPM/100 mL for class A water. Drinking water (class AA water) requires a maximum of 1 MPM/100 mL. Any of these levels would be impossible to meet without significant disinfection efforts.

Another set of reuse guidelines has been developed in California and are shown on Table 2-4. These guidelines were developed for the reuse of high quality secondary domestic wastewater effluent. The median total coliform bacteria criteria are very stringent (to product the public from likely associated pathogens) and would also not be possible to be met without very significant disinfection efforts. The only uses where primary treatment alone (similar to detention) is needed, and for which no total coliform bacteria criteria are given, are for the irrigation of fodder crops, fiber crops, seed crops, and for surface irrigation of processed produce. As indicated in Table 2-4, irrigation in areas where public contact is likely requires disinfection and very low levels of total coliform bacteria.

Table 2-4. California Reuse Guidelines (Metcalf and Eddy 1991)

Use of reclaimed water	Secondary treatment and disinfection	Secondary treatment, coagulation, filtration, and disinfection	Total coliform bacteria criteria (MPN/100 mL, median of daily observations)
Landscaped areas: golf courses, cemeteries, freeways	required		23
Landscaped areas: parks, playgrounds, schoolyards		required	2.2
Recreational impoundments: no public contact	required		23
Recreational impoundments: boating and fishing only	required		2.2
Recreational impoundments: body contact (bathing)		required	2.2

Metcalf and Eddy (1991) state that primary treatment (similar to settling in a storage tank) reduces fecal coliform bacteria by less than 10%, whereas trickling filtration (without disinfection) can reduce fecal coliform levels by 85 to 99%. Chemical disinfection is usually required to reduce pathogen levels by 99.9+%, as likely needed to meet the above bacteria criteria for even the most basic water uses. Because of the risks associated with potential pathogens, reuse of stormwater in residential areas should only be considered where consumption and contact is minimized, restricting on-site reuse to classifications B and C, and only after adequate disinfection and site specific study to ensure acceptable risks. To further minimize risks, only the best quality stormwater (from a pathogen perspective) should be considered for reuse. As an example, residential area roof runoff generally has lower fecal coliform concentrations than runoff from other source areas, although very high levels are periodically observed from this source area. Therefore, stormwater “harvesting” efforts could be limited to residential area rooftops to reduce risks associated with pathogens. The following subsection explores this example of reuse.

The Urban Water Budget and Stormwater Reuse in Residential Areas

Developing an urban water budget is the initial step needed when examining potential beneficial uses of stormwater. The urban water budget comprises many elements, stormwater being just one. As an example, it is possible to determine the likelihood of supplying needed irrigation water and toilet flushing water (reuse classifications B and C) from the stormwater generated from roof runoff by conducting an urban water budget. This budget requires a knowledge of all water sources and uses, and the associated quality requirements. Another important element is understanding the timing of the water needs and supplies. For example, the following lists household water use for a typical home (2 working adults and one child) in the southeast, where the rainfall averages about 50 inches per year:

- bathing 42%
- laundry 11%
- kitchen sink 15%
- dishwasher 8%

- bath sinks 12%
- toilet flushing 12%

Because this was a working family and the child was in school, bathing water use was relatively high, while the toilet flushing water use was relatively low. There were also wide variations in water use for different days of the week, with weekday water use (especially toilet flushing and laundry) being substantially less than for weekend water use. The household water use was relatively constant throughout the year and averaged about 90 gpcd (gal/capita/day), ranging from 77 to 106 gpcd. There were no water conservation efforts employed during the two year observation period. Outside irrigation water use during the dry months averaged about 50 gallons per day (for a ½ acre landscaped area) above the inside water uses listed above. Landscape irrigation may occur for about 2 months at this level of use in this area.

The estimated roof runoff for a typical 2,000 ft^2, 1- ½ level, house (roof area of about 1300 ft^2) would be about 40,000 gallons per year, for this area having about 50 inches of rain a year. The total water use for this household is about 100,000 gallons per year, with the amount used for toilet flushing being about 12,000 gallons, with another 3,000 gallons used for landscaping irrigation. For this example, the roof runoff would supply almost three times the amount of water needed for toilet flushing and landscape irrigation. None of the other household water uses would be suitable for supply by roof runoff. The rainfall varies between about 3 to 5 inches per month, with a rain occurring about twice a week on the average. Rainfall only once every two weeks can occur during the most unusual conditions (the driest months when landscaping irrigation is most needed). Therefore, a simple estimate for required roof runoff storage would be two weeks for average toilet flushing (450 gallons), plus two weeks for maximum landscaping irrigation (700 gallons). A total storage tank of 1250 gallons (a typical septic tank size) would therefore be needed. Of course, a factor-of-safety multiplier can be applied, depending on the availability of alternative water sources.

For a typical 0.5 acre residential lot in the southeast, the annual stormwater generated would be about 170,000 gallons per year. The roof would produce about 25% of this total, pavement would produce another 25%, and the landscaped area would produce about 50% of this total. Therefore, the amount of stormwater used on-site for toilet flushing and irrigation of landscaped areas would be only about 10% of the total generated. Therefore, most of the runoff would still have to be infiltrated on-site, or safely conveyed and discharged.

Other locations would obviously result in different water needs that could be supplied by runoff, depending on rainfall, soil conditions, and household water use patterns. Mitchell, *et al*. (1996) reported that on-site graywater and rain storage for re-use resulted in about 45% reductions in imported water needs, about 50% reductions in stormwater runoff, and about 10% reductions in wastewater discharges at two test developments in Australia. In most areas, Heaney, *et al*. (1998) reports that indoor water use is relatively constant at about 60 gpcd, with conservation practices, especially the use of low-flush toilets, possibly reducing this need to about 35 to 40 gpcd. Toilet flushing is about 30% of this use. In the arid parts of the U.S., landscaping irrigation can be the most important use of domestic water.

Heaney, *et al.* (1998) also reported the results of using water demand models to estimate the fraction of typical household irrigation water needs that could be satisfied by storing and using stormwater. Most eastern and west coast areas were able to satisfy their irrigation needs by storing stormwater for use on-site. Over 90% of the irrigation needs could be satisfied by stormwater re-use in the Rocky Mountain area and in the semi-arid southwest. The desert southwest was only able to supply about 25% of their irrigation needs with stormwater. Either supplemental irrigation, or the more appropriate selection of landscaping plants, would therefore be needed in these desert areas. Storage tank sizes varied widely and were quite large. Central Texas (San Antonio) required the largest tank size (25,000 gallons), while most of the eastern areas of the U.S. required less than 5,000 gallon tanks.

There are many areas that benefit from using poor quality water. A review by Paret and Elsner (1993) reported that some Florida golf courses use about 2,000 gal per acre per day of reclaimed sanitary wastewater. Other major Florida users of reclaimed sanitary wastewater include agricultural, horticultural and commercial users at about 1,500 gal per acre per day, and multifamily residential developments using about 3,000 gal per acre per day. The service fees for this reclaimed water ranged from about \$0.05 to \$0.64 per 1,000 gallons. Obviously, stormwater could be used for similar purposes, if stored and adequately treated. As an example, several new Veterans Affairs hospitals in the Los Angeles area are heavily landscaped using wet detention ponds holding stormwater tied into their fire fighting systems.

Besides on-site reuse of stormwater, dual distribution systems may be a feasible choice for many conditions. A dual water supply system includes a conventional domestic water supply system carrying class AA water for human consumption and bathing. Another water supply system is also used in a dual system carrying water of a lesser quality. This water is typically used for B and C uses, plus fire fighting. In areas having dual distribution systems, the poorer quality water is typically secondary sewage effluent that has received additional treatment, as noted above. Okun (1990) states that "throughout the world, dual distribution systems are proliferating, speeded up by policies adopted by states in the U.S. and governments elsewhere." He points out that a common feature of these water reuse/dual distribution systems is that customers pay for the reclaimed water, but at a significantly reduced price, compared to typical domestic water. He concluded that a sustainable wastewater reclamation program can only exist with cost recovery.

Even though most of the examples of dual distribution systems and wastewater reclamation are for sanitary wastewater, stormwater may be a much preferable degraded water source for reclamation (NAS 1994). Stormwater does not require nearly as high of a level of treatment, but it is not conveniently collected at one location such as at a wastewater treatment plant, nor is it available at such a constant and predicable flow as sanitary wastewater. However, the large volumes available and its generally better quality may make stormwater a more feasible water for dual distribution systems in many situations.

The Need for Change in Urban Water Management

As indicated above, stormwater can be considered a valuable resource in urban areas, not just a waste that must be rapidly discarded. Many have recognized this potential resource, as briefly outlined above. The *Symposium on Water, the City, and Urban Planning* was held in Paris, France, on April 10 and 11, 1997. The 300 participants formulated the *Paris Statement* outlining needed changes in urban water management. Even though stormwater management is usually considered a luxury of the developed countries (especially North America, Western Europe, and a few major Asian cities), this symposium stressed the need for recognizing the important role that stormwater management can play in the developing countries. Some of the major points of the *Paris Statement* are briefly outlined below:

- The marked process of urbanization in most countries, and especially in the developing world, is causing very rapid increases in water demands, often far outstripping available resources. Water management needed for sustainable urban development, let alone long-term survival of cities, requires immediate attention.

- Water related problems are affected by all elements of the water cycle, including water, land, air, and energy. Social, cultural, political, institutional, and economic aspects are integral and may even be dominant components of urban water management issues. Therefore, an integrated approach for solving urban water resource problems is necessary.

- Each city has a unique set of conditions and problems that require site specific solutions. However, a great deal of information from cities throughout the world is available for helping to solve these local problems.

- Demand management measures to encourage water conservation needs to be implemented, along with the timely consideration of environmentally sound projects to increase the availability of water when and where it is needed. Water problems are recognized mostly as temporal and spatial distribution problems, not because there is a fundamental shortage of water.

• An integrated management approach to surface and groundwaters is needed. Groundwater contamination by urban wastes must be controlled and safe recharge of groundwaters by wastewater and stormwater needs to be investigated.

• Appropriate approaches for urban drainage must consider variations in local climate, types of problems, and economic and maintenance capabilities. In addition, non-structural solutions need to be implemented as part of an integral approach to flood control in urban areas.

• There is a great need to conceive and apply new innovative solutions to solve urban water resource problems. This is especially likely and needed in areas with little drainage and sanitation infrastructure currently in place.

• The symposium recommended the creation of a single and integrated entity for coordination and management of water resources in each urban area.

Numerous papers were presented at the Engineering Foundation/ASCE sponsored symposium on *Sustaining Urban Water Resources in the 21st Century*, held in Malmo, Sweden, in September 1997, describing many international examples of effective urban water resources management. Sulsbrück and Forvaltning (1998) describe renovations being made to the drainage systems in Hillerød, Denmark. The town has 34,000 inhabitants, with about 600 mm or rainfall per year. The receiving water streams are quite small, being about 1 to 3 m across and have an annual average flow of about 600 L/s. About 3.5 km^2 of the drainage area has separate sanitary and storm sewers, while about 12.5 km^2 has combined sewers. The average dry weather flow to the treatment plant is about 14,000 m^3/day, and about 5,000 to 6,000 m^3 per day is lost to infiltration through leaky sewers. The amount lost through infiltration is about equal to the annual stormwater flow. Major sewer renovations are occurring to correct the leaking sewers and to minimize CSOs. Residential roof runoff is required to be infiltrated in newly developing areas, unless building moisture problems prevent its use. Industrial area runoff in new areas is directed to separate storm sewers, and detention facilities are being built to reduce stormwater flows to the streams to a maximum of 0.6 to 1 L/s/ha of drainage area. The sizes of the detention ponds range from 500 m^2 to 65,000 m^2. The total capacity of the retention ponds were 60,000 m^3 in 1997, with an additional 15,000 m^3 planned. The volume of CSOs was about 470,00 m^3 in 1990 and is expected to decrease to about 130,000 m^3 by 2001. Residential area roof runoff is not considered to cause pollution problems to soil or groundwater, while roadway runoff is usually not allowed to be infiltrated because of contamination concerns. Infiltration trenches are being retro-fitted at private homes, with labor provided by unemployed workers, who are paid by the government. The trenches are designed for a 2-year return period storm, the same as the storm sewers. The trenches for a typical 150 m^2 home range from 6 m long for gravelly soil sites to 24 m long for silty soil sites and cost about US$2,000 to construct (for a typical 9 m trench). They found that the use of combined sewers with infiltration is comparable in cost and pollutant discharges with a separate stormwater system. However, the infiltration system dramatically improves groundwater conditions, especially with the repair of the leaky sewers. The local residents also have had a change in attitude towards stormwater management. Runoff is now regarded as a resource instead of a waste. Sulsbrück and Forvaltning (1998) state that “many small, fine, green oases have been provided at the detention pond sites for citizen enjoyment and as habitat for plants and animals.”

A paper presented by Geldof (1998) at the Malmo conference on *Sustaining Urban Water Resources in the 21st Century* described changes that are occurring in the Netherlands. He stated that Dutch urban surface waters tended to be neglected in the past because of their poor water quality. However, current thinking is stressing significant changes in urban water management that will decrease many current problems (such as leaking sanitary and combined sewerage, discharges caused by peak flows, groundwater elevation variations and subsidence, and eutrophic surface waters). Two main changes are being used: changes in the sewerage systems, and increased source controls with on-site reuse of stormwater. In the Netherlands, combined sewers serve about 75% of the urban areas and have a capacity for about 7 mm or rain. Overflows occur when the rainfall exceeds this amount (as often as ten times a year). Separate sewers have been mostly built since the 1970s and now serve most of the remaining urban land area. The separate sewers solved the combined sewer overflow problems, but surprisingly did little to improve the annual mass discharges of pollutants. With separate drainage systems, none of the stormwater is treated at the municipal wastewater treatment plant. In addition, inappropriate discharges of sanitary sewage to the storm sewers are periodically found from inadvertent connections. A new system, termed an “improved separate system”, was therefore developed. This drainage system consists of separate sanitary and storm drainage, but they are cross-connected with one-way gate valves enabling some stormwater to enter the sanitary drainage and be treated at the municipal wastewater treatment facility. The one-way gate values prevent sanitary sewage from entering the storm drainage. Pressurized sanitary sewerage is also sometimes used, with pumps used to discharge appropriate amounts of stormwater into the sanitary sewage system. An important aspect of the improved separate system is that only the most contaminated stormwater enters the stormwater drainage system and then the sanitary wastewater collection system for conveyance to the treatment facility. The least contaminated stormwater (typically just the roof runoff) is infiltrated on site, or potentially also used for toilet flushing, laundry, or irrigation purposes. The improved separate systems typically have a conveyance capacity to handle a 4 mm rain, which is capable of directing about 75 to 90% of the paved area stormwater runoff to the treatment facilities. Geldolf reported that a surprising side effect of source control is that it tends to upgrade people’s perception of stormwater: “it becomes a pleasure rather than a nuisance.” He also reports that residents have even become competitive about how they can most effectively use stormwater on site.

References

Dreiseitl, Herbert. “The role of water in cities.”Presented at the Engineering Foundation/ASCE sponsored symposium on *Sustaining Urban Water Resources in the 21st Century*, Malmo, Sweden, Edited by A.C. Rowney, P. Stahre, and L.A. Roesner. September 7 – 12, 1997. ASCE/Engineering Foundation. New York. 1998.

Fujita, S. “Restoration of polluted urban watercourses in Tokyo for community use.” *Sustaining Urban Water Resources in the 21st Century*. Proceedings of an Engineering Foundation Conference. September 7 – 12, 1997. Malmo, Sweden. ASCE/Engineering Foundation. New York. 1998.

Geldof, Govert D. “The blue transformation in the Netherlands.”Presented at the Engineering Foundation/ASCE sponsored symposium on *Sustaining Urban Water Resources in the 21st Century*, Malmo, Sweden, Edited by A.C. Rowney, P. Stahre, and L.A. Roesner. September 7 – 12, 1997. ASCE/Engineering Foundation. New York. 1998.

Göransson, Christer. “Aestheric aspects of stormwater management in an urban environment.” Presented at the Engineering Foundation/ASCE sponsored symposium on *Sustaining Urban Water Resources in the 21st Century*, Malmo, Sweden, Edited by A.C. Rowney, P. Stahre, and L.A. Roesner. September 7 – 12, 1997. ASCE/Engineering Foundation. New York. 1998.

Heaney, J.P., L. Wright, D. Sample, R. Pitt, R. Field, na dC-Y Fan. “innovative wet-weather flow collection/control/treatment systems for newly urbanizing areas in the 21st century.” Presented at the Engineering Foundation/ASCE sponsored symposium on *Sustaining Urban Water Resources in the 21st Century*, Malmo, Sweden, Edited by A.C. Rowney, P. Stahre, and L.A. Roesner. September 7 – 12, 1997. ASCE/Engineering Foundation. New York. 1998.

Hittman Associates. *The beneficial use of stormwater*. Report No. 11030DNK08/68, NTIS No. PB 195160, U.S. Environmental Protection Agency. Washington, D. C., 1968.

Mallory, C.W. *The Beneficial Use of Storm Water*. EPA-R2-73-139. U.S. Environmental Protection Agency. Washington, D. C., January 1973.

Metcalf & Eddy. *Wastewater Engineering: Treatment, Disposal, and Reuse*. 3rd edition. McGraw-Hill, New York. 1991

NAS (National Academy of Science, Groundwater Recharge Committee). *Ground Water Recharge using Waters of Impaired Quality*, National Academy Press, Washington, D.C. 284 pages. 1994.

Okun, D.A. “Realizing the benefits of water reuse in developing countries.” *Water Environment & Technology*. pp. 78-82. Nov. 1990.

Paret, M. and M. Elsner. “Reclaimed water perspectives.” *Water Environment & Technology*. pp. 46-49. February 1993.

Sulsbrück, P. and T. Forvaltning. “The first steps towards sustainable storm water management in Hillerød, Denmark.” Presented at the Engineering Foundation/ASCE sponsored symposium on *Sustaining Urban Water*

Resources in the 21st Century, Malmo, Sweden, Edited by A.C. Rowney, P. Stahre, and L.A. Roesner. September 7 – 12, 1997. ASCE/Engineering Foundation. New York. 1998.

Symposium on Water, the City, and Urban Planning. “The Paris Statement.” Paris, France, April 10 and 11, 1997.

Section 3
Historical Review of Wet Weather Flow Management and Designs for the Future

The management of wet weather flows is an age old problem. Ancient civilizations grappled with the quandary of flood prevention and waste disposal in their cities of stone long before engineering was a recognized profession. They devised strategies to mitigate flooding in cities which resulted in occasional success and constructed drainage appurtenances such as open channels and pipes that remain intact today. It is evident from recorded histories that lessons concerning wet weather flow management can be learned from the past.

Examples of well constructed sewerage systems exist in history. From the ancient Mohenjo-Daro civilization to the Roman Empire, drainage systems proved to be sources of civic pride. Even today, the sewer system of Paris is the destination of many a tourist. The methods used in the past to lessen the impacts of stormwater can provide insight into new methods applicable today. But to find applicable concepts from the past a thorough search must be conducted. One aspect of this EPA funded project to develop a guidance manual for wet weather management in newly urbanizing areas involved just such a literature review. The literature search began with historical books which reviewed ancient and medieval drainage practices. The purpose of this part of the literature review was to develop an understanding of the past strategies utilized in wet weather management. The second part of the literature review entailed an exhaustive review of technical material from the previous 130 years. The technical literature reviewed included journals, books, reports, government documents, and other print media relevant to the subjects at hand. The purpose of this part of the literature review was to trace the development of wet weather management, possibly uncovering discarded concepts or practices that could be applicable today.

This discussion of the literature is divided into five subsections. The first subsection will detail the methodology and breadth of the literature review. The second subsection will discuss the ancient wet weather management strategies uncovered in the literature. The third subsection will detail the literature relevant to wet weather management dating from the middle ages to the nineteenth century. The fourth subsection will present the literature from the late nineteenth century to the early 1960s. The last subsection presents the recent literature from the past thirty years with special reference to current conditions. The conclusion of this part of the report summarizes the literature review and describes the future outlook for wet weather management based on current trends in the literature.

Literature Review Methodology

One of the first steps in the development of the wet weather management guidance manual was the review of current wet weather flow management practices and historical incidents that resulted in the institutionalization of current practices. There are many ideas that have been proposed, some tried and others not, over the years that may be applicable in current conditions. We feel that a review of the historical developments may provide some insights lost over time.

Journals dating from 1860 to the present were searched for articles pertaining to municipal stormwater design and management. In addition books, reports, conference proceedings, and other forms of print were also searched. References located pertinent to wet weather flow to any degree were recorded into ProCite (Personal Bibliographic Software, Inc. 1995), a bibliographic software application, for future reference. As references accumulated, a simultaneous critical review was conducted for each reference to determine its applicability to the current project. The critical review involved considering the title of the piece of work, possibly reading the abstract or perusing the article, and occasionally reading the entire piece. Papers of note were recorded and set aside for later synthesis with other important pieces in the development of an historical perspective of stormwater management.

In addition to the search of journals and their indices, electronic searches were conducted. The University of Alabama library system supports the Ei Page One Engineering Index for periodicals. This database was searched with key words related to wet weather management. Some of the key words used during the search were:

- sewer
- urban runoff
- stormwater
- wet weather flow
- best management practices
- detention basins
- urban hydrology

This list is just a sampling of the key words used. However, following key word searches with these terms additional searches resulted in a high frequency of repeat hits. Thus, it became fruitless to continue searching with more obscure key words in the same database and the search was discontinued. At that time other databases and search engines would be consulted for additional references.

Another computer search engine utilized was the ProQuest service for dissertation abstracts. The same key words were used as in the Ei Page One search and again the diminishing amount of new hits with additional key word searches was observed. The dissertation database was far less comprehensive than the periodical index searched, consequently far fewer dissertation and thesis abstracts were located compared to the periodical indices.

Other databases searched electronically included the National Technical Information Service (NTIS) index, COMPindex, and the Internet at large. These databases did not provide a large amount of references and even seemed counterproductive at times. For instance, the Internet search consumed a lot of time and only resulted in small amounts of literature located. Some of the poor results using these search procedures may be attributable to the search methodology implemented.

Regardless of the search methodology, be it electronic or manual, the located sources were either recorded by downloading to a disk or written by hand, depending on the type of source and if it could be uploaded directly into the ProCite database. If the source was recorded by hand it was subsequently entered into the ProCite database by hand and if it were downloaded to disk it would be uploaded into the ProCite database. Overall, slightly more than half of the references in the database were manually entered into ProCite from a printed source, whether it be an index, literature review, or some other compilation of bibliographies.

Ultimately, the goal of this initial work was to determine the general stormwater design philosophy utilized to design and manage municipal stormwater systems, and to chart the progress or regress (depending on your point of view) in the development of wet weather flow design and management strategies. Also, schisms which occurred in design and management philosophy will be apparent from the accumulated literature. It is necessary to document and understand the history of stormwater design and management to devise a future strategy. By observing past trends and decisions, prior mistakes can be avoided, previously discarded ideas can be reevaluated, and eventually future needs can be determined. A copy of the database, in both Microsoft Word and ProCite versions, is available on the www page of the Cahaba-Warrior Student Section of the American Water Works Association at: http://www.eng.ua.edu/~awra/

Journal Papers

Several technical journals publish annual literature reviews or indexes divided into specific subject matter which provided an excellent starting point for this review. Specifically, the following journals were utilized in this capacity for this study:

Journal Water Pollution Control Federation (and its current descendents)

Transactions of the American Society of Civil Engineers

Overall, 124 journals are referenced in the complete ProCite database. The journal article review consumed most of the time in the early parts of this project.

Today, technical journals are ubiquitous with many publishing material germane to wet weather flow management. However, the development of the wet weather management strategies in the U.S. can be traced accurately through two organizations' journals in particular. The American Society of Civil Engineers (ASCE) and the Water Environment Federation (WEF) and its predecessor organizations have published journals dating back to the late eighteen hundreds. Since these two journals provided many sources, flow charts and explanations of the development of ASCE and WEF journals is provided below to facilitate the discussion.

American Society of Civil Engineers (ASCE)
ASCE has been an institution since 1852 and the published transactions for the society dating back to 1878 were readily available in the University of Alabama's library. The *Transactions of the American Society of Civil Engineers* published papers which were associated with society members. The papers in this journal provided coverage for the ASCE literature review from 1880 to the early 1950s. In the 1950s, the divisions of the ASCE began to be represented by separate journals, as is shown on Figure 3-1. ASCE publishes many other journals, but only the journals in the flow chart contained material relevant to this project.

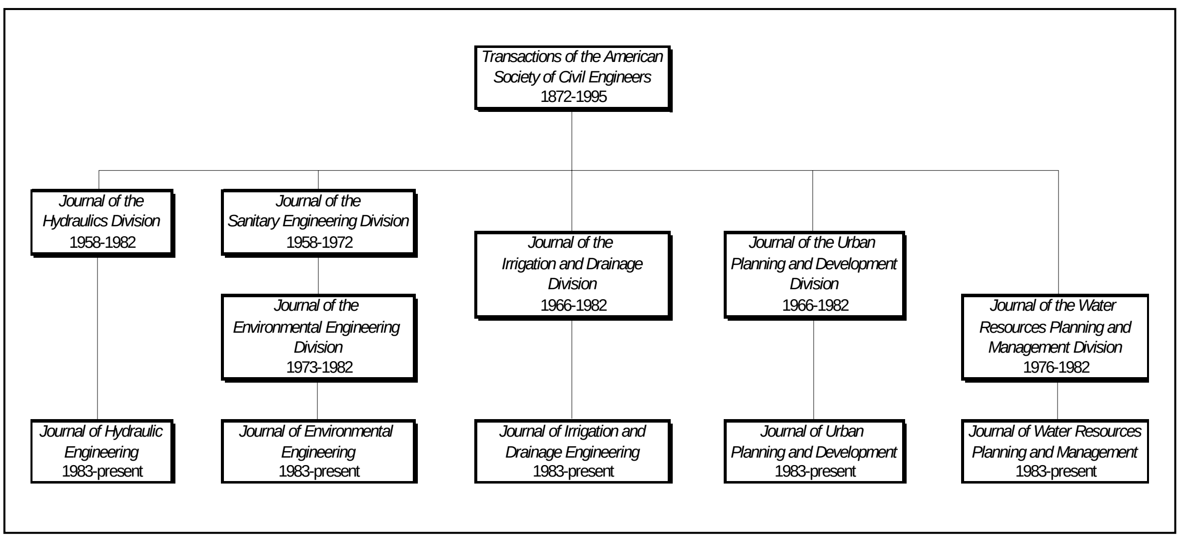


Figure 3-1. American Society of Civil Engineers' (ASCE) Journals Reviewed.

Water Environment Federation (WEF)
The Water Environment Federation evolved from the Water Pollution Control Federation. The *Sewage Works Journal* was the primary publication of the Water Pollution Control Federation from 1928 to 1949 as shown in Figure 3-2. The title of the journal was changed to *Sewage and Industrial Wastes* in 1950 and subsequently to *Journal Water Pollution Control Federation* in 1959. The journal kept this name for thirty years, until 1989, when the journal split into two journals, one a research journal (*Water Environment Research*) and the other a trade journal (*Water Environment & Technology*).

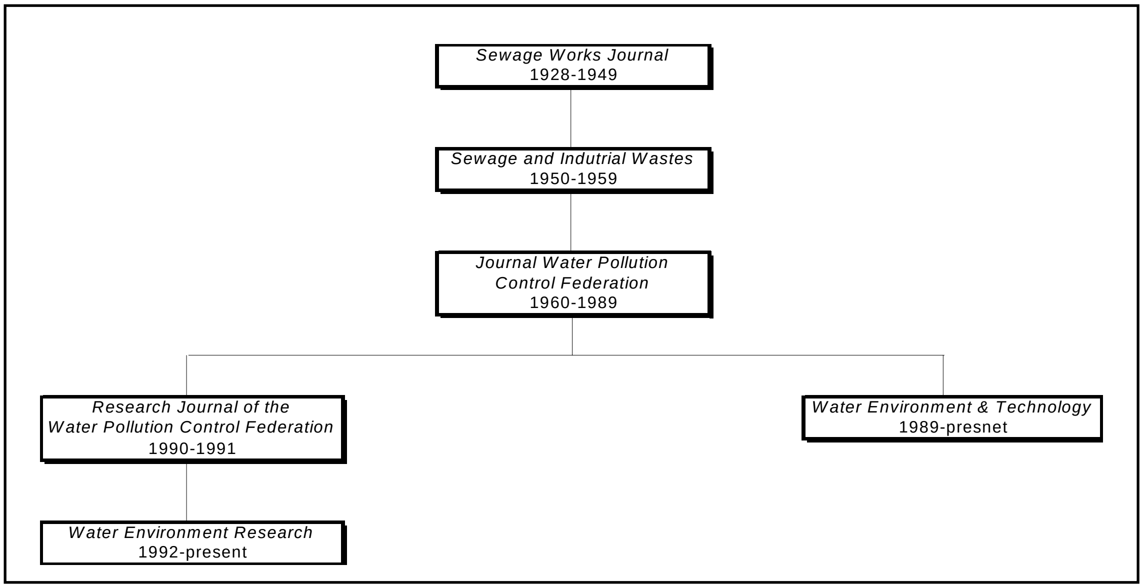


Figure 3-2. Water Environment Federation's (WEF) Journals Reviewed.

Additional Literature Reviewed

Besides the ASCE- and WEF-sponsored journals, many other journals also contributed to the database. A complete list and their relative contributions of the more frequently referenced journals is discussed below.

The government documents database (mainly NTIS) was also searched for reports related to stormwater management. Federal agencies with major contributions to the field included: the United States Environmental Protection Agency (EPA), the United States Geological Survey (USGS), and the Federal Highway Administration (FHWA). A good source for wet weather management reports published by the EPA is an EPA report entitled *Bibliography of Storm and Combined Sewer Pollution Control R&D Program Documents* (Field 1995). Over 340 EPA reports are cited in this document. Local and state agency reports were also documented in the database.

Conference proceedings were another area targeted for published material pertaining to wet weather management. Proceedings are not easily attainable, even if one knows the location and date of the conference. For this reason, most proceedings are considered a form of "gray" literature. Proceedings may be located in libraries, through interlibrary loan, and from authors and sponsoring agencies. This area is considered to be quite an important vein of knowledge that has been relatively unorganized in the past.

The other references examined included books, private reports, unpublished documents, theses, dissertations, and other sources discovered during the above mentioned searches. Information concerning ancient and middle age wet weather management was generally located in historical books and papers reviewing historical drainage practices.

Summary Statistics

The complete ProCite database contained over 3,700 references at the time of publication. The chronological breakdown of the references is shown in Table 3-1. Almost half of all references cited were published since 1990. The large amount of material referenced during the past few years likely reflects the tremendous increase in researchers involved in wet weather flow issues and who are publishing their results.

Table 3-1. Breakdown of References Chronologically

Decade	Number of References
Before 1880	3

1880 - 1890	10
1890 - 1900	14
1900 - 1910	10
1910 - 1920	10
1920 - 1930	11
1930 - 1940	33
1940 - 1950	42
1950 - 1960	15
1960 - 1970	97
1970 - 1980	975
1980 - 1990	994
1990 – 1996 ½	1574

If the number of references is further broken up into five year segments from 1970 onward, another noticeable trend is observable. As shown in Table 3-2, the second half of the 1970s showed a significant upswing in publishing followed by a steady decrease over through the 1980s. The number of publications is increasing rapidly (by a factor of 2) during the current decade. These fluctuations generally reflect the changes in national funding available for wet weather research. The 1970s were noted for significant and massive demonstration projects supported by the EPA in the area of CSO control. EPA funding abruptly ended for wet weather flow research in 1980 and did not start again until 1988. In the U.S., wet weather flow research during the 1980s was mostly sponsored by state and local governments and was not widely published. U.S. funding during the past several years has significantly increased, with a concurrent upsurge in reported research findings. In addition, European and other international wet weather flow research efforts dramatically outpaced U.S. efforts during the 1980s and current international research remains a very important source of information. For this reason, numerous international conference proceedings (such as those sponsored by the IAWQ, the International Association on Water Quality, based in London) remain extremely important to U.S. researchers.

Table 3-2. Further Breakdown of References Chronologically

Time Period	Number of References
1970 - 1975	313
1975 - 1980	662
1980 - 1985	547
1985 - 1990	447
1990 - 1995	1020
1995 - present	554

The breakdown of the quantity of journal papers found within each specific journal is listed in Table 3-3. About 75 journals having contributions of less than 10 papers to the database are not listed. In sum, more than 1,600 journal papers are referenced in the ProCite database.

The database contains over 350 EPA documents and 22 USGS reports. These two government agencies are the largest single contributors, with the remaining 175 plus reports being distributed among many state, local, academic, and private entities. Over 100 conference proceedings contributing 1,350 papers are include in the database as well. Supplementary to the above references, over 100 theses and dissertations are also included.

ProCite has the capability to store very descriptive details about a reference. But not all of this descriptive capacity was available for each citation. In ProCite, each different type of media has fields that are specific to it and some that are general for all types. For instance, the author is specific to each type of reference, whether it is a journal paper, book, EPA report, etc. However, this information, like all else, is not required.

For this study, the information necessary for locating a reference was given highest priority (authors, titles, date of publication, page numbers, and publisher). Other information would also be entered if readily available. Figure 3-3 shows an example of a journal paper ProCite citation. Each field has its own line, with additional lines provided when appropriate. The input fields can be formatted by the user to display the information that is desired. The available templates in ProCite include journal paper, book, dissertation, report, patent, and many others. The user can also create their own template specific to their needs. ProCite is a Windows based application with memory requirements based on the size of the bibliography. Figure 3-3 does not display all the icons that support the use of the application.

The key words are selected based on the title, abstract, or the entire paper. In total, for the more than 3,700 references, approximately 700 different key words have been entered. Some of these are redundant, but often the words selected by different individuals will be different based on their backgrounds. Therefore, the redundancy is viewed as advantageous for the database as a whole. Several example key words include:

- CSO treatment
- toxicity
- drainage design
- detention basins
- heavy metals
- sewer solids
- infiltration/inflow
- deterministic modeling

Table 3-3. Listing of Individual Journal Citations

Journal	Number of References
American City and County	25
APWA Reporter	22
Canadian Journal of Civil Engineering	12
Civil Engineering, ASCE	65
ENR (Engineering News - Record)	26
Journal of the Sanitary Engineering Division, ASCE	10
Journal of the Environmental Engineering Division, ASCE	50
Journal of Environmental Engineering, ASCE	37
Journal of Hydraulic Engineering, ASCE	26
Journal of the Hydraulics Division, ASCE	95
Journal of Hydraulic Research	54
Journal of Hydrology	11
Journal of the Irrigation and Drainage Division, ASCE	13
Journal of Irrigation and Drainage Engineering, ASCE	14
Journal of the Urban Planning and Development Division, ASCE	9
Journal of Urban Planning and Development, ASCE	2
Journal of the Water Res. Planning and Management Div., ASCE	27
Journal of Water Res. Planning and Management, ASCE	47
Journal Water Pollution Control Federation	112
Nordic Hydrology	10
Public Works	93
Science of the Total Environment	33
Sewage Works Journal	10
Transaction, American Geophysical Union	11
Transactions of the American Society of Civil Engineers	70
Water/Engineering and Management	25
Water Environment & Technology	59
Water and Sewage Works	16
Water and Wastes Engineering	11
Water Research	29
Water Resources Bulletin	57
Water Resources Research	21
Water Science and Technology	211

This sample of key words, and the remainder in ProCite, are more than adequate to conduct searches, but can be expanded by the ProCite user to provide a more expansive search capability.

The bibliographic format used for the hard copy of the reference database and within ProCite is according to a standard EPA format. Although this is the format selected, ProCite can accommodate any bibliographic format required. ProCite offers a wide range of sorting criteria, or the user can define the criteria as desired. For this report, a custom sort was constructed within the ProCite framework to organize the references. The primary sort is alphabetical, according to the author's name, or authors, if there is more than one. The secondary sort is chronological, and the tertiary sort is an alphabetic sort by the title of the work. Although this is the custom sort set in ProCite for this project, other sorting methods can be used. ProCite offers a wide variety of sorting, searching, citing, and other functions to facilitate bibliographic work. The reader is referenced to the ProCite User's Manual (Personal Bibliographic Software, Inc. 1995) for additional information.

The progression of wet weather management as seen in the literature sources described above is presented in the following subsections.

Author, Analytic (01):	Kuichling, Emil
Article Title (04):	The relation between the rainfall and the discharge of sewers in populace districts
Medium Designator (05):	
Journal Title (09):	Transactions of the American Society of Civil Engineers
Translated Title (11):	
Date of Publication (20):	1889
Volume Identification (22):	20
Issue Identification (24):	
Page(s) (25):	1-60
Language (35):	
ISSN (40):	
Notes (42):	The introduction of the rational method of storm sewer design in the U.S.
Abstract (43):	
Call Number (44):	
Key Words (45):	rational method/storm sewer design/time of concentration/rainfall-runoff/

Figure 3-3. Example ProCite Citation

Ancient Wet Weather Management Practices

Modern engineering has become so extended and specialized in all disciplines that its relation to ancient engineering is almost inconceivable. Sophisticated computers and other design tools provide today's engineer with a decisive technical advantage over the ancient engineer. But, one must not forget that today's methods and practices have evolved from their roots in history parallel to the progress of civilization. If engineering evolution followed Darwin's theory, then the 'fittest' methods and principles would have survived. However, the 'fittest' practices have not always been those initially accepted by engineers. The literature documents incorrect practices embraced and insightful ideas ignored in the past.

The use of planned sewer systems to transport stormwater from an urban area to a receiving stream is thought by some to date back to the time people began to gather and live in cities. The drainage systems often accompanied well-planned sanitary sewage systems in an effort to provide a cleaning mechanism. Several contemporary civilizations can be credited with developing innovative wet weather and sanitary sewerage systems in the third millennium B.C.

The Indus civilization of circa 3000 B.C. presents one example of a sewerage system well advanced of their time. Evidence exists that the dwellers of the city of Mohenjo-Daro (now West Pakistan) used sanitary sewer systems and had drains to remove stormwater from the streets (Webster 1962). The discovered ruins of this ancient system show the great care used to construct the sewers which would make the engineer of today envious. Judging from the foundations of the city, archeologists have concluded that the city was laid out according to some prearranged plan. Knowing that a civic body was responsible for the planning of the city lends to the conclusion that a planning authority also influenced the development of the sewer system.

One feature of the Mohejo-Daro sewer system of note was the use of a cunette in conjunction with the storm drain (Webster 1962). This practice is seen today in allowing for normal flows to pass through wet weather structures without utilizing its entire capacity. The masonry work and clever design of the storm drain system show that in some instances, much more care was taken with the sewers than some of the buildings.

Other cities in the middle east region about 5000 years ago also exhibited wet weather management planning. For instance, the city of Ur, in present day Iraq, had an effective drainage system for stormwater control (Jones 1967). Although the system ruins did not indicate an overall system design, it did show the breadth of coverage that the system had over the whole city.

Civilizations contemporary to the Indus also had excellent sanitary and wet weather management systems. The Mesopotamian Empires of Assyria, Babylonia, and their antecedent Sumerian and Akkadian states, marked great advances in civilization. The ruins from cities in these empires have uncovered the viable sanitary and storm drainage systems implemented, displaying their advanced technical knowledge. As early as 2500 B.C., Mesopotamian engineers planned and built efficient drainage and sanitary works including vaulted sewers and drains for household waste, gutters and drains for surface runoff, and other appurtenances (Maner 1966). All the structures were built of baked brick and asphalt.

The Middle Minoan Period dates about 1000 years after the above civilizations. The ruins from this civilization located on the Aegean Sea revealed elaborate systems of well-built stone drains, which carried sanitary sewage, roof runoff, and general surface drainage (Gray 1940). The drains emptied into a main sewer that disposed of the sewage a considerable distance from the origin of the wastes. The frequent and torrential rains in ancient Crete, an island in the Minoan civilization, resulted in excellent flushing of the system. A testament to the durability of the system developed by the Minoans was a statement made by A. Mosso in describing the ruins of villa Hagia Triada (Gray 1940):

> One day, after a heavy downpour of rain, I was interested to find that all the drains acted perfectly, and I saw the water flow from the sewers through which a man could walk upright. I doubt if there is any other instance of a drainage system acting after 4000 years.

It will be interesting to see if the drainage systems constructed today, with supposed advanced technology, can function adequately after 4000 years.

The next wet weather management practice of note dates to the tenth century B.C. Ruins in Jerusalem indicate that two independent systems of sewerage, one for street drainage and household wastewater and the other for sanitary sewage, were implemented in small sections of the city (Hodge 1992). This marked a change, although at a very small scale, from the past practice in Mohenjo-Daro, which had storm drainage systems being used to convey sanitary wastes to a suitable disposal location. Arched sewers also existed in Ninevah and Babylon dating to the seventh century B.C. (Metcalf and Eddy 1928). These sewers were utilized to transport combined sewage similar to those in Mohenjo-Daro (Webster 1962).

On a scale larger than small towns or sections of cities, wet weather management in urban settings appears to have been first consistently addressed during the design of roadways. Of all the societies of western Asia and Europe, from Antiquity until the nineteenth century, only the Romans set out to build a carefully planned road system with properly drained surfaces (Hill 1984). But the question is did the Romans develop the drainage of roadways or did they borrow the technology from previous civilizations. It is known that roads of ample design date back to the period of Etruscan domination in Italy (800-350 B.C.) (Hill 1984). Most of the streets were paved and well drained, with raised sidewalks and stepping-stones at street crossings to protect pedestrians against overflow from the aqueducts and stormwater flowing on the street surfaces. When the Romans came to power, they rebuilt the Etruscan sewers and paved streets. Therefore, some believe that the Romans developed their drainage strategies from the Etruscans. Regardless of the originator of the strategy, the intentions of both the Etruscan and Roman road drainage systems was to mitigate the impact of stormwater runoff and aqueduct overflow on areas adjacent to roadways and on the roadways themselves.

Specific drainage structures utilized by the Romans included occasional curb and gutters to direct surface runoff to open drainage channels alongside roadways. However, the ruins of Roman roadways do not indicate an abundance of curb and gutter usage and the exact date in which this drainage strategy became implemented is not clear (Hill 1984). Many Roman roadways also had rock lined open drainage channels on either side of the paved street surface. The roads would be graded in such a fashion to direct the surface runoff from the streets toward the drainage channels. Although some of the channels were lined, the most often used drainage channel was simply the open ditch.

Besides the Romans, evidence has also shown that the Greeks designed paved surfaces for travel during the same time period as well. However, mainly due to the terrain of Grecian lands, the roadway system was not nearly as intricate or finely planned as the Roman roadway system. Gutters and drains were provided and grading was done such that roadways would remain free from inundation.

The roads were not the only engineering structure that was designed for drainage. Typically, rainwater was disposed of depending on where it fell. If it fell on a house, for instance, the roof was constructed such that it funneled the rainwater into a cistern somewhere in the interior where it was used as a water supply (Hodge 1992). This management practice effectively reduced the amount of surface runoff requiring control, simultaneously reducing the required size of the drainage system. A great deal of rain falling on a town, therefore, never did get drained away. This management strategy of on-site detention continues to be utilized today (Debo and Reese 1995) as a strategy to reduce surface runoff. Fewer areas continue to utilize direct reuse of stormwater on-site.

The well-known Roman aqueduct system used for water supply to the populace, was also the impetus for drainage in many parts of the Roman Empire. Once an aqueduct was brought in, and with it the overflow of unused water from street fountains and, especially the baths, then the water to be drained away could be a great amount (Hodge 1992). Therefore, it is often argued that the drainage structures constructed by the Romans were planned more for the overflow from the aqueducts than the drainage of surface runoff, nonetheless their effectiveness at managing stormwater cannot be disregarded.

Although the drainage of excess water from the aqueducts and rainwater was the primary function of the drainage system, it was not the only function. More and more in populace regions in the Roman Empire, domestic sewage and wastes were requiring disposal. The easiest ways were to discharge the wastes into the drainage system or develop a pipe system especially for domestic waste. The need to adequately discharge wastes initiated the development of underground sewers. Initially, open trenches or channels ran down the center of city streets to convey the stormwater and excess public water. Soon, it was discovered that disposal of wastes in these trenches removed the waste from the area. However, the trenches relied on cloudbursts to flush them of waste and debris adequately, since the overflow from the aqueducts was not sufficient to convey the wastes in great quantity. The wastes would accumulate and cause unsanitary, not to mention repugnant, conditions. The solution to this was to cover the trenches. The covered channels evolved into planned sewers. Thus, many of the early sewers were typically natural open drainage channels and streams which started to accumulate domestic wastes requiring them to be covered to prevent odors from escaping to the surrounding community.

The Romans constructed the *cloacae*, or sewers, to drain their uplands to the nearby network of low-lying streams (Gest 1963). As mentioned, sewers were originally open streams that drained most of the land prior to urbanization. The onset of paved roadways and stone structures reduced the infiltration capacity of the area resulting in flooding. The Romans understood that drainage needed to be considered in urbanizing areas to mitigate flooding caused by aqueduct overflow and rainwater. Their philosophy was to use the existing natural drainage channels to remove wet weather flows. It was decided that the proper way to use the channels was to build the city over them and provide drains from the surface to the underground streams. This would provide alternate routes for infiltration from impervious surfaces during urbanization. As time progressed, the Romans became more elaborate with their construction of the sewers, this is evidenced by the increased care and detail given to the construction in later times. For instance, ornamental and finely crafted inlet covers have been discovered in ruins of Roman city streets (Gest 1963).

The first of the *cloacae* was the *Cloaca Maxima* (Gest 1963); constructed to drain the lowest parts of Rome, about the Forum, which were too flat to remove the stormwater easily. The *Cloaca Maxima* also had the dual purpose of draining swampland for land reclamation purposes. Therefore, constant flow of water was present with intermittent high flows during wet weather events. This provided excellent conditions for the disposal of sanitary wastes via the sewer system.

The oldest part of the existing structure dates to about the third century, B.C. (Gest 1963). The *Cloaca Maxima*, which was 4.3 meters high and 3.2 meters wide in places (Garrison 1991), discharged directly into the nearby Tiber River. Roadways, common areas, and stone structures were constructed with drains adequate to allow the stormwater to enter the sewers, thus relieving Rome of flooding problems. Besides simply removing the rainwater, the drains and sewers also acted to funnel the filth and accumulated garbage scoured from the surface of the city to the nearest waterway during wet weather events. No consideration was given to the impacts that the wet weather flows were having on the receiving water, although it most likely was minimal, due to the relatively small populations in the ancient cities.

The sewers of Rome became a source of civic pride. The residents viewed the system as symbolic of their advanced civilization, and later some French and English engineers tried to instill similar pride amongst citizens during their push to improve wet weather management systems in the 1800s (Hodge 1992). Although the sewers were successful in their function and well constructed, they didn't epitomize the perfect sewer design strategy. In fact, the design was simply trial-and-error based on drainage experience. Lewis Mumford (1961)observed that the sewer systems of ancient civilizations, including the Romans, were an "uneconomic combination of refined technical devices and primitive social planning." Therefore, the pinnacle of wet weather management had not yet been attained.

Wet Weather Management Practices: Middle Ages to the Nineteenth Century

From the time of the Roman Empire to the eighteenth century, wet weather management strategies experienced few noteworthy advancements, and even regressed considerably in terms of sanitation. However, as disease epidemics occurred in major metropolitan areas of Europe, some believed proper sanitation was dependent on adequate wet weather management. The proper utilization of stormwater provided an urban area with the required flushing mechanism to remove wastes that accumulated in city streets as well as reduced the damages and dangers associated with urban flooding. The consequence of developing wet weather and sanitary systems in response to maladies was an incoherent and varied overall system. Paris and London provide examples of cities which developed piecemeal drainage systems in response to crisis situations and funding availability. The development, from inadequate to adequate wet weather management systems required 500 years, dating from approximately 1300 (when ditches were first used to convey drainage waters) to the 1800s (the advent of modern engineering drainage design).

The first sewers to develop in Europe following the fall of the Roman Empire were simply open ditches. Previously, the inception of sewers in the Roman Empire had developed in the same fashion. Examples in Europe of this type of sewerage system is evident in both Paris and London (Kirby and Laurson 1932; Reid 1991) during the 1300s and 1400s. The open ditches used for drainage of stormwater were usually constructed in existing drainage pathways (Kirby and Laurson 1932). Besides being conveyances for stormwater, the open drainage channels became receptacles for trash, kitchen wastes, and sanitary wastes, the accumulation of which caused a great nuisance. To remedy this situation, Europeans covered the drainage channels, or sewers, which were emitting a terrible odor or providing unsightly conditions. Interestingly, this solution is also similar to that used 1500 years earlier by the Romans during the construction of the *cloaca*. It seems that strategies commonly utilized in the past to mitigate a sanitation problem was to remove it from sight; which is still the case in many situations today.

In Paris, the first covered sewer dates back to 1370 when Hugues Aubriot constructed the Fosse de St. Opportune (Reid 1991). This sewer, which became known as the beltway sewer (Reid 1991), discharged into the Seine River and acted as a collector for the sewers on the right bank of the Seine. The covered sewer concept was not instituted immediately throughout Europe. Paris, for instance, continued to rely on the open drainage channels well into the 1700s and London didn't construct a planned covered sewer until the 1600s (Kirby and Laurson 1932).

Before the covered sewer, the open sewers usually were little more than gullies running down the center of the street (Reid 1991), which a heavy downpour could turn easily into torrents overflowing their banks. Well into the nineteenth century, *pontonniers volants* appeared with planks on Paris streets during rainstorms and charged pedestrians a fee to accompany them across open sewers on their boards (Reid 1991). During dry periods, the sewers in the streets, which relied on the rainwater for cleansing, literally became garbage dumps due to the accumulation of municipal wastes. Therefore, the drainage systems functioned unacceptably during both wet and dry periods.

The few covered sewers which did exist received insufficient maintenance during the early middle ages. During periods of dry weather, the sanitary wastes remained stagnant in the sewer system, producing a repugnant odor. The maintenance problems unheeded, the municipal authorities continued to cover sewers in European metropolises. By 1663, almost one-quarter of Paris' more than ten kilometers of sewers were enclosed (Reid 1991). Maintenance of the sewers continued to be difficult to the point that blockages and backups were common. The solution in Paris during the 1700s was to build magnificently large underground sewers for the drainage of stormwater. These sewers provided enough space for a man to clean the sewers comfortably. However, opposition to the large sewers was heard from many - 'What good is such luxury underground?' (Reid 1991). The lack of government attention and the poor practices of planning, design, and construction of the sewers caused much of the deposition and subsequent clogging problems. In 1826, the Amelot in Paris had its entire six foot by five foot opening blocked with accumulated waste (Reid 1991), just one of the many recorded examples of poor maintenance of middle age civil infrastructure systems. In retrospect, the sewer systems of urban areas in Europe during the seventeenth and eighteenth centuries were grossly under-planned, poorly constructed, and inadequately maintained.

Innovations in construction practices improved sewerage systems in the early 1800s. Until the 1820s in Paris, sewers had been constructed of cut stone or brick with rectangular or roughly rounded bases, conditions conducive to deposition problems (Reid 1991). Engineers substituted mill stone and cement mortar for the hewn stone which allowed for the construction of curved sewer floors that were smooth. This innovation ameliorated the cleansing of sewers by flushing.

Another problem with the design and construction of sewers was the grade at which they were laid. Often, caution was not exercised either during design or construction and the sewers did not have a sufficient slope to transport wastewater during dry weather flow. Addressing this situation, engineers and laborers began to construct sewers on inclines sufficient to prevent ponding in the system.

The onset of numerical standards for sewer design began in the mid 1800s. The basis for the standards was both experimental results and practical experience. Bazalgette provided much of the European design standards for drainage systems in his designs for London sewerage (Metcalf and Eddy 1928). His standard of using 2 to 3 feet per second for a minimum velocity to avoid silting was well accepted throughout Europe and institutionalized in London in 1855. The minimum velocity was not arbitrary but based instead on actual tests of deposition of sand from running water. These tests indicated that a velocity of 2 feet per second would move solids along in a sanitary sewer, but that a velocity of 3 feet per second was needed to prevent deposition of sand, gravel, and debris washed into the system during wet weather. Other standards or suggestions utilized included slope restrictions, materials, size, and others. However, these standards were not as universally accepted as the minimum velocity standard.

In addition to the improvements in construction, the design of the sewer pipes realized several advancements. The shape of sewers had been constrained by construction and material capabilities, but with the advent of new pipe materials mentioned above, they could be constructed curved instead of simply rectangular. As a result, new innovative shapes of sewers developed in the early 1800s that included egg-shaped, oval, and v-notched patterns for combined sewer systems. These shapes provided improved hydraulic transport efficiency over the rectangular sewer shape. Studies in England indicated that the lower part of a v-notch channel could carry sanitary waste flow along well while the upper portion could provide sufficient capacity to transport storm water from the streets (Gayman 1997). Smooth pipe interiors resulting from the improved construction practices also contributed to the increased efficiency of the sewerage systems.

The improvement in construction practices and pipe designs didn’t eliminate the problems with sewer systems in Europe. System design strategy became the focus of the next wave of innovations in sewerage practice. The precursor to the overall design of urban wet weather management systems was the improved design of parts of the system. For instance, H. C. Emmery, head of the Paris sewer system from 1832 to 1839, replaced the channels down the center of streets with gutters constructed under sidewalks which periodically emptied into sewers (Reid 1991). The sewers he constructed had a regular incline and, like sewers built later, were large enough to allow a man to move about standing up. However, even design advancements such as this could not mitigate the impacts of urbanization. The runoff caused by an increase in impervious surfaces put further strain on the sewer system causing overflows with nearly every downpour (Kirby and Laurson 1932). Also, adding to the flooding problems during this period, sewer pipe was made by ‘persons not overly scrupulous, eagerly purchased, and hastily laid by parties utterly ignorant of any role of correct drainage’ (Gayman 1997). As standards, regulations, and inspections became more stringent for public works projects, these problems gradually began to subside.

The next logical step in the advancement of wet weather management addressed planning for entire urban systems of drainage and sanitary sewage removal. Hamburg, in 1843, is considered to have implemented the first comprehensively planned sewerage system (Metcalf and Eddy 1928). Although previous systems had accounted for both sanitary wastes and stormwater, they were not designed with that intention. Hamburg marked the first system that from its conception was planned to manage both sanitary wastewater and stormwater runoff. The circumstances were advantageous for this type of holistic design since a large part of the city had been destroyed by conflagration in 1842. William Lindley, an Englishman in residence in Hamburg, was commissioned to plan and design the system. It was designed uniquely in that sanitary sewage and stormwater were conveyed separately, constituting a separate system of sewerage. The separate system was not planned for the sanitary benefits as is often assumed, but was rather the result of shrewd business decisions in taking advantage of exceptional local conditions to plan streets and sewers to meet the recognized needs of the community (Metcalf and Eddy 1928). Therefore, then, as it is today, economics ultimately influenced civil infrastructure system design.

London followed suit with a detailed study by many engineers of note, one of which was Sir Robert Rawlinson, resulting in the decision to devise a comprehensive plan of sewerage. Joseph William Bazalgette was commissioned in 1852 to plan and design the system (Kirby and Laurson 1932). Actual work on the Main Drainage of London began in 1859 and it was practically completed in 1865. Features of this ambitious enterprise were the early experiments with rainfall calculations and a version of portland cement. Meanwhile, the sewers of Paris were still being constructed without any coordinated plan until 1823. At this time, construction practices began to improve which allowed engineers such as Duleau to plan an adequate system of drainage for portions of the city. The planned interceptor sewer concept dates to this period in Paris (Kirby and Laurson 1932).

In The United States of America, Chicago had the first comprehensive design implemented by an American city. The system was designed by E. S. Chesbrough in a report completed in 1858 (Metcalf and Eddy 1928). He soon consulted on similar comprehensive plans for many other cities. Prior to this initial design, the history of American sewage is paltry. In many of the towns, the early drains were built, maintained, and even owned by private individuals or groups of individuals who charged for their use by others. This was the situation in Boston, for example, where the sewers were originally constructed in 1700 but the city did not acquire control of them until 1823 (Kirby and Laurson 1932). Cumulatively, the work done by engineers and others in the laying of American sewers, at least until the middle of the nineteenth century, should not be described with the term “design.”

Other important designers of sewer systems in the U.S. included Moses Lane, James P. Kirkwood, and Col. Julius W. Adams. The designs implemented in the U.S. made use of empirical data obtained from European practice as to capacity and probable quantities of rainwater to be carried by the sewers (Webster 1921). The use of this empirical data caused deficiencies in the drainage systems because of the climatologic and topographic differences between parts of the U.S. and Europe.

Of all the important American engineers, Adams was probably the most influential of his day. His treatise on “Sewers and drains for populous districts,” published in the *Transactions of the American Society of Civil Engineers* in 1880, was widely used by engineers for at least twenty-five years (Metcalf and Eddy 1928). What Adams did for “quantity” design, Hering can be considered to have done for “quality” planning. He studied European sewerage systems and wrote about the benefits and shortcomings of combined and separate systems of sewerage (Hering 1881) in terms of sanitation. His discussions brought the argument between those supporting separate systems and those supporting combined systems to a head. He offered recommendations for the use of each only in certain situations. The debate between the proponents of separate systems and those of combined systems continued into the new century. Additional discussions of Hering’s ideas concerning combined and separate sewer systems continue in the *Wet Weather Management: 1860-1960* section below.

The planning of early American sewerage was influenced by two general factors, the topography of the city and the place of disposal (Metcalf and Eddy 1930). The grade of the ground surface affected decisions concerning the mode of sewer transport (open channels or below ground conduits), the size of the sewers, and the arrangement of small and large sized sewers. With gravity being the desired vehicle for transportation, it can be understood why the topography would play such an important role. In most situations, the use of natural drainage patterns in conveying stormwater was preferred, especially when streets were planned according to the lay of the land. Specific considerations also included the dilution capability of the receiving stream and the location of the proper disposal location. The factors affecting sewerage design increased after Hering’s trip to Europe in the late 1870s.

The amount of runoff emanating from a catchment is paramount in the design of drainage structures. The design methods utilized in the middle of the nineteenth century can be described as simple estimations or percentage calculations and sometimes weren’t based on the hydrological sciences at all. For instance, the new sewers built in Paris from 1833 onward were made six feet or more high whenever possible, in the belief that the workmen employed in cleaning them would perform their duties more efficiently if they could labor without being forced to take unnatural positions (Metcalf and Eddy 1928). In London, during the same time period, an accident involving sewer workers prompted a commission to resolve that ‘it shall be laid down as a first principle that no common sewer shall be so small that an ordinary sized man shall not be able to cleanse it’ (Gayman 1997). Therefore, the sizing of sewers in some instances was based on human physiology rather than sound engineering calculations.

The basis for the determination of surface runoff was based on empirical results. For example, the English-speaking engineering community used Roe’s Table (Figure 3-4) predominantly during the middle of the nineteenth century (Metcalf and Eddy 1928).

Inclination Fall or Slope of Sewer	Inner Diameter, or Bore of Sewer in Feet									
	2	2.5	3	4	5	6	7	8	9	10
	Acres	Acres	Acres	Acres	Acres	Acres	Acres	Acres	Acres	Acres
Level ……………………….	39	67	120	277	570	1020	1725	2850	4125	5825
1/4-in. in 10 feet or 1 in 480	43	75	135	308	630	1117	1925	3025	4425	6250
1/2-in. in 10 feet of 1 in 240	50	87	155	355	735	1318	2225	3500	5100	7175
3/4-in. in 10 feet of 1 in 160	63	113	203	460	950	1692	2875	4500	6575	9250
1-in. in 10 feet of 1 in 120	78	143	257	590	1200	2180	3700	5825	7850	11050
11/2-in. in 10 feet of 1 in 80	90	165	295	670	1385	2486	4225	6625		
2-in. in 10 feet of 1 in 60	115	182	318	730	1500	2675	4550	7125		

Figure 3-4. Roe's Table, Showing the quantity of covered surface, from which circular sewers will convey away the water coming from a fall of rain of 1 inch in the hour, with house drainage, as ascertained in the Holburn and Finsbury Divisions (McMath 1887).

Although some London engineers refused to use the Table, most respected Roe and therefore implemented some of his design strategies nevertheless. The Table was supposedly empirically derived from observations of London sewers in the Holborn and Finsbury divisions by Roe over a span of twenty years. It gave the catchment areas which could be drained by sewers of various sizes and on various slopes, as indicated by his experience. Numerous equations and tables existed similar to Roe's Table in basis and function.

Bazalgette, a prominent London engineer in the 1850s and designer of the Main Drainage of London, planned for exceptional rainfall events in his design of sewer systems (Metcalf and Eddy 1928). He calculated the volume of sewerage which would be consumed by a certain frequency event then estimated the limit of overflows desired. From this information he determined the additional volume of pipe required for the system to function adequately (Bazalgette, as referenced in Metcalf and Eddy 1928). It should be noted that these calculations were implemented in the designs by Bazalgette for the Main Drainage of London in the 1850s.

Although sanitary waste was a constant input to the sewer systems of Europe, designs did not anticipate this addition until 1843 in Hamburg and the late 1800s in most areas. The sewers and drainage appurtenances were for surface waters and rainwater drainage exclusively. Of course this is not to imply that illegal connections were not present, when in fact it was often the case. The first type of wastewaters legally allowed into the sewer system were dishwater and other liquid kitchen wastes. The provision in the laws for sanitary connections from house to sewer did not come until later. Specifically, Paris did not allow legal sanitary connections to its sewer system until 1880 (Reid 1991) and London did not allow sanitary connections until the first Act made it possible it 1847 (Kirby and Laurson 1932). An increase in manpower and improved maintenance techniques, in addition to the improved planning, design, and construction, ultimately led to the Paris and London sewer systems successfully transporting stormwater and wastewater to the receiving stream. Despite the fact that wet weather management progressed in urban areas, little consideration was yet given to receiving water impacts.

The wet weather management systems of many European cities required years of attention and effort from many individuals to develop them to the standards they attained in the late 1800s. Even though the systems functioned with marginal success by today's criteria, once in a completed stage, society viewed them with amazement and considered them a grand achievement of their time (Reid 1991). Some cities touted their sewerage systems in an effort to rally public support. This enthusiasm was exemplified by the introduction of tourism to the sewer systems. In Paris, for instance, guided boat tours through the sewers offered the tourist an opportunity to view the mysterious underground labyrinth (Reid 1991). London had a similar trip for tourists wishing to view the sewers and drainage tunnels. An open air trolley conducted interested riders under the Thames and to various parts of the drainage and sewer system (Gayman 1997). The fascination with the Paris sewer system continues to this day and a guided tour is still possible.

Additional sewer system design improvements came in the latter part of the nineteenth century with rainfall-runoff predictions, hydraulic calculations and sewage disposal practices becoming infused into the wet weather system designs. These advancements are discussed in the following section.

Wet Weather Management Practices: 1860-1960

The above section discussing the middle ages culminated in the development of wet weather management strategies to the point of comprehensive design for sewerage systems at the conclusion of the nineteenth century. Hamburg, in 1843, is considered the first city to be designed according to comprehensive planning with other major European cities such as London and American cities such as Chicago following soon thereafter. Although the comprehensive planning was a definite step forward, the design practice remained empirically based and often improperly conducted. Much work was still needed in advancing design strategies for quantity, but in addition, the quality issues required attention. The technical literature from 1860 to 1960 addresses these topics as well as others and this portion of the review will detail those advancements. Since the literature sources originate mostly from U.S. publications, a bias toward American sewerage development is unavoidable. It is noteworthy that American sewerage among the branches of engineering is exceptional for the overwhelming influence of experience, rather than experiment, upon the development of many of its features (Metcalf and Eddy 1928). We shall keep this in mind as the development of wet weather management is explored.

In the second half of the nineteenth century the hydrologic and hydraulic design methods used to size sewers became enhanced. Most notably, the rational method was developed in this time period by Mulvaney (1851), Kuichling (1889) in the United States, and Lloyd-Davies (1906) in Great Britain. The major advancement to the determination of runoff quantity with the rational method of Kuichling was the introduction of the time of concentration as a design parameter. Essentially, Mulvaney assumed a constant rate of rainfall and was concerned with the maximum rate of runoff, whereas Kuichling discussed the need to incorporate the relation between rainfall intensity, drainage area. and the time of concentration. The rational method, in general, was based on the assumption that a realistic flow of the chosen frequency can be obtained if the rain intensity of duration similar to the travel time of water in the sewer system was applied to the drainage catchment. The flow was subsequently used to design the size of the sewer pipes.

Prior to the rational method, runoff determinations took the form of empirical formulae. Most of these formulae calculated the runoff reaching a sewer system based on drainage basin size, sewer slope, and other parameters, while others calculated the size of the pipes directly from the input parameters. Some of the equations used can be attributed to Adams, McMath, Hering, Parmley, Gregory, Burkli-Zeigler, Roe, and Hawksley (Hoxie 1891; McMath 1887; Buerger 1915). These equations all were derived based on site specific data and conditions, consequently they provided poor results when applied to other drainage basins (Buerger 1915), especially in the U.S.

Some of the more popular equations used to design sewer systems in the U.S. during the early 1900s are presented below (Buerger 1915):

Hawksley (or Bazalgette):

$$\log d = \frac{3\log A + \log N + 6.8}{10}$$

where d = diameter of sewer (inches);
N = length of sewer per foot of drop; and
A = drainage area (acres).

Adams:

$$q = CR^{0.83}\frac{S^{0.083}}{A^{0.167}}$$

where q = discharge (cubic feet per second, cfs);
C = an empirical coefficient;
S = slope (feet per 1000 feet);
A = drainage area (acres); and
R = rainfall (inches per hour).

McMath:

$$q = CR\frac{S^{0.20}}{A^{0.20}}$$

Burkli-Ziegler:

$$q = CR\frac{S^{0.25}}{A^{0.25}}$$

The Hawksley equation is distinct from the other three displayed in that it calculates the size of the sewer directly. This formula reflects the older attitude in design more in line with Roe's Table (shown above) in that the formula calculates the size of the pipe. The other three formulae, which were develop to replace Roe's Table and other formulae such as the Hawksley, calculated the discharge from the drainage basin for a storm event of a particular intensity. This flow was then used to design the size of the pipes.

The Adams, McMath, and Burkli-Ziegler formulae are very similar, especially the McMath and the Burkli-Ziegler. The equations were derived from empirical observations, consequently they reflect the specific situations from which they were derived. This results in the small amount of variance noticed in the formulae. The differences between each provide the reason why one method is more accurate for a specific set of conditions, but less accurate for a different situation. The older literature that compares these methods displays the observation that in some situations the Adams formula is the best, but in others the McMath is the best, and so on (Gregory 1907; Grunsky 1908; Buerger 1915). This indicates that a formula can be derived to fit some situations, but it most likely will not be the best for all the situations.

The application of the equations and tables required knowledgeable and experienced engineers, because, in addition to the usage of the calculations, certain contingencies had to be anticipated in designing the system. Therefore, not only were the formulae influenced by the site conditions, but the influence of the design engineer was also imparted on the results.

Buerger (1915) presented a formula method that was not based on site specific criteria. He compared his method to much of the observed data that was available at the time and concluded that his method was superior to previous formula methods. The results obtained from the rational method are used for comparison because at that time it was considered to produce the best results. He reasoned that his method was preferable to the rational method since it is a singular formula, although it was complicated in form.

The rational method did not seize the engineering community immediately. Well into the twentieth century, the older empirical formulae mentioned above were still being utilized in practice (Buerger 1915). Only after a slow transition in the early part of the twentieth century did the rational method become the dominant technique for drainage design in the U.S. and worldwide.

Drainage became a legal concern as well as an engineering concern in the middle 1800s. Courts found municipalities liable for the damages caused by negligent drainage design. In Wisconsin, The State Supreme Court ruled that if a sewerage system was constructed without a properly adopted plan, the city was liable for any damages that may result (Metcalf and Eddy 1928). It was also ruled that the city was not liable for defects in construction or materials, but only for improperly planned systems. Although the courts did find some municipalities liable, they also ruled in favor of the city on occasion. The Missouri Supreme Court supported the sufficiency of a sewer system although several failures had resulted in three occurrences of floods on a commercial property (Metcalf and Eddy 1928). The court ruled that since the floods were caused by unusual storm events the municipality couldn't have planned for, no liability existed. In other words, exceptional storms did not have to be taken into account by the engineer designing sewerage systems.

Combined sewerage was the usual method of removing wastes from urban areas in Europe during the late nineteenth century, but separate sewerage systems had proven successful, for example at Hamburg, Germany (Metcalf and Eddy 1928). The combined sewers were not originally designed for sanitary wastes, but the ease of which sanitary wastes could be disposed of in the sewers became apparent resulting in the practice of adding sanitary waste to storm sewers creating combined sewers. A debate began in the late nineteenth century between the use of combined versus separate sewerage systems in the U.S. and elsewhere. Bourne (1966) provided one of the first American arguments for separate sewerage. He advocated the separate system for reasons of sanitation.

Another adamant supporter of separate sewer systems in the U.S. was Col. George E. Waring, Jr. (1878 and 1879). He designed several of the early separate systems including one for the City of Memphis in 1880 (Odell 1881). Some of the systems performed adequately, but others failed miserably with repeated blockages and backups in the sanitary sewer lines. Part of the problem attributed to Waring's designs was his insistence that the size of the house connection to the lateral sewer be small (typically four inches). This small size in comparison to other designs of six inches or more is what many believed to be the root of failures in Waring's systems. To learn more about separate and combined sewer systems, Rudolph Hering visited Europe in the late 1870s at the behest of the U.S. National Board of Health. His findings from the trip became a report to the National Board of Health on the benefits and drawbacks of each type of system (Hering 1881a; Hering 1881b). Hering's recommendations included using combined systems in extensive and closely built-up districts-generally large or rapidly growing cities, while using separate systems for areas where rain-water did not need to be removed underground. Despite Hering's report and the support of his conclusions (White 1886), the discussion continued, some may say even till today.

The turn of the century ushered in a change of philosophy in terms of waste treatment. Typically sewage and stormwater were simply discharged into a stream or river of adequate capacity to dilute the waste. The dilution of waste was an engineering discipline with design calculations determining if a stream had the capacity to dilute the waste to prevent objectionable conditions from developing. The sewerage systems would be designed such that the maximum amount the receiving system could dilute would be discharged. The placement of the outfalls would be changed to accommodate this requirement, not the actual amount of waste being discharged. Unfortunately, the dilution strategy completely ignored any unseen impacts imparted on a receiving water system.

Besides the increased attention given to treatment of sanitary waste, stormwater treatment was also being addressed. Whipple, *et al.* (1906) discussed the stormwater treatment operations being utilized in the U.S. The usual method instituted for combined sewer systems entailed sending as much of the storm flow/sanitary sewage mixture to the treatment plant by way of the intercepting sewer. The plant capacity was the limiting design factor for this action. The interceptor sewer conveyed a certain amount of the waste stream to the plant with the remainder being overflowed directly to the receiving water system, in most cases. Treatment plants and collection systems were typically designed to treat twice or more the dry weather flow (Whipple, *et al.* 1906). During wet weather, flows were observed to increase in sewer systems by a factor of one hundred over dry weather flows on occasion. Occurrences such as this could not be designed for economically, thus the sewage flows greater than the design capacity of the conveyance system would result in frequent overflows. Alternate treatment methods for combined sewage and stormwater discharges included spreading the flow on beds of coarse rocks or spreading on land

(Whipple, *et al.* 1906). It should be stated that municipal sanitary sewage treatment was still in its infancy and therefore, the application of these concepts to wet weather flows was rather rudimentary.

Intensive efforts in rainfall data collection and analysis occurred in the second half of the nineteenth century in the U.S. (Berwick, *et al.* 1980). The primary motivation was to study the relationship between the intensity of the rain and its duration for the needs of storm drain design. Talbot in 1899 performed some of the initial work, using U.S. Weather Bureau records at 499 stations to plot storm intensities versus durations on a cross-section paper. Two envelope curves were drawn, one depicting the very rare rainfalls, and the other the ordinary rainfalls. These curves became the forerunner of the present day intensity-duration-frequency curves for drainage design. Since Talbot constructed his curves, many cities, public agencies, and engineering firms have developed similar equations for specific locations (Berwick, *et al.* 1980).

The rain gage was the instrument used to record rainfall data. Rain gages have been in existence since man first began studying the weather and hydrology. They have developed from their beginnings as simple containers that could capture and hold rainwater. The measurement would be done manually following a storm, or a specific period of time. Gradually, the gage became more of a standardized instrument. In the mid 1800s, detailed records began to be kept for daily, monthly, and annual rainfall amounts at many stations throughout the U.S. The U.S. Weather Bureau became responsible for the administration of these stations. By the early 1900s, the rain gauge had become standardized by the U.S. Weather Bureau. The standard rain gage used consisted of a cylinder 8 inches in diameter and 2 feet high (Steel 1938). In the upper end was a funnel which discharged into a collecting tube. The tube had a cross-sectional area one-tenth that of the cylinder. A measuring stick was used to determine the height of the water in the tube. This type of measurement only provided rainfall between daily readings. Automatic recording gages were also in use in the early 1900s to determine rainfall during short periods of time (Steel 1938).

The early twentieth century witnessed the attempt to describe the rainfall-runoff process more accurately (Rafter 1903; Gregory 1907; Hoyt 1907; Grunsky 1908; Justin 1914; Buerger 1915; Meyer 1915; Grunsky 1922, to mention a few). Prior to this time drainage design formulae had not considered the rainfall-runoff process carefully, instead empirical relationships were used which related pipe size to watershed characteristics such as size, slope, etc. (Roe's Table or Hawksley's formula for instance). By the 1920s, the accumulation of rain gage records enabled more typical "design storms" to be used, in which rainfall intensity rose to a peak and then died away. The unit hydrograph (UH) concept is an example of these enhanced procedures based on design storms. Sherman (1932) developed the concept of the UH for gaged watersheds and others modified it or applied in different manners subsequently (Pettis 1938; Brater 1939). Since reliable rainfall-runoff data were rare, it was difficult to develop unit hydrographs for most drainage basins. To solve this problem, others developed methods to utilize the UH principles on ungaged watersheds. The derivation of these synthetic unit hydrographs was typically based on the characteristics of the watershed (Snyder 1938; Clark 1945).

Economical and adequate design of wet weather sewer systems was possible with a knowledge of only the magnitude and timing of the expected peak flow in the absence of contributing laterals. The proper sizing of more complex systems and the testing of the capacity of existing systems requires a knowledge of the time-history of flow in the sewers in addition to the time-history of rainfall (Eagleson 1962). Until the introduction of unit hydrographs (UH), no design strategy had considered using the runoff hydrograph and storm hyetograph, only the peak rate of runoff was utilized.

Following from the UH applications, a renewed interest in the rainfall-runoff process was observed in the 1940s. Methods for determining runoff from rainfall had been based on coefficients of some type to account for the losses of rainfall that were observed. In the late 1930s and early 1940s, the abstractions from rainfall became a concentrated topic of research. This extended the idea of using hydrograph techniques for design in lieu of the peak discharge rational methods. Horner and Flynt (1936) first applied the hydrograph techniques to storm sewer design (Horner and Flynt 1936; Eagleson 1962). They considered the variability of rainfall both spatially and temporally in their design methodology. Horner and Jens (1942) developed a methodology to mathematically describe the process of infiltration, among other abstractions and apply the hydrograph techniques to a small basin, with the opportunity for application to a larger basin. Linsley and Ackerman (1942) also presented rainfall losses as being an important part of the rainfall-runoff process that had previously been dealt with using coefficients.

Procedures for UH synthesis from watershed characteristics were developed by Snyder, Clark, and others (Snyder 1938; Clark 1945). The idea that urban runoff hydrographs could be synthesized was originally developed by Hicks. He determined correlation's of certain drainage area properties that could be utilized in the estimation of runoff hydrographs for the City of Los Angeles (Hicks 1944). Practical applications of hydrograph techniques to wet weather design in urban areas also were reported for Chicago and Cleveland soon after Hicks presented the method applied to Los Angeles (Stanley and Kaufman 1953). Hicks' method was criticized because it was too complicated for practitioners to apply, but a revised methodology was utilized in the Chicago and Cleveland applications (Eagleson 1962).

Progress in sewer design during the 1950s was realized in the improved inlet hydrograph and maximum sewer flow rate predictions. Tholin and Keifer presented information and techniques which permitted estimation of runoff from urban areas of various physical properties for a range of storm rainfall characteristics (Tholin and Keifer 1960; Eagleson 1962). In addition, the routing of the flows through the wet weather system (gutters, lateral sewers, main sewers, etc.) to the outfall was conducted. Essentially, the hydraulics of each component of the system were described thus removing most of the fundamental objections to the rational method of design (Eagleson 1962). However, the method was too complicated and found little application amongst most practitioners, although cities such as Chicago, Baltimore and Philadelphia applied the ideas with some success (Tholin and Keifer 1960).

By the 1940s and 1950s, formulae relating rainfall intensity and duration were extended by researchers to include a term for the frequency of occurrence of specified storms (Williams 1978). Such knowledge permitted the selection of a design storm according to the extent of flood damage which might be tolerated in the event of inadequacy of the sewers. This methodology coupled with the advancements in the intensity-duration-frequency curves greatly improved the drainage design strategy. Another advancement in rainfall-runoff modeling was presented in the 1950s. Miller and Paulhus (1957) presented a technique for interrelating antecedent precipitation with season, rainfall depth and runoff response, but routine urban drainage design practice failed to reflect their contribution.

The 1930s and 1940s also became years for research into the pollution of receiving waters from overflows of combined sewage. Intercepting sewers had been the answer to limit the number of overflows, but now designs for retrofits or replacement systems were being designed with sufficient interceptor capacity to limit overflows to a predetermined amount based on receiving water quality impacts (Howell 1930; Gregory, *et al.* 1934; Stegmaier 1942). The impact on the receiving water system was based on the ability of the receiving stream to dilute the waste stream discharged. This and other environmental concerns would become increasingly important as environmental awareness increased. The development of the quality aspects of drainage design and the continued advancement of quantity aspects from 1960 to the present is detailed in the next section.

Wet Weather Management Practices: 1960 to the Present

Much of what occurred in the late 1960s and early 1970s is still being debated and updated today. Therefore, a chronological discussion of wet weather management similar to that above is not prudent. Instead individual subjects must be addressed from their inception, documenting their development to the present day. The remainder of this section will therefore be divided into subsections pertaining to a general subject within the wet weather management genre. These subject headings are considered to be the major topics in wet weather management over the previous thirty years. The evolution of each subject heading will be discussed chronologically within the subsection. Overall, legislation, planning and design, control and treatment, best management practices, modeling, CSO and stormwater characterization, sampling and monitoring, receiving water impacts and urban hydrology constitute the major categories related to wet weather management over the previous thirty years discussed below. This list is in no way all-encompassing of the literature and topics germane to the wet weather field, but the amount of material available is extremely voluminous and consequently prohibitive to an exhaustive coverage.

The main purpose of the following discussions are to shed light on some of the major topics in wet weather management and to display chronologically the development of these topics. The review of these topics provide researchers with insights to facilitate the development of future strategies. The review of the literature should indicate areas that need improvement, areas that are saturated with attention with only small gains, and the areas that will become important in the future. Another benefit of the literature review is to accommodate researchers with a head start in their own personal work. The reviews combined with the database of references developed as part of this work, eliminate much of the library time and footwork necessary in the literature review process. This will allow researchers to conduct more thorough and detailed searches given that the preliminary work has already been done.

Legislation Affecting Wet Weather Management Practices

In order to fully appreciate the development of wet weather management an overview should be conducted of important relevant legislation. Since it is sometimes difficult to tell whether the legislation brought about the scientific studies or if the scientific studies initiated the legislation and what influence public opinion had, these points are not investigated here. Rather, a review of the basic environmental laws and regulations and how they impacted wet weather management strategies shall be presented regardless of the impetus for the law.

The first environmental law passed in the United States is considered to be the Refuse Act of 1899, which made it unlawful to discharge wastes into navigable waters. The lack of improved legislation required this law to be utilized in a regulatory capacity well into the 1960s.

The original Water Pollution Control Act of 1948 (PL 80-845) provided for the organization of several water pollution control agencies within the Federal Government, but provided little in terms of regulatory “teeth.” The act was amended several times from 1948 to 1972 authorizing, among other things, several environmental research centers, the Division of Water Pollution Control within the Public Health Service, and provided for some government control over water pollution (Novotny and Olem 1994).

In response to the increased environmental awareness of the 1960s on the part of its citizens, the United States passed *The Federal Water Pollution Control Act of 1972* (PL 92-500), later renamed the *Clean Water Act (CWA)*). Specific goals set forth by the act included (Lager, *et al.* 1977):

> 1. “To restore and maintain the chemical, physical and biological integrity of the Nation’s waters.” [Section 101(a)].
>
> 2. “Where attainable, an interim goal of water quality which provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water be achieved by July 1, 1983.” [Section 101(a)].

This act defined a national water quality management plan and required the federal government to lead the pollution control efforts with the assistance and participation of the states. The act also required EPA to set water quality standards and develop the National Pollution Discharge Elimination System (NPDES) permitting program (Dodson 1995). Initial efforts to control pollution focused on traditional point sources of pollution, such as discharges from industrial manufacturing processes and municipal wastewater treatment plants. Although the act was meant to be a comprehensive water quality program, in practice the majority of the attention was given to point sources, while nonpoint sources of pollution received less attention (Novotny and Olem 1994).

Section 208 of the act provided for a comprehensive land-use planning process to be institutionalized. Although many planning reports were completed because of the legislation, actual implementation of them was not as ambitious. Planning and enforcement tools were extensive for point sources, but nonpoint sources became neglected in terms of regulatory enforcement (Novotny and Olem 1994).

In 1973, EPA issued its first stormwater regulations. EPA recognized stormwater discharges as point sources, but understood that stormwater discharges could not be easily controlled by traditional, “end-of-pipe” controls. Also the daunting task of issuing permits for all stormwater discharges was considered impractical (Dodson 1995). Therefore, EPA selected particular discharges considered to be significant contributors of pollution (Dodson 1995;

38FR 13530 (May 22, 1973)). Court decisions altered the regulations to require the permitting of other discharges such as municipal stormwater outfalls in 1975 (Dodson 1995).

The CWA is periodically “re-authorized” by Congress, which is usually accompanied by amendments to the act. One such reauthorization was the *Clean Water Act of 1977* (PL 95-217). This piece of legislation affected the combined sewer problem through the innovative and alternative provisions section. This act clearly established Congress’ intent to encourage the development and use of alternative and innovative technology in wastewater treatment (General Accounting Office 1979). Although the act primarily mentioned treatment facilities, EPA stated that its provisions would apply to combined sewer treatment facilities as well (General Accounting Office 1979). However, the application of the act to combined sewer collection systems was never clear.

Another important set of amendments to the *Clean Water Act* was the *Water Quality Act of 1987* (PL 100-4). Important points from this act included the establishment of the National Storm Water Program (NSWP) and Section 402(p) which required a NPDES permit for separate storm sewers (Novotny and Olem 1994). The NSWP consisted of two phases (Dodson 1995):

1. Phase I provides for the regulation of the following discharge categories:
    - Discharges permitted before February 4, 1987;
    - Discharges associated with industrial (and construction) activity;
    - Discharges from large (population > 250,000) municipal separate storm sewer systems (MS4s);
    - Discharges from medium (population between 100,000 and 250,000) MS4s;
    - Discharges which the director of the NPDES program designates as contributing to a violation of a water quality standard or as a significant contributor of pollutants to the water of the United States.

2. Phase II is to conduct studies on stormwater discharges other than those covered under phase I. The studies are to characterize the pollutants in the discharges and establish procedures and methods to control the discharges as necessary to mitigate receiving water quality impacts (Dodson 1995). The EPA and state and local officials will decide the additional discharges to be permitted. Phase II was originally scheduled to begin October 1, 1992, but due to delays did not begin on schedule. It is anticipated that additional permit requirements will be made for small municipalities and urbanized areas, as well as some commercial businesses that handle industrial-type materials (e.g. gas stations) (Dodson 1995).

The EPA published its control strategy for combined sewer overflows (CSO) in 1989 (*Federal Register*, August 10, 1989). The control strategy was dependent on the NPDES permitting system. The goal was to bring all CSO discharges within compliance of the technology-based standards promulgated in the *Clean Water Act*. Other considerations of the control strategy include compliance with state standards and the minimization of water quality, aquatic biota, and human health impacts from wet weather overflows (Novotny and Olem 1994).

EPAs *National Water Quality Inventory, 1994 Report to Congress* noted that pollution from wet weather discharges was cited by States to be the leading cause of water quality degradation. Based on this report and others, EPA has concluded that wet weather discharges, both point and nonpoint sources, are one of the largest inhibitors of water quality. EPA believes that urban wet weather discharges, such as stormwater discharges, SSOs, and CSOs, should be addressed in a coordinated and comprehensive manner. To remedy this, EPA has established the Urban Wet Weather Flows Advisory Committee with an SSO subcommittee and a NSWP Phase II subcommittee. The committee will address urban wet weather problems consistent with the principles identified in the March, 1994, NPDES Watershed Strategy (Wet Weather Advisory Committee 1995). These include a place-based focus for identifying sensitive areas, targeting monitoring and watershed assessment resources to achieve the most cost effective environmental benefits, involving both watershed stakeholders and the public, and measuring progress in environmental terms (Wet Weather Advisory Committee 1995).

Wet weather discharges of concern often occur in urban areas from both point and nonpoint sources. Currently, wet weather sources which must be authorized by NPDES permits include the following (Wet Weather Advisory Committee 1995):

- Municipal and industrial stormwater discharges;
- Sanitary sewer overflows (SSO), which occur when the municipal separate sanitary sewer system's capacity is exceeded due, in large part, to unintentional inflow and the infiltration of stormwater;
- Combined sewer overflows (CSO), which occur when a combined sewer system, consisting of storm and sanitary sewage, is overwhelmed during wet weather events; and,
- Wastewater treatment bypasses, which may be used during wet weather events to prevent treatment process hindrance.

Nonpoint sources, such as agricultural runoff and drainage, are not regulated under NPDES.

The legislation pertaining to wet weather flows appears to have originated from environmental acts of Congress not specifically directed towards wet weather management. But the previous ten years has seen the expansion of the NPDES permitting system for many discharges of stormwater (MS4s, constructions sites, etc.) as a result of specific mention of stormwater in regulations.

One piece of legislation that has recently gained attention that could influence wet weather management strategies in the future is the Total Maximum Daily Load (TMDL) Program. The TMDL Program's basic goals are to identify remaining sources of pollution and allocate loadings in those places where water quality goals are not being achieved (EPA 1997). The background of the program is rooted in the CWA. The CWA has a number of provisions to restore and maintain the quality of the nation's water resources. One of these is for the States to establish water quality standards for desirable conditions of their water bodies.

Despite many provisions to improve water quality, there are still waters in the nation that do not meet State water quality standards. CWA Section 303(d) addresses the remaining waters by requiring States to identify the waters and develop TMDLs for them, with oversight from EPA. Currently, EPA is developing implementation plans for the TMDL program. The development process is incorporating feedback from States, Tribes, and the public to meet the requirements of the TMDL program. This program will impact wet weather management in areas that discharge to water bodies that do not meet State water quality goals.

Wet Weather Management Planning and Design

Planning in the late 1960s was not conducted in a holistic sense. Some strategies had been presented to plan wet weather management comprehensively, but few had actually been implemented. For instance, Boyce (1949) presented a methodology for engineering planning of sewage and addressed stormwater and wastewater in the same paper, but observed them as separate systems, not in conjunction. The concept of watershed management took shape in the 1960s with the formation of Departments of Watershed Management at Colorado State University and the University of Arizona (Renard and Hawkins 1995). Additionally, the American Society of Civil Engineers (ASCE) sponsored task committees devoted to watershed management. These early institutions primarily focused on rural regions and the development of forested land to agriculture. Symposia organized by the committees covered many diverse subjects, including urbanization, water quality, and watershed development and management. Most of the topics are considered applicable today even though more than thirty years have elapsed (Renard and Hawkins 1995).

Comprehensive urban drainage became a primary concern in many metropolitan areas in the late 1960s when it was evident that different sections of a municipality had sewer systems designed by different methods and according to different standards. Often times, the surrounding communities would not organize a regional drainage plan because of competitive and antagonistic attitudes between nearby communities. The situation in Denver and surrounding suburbs displayed such characteristics and to compound the problem was expanding at a rapid rate. In the late 1960s, the Denver Regional Council of Governments contracted Wright-McLaughlin Inc. to develop a standard method of practice for drainage design in the Denver Metropolitan region. The result was a design manual for the area to encourage design engineers to use identical methods and standards during the design process resulting in a more cohesive system. The manual entitled *Urban Storm Drainage Criteria Manual* (Wright-McLaughlin Inc. and Wright Water Engineers, Inc. 1969) was used not only in the Denver region but became a template for other manuals throughout the country (Urbonas and Stahre 1993). Although the manual was thorough in its consideration of quantity control, stormwater quality control was given low priority, which is to be expected since the manual was devised for use in a flood concerned region such as Denver. But, recent improvements and updates to the manual have addressed water quality concerns.

The passage of the *Federal Water Pollution Control Act of 1972* (PL 92-500) provided for areawide planning by virtue of Section 208 of the act. The areawide planning concept was enthusiastically embraced by the planning community. Regional planning boards were organized and began to initiate the planning process in the early 1970s. The areawide, or watershed, planning philosophy became pervasive in government and community institutions. For instance, the U.S. Army Corps of Engineers invoked an *Urban Studies Program* in 1973 to develop, in conjunction with local government, realistic plans which would solve regional water resources problems (Fulton 1974). Others researched particular aspects of the planning process and how it interacted with the watershed planning concept. Walesh (1973), from a practitioners perspective, stated that hydrologic and hydraulic simulations complemented the comprehensive watershed planning technique and should be considered effective tools. One interesting environmental planning philosophy was instituted in The Woodlands subdivision, located north of Houston, during its construction in 1973 (Everhart 1973). The McHarg planning technique (McHarg 1969 and 1970) was utilized to develop a plan that observed environmental constraints in addition to the usual economic and engineering constraints. The utilization of the natural drainage corridors of the land, regardless of the cost effectiveness, constituted a major adjustment in design practice for the time (Everhart 1973). It was the philosophy that an environmental design might cost more in the short term, but over the long term would prove the most cost effective.

The EPA influence in areawide planning took the form of a voluminous planning strategy and design manual entitled *Areawide Assessment Procedures Manual* (EPA 1976). The objective of this series of documents was to provide a "unified technical framework for the analysis of complex areawide wastewater problems." In addition to this manual, other published planning guides influenced the regional planners in addressing wet weather management concerns. For example, *SWMM Level I: Preliminary Screening Procedures* (Heaney, *et al.* 1976) documented a simplified approach to permit preliminary screening of alternate urban stormwater quality management plans, which included the 208 plans. Another planning guide entitled *Water Quality Management Planning for Urban Runoff* (Amy, *et al.* 1974) provided planners with a tool to obtain a first approximation, or assessment of the magnitude of the stormwater management problem. Other planning strategies continued to be presented (Field, *et al.* 1977a), some became implemented, others not.

None of the manuals published addressed design or implementation extensively. Examples of 208 planning projects began to surface in the late 1970s in the literature (Spooner, *et al.* 1978). However, problems still existed concerning implementation of the developed plans. McPherson (1978b) outlined considerations needed for planning agencies to better understand the concerns of local governments to facilitate implementation of areawide plans for stormwater management. McPherson (1978a) also addressed the fractionalized authority of administrative agencies and balkanized governments in metropolitan areas as causes of some of the problems with 208 implementation. The gap in communication between the local governments implementing stormwater management plans and the regional planning agencies is still in existence today. Whipple (1980) later reviewed the 208 planning projects and determined that most had been poorly done. He attributed this to the inadequate data used in the planning process and the lack of anticipated technological advances. His recommendation was to define the environmental objectives prior to optimizing the system from the economical standpoint. Although much of the 208 planning did not produce anticipated results, some did. Poertner (1980) discusses some of these innovative successes in drainage planning.

The late 1970s saw the relationship between land use and stormwater management being defined. Much was published indicating that land use had an impact on the surrounding environment, therefore management schemes could be developed specific to certain land uses. However, the pollution and hydrologic characteristics of each land use had to first be described (Grigg 1985). Papers and reports were prepared, exemplified by the American Public Works Association (APWA) publication *Urban Stormwater Management* (APWA 1981).

The impact of urbanization was a recurring theme in much of the land use studies. It was shown that increased urbanization had a myriad of adverse impacts to the hydrology, water quality, geomorphology, and other characteristics of the watershed. Therefore, it was important to address wet weather management in urbanizing areas to mitigate the impacts caused by the urbanization. A study was undertaken by Berwick, *et al.* (1980) sponsored by EPA with the purpose of formulating planning strategies for residential developments to reduce the documented impacts of urbanization. The report discussed several aspects of the planning process from the wet weather management perspective including: estimating pollutant accumulation and washoff from street surfaces, the development of production functions for evaluating stormwater control options, stochastic models, cost models, and the evaluation of political and social problems concerning wet weather management in residential areas.

Besides improvements in the overall planning strategy, improvements were also realized in design, particularly of storm sewer networks. However, quantity consideration was the common improvement researched. Optimization techniques to determine the optimal cost designs of sewer networks developed in the late 1960s. Linear programming optimization was an early method utilized to determine the least cost sewer network design (Hollang 1966; Deininger 1969; Dendrou, *et al.* 1978; Froise and Burges 1978; Elimam, *et al.* 1989). Elimam, *et al.* (1989) presented a recent method applying a heuristic approach to determine the optimal cost design by linear programming. The early applications stressed wastewater collection systems, but the methodology was applicable to storm sewer networks as well.

Dynamic programming also became a tried method for optimization of sewer networks by a number of researchers (Tang, *et al*. 1975; Mays and Yen 1975; Miles and Heaney 1988). Miles and Heaney (1988) implemented a dynamic programming algorithm on a spreadsheet showing that the spreadsheet was a tool capable of performing engineering design calculations.

The new methods of optimization improved the design of sewer networks, but the major innovation in design was, of course, the development of computer applications and models in the late 1960s. The advancement of wet weather management modeling is discussed below so only a brief mention will be made here. Yen and Sevuk (1975) compared two computer models (ILLUDAS and SWMM) with several other calculation methods and simple routing procedures. Their results indicated that supposedly innovative methods such as the British RRL (a method from England that was applied to U.S. storm sewer network design in the early 1970s (Terstriep and Stall 1969; Stall and Terstriep 1972)) and the Chicago Method did not perform better than the simple routing procedure, although they entailed more complex calculations. In addition, they also determined that the computer models produced the most accurate results consistently, supporting the contention that computer simulations were superior to empirically derived relationships for design purposes.

Although these new methods for sewer network design had been developed, design engineers continued to use the simpler methods such as the rational method (Yen, *et al.* 1974). A survey conducted in 1969 of design engineers throughout Wisconsin attempted to document the storm drainage design practices of 32 cities in Wisconsin (Ardis, *et al.* 1969). The survey indicated that comprehensive planning of cities was taking place, but some plans did not consider urban drainage (Ardis, *et al.* 1969). The design of storm sewers in the 32 cities was primarily done (95.8%) by city engineering departments, under the supervision of a professional engineer. The dominant design strategy employed was the rational formula, however, only a small fraction of the cities utilized it correctly. The primary problem in the application of the rational method involved the runoff coefficient and the time of concentration and its relation to the intensity of rainfall (Ardis, *et al.* 1969).

As part of this current project, a survey has been conducted of many design engineers similar to that conducted twenty-eight years ago by Ardis, *et al.* (1969) except this survey is on a national scale. The results of this survey are presented in Section 4 of this report and provide interesting comparisons between current practices and those of thirty years ago.

Since the late 1970s, sewerage design research has stressed quality considerations more than quantity. The last decade and more has witnessed little improvement in the capabilities design engineers have in the sizing of sewer pipes in networks. However, major advances have been made in the use of these older methods through the use of computer methods (such as the EPA's Storm Water Management Model, or SWMM). New methods have been developed, but often the practitioner is content to remain with the old method that addresses the quantity issue adequately. More emphasis is placed on management practices to reduce the impact of pollutants on the receiving water systems. Since quantity and quality concerns are often competing ends, an optimal point must be attained whereby the most cost effective design procedure is devised to address the quantity and quality issues optimally for a given watershed. Appendix A presents a detailed discussion of integrating quality and quantity objectives in drainage design.

The traditional design storm concept of wet weather management has been criticized for the better part of thirty years. Yet, the rational method and other design storm concepts continue to be applied. The design storm method does not provide an ecosystem-sensitive design, and over long terms could be detrimental to the environment (James 1994 and 1997). James concludes that the attainment of eco-sensitive stormwater drainage design demands the use of continuous modeling (James 1994 and 1997). Many applications of continuous simulation in wet weather design have been documented. Continuous simulation has been shown to be applicable to watershed management (Ellis, *et al.* 1981) and to the design of detention structures (James and Robinson 1982; Loganathan, *et al.* 1985; Ormsbee 1987). Ormsbee views the most lacking aspect of design storm methodologies as being the ignorance of antecedent moisture content, resulting in the assumption that the runoff event has the identical frequency as the rainfall event. Klemes looked at this problem and found that the assumption is, in fact, not true (Klemes 1987) and the runoff event frequency rarely is equivalent to the rainfall event frequency. The motivation and capabilities for continuous simulation design procedures exist, yet many practitioners fail to embrace the technology in wet weather design strategies.

The recent emphasis in wet weather planning continues to include watershed management considerations which were introduced in the 1960s. This is evidenced by the numerous conferences that have convened over the previous five years dedicated to watershed management (e.g. National Conference on Urban Runoff Management: Enhancing Urban Watershed Management at the Local, County, and State Levels (1993); Watershed '96: A National Conference on Watershed Management (1996); Watershed Management: Planning for the 21st Century (1995); Effects of Watershed Development and Management on Aquatic Ecosystems (1996)) not to mention the numerous papers and reports presenting watershed management techniques. Current issues related to wet weather management being addressed at many of these conferences and symposia include:

- Geographic information systems
- Remote sensing
- Decision support systems
- Sustainability and risk analysis
- Watershed planning
- Ecological planning
- Integrated water resource planning and design

Although the watershed management terminology has been around for twenty five years, it does not retain exactly the same definition. Previous watershed planning strategies accounted for wet weather management on a watershed scale for both quantity and quality. However, currently, the trend is watershed management in an integrated fashion. Field (1993) presents a description of what is meant by integrated stormwater management. He indicates that the most effective solution for wet weather management problems must consider (1) wet weather pollution impacts on receiving water systems, (2) structural versus non-structural techniques for control, (3) integrating dry and wet weather control/treatment systems to maximize the usage of dry weather facilities during wet weather events and conversely wet weather facilities during dry weather, and (4) the optimally cost-effective degree of control/treatment required dictated by load discharge or receiving water requirements (Field 1993). Overall, the flood and erosion control technology must be integrated with pollution control technology to provide comprehensive planning that is effective. Research addressing the topic of integrated wet weather management is also taking place in Europe (Harremoës and Rauch 1996; Rauch and Harremoës 1996). Their comprehensive plans entail considering the sewer systems, treatment plants, and receiving waters in a coordinated fashion.

Wet Weather Control and Treatment Practices

This section will focus on the development of downstream, or "end-of-the-pipe," control and treatment technology in wet weather management. The next section pertains to best management practices consisting of source controls, regulations, and education. Many control and treatment options can be implemented at the end of a sewer system to provide flood and pollution mitigation benefits. The mechanisms used to control or treat the wet weather flow can be physical, chemical, biological, or some combination of these. The process is generally structural and man-made, but nonstructural, natural techniques such as wetlands have been applied successfully. With these thoughts in mind, the highlights of the development of wet weather control and treatment options will be presented.

The impacts of CSO and stormwater discharges on receiving waters became increasingly apparent in the early 1960s. Prior to 1960, the impacts of the CSO problem on receiving waters had been studied by some (Stegmaier 1942; Hess and Manning 1950; Palmer 1950; Camp 1959), but was not accepted as a problem by all. The proponents of the dilution strategy still existed (Adeney 1928). The main thrust of the research was water quality studies and the effects that CSOs imparted to the receiving system. The CSO problem was viewed by some to be a nationwide problem in the 1950s (Palmer 1950; Camp 1959), but the funding was not available to remedy the situation.

Increased public environmental awareness in the 1960s spirited by, among other things, the publishing of Rachel Carson's *Silent Spring* (1962) and a general outcry for cleaner water provided the impetus for additional research into water pollution control. The CSO was targeted as a significant pollution source, and thus required attention. The above discussion of wet weather management from 1860 to 1960 mentioned the primary method for treatment during the late 1800s through the first half of the 1900s of combined sewerage was to intercept a certain amount and transport it to the dry weather wastewater treatment plant. The inability of the intercepting sewer to adequately transport the entire combined sewage load during wet weather events resulted in CSO. The only way to guarantee the capture of all combined sewerage was to build uneconomically large interceptor sewers. This was not practical so researchers sought alternate solutions that restricted the occurrence of CSOs to a minimum. Alternate solutions included separating the sanitary sewer system from the stormwater system, in-system storage, ponding, holding tanks and screening and chlorination of remaining CSOs (Dunbar and Henry 1966). Similar to increasing the size of the intercepting sewer, these methods also proved uneconomical, impractical, or ineffective. In turn, physical, chemical, and biological treatment techniques, some borrowed or adapted from dry weather wastewater treatment technology, became applied to CSO and stormwater discharges as unit processes or as part of an overall treatment train.

The remainder of this subsection is divided into four categories depicting the major areas of control and treatment of wet weather flows. The categories are based on the underlying processes that result in the control and treatment of the flow. The four sections are physical control and treatment, chemical treatment, biological treatment, and storage/release systems. There is overlap between these sections by many of the techniques utilized in managing wet weather flows, but processes are only discussed in one section when applicable. For instance, a detention basin relies on the physical process of settling to remove suspended material, but under certain circumstances, biological activity can occur that further treats the runoff. The same can be said of storage/release systems which might utilize physical processes in detention, then chemical and biological processes during treatment. Appendix D of this report details the literature pertaining to many of the control and treatment processes briefly introduced here, as they are applied in the Source Loading and Management Model (SLAMM).

Physical Control and Treatment Processes

Physical treatment processes offer several advantages for the treatment of wet weather flows (Field 1990). First, they are adaptable to automatic operation, including rapid startup and shutdown. Second, their resistance to shock loads is a requirement when considering wet weather events. And third, physical treatment methods have the ability to consistently produce a low suspended solid (SS) effluent. Physical treatment unit operations include screening, straining, filtering, settling, and flotation. The application of these processes are incorporated into many control techniques.

One type of physical control technique involved the application of swirl and vortex technologies. Smisson utilized a cylindrical vortex-type CSO regulator/settleable-solids concentrator in England during the 1960s (Smisson 1967; Field and O'Conner 1996). The U.S. Environmental Protection Agency (EPA) funded a series of research projects in the mid 1960s through the early 1970s investigating swirl technology (Sullivan, *et al.* 1972; 1974; 1976; 1977; 1978; and 1982). The EPA-sponsored projects developed the swirl concentrator/regulator for controlling CSOs (Sullivan, *et al.* 1972). The dual functioning swirl concentrator/regulator could achieve both quantity and quality control of CSO and stormwater discharges. Settleable solids removals have been observed in field studies to be as high as 40-50% (Field 1990) for the swirl concentrator. Combine these benefits with the fact that the swirl has no moving parts, and the result is a viable option for CSO and stormwater discharge control.

A product of the EPA-sponsored studies included several general conclusions regarding the application of swirl technology in controlling and treating CSO and stormwater discharges. It was concluded that the swirl technology in principle could be utilized to obtain clarification of wastewaters, including CSO and stormwater discharges (Sullivan, *et al.* 1978). The absence of moving parts in the swirl concentrator made it an easily maintainable device with minimal operation and maintenance costs (Sullivan, *et al.* 1982). Another benefit observed during the studies was the effective use of limited space by the swirl concentrator. Generally, areas requiring CSO or stormwater discharge control and treatment are urban and therefore space constrained. A device such as the swirl concentrator utilizes a minimum of space to accomplish its task, which is highly desirable (Sullivan, *et al*. 1978). Other control technologies similar to the swirl concentrator include the helical bend regulator/concentrator and several commercial products such as the Storm King and Fluidsep vortex-hydrodynamic separators (Field and O'Conner 1996). Unfortunately, swirl concentrator technology alone seldom results in large improvements in CSO quality.

Additional research in the 1970s and 1980s supplemented the findings of the Sullivan-led research group. Some of these researchers include Field and Masters (1977) and Pisano, *et al.* (1984). The use of the swirl technology continues to be refined today (Moutal, *et al.* 1994; Field and O'Conner 1995; Field and O'Conner 1996).

Other physical control and treatment options that were researched included filtration and screening. Filtration, using different media types and arrangements, was shown to be a viable option for the treatment of CSO and stormwater discharges in the early 1970s (Accoustica Associates, Inc. 1967; Fram Corporation 1969; Rand Development Corporation 1969; Harvey and Fan 1972; Lee, *et al.* 1972). Applications included both flow rates utilized in conventional dry weather wastewater treatment and high flow rates tailored to the wet weather event (Lager, *et al.* 1977). Dual media high-rate filtration was found to be effective in reducing the suspended solids and heavy metal concentrations in wet weather flows (Field 1990). Currently, the use of filtration is being targeted for upland and source controls in addition to 'end-of-the-pipe' controls.

The screening of wet weather flows, similar to filtration, proved effective at reducing the suspended solids loading and loading of pollutants associated with suspended solids (Cornell, *et al.* 1970; Envirogenics Company 1970; City of Portland 1971). Screens of various types and with various size openings were implemented with varying degrees of success. Benefits of screening were also realized by applying the process as pretreatment for other processes such as microstraining, dissolved air flotation and disinfection (Rex Chainbelt, Inc. 1972; Gupta, *et al.* 1977; Meinholz 1979). Advantages of dissolved air flotation over conventional settling include higher overflow rates, shorter detention times, and the ability to remove particles with densities higher and lower than the liquid flotables such as oil and grease (Field 1990). The advantages of dissolved air flotation are especially apparent in applications to CSO control and treatment.

The retention or detention of stormwater and CSO was also researched to determine its efficacy for treatment (Springfield Sanitary District 1970). Storage in one form or another is the best documented abatement measure, and can equalize flows and reduce flood peaks as well as facilitate the removal of pollutants through settling. Storage has been a planned element of wet weather management since the 1800s (Chittenden 1918). It was originally applied in the form of detention basins in Germany and England before being implemented in the U.S. Wet weather storage facilities can be classified as either in-line or off-line. In-line storage requires no pumping, and consists of storage within the sewer system itself or in-line basins (Field 1990). Off-line facilities for storage include basins and tunnels, and typically require pumping facilities for operation (Nix and Durrans 1996).

Currently, detention in one form or another is the most often implemented form of wet weather control (Urbonas, *et al.* 1994). Planning methods for detention on both the small scale and large scale have been developed over the previous thirty years (Wenzel, *et al.* 1976; Mays and Bedient 1982; Ormsbee 1983). Besides planning, the design of detention basin has also been an oft researched topic (Rao 1975; Ormsbee 1987; Segarra-Garcia and Loganathan 1994). The use of detention for the dual purpose of flood control and pollutant removal has been studied in more recent times (Whipple 1979; Jones 1990). The topics introduced here are only a brief indication of the ubiquity of the practice of detention in stormwater management. Further support is observed in the number of textbooks and design manuals that have been published pertaining to the subject, Urbonas and Stahre (1993) for example and conferences covering the topic, DeGroot (1982) for example.

In addition to traditional detention devices, underwater storage and in-receiving water storage were determined to be marginally successful in the control of CSO and stormwater discharges (Melpar 1970; Karl R. Rohrer Associates, Inc. 1971). Karl Dunkers, from Sweden, developed unique and effective in-receiving water approaches to wet weather management to protect lake water from pollution (Field 1990; Forndran, *et al.* 1991). The technology has since been applied in the United States (Field, *et al.* 1992). Tunnel storage has also become an option for some large urban areas that need storage space but do not have the real estate to devote to detention. Chicago is a prime example of this type of alternate strategy for detention (Robinson 1986).

Alternative techniques for CSO treatment have continued to develop up to the present. One alternative disinfection technique which requires short detention times and precludes the development of toxic by-products is disinfection by ultraviolet (UV) light irradiation (Scheible and Forndran 1986; Scheible, *et al.* 1991). Other alternative treatment techniques that can attain high pollutant removal rates include high gradient magnetic separation (Allen 1977; Allen 1978) and powdered activated carbon (Lager and Smith 1974). These advanced techniques are cost prohibitive and therefore are implemented only in cases when the effluent quality must be very high.

Chemical Treatment Processes

Chemical disinfection had been the traditional method for treatment of sanitary wastewater, but stormwater and combined sewage were generally not treated in a comparable manner due to the assumption that disinfection of dry weather flow resulted in effective protection of receiving water systems (O'Shea and Field 1993). Several studies which addressed the treatment and disinfection of stormwater and CSO were conducted during the 1960s providing evidence that treatment should be required and that the large variations in flows were the principal problems to be overcome for the chlorination procedure to be effective (O'Shea and Field 1993). The use of chlorine (Cl_2) and chlorine dioxide (ClO_2) and other chemical disinfectants was shown in several applications of high-rate disinfection processes to result in significant bacterial population reductions in CSO (Cochrane Division, Crane Company 1970; Roy F. Weston, Inc. 1970; Moffa, *et al.* 1975; Drehwing, *et al.* 1979). Other chemical oxidizing agents that can be applied include bromine and hydrogen peroxide and their compounds.

To improve the disinfection process, microstraining and screening and various other unit processes were added to the treatment train to remove and/or fragment particulate and organic matter containing bacteria prior to disinfection (Cochrane Division, Crane Company 1970; Shuckrow 1973; Glover and Herbert 1973; Maher 1974; Drehwing, *et al.* 1979). The reduction of coliforms across the microstrainer were found to be minimal, but the effluent required less chloride for disinfection and shorter detention times (O'Shea and Field 1993). Drawbacks with the screening process included operational problems during start-up and initial performance (Drehwing, *et al.* 1979). However, overall, the research into the application of high-rate physical and chemical treatment processes was found to be a viable and economical technology in most situations (Drehwing, *et al.* 1979).

Biological Treatment Processes

Biological methods also garnered some attention for CSO treatment (Storm and Combined Sewer Pollution Control Branch 1970; Welch and Stucky 1974; Agnew 1975). Due to the random, intermittent nature of wet weather flows, CSO and stormwater discharges are a difficult waste stream to treat, especially with biological methods which require a specific range of conditions to remain viable. Biological treatment methods applied to CSO and stormwater treatment include rotating biological contactors (Welch and Stucky 1974), contact stabilization, trickling filters (Homack, *et al.* 1973; Parks, *et al.* 1974) and treatment lagoons (Connick, *et al.* 1981). Biological treatment methods can have high pollutant removal efficiencies although they are susceptible to shock loadings. The biological treatment processes are typically termed secondary, and depending on the situation, can remove 70-95% of the BOD_5 and SS for ranges of 30 to 10 times dry weather flow, respectively (Field 1990). The biological treatment processes utilized for wet weather management are typically part of dry weather treatment facilities.

Wetlands are becoming an increasingly popular method for the control and treatment of wet weather flows. They have the advantage of providing flood control and pollutant removal capability similar to the detention basin. Natural wetlands can be used for stormwater management, but in most situations engineered and constructed wetlands provide for the best compatibility between the system and the desired control and treatment. Another advantage of the wetland over most other control and treatment technologies is the fact that it offers a sustainable option for wet weather management which is becoming more and more important. A thorough review of the literature pertaining to stormwater wetlands was conducted by Strecker (1993) therefore the reader is directed to this source for additional references.

Storage/Release Systems

During the 1970s, the prominent means of control of urban stormwater quantity and quality was through some type of storage/release system (Heaney, *et al.* 1977; Lager, *et al.* 1977; Finnemore 1982). The storage/release system remains an integral part of wet weather management strategies in the present day. Storage/release systems provide storage to capture a portion of the highly variable stormwater flows and pollutant loads and a release process through which the contents are released in a more controlled fashion (Nix 1982). If the release is input to a wastewater treatment plant or a treatment unit process, the terminology storage/treatment is applied to the system. The storage of wet weather flows can also act as a treatment process, with settling and biological mechanisms improving the water quality. Therefore, often the terms storage/release and storage/treatment are used interchangeably. Although detention basins are the primary structure used for storage/release systems other appurtenances, such as rooftops, parking lots, catch basins, and sewer systems, can be utilized in this capacity (Nix 1982).

An example of a successful implementation of a storage/release system in the late 1960s was documented by EPA for a site located in Chippewa Falls, Wisconsin (City of Chippewa Falls 1972). The demonstration was undertaken to determine if CSO could be mitigated by storing the overflow and subsequently pumping it to a dry weather wastewater treatment plant. The results indicated that storage with ensuing treatment was a viable alternative for wet weather management.

The benefits of storage/release combinations for controlling wet weather flows continued to become evident. The progression during the 1970s resulted in the inclusion of storage/treatment options in the state-of-the-art update for urban runoff pollution control compiled by Field and Lager (1975). At that time, storage/treatment strategies were considered the most promising approach to urban stormwater management. Following the study conducted at Chippewa Falls, other investigations were conducted and resulted in additional support for the effectiveness of storage/release systems (Consoer, Townsend, and Associates 1975; Lager, *et al.* 1977).

The storage/release system might have been shown to be a viable alternative by these case studies, but the incremental amounts of storage constructed and treatment capacity provided were not being determined in an optimal fashion in most cases. Original methods of determining the best combination were characterized by trial and error economic calculations and design storm calculations (City of Chippewa Falls 1972; Field and Lager 1975). The application of optimization techniques to determine the most cost effective combination of storage and treatment for a specified performance standard came in the mid 1970s.

The central focus of most of the research into optimization of the storage/release alternatives involved the application of microeconomic theory, of which a characteristic was the production function. The production function, as applied to the storage/release system, was represented by a series of plotted curves depicting the combinations of storage and treatment required to attain specified levels of system performance. These curves were termed isoquants and could be used in combination with cost data and an optimization algorithm to determine the least cost design for a specified level of pollutant control.

Storage/release system optimization applying microeconomic theory became a thoroughly researched area during the 1970s (Heaney, *et al.* 1976; Howard 1976; Heaney and Nix 1977; Heaney, *et al.* 1978; Flatt and Howard 1978; DiToro and Small 1979; Small and DiToro 1979; Howard, *et al.* 1981; Medina, *et al.* 1981a and 1981b; Nix 1982). A cost effective use of storage and release or treatment strategies was sought that would optimize the runoff attenuation and pollutant removal capabilities of the system for the minimal cost. The effectiveness of a storage/release strategy is based on the long-term pollution control performance. Methods to estimate this performance can be divided into three categories: (1) empirical relationships, (2) statistical techniques, and (3) deterministic simulation (Nix 1982; Nix *et al.* 1983; Nix and Heaney 1988). Sediment trap efficiency curves developed by Brune (1953) and others exemplify empirical relationships. Performance data from a number of reservoirs were used to derive the trap efficiency curves.

Statistical approaches were developed, based on several simplifying assumptions concerning the statistical nature of runoff events as well as the operation of a storage/release system (Howard 1976; Flatt and Howard 1978; DiToro and Small 1979; Hydroscience, Inc. 1979). Howard (1976) introduced a statistical methodology to analyze the long-term performance of storage/treatment systems for controlling CSO. In the procedure, probability distribution functions of precipitation volume, duration, and interevent time were derived. Together these functions coupled with other estimated parameters determined the probability distribution function of overflow volume. From this derived distribution, the frequency of overflow and the magnitude of overflow volumes were derived. This method, in combination with other analyses, was useful for estimating the overall cost of pollution control alternatives.

In the same time period as Howard, others were also developing statistically based methods to analyze storage/release systems (DiToro and Small 1979; Hydroscience, Inc. 1979). Adams and Bontje (1983) extended the principles of these researchers in developing analytic probabilistic models to predict the performance of storage/release systems. This technique was formulated into a computer package, termed Statistical Urban Drainage Simulator (SUDS) (Guo and Adams 1994). SUDS was expanded in the early 1990s to include water quality aspects of wet weather management (Li 1991; Li and Adams 1993).

Another extension of the statistical methods developed in the late 1970s used to determine the optimum storage/release strategy was presented by Segarra and Loganathan (1989). This method was based on a first-order pollutant washoff model for defining the pollution control isoquants. Enhancements to this methodology continued to be developed in the 1990s (Segarra-Garcia and Loganathan 1994; Segarra-Garcia and El Basha-Rivera 1996).

Computer simulation approaches were developed prior to Howard’s statistical approach in the early 1970s (Howard 1976). The U.S. Army Corps of Engineers developed a model titled Storage, Treatment, Overflow, Runoff Model (STORM) (U.S. Army Corps of Engineers 1977). This model was developed with the intent to simulate stormwater storage/release systems for performance analysis purposes. The early versions of the EPA Storm Water Management Model (SWMM) did not have the capability to perform the continuous simulations required to conduct the proper analyses, therefore STORM was predominantly used in research efforts in the 1970s. As SWMM was updated in the late 1970s and the early 1980s, it became the preferred tool compared STORM.

One computer simulation approach, presented by Heaney, *et al.* (1976) introduced a preliminary screening model to determine the optimal use of storage-treatment options in wet weather pollution control. They used the production function to devise optimal combinations of storage and treatment based on unit costs of storage and treatment alternatives (Nix 1976 and 1982; and Heaney and Nix 1977). Nix (1976) extended the storage/treatment optimization approach applied by Heaney, *et al.* (1976) to include other wet weather management options such as source controls, best management practices, and other structural and non-structural controls. Additional adjustments to the computer simulation approach introduced by Heaney, *et al.* (1976) were made by Heaney and Nix (1977), Heaney *et al.* (1978), and Heaney (1979). Nix (1982) reviewed most of the statistical and simulation approaches developed in the 1970s and developed an improved Storage/Treatment Block for SWMM. Nix and Heaney (1988) capitalized on the improved electronic spreadsheets and spatial analysis software available to enhance the optimization procedure.

Computer modeling capabilities continued to improve in the early 1980s which enhanced the application of the optimization methods developed in the 1970s (Medina, *et al.* 1981a and 1981b; Nix 1982; Huber, *et al.* 1984; Huber and Dickinson 1988). The EPA SWMM (Huber and Dickinson 1988) and STORM (U.S. Army Corps of Engineers 1977) models remained the two more popular models utilized to simulate storage/release systems.

The traditional strategy of storage/release system implementation revolved around the construction of additional storage and treatment facilities. Field, *et al.* (1994) adjusted this focus somewhat by stressing the use of in-system storage and improving current treatment plant operating efficiency prior to constructing additional units of storage and treatment. This "integrated" optimization strategy attempts to minimize the construction of additional storage and treatment facilities by (Field and O'Conner 1997):

- Maximizing storage and treatment in the current system through operational and low-cost inline improvements,
- Considering the sedimentation which occurs when storage tanks overflow,
- Selecting design capacity of control options in the most economical fashion by choosing the point of diminishing returns on the curve of pollution control versus cost, and
- sizing the storage/treatment system in the most optimal fashion.

The strategy stresses that the cheapest potential wet weather management components should be analyzed first, and then the less economical retrofits and additional construction options should be evaluated. This is similar in theory to a strategy that has been implemented in Europe for the previous ten years which involves optimizing the location and then size of controls. In addition, the European method concentrates on improving short-term control goals providing a platform for long-term goal achievement (Wildbore 1994). Wildbore (1994) explains that implementing smaller structures higher up the system allow much less pollutant load per unit of expenditure and that system wide searches for improvements should be conducted to provide overall cost savings.

Control and Treatment Planning

As individual treatment techniques developed, comprehensive strategies for mitigating CSO and stormwater discharges progressed. The discussion of CSOs continued in the literature with more refinement in treatment techniques, including increased case studies of bench and full scale applications (Field and Lager 1975; Lindholm 1976; Larson 1979). Due to the increased knowledge pertaining to CSO control and treatment, efforts of the engineering community could be directed towards the development of planning strategies to mitigate CSO and stormwater impacts from a watershed perspective. This ideology supplemented the watershed planning schemes already being advanced from the 1960s. The previous subsection discussed wet weather planning and design from a general perspective, therefore only a brief mention of specific planning for CSO control and treatment will be made here.

There was enough knowledge being gathered to facilitate the initiation of conceptual planning for CSO control (Field and Struzeski 1972; Parks, *et al.* 1974; Field and Lager 1974; Giessner, *et al.* 1974; Labadie, *et al.* 1975; Mahida 1975; Janson, *et al.* 1976; Griggey and Smith 1978). Giessne, *et al.* presented a master plan for wastewater management in the San Francisco area (Giessner, *et al.* 1974). The main goal of the plan was to adequately and economically treat dry weather flows, provide for flood protection from the 5-year frequency design storm, and to mitigate the combined sewer overflow impacts on the receiving water system. These goals could be applied to most urban areas which have combined sewerage systems. Some of the other strategies included such topics as real-time control.

Comprehensive planning of wet weather management systems can be implemented in a number of ways. One way, which is the most popular, is to insert control and treatment options throughout the urban watershed that operate as standalone units with some collaboration. Another, improved but more expensive, manner to implement a planning strategy is through real-time control (Anderson 1970; Labadie, *et al.* 1975; Roesner 1976 Coffee, *et al.* 1983; Grigg and Schilling 1986). Real-time control refers to the control of a wet weather systems during a wet weather event by using monitoring and remote control of control and treatment units in conjunction. The optimal use of this technology has indicated that it can be an effective means to manage wet weather flows (Nielsen 1994).

"Best Management Practices"

"Best management practices" (BMP) are the first line of action to control wet weather pollution. By treating the problem at its source, or through appropriate regulations and public education, multiple benefits can be derived (Lager, *et al.* 1977). Some of the benefits realized as a result of BMP implementation include lower costs for downstream controls and treatment, lower cost for conveyance and collection systems, erosion and flood control benefits, and an improved and cleaner neighborhood. BMP success is dependent on many factors, but primarily on legislation or ordinances promulgated to force or encourage conformance with the intended BMP, and a concerted effort to monitor compliance and educate not only those responsible for regulation, but the public as well (Lager *et al.* 1977). The greatest difficulty faced by BMPs is that the action-impact relationships are almost totally unquantified. The reader is referenced to Appendix D of this report for a thorough discussion of source quality controls and the literature pertaining to selected stormwater management controls.

Wet Weather Modeling

A mathematical model can range in sophistication from the very simple empirical equation to complex physically based equations. Countless models are in existence, but a few have had a significant impact on wet weather management. Mathematical models were developed many years ago, and range in complexity from the so called rational method (Mulvaney 1851; Kuichling 1889) to the unit hydrograph procedures (Sherman 1932; Snyder 1938) up to comprehensive computer models. The application of computers over the past thirty-odd years to the modeling procedure greatly improved the capabilities to manage wet weather flows. The use of mathematical equations in the planning and design of wet weather controls constitute elementary models. The advent of the computer greatly enhanced the capabilities of these elementary mathematical models as well as opening doors to improved approximations of the physical processes shaping the hydrology of a watershed. Besides computer models, planning and desk top models also were developed in the 1970s that had a significant impact on wet weather management. But, since some of these models are discussed in other sections of the literature review, this section concentrates solely on computer modeling.

The early applications of the computer to modeling wet weather systems involved using the swift calculating ability of the computer to perform the calculations previously done by hand. However, this process was rarely applied in practice since computers were expensive and mostly inaccessible to practitioners. Watershed modeling applications did develop at university settings during the early 1960s.

Early model developments highlighted by the Storm Water Management Model (SWMM) (Metcalf and Eddy, Inc., *et al.* 1971) had the capability to simulate individual storm events. The optimal solution to a problem was not found by the model, but rather numerous alternatives would be simulated separately and the user would have to select the optimum solution. One drawback with the individual storm event simulations was that the storm event selected did not represent the random occurrence and probabilistic nature of the real hydrologic phenomena (Metcalf and Eddy, Inc. 1971). Others were discussed in an earlier section of this report (See the *Wet Weather Planning and Design* subsection). It became apparent that most planning efforts required data on the probability of occurrence of events of various magnitudes. In most urban situations this could only be provided by the use of continuous simulation models.

Continuous simulation models differ from single event and other simulation models in that they operate under the necessity of a water balance (Linsley and Crawford 1974). In order to execute on rainfall data over long time periods, the model must contain a feedback mechanism that continuously updates and modifies various processes of the model which are dependent on the quantity of water in storage. The earliest of the modern, computer-based continuous simulation models was the Stanford Watershed Model (Linsley and Crawford 1960; Crawford and Linsley 1966), better known as the Hydrocomp Simulation Program (HSPF). In the late 1960s, numerous modifications and various applications of the model were elaborated (James 1965; Drooker 1968; Lichty, *et al.*

1968; Ligon, *et al.* 1969). This model was originally developed to simulate runoff from mostly rural basins, thereby reducing its applicability to urban drainage design. Linsley and Crawford (1974) discussed its applicability to urban watersheds.

The true dawn of the modern computer modeling age directly applied to urban drainage concerns can be placed at the time of development of SWMM in the late 1960s (Metcalf & Eddy Engineers, *et al.* 1971). Throughout the 1970s and 1980s SWMM was adjusted and updated (Heaney, *et al.* 1973; Huber, *et al.* 1975; Huber, *et al.* 1984; Huber and Dickinson 1988) developing it into the forefront of technology utilized in wet weather management. As a testament to its popularity, there are numerous proceedings from user group meetings sponsored by EPA that contain papers pertaining to practical and theoretical applications of the model (for example: EPA 1980a; EPA 1980b). In addition to SWMM, other computer models included the U.S. Army Corps of Engineers Storage, Treatment, Overflow, Runoff Model (STORM) (Hydrologic Engineering Center 1973; Hydrologic Engineering Center 1977) and the Illinois Urban Drainage Area Simulator (ILLUDAS) (Terstriep and Stall 1974). These models all contained the capability to generate runoff hydrographs and pollutographs as well as perform simple routing, which are important in the designing of drainage systems (Nix 1994). SWMM was more advanced, with the capacity to perform more sophisticated routing.

In the 1980s, computer models began to appear that would perform more than the cursory functions of generating hydrographs and pollutographs and simple routing. Models such as the updated EPA SWMM (Huber and Dickinson 1988; Roesner, *et al.* 1988) and the Quantity-Quality Simulator (QQS) (Geiger and Dorsch 1980) developed which had the capability to route flows through gutters, channels, and sewers in addition to developing hydrographs and pollutographs (Nix 1994). Many other models perform similar functions, but are not mentioned here. Brandstetter (1976) provided a thorough review of the models available for urban stormwater management modeling. Other sources should also be consulted for a more thorough review of the available commercial models (Whipple, *et al.* 1983; Huber 1986).

Applications of computer models to wet weather management had various purposes and results. The application to CSO control and treatment was a necessary step to supplement the monitoring studies that were being conducted during the mid 1970s. As far as applications, Cermola, *et al.* (1979) presented a study using the EPA SWMM model (Huber *et al.* 1975) to investigate CSOs for the City of New Haven, CT. The study investigated a plan to reduce the discharges by implementing various control measures. It was concluded that site specific characteristics and storm data were required for proper calibration and utilization of the SWMM model (Cermola, *et al.* 1979). Additional information on modeling CSO impacts and control and treatment alternatives can be found in various sources (Nix 1990; Nix, *et al.* 1991).

The 1990s witnessed the proliferation of models being integrated with geographic information systems (GIS) and graphical pre- and post-processors which greatly enhanced the input and output capabilities, but did not change the internal structure or theoretical basis of the models to any noticeable extent. Examples include XP-SWMM (XP Software 1993) which has a graphical interface for pre- and post-processing the input and output data from EPA SWMM version 4 (Huber and Dickinson 1988; Roesner, *et al.* 1988). These advancements in wet weather modeling do not impact the accuracy or theoretical basis of the models, but attempt to increase the efficiency in which the models can be utilized. Thereby, the computer models of today are more user friendly for those learning the model, but some still consider the graphical interfaces and GIS packages to be unnecessary some of the time.

Besides the modeling of the actual runoff process in the urban drainage system, models were developed to simulate loading of pollutants and others were developed to simulate the impacts of the pollutants on the receiving water system. Source models such as the Source Loading and Management Model (SLAMM) (Pitt and Voorhees 1996) were originally developed to evaluate the effectiveness of source controls.

Receiving water quality models include the Hydrological Simulation Program - Fortran (HSPF) (Johanson, *et al.* 1980; Johanson, *et al.* 1984; Bicknell, *et al.* 1993). This model includes a complete water balance accounting for both surface water and groundwater and for interactions between them. HSPF has an exceptional water quality modeling capability represented by the ability to simulate a suite of pollutants and lower level organisms. Medina

(1979) developed a simplified receiving water quality model that provided continuous simulations. Its purpose was to provide preliminary screening of areawide wastewater treatment strategies for planning decision making. The model can simulate the response of a steam or tidal river system to effects from wet weather sources, dry weather sources and upstream sources. The model output included a dissolved oxygen sag curve and dissolved oxygen profiles at selected points downstream.

The EPA developed some stream models in house for determining the effects of stormwater runoff on the receiving water system (Smith and Eilers 1978). These mathematical models simulated the physical, chemical, and biological reactions that occur in a flowing stream. The pollution loads on the stream could be specified as steady-state or transient. One model computed the dissolved oxygen (DO) deficit in the stream as a function of time and distance along the stream caused by specified stormwater overflows. The other model simulated the hydraulic effect on the stream from large overflow volumes.

Many other models are in existence, some developed by commercial software companies and some developed by government agencies (U.S. Army Corps of Engineers, EPA, for example) that are more than adequate for wet weather modeling. The studies that have tried to compare the accuracy of the models have resulted in inconclusive results. Usually it is recommended that the model be selected to meet the needs of the user. It is also often mentioned that the model cannot replace reliable data gathered with careful monitoring and sampling.

CSO and Stormwater Characterization

Logic would dictate that prior to attempting to solve a problem, the problem must first be defined. Following this philosophy, in order to address a stormwater runoff or combined sewer overflow problem, an investigator must have knowledge of the characteristics of the problem. The characteristics of stormwater runoff and CSO can be divided into source characteristics and quality characteristics, among other ways. Sources of pollutants can originate from the air, land, or other water sources. The source of pollution known, measures can be implemented to mitigate the impacts caused by the source, through source controls, best management practices, etc. In addition, if the stormwater quality characteristics are known control measures specific to those quality parameters can be implemented in-system or at the “end-of-the-pipe.” Detailed studies to determine the sources and quality of wet weather flows originated in the late 1960s, parallel to the development of specific treatment techniques for CSO.

An understanding of the potential sources of wet weather pollutants is of primary importance when studying the impact of urban runoff. Several early studies concentrated on runoff from roadways and other impermeable surfaces. Runoff from impermeable surfaces in an urban environment has been shown to be a significant source of pollutants. Sartor and Boyd (1972), for instance, developed relationships for the accumulation and washoff of pollutants from street surfaces. They also characterized the quality of the stormwater from several types of land uses. Pitt and Amy (1973) characterized the toxic pollutants that originated from the surface of streets in urban areas. Other studies around the United States determined the quality of stormwater runoff (Davis and Borchardt 1974; Colston 1974; Black, Crow & Edisness, Inc., *et al.* 1975; Betson 1976; Mason 1977) in specific cities. The conglomeration of data from different cities eventually provided a diverse database from which other localities in the vicinity of a studied area could use the data previously collected for management purposes. Much of this runoff quality data was gathered into the *Urban Rainfall-Runoff-Quality Data Base* in the late 1970s by Huber *et al.* (1977; 1979). This database was eventually inserted into the STORET system under the control of EPA. Much of this data is summarized in Appendix B.

In Europe, researchers have also been characterizing the pollutants that originate from urban roadways. J. B. Ellis, working in the UK, has conducted and reported several investigations describing the characteristics and pollutants of wet weather flows (Ellis 1977; Ellis and Revitt 1982; Ellis 1985). One of his motivations was to correlate the pollutants found in stormwater and the impacts that these pollutants were having on the receiving waters. Brunner (1975) found that roadways in Germany could erode at surprisingly rapid rates, showing an increase in erosion as the traffic intensity increased. Others throughout Europe have also conducted studies characterizing the quality of wet weather flows.

Another major pollutant source from impermeable surfaces, for cold climate regions specifically, is material used for ice control such as salt, sand, etc. Field, *et al.* (1973) reported a study investigating the water pollution caused by street salting. Street salting can have adverse impacts on several species of fish in waters receiving high quantities of snowmelt in urban regions (Ellis 1985a). It has been shown that chlorides can be detrimental to roadside vegetation as well (Field 1973). Some regions use sand and dirt in an effort to mitigate the impacts of harsh weather on driving conditions. These materials also can contribute to significant increases in suspended sediment observed in receiving water systems (Lorch 1997). Overall, ice control in urban areas can contribute several pollutants to the runoff from those regions.

There are many different types of pollutants that can emanate from the sources discussed above. Whipple, *et al.* (1983) classified the pollutants into the following nine types:

- suspended sediment
- oxygen-demanding substances
- heavy metals
- toxic organics
- nutrients
- microorganisms
- petroleum products
- acids
- humic substances

Other types of pollutants exist which might not fit exactly into one of these categories. For example, thermal enrichment of receiving waters (Xie 1994) caused by stormwater discharges can have detrimental effects and does not fit into any of the above categories explicitly.

Preul and Papadakis (1976a; 1976b) conducted investigations into analytical and field methods to characterize stormwater runoff. Their findings were compiled into two published reports by EPA detailing the project. The microbiological components of stormwater also were investigated in the late 1970s. Olivieri, *et al.* (1977) determined that runoff from urban areas contained high densities of microorganisms and high levels of bacterial indicators of fecal contamination. The impacts of these findings were debated since storm runoff is usually not consumed and is diluted in the receiving system prior to any possible contact. Qureshi (1977) investigated the microorganism characteristics of separate storm sewers in Toronto, Canada. The findings of this investigation were similar to those found by Olivieri, *et al.* Ellis and Yu (1995) have recently investigated the microbiology of sewers and runoff in an attempt to describe the sewer from the perspective of a bacterial reactor.

The Nationwide Urban Runoff Program (NURP) administered by the U.S. EPA and the USGS in the late 1970s and early 1980s produced great amounts of runoff quality data (EPA 1983). The overall goal of the study was to collect data and develop information for use by local decision makers, States, EPA, and other interested parties. The information ultimately would provide a basis for determining whether or not urban runoff is causing water quality problems, and if it is, for planning and implementing water quality management schemes and control options (EPA 1983). Of the priority pollutants monitored at the numerous study sites, heavy metals were by far the most prevalent (especially copper, lead and zinc). Additionally, coliform bacteria were found to be in high concentrations in receiving waters during and immediately after storm events and total suspended solids were high as well (EPA 1983). The final report provides a summary characterization of urban runoff appropriate for use in estimating pollutant discharges from sites where monitored data are lacking at the planning level. Appendix B summarizes some of the NURP data.

Bannerman, *et al.* (1996) have conducted a recent comprehensive study to characterize the quality of urban runoff. Their study identified several pollutants as potential problems in Wisconsin stormwaters including lead, zinc, copper, silver, cadmium, PAHs, DDT, atrazine, suspended solids, and others. This long list of possible contaminants is indicative of many studies. This shows that the accurate characterization of runoff water quality is difficult due to the site specific pollutant sources that must be considered and the suite of pollutants that can become part of runoff.

The many other studies conducted are too numerous for a thorough coverage. These studies, both large and small, continue to refine and expand the characteristics of stormwater discharges and CSOs. In the recent past, the toxicity of stormwater has become a much studied subject. Along with these ideas came the need to perform proper sampling and monitoring to accurately identify the sources and the pollutants themselves. The next subsection details the development of sampling and monitoring for the purposes of wet weather management.

Wet Weather Sampling and Monitoring

Sampling and monitoring are important topics to review since many of the other topics discussed in this report are dependent on reliable sampling and monitoring data. For instance, computer modeling requires accurately recorded data to perform a calibration process. In addition, the wet weather impacts on receiving waters can only be quantified adequately by an organized and thorough sampling and monitoring program. Indeed, each of the sections contained in this section of the report require consideration of sampling and monitoring either during planning, design, or implementation. Despite this importance, it seems that much of the other technology has advanced more rapidly. But, with the NPDES regulations requiring monitoring of stormwater outfalls more attention has recently been given to sampling protocols and methods and monitoring programs during wet weather events.

This subsection will introduce some of the literature discussing sampling, measurement, and monitoring for wet weather management. First, sampling and measurement devices will be briefly introduced. Second, sampling and measurement protocols will be discussed. The last part of this subsection will touch on some sampling and monitoring planning strategies and guidelines for use in wet weather management.

Sampling and Measurement Devices

Before the advent of discharge permits, the sampling of wastewater and wet weather flows was inelegant. Sampling was conducted when convenient or on an as-needed basis. The instruments used consisted of cans, bottles and other containers that held water without leaking. Rigorous quality control techniques were unknown. The samples collected were manually collected in a grab fashion. Although some cities and industries used automatic samplers for process control in the 1930s, it was not until the 1950s that automatic sampling became popular. The main reason was the fact that sewer use charges became a revenue producer. Naturally, the collection of 24 hour composites required by permits called for new and more frequent composite samplers. This was the impetus behind the development of the commercial automatic samplers in the late 1960s and early 1970s. In the early 1970s, the need to perform composite sampling and more frequent sampling of wet weather flows prompted the automatic samplers used in the wastewater industry to be applied to wet weather sampling and monitoring. However, the durability requirements and other needs required that adjustments be made to the samplers for sewer applications. New samplers were also developed specifically for use in sewer sampling.

The EPA became involved in the development of sewer sampling and monitoring devices not to mention flow measurement devices during the early 1970s. The state-of-the-art in sewer flow measurement was discussed by Shelley and Kirkpatrick (1975). This report detailed the reason for accurate sewer flow measurement and then reviewed over 70 generic devices and methods for determining wastewater flows. They observed that the state-of-the-art in flow measurement, especially from the electronics standpoint, was advancing very rapidly.

Foreman (1979) developed and tested an innovative sewer flow measurement device. The device was designed by Grumman Aerospace Corporation (GAC) for EPA in the mid 1970s (Foreman 1976). This device can be described as a passive, nonintrusive flowmeter based on acoustic theory. The flowmeter utilizes the local, nonpropagating sound resulting from the partial transformation of flow pressure loss at a discontinuity in a channel or conduit. The field testing of the instrument during wet weather flow events had the goal of determining the durability and accuracy of the measurement device. The investigation verified the operational principles of the acoustic emission flowmeter under actual environmental conditions. In addition to testing the instrument, the researchers also investigated the validity of calibrating the instrument to lab-scale data and using the sewer manhole as sensor installation locations.

Shelley (1976) was also involved in another EPA sponsored project to develop an automatic sewer sampler. Four commercially available samplers were tested under the same flow conditions in a side-by-side fashion. The sampling consistency was erratic for each of the samplers, especially when an appreciable bed load was present. A prototype sampler was developed as part of the study and was shown to be capable of collecting reasonably representative samples compared to those commercially available. Many of the recommendations in this early report have been implemented by current manufactures of automatic sampling equipment, especially the use of "super-speed" pumps and small diameter tubing to maximize particulate transport in the sampler.

Before, during and after the EPA sponsored research effort, other automatic samplers were being developed by private organizations. However, the market for automatic sampling was not that lucrative for wet weather management in the late 1960s and early 1970s. But, with the increased concerns for the environment and more stringent regulations, monitoring efforts were undertaken to collect data for a number of purposes. In addition, monitoring required as part of the National Pollutant Discharge Elimination System (NPDES) for point sources necessitated the use of automatic samplers for effluents from industrial and manufacturing wastewater treatment plants, as well as municipal wastewater treatment plants. The expansion of the NPDES program to cover urban stormwater initiated widespread application of the automatic sampler in the wet weather field (Baily 1993).

Currently, a wide assortment of commercial automatic sampling products are available suiting a number of needs. The reliability and quality assurance associated with many of the automatic samplers has risen dramatically. The reason for this can be attributed to the increased demand for higher quality products from the vendors due to the more stringent permitting and increased concern for the environment. Many companies, such as N-CON Systems Co., Inc., Isco, Inc., and YSI Incorporated to mention a few, have divisions which specialize in providing equipment that can be tailored to a specific water or sewer sampling or monitoring situation. Research continues to develop innovative devices with the added benefit of being economical, such as a flow-weighted culvert sampling device (Dowling and Mar 1996).

In many instances, the needs of the user are not as advanced as the technology has developed. The operator should choose equipment that suits his or her basic needs without the expense of special features that will remain unused. In essence, the sampling and monitoring equipment should match the requirements of the sampling and monitoring program.

The need for quality monitoring equipment reaches beyond the water sampling needs. Besides water quality, another category of data required for many wet weather analyses is precipitation. As mentioned in a previous section, rainfall records are much more available than streamflow records and thus the need for rainfall-runoff relationships in design. There are numerous types of recording and non-recording rain gages that can be implemented. There are also numerous ways in which the rain gage network can be arranged. It is important to organize the network to best suit the needs of the study. The most common rain gage used in the U.S. is the 8 inch diameter, sharp edged gage placed 3 feet above the ground surface (Elliot 1995). There are variations for different climatic conditions. It is noteworthy that this type of rain gage has been in use for nearly one hundred years. However, technological advances have improved the recording and data management capability of the instrument.

Sampling and Measurement Protocols

The development of instruments utilized in sampling and monitoring efforts was introduced above. But, in order for the equipment to serve their purpose it must be used properly. The proper use of most equipment is detailed in instructions provided when the equipment is purchased. The additional protocols required depend on the constituent being measured or sampled. Government regulating agencies have stipulated specific procedures for sampling and analysis of water and wastewater when sampling and analysis were required. Prior to that time, sampling and analysis methods were left to the person performing the actual work. In the 1960s and 1970s environmental regulations became increasingly more stringent and therefore the required sampling and analysis procedures likewise became increasingly more stringent. *Standard Methods for the Examination of Water and Wastewater* (1992) has become an institution in terms of water quality analysis and basic sampling protocols. Additionally, sampling and monitoring protocols have been developed by EPA and other regulatory agencies. Keith (1992 and 1996) provides a compilation of the EPA sampling and analysis methods according to parameters being measured.

These procedures are general to environmental studies but have applicability in wet weather situations. Keith (1991 and 1996) also provides additional information concerning environmental sampling which again can easily be applied to wet weather scenarios.

Wet weather sampling and analysis has its own specific regulations suited to the unique situations encountered that are not experienced in municipal and industrial wastewater and water quality sampling efforts. For instance, EPA (1992 and 1993) published a guidance manual for stormwater sampling. This document was prepared specifically to address the issues surrounding the NPDES permitting program. NPDES permits require specific sampling and monitoring plans that are often tailored to the individual site characteristics. The manual has the purpose of assisting operators/owners in planning and fulfilling the NPDES storm water discharge sampling requirements for permit applications and other needs.

Planning of Sampling and Monitoring Efforts

The planning of sampling and monitoring efforts is highly dependent on the type, resolution, and accuracy of results desired. To meet regulatory requirements requires a certain level and frequency of sampling, while the planning and design of wet weather controls will require a different level. The data needs can often direct the monitoring effort or in the least provide constraints from which the monitoring effort can be devised. Models have been developed to facilitate the development of sampling programs with the use of computers (Reinelt, *et al.* 1988).

Planning requirements include selecting the data needs and instruments to be used, developing protocols for sampling and analysis, and devising strategies for organization and management of the monitoring network. Once again the regulating agencies and other references can be sought for information concerning the planning of a sampling and analysis effort.

In 1994, a conference was entirely devoted to NPDES sampling and monitoring (Torno 1995). The conference had several important topics addressed by papers, including sampling (Dudley 1995), monitoring (Cave and Roesner 1995; James 1995), toxicity (Herricks, *et al.* 1995), and illicit connections (Lalor, *et al.* 1995; Minor 1995) to mention a few. The occurrence of such a conference exemplified the recent attention given to sampling and monitoring of wet weather flows for a variety of reasons. With the importance of regulations and modeling in wet weather management, sampling and monitoring will continue to be one of the more important topics in the future.

Receiving Water Impacts

To begin discussions on receiving water impacts, the term impact must first be defined. The term impact is subjective in nature depending on the viewpoint of those doing the defining. In a previous study conducted by Heaney and Huber (1984), the impacts of urban runoff on receiving water systems were defined as resulting in the loss of beneficial use. They considered beneficial uses to be comprised of those listed in local, state, and federal laws such as drinking water use, fishing and shellfishing, swimming, boating, manufacturing process water use, etc. To develop a more general definition the inherent values of water quality and wildlife should also be included when considering impacts to the receiving water systems in addition to the economic ramifications from the human standpoint.

The possible impacts of urban runoff on receiving water systems are well documented in the literature. However, some still disagree with the results of those studies, claiming that the myriad sources of pollution (point and nonpoint) in an urban environment are difficult to separate. To combat this argument, many researchers have painstakingly insured that urban runoff was the major contributor of pollution to the receiving water thereby validating their investigation. The results and conclusions from studies following this methodology can be reviewed with confidence. But, one must be cautious when considering the conclusions from a receiving water impact study without knowing the circumstances of the investigation in full.

Prior to 1960 the water quality impacts of wet weather pollution received almost no attention (EPA 1983). However, as point source discharges were brought under control the nonpoint sources such as urban runoff were noticed to be significant contributors to the degradation of water quality. Extensive research was conducted in the 1970s to determine the impacts of urban runoff and to develop mitigation measures. The culmination of much of the decade's efforts to characterize urban runoff is manifested in the EPA-sponsored Nationwide Urban Runoff Program (NURP) mentioned above (EPA 1983). One of the goals of NURP was to characterize urban runoff in order to describe its impacts on receiving water systems.

The effects of urban runoff on receiving water quality are highly site specific. It depends on the type, size and hydrology of the water body; the urban runoff quantity and quality characteristics; the designated beneficial use; and the concentration levels of specific pollutants that affect the beneficial use (EPA 1983). In addition, as was mentioned above, the effects of urban runoff are difficult to distinguish from the other pollution sources present in an urban environment.

In evaluating the effects of urban runoff, one must discern between two types of impacts. One type is the short-term, or acute, water quality deterioration imposed during the wet weather event, such as turbidity, dissolved oxygen depression, toxicity and others. The second type is long-term, or chronic, impacts related to the bioaccumulation of contaminants in wildlife and the corresponding accumulation of contaminants in the sediment of the receiving water. Both types of impacts are included in this discussion. One must also consider the fact that urban runoff contains a suite of pollutants whose individual impacts are not easily identifiable. Therefore, the combined, and often synergistic, impacts of urban runoff pollutants is also evaluated in the ensuing discussion. The following discussion provides a highlight of some of the studies conducted and the results discovered. Therefore, this review should not be considered exhaustive of the literature available.

Generally, impacts can be divided into categories depending on the type of receiving water body into which they discharge. Many types of water systems exist, but most can be classified into two general categories: surface water systems and groundwater systems. Of course, surface water systems interact with groundwater systems, but for the sake of discussion the classification below will be based on which type of water body that initially experiences impacts from urban runoff. The following two subsections will highlight some of the more prominent literature covering the past thirty-odd years pertaining to surface water and groundwater impacts from urban runoff. The modeling of receiving water impacts was briefly mentioned in the *Wet Weather Modeling* subsection above, therefore it is neglected in this section.

Surface Water Impacts

Wanielista, *et al.* (1982) found that urban runoff was the sole cause of lake degradation in Lake Eola in Orlando, Florida. The primary reason for the degradation was attributed to nutrients (phosphorus in particular). Nutrients contributing to a receiving water system can lead to accelerated eutrophication, especially in stagnant lakes or ponds. Additionally, phosphorus is often a limiting nutrient in algal production, therefore an increase in phosphorus should concomitantly increase the algal production leading to increased eutrophication.

Porcella and Sorensen (1980) compiled a survey of literature pertaining to urban nonpoint surface runoff to determine the effects of that source of contaminants to stream ecosystems. They discovered that very little information existed on detailed studies of ecosystem effects caused by urban runoff. They did however compile a review of literature found that discussed the impacts of flooding, pollutants, and runoff on stream ecosystems. They also introduced a methodology to conduct future experimental studies to elucidate the effects of urban runoff impacts on stream ecosystems.

Pitt and Bozeman (1980 and 1982) carried out a series of studies investigating water quality and biological impacts of urban runoff. Their study concentrated on Coyote Creek, a creek which passes through an urban area in California. The preliminary report (Pitt and Bozeman 1980) presented some initial results from their study. Specific characteristics of urban runoff, effects of urban runoff and the potential controls for urban runoff were all addressed in the report. It was noticed that the urbanized reaches of the creek were degraded in comparison to the non-urbanized reaches. This conclusion was based on short- and long-term biological sampling and water and sediment sampling for a period of several years. The final report (Pitt and Bozeman 1982) further supported the conclusions of water quality degradation in urban reaches. Quantitatively, they observed pollutants such as lead and nitrate in concentrations more than seven times greater in urban reaches of the stream compared to the non-urban reaches.

Dissolved oxygen in the urban reaches was also noticed to be lower compared to that observed in the non-urban reaches.

In their studies, Pitt and Bozeman also discovered that bioaccumulation of lead and zinc had occurred in many of the samples of algae, crayfish and cattails (Pitt 1995). The measured concentrations of these metals in organisms (mg/kg) exceeded concentrations in the sediment (mg/kg) by up to a maximum factor of six and exceeded concentrations in the water column by factors of 100 to 500 times, depending on the organism.

Besides Pitt and Bozeman, others were also investigating the impacts of CSO and stormwater discharges with EPA sponsored projects. McConnell (1980) investigated the impact of urban runoff on stream quality near Atlanta, Georgia. This investigation detailed how rapid urbanization was impacting stream water quality. Also, Moffa, *et al.* (1980) were observing the impacts of CSOs on Onondaga Lake in Syracuse, New York.

Field and Turkeltaub (1981) stressed the need to identify the impacts of urban runoff in order to develop control technologies. Quantification of the impacts was also noted as a key point. This paper reviewed several studies investigating various impacts of urban runoff. Specifically, the paper addressed dissolved oxygen depletion, pathogens, biological investigations, nutrients and toxicity. Each of these subject areas was briefly introduced followed by a discussion of recent studies performed investigating the specific topic. The paper concluded that dissolved oxygen (DO) depletion could not be directly attributed to wet weather events based on several studies (Ketchum 1978; Keefer, *et al.* 1979; Stiefel 1980) although lower DO readings were measured in urban areas compared to non-urban areas. Additionally, the presence of bacterial indicator organisms in CSO in several studies (Meinholz, *et al.* 1979; Moffa, *et al.* 1980; Tomlinson, *et al.* 1980) suggested that viruses could be present in receiving streams. It was also mentioned that the fauna in urban reaches of streams were observed in several studies to be dominated by pollutant tolerant species compared to the more diversified organisms residing in non-urban reaches of the same stream (Tomlinson, *et al.* 1980; Pitt and Bozeman 1982; Shutes 1984). Field and Turkeltaub (1981) used these conclusions and others to develop an urban runoff control methodology.

Heaney and Huber (1984) summarized their efforts searching for case studies demonstrating the cause-effect relationship between urban runoff and the impairment of receiving waters. Part of their work classified the receiving waters of the 248 urbanized areas in the U.S. according to what type they were and how much dilution capacity they had (Heaney, *et al.* 1981). For instance, it was determined that 84% of the primary receiving waters in urban areas were rivers, 4% were lakes, and 11% were estuaries or oceans. Their conclusions indicated that documented case studies of receiving water impacts were scarce for a number of reasons. Some of the reasons for this conclusion included that receiving water impacts were not important from a regulatory viewpoint, impacts of urban runoff and CSO difficult to separate from other sources of pollution, impacts could be subtle, uniform definition of impact did not exist, and others.

Ellis (1979; 1982; and 1985b) has studied the impacts of urban runoff on receiving water systems in a number of investigations. Some of his findings concluded that 40-50% of the annual biochemical oxygen demand (BOD) loading to benthal sediments in London receiving water bodies was contributed by storm sewered runoff. The increased BOD in the sediment presents a problem, especially when the sediment is disturbed. Ellis also concluded that urban runoff caused water quality degradation due to substantial pollutant and shock hydraulic loadings discharged from stormwater outfalls. This was based on his own investigations as well as those of others.

Conferences proceedings can be the location of a plethora of papers pertaining to a particular subject. This possibility was considered when searching for literature discussing receiving water impacts. Conferences found which had the theme of receiving water impacts would have many papers concentrating on the subject contained in the proceedings. One such conference was held in Orlando, FL in November 1979 (Yousef, *et al.* 1980). This large proceedings was published as an EPA report and consisted of more than 25 papers, some of which are mentioned individually in this review.

It was stated above that it is difficult to discern the effects of urban runoff and CSO in an urban environment since many pollutant sources contribute to the receiving water systems. To solve this dilemma some studies have not attempted to separate the impacts of urban runoff from the other sources in order to observe the cause-effect relationship of the wet weather sources explicitly, but rather studied the effects of urbanization in general (McPherson 1972). It is understood that a major component of urbanization is the creation of increased runoff that contributes to the degradation of water quality. Therefore, reviewing a few of the studies documenting impacts on receiving waters due to urbanization will be time well spent.

Graf (1975) studied the Denver area fluvial system and noticed that the region was largely impacted by suburban development. A large part of the problem was attributed to large quantities of sediment and the increased amounts of impervious surfaces contributing higher surface runoff rates and volumes. He observed that the increased surface runoff caused increased erosion to the streambed leading to incision of the stream in many areas. Consequences of this action include upsetting the delicate balance of the ecosystem and loss or alteration of property due to erosion of streambanks and the deposit of sediment in specific locations of the stream.

Klein (1979) studied 27 small watersheds having similar physical characteristics, but different land uses, and found definite relationships between land use and water quality. It was found that stream aquatic life problems were first identified in watersheds with impervious area comprising at least 12% of the watershed. Other studies have supported this 12% impervious ratio, with the range of 8 to 15% being documented by the cumulative results of many studies (Claytor 1996b; Schueler 1996; Stephenson 1996). It was also observed that at more urbanized sites with a steady sediment source, sand covered the natural stream bed in 2 to 3 months. Sand, when it is of the shifting, unstable variety, provides one of the poorest substrates for benthic life (Klein 1979). Klein (1979) also observed that generally urban streams exhibited a paucity of life characterized by inhabiting organisms being of the pollution resistant variety. These findings are similar to those observed by others investigating the impacts of urban runoff (Pitt and Bozeman 1980 and 1982; Shutes 1984).

Many other individuals and organizations also investigated the impacts of urbanization on the receiving water system. Most of these studies attempted to characterize the impacts associated with the quantity of water. For instance, some quantified the alterations to peak runoff rate and runoff volume which occur during the urbanization of a watershed (Bras and Perkins 1975; Task Committee on the Effects of Urbanization 1975; Walesh and Videkovich 1978; Beard and Chang 1979). These studies confirmed the expected outcome that increased impervious surfaces increases surface runoff volume and peak rate and concomitantly decreased subsurface flow and infiltration. Essentially, studies have shown that the hydrology of a watershed is altered, sometimes severely, during the urbanization process.

The water quality impacts of CSO and stormwater discharges on receiving water systems became a widely studied subject (Pitt and Bozeman 1980 and 1982; Field and Turkeltaub 1981; Heaney and Huber 1984). Gradually a shift from water quality impacts to the impact on aquatic life and fauna began to occur. Studies of urban runoff began to observe the impacts on specific aquatic organisms. For instance, Pitt and Bozeman (1980 and 1982) and Shutes (1984) determined that receiving water impacts from urban runoff included a less diverse species population downstream from wet weather discharges. As described above, these studies were significant because they quantified the effects, not just stating that the wildlife and/or water quality was observed to be impacted. This method of determining impacts has continued to evolve such that presently assessing stormwater impacts is much more complex. Biological assays are needed to determine if the urban runoff impacts are toxic to wildlife in the short-term and long-term.

Burton (1994) observes that due to the complexity of assessing receiving water impacts it is imperative that wet weather evaluations use an integrated approach. He recommends focusing on toxicity, indigenous biota, and habitat during initial surveys, followed by focused contaminant analysis of sediments and runoff from impacted areas. For the toxicity testing, it is recommended that a tiered toxicity testing approach be utilized (Burton 1994). Pitt, *et al.* (1996) also propose the use of toxicity testing in assessing stormwater impacts. They compared a relatively simple toxicity evaluation procedure to the more rigorous alternatives and concluded that the simpler test provided accurate results for preliminary assessment purposes. For more detailed analysis they suggested using multiple complementary tests, instead of any one test method (Pitt 1996).

Johnson, *et al.* (1996) and Herricks, *et al.* (1996) describe a structured tier testing protocol to assess both short-term and long-term wet weather discharge toxicity. These researchers have developed and tested the assessment procedure. The procedures recognize that the test protocol must correspond to the time-scale of exposure during the discharge event. To solve this problem, three time-scale protocols were developed, for intraevent, event, and long-term exposures. Additional results from the investigations indicated that standard whole effluent toxicity (WET) tests overestimated the potential toxicity of stormwater discharges.

Another approach for assessing receiving water conditions was summarized by Claytor (1996a). This methodology was developed by the Center for Watershed Protection as part of their EPA-sponsored project on stormwater indicators (Claytor and Brown 1996). The stormwater indicators were divided into six broad categories: water quality, physical/hydrological, biological, social, programmatic, and site. The goal of these indicators is to measure receiving water impacts, to assess the water resource itself, and to evaluate runoff control program effectiveness.

Groundwater Impacts

An often neglected destination of urban runoff is the groundwater. Runoff can be directed to the groundwater either intentionally (infiltration basins, unlined detention basins, grass swales, etc.) or unintentionally (leaking sewers, breached linings in control structures, etc.). Regardless of the means by which runoff reaches the groundwater, it must be considered in wet weather management strategies. Investigations have concentrated specifically on the impacts associated with stormwater infiltration, both intentional and unintentional and some are introduced in the following discussion.

Nightingale and Bianchi (1977a; 1977b) studied the impacts of artificial recharge of stormwater and other sources on the groundwater quality. Part of these studies focused on how the inorganic chemical quality of the recharge water related to the changes observed in groundwater quality beneath recharge basins and in nearby urban water wells. Other focuses of the study included investigating the soil and groundwater characteristics and their relationship with the impacts caused by the recharge water.

Nightingale (1975) and Wigington (1983) investigated the accumulation of contaminants in soils beneath recharge and infiltration facilities. They documented the accumulation of arsenic and trace elements (lead, zinc, copper, and cadmium) in the soils. The accumulations at the time of the study did not pose a threat, but eventually the levels could become unacceptable (Nightingale 1987). Another concern is the classification of the soils as hazardous material if they contain a level of contaminant of a sufficient level. This would pose a management problem during maintenance and for future use of the soils in the recharge zone.

Eisen and Anderson (1979) looked at the impacts of urbanization in general on the quality of groundwater. They observed trends in groundwater quality that supported the results of other researchers. It was found that chloride and sulfate were the principal products of urbanization which affect the quality of groundwater. Evidence pointed to the causes of this contamination being road salting, leaking sewer pipes, and infiltration of contaminated surface water. Stormwater is a common link between each of these contamination avenues and therefore must be considered in prevention plans.

Ku and Simmons (1986) studied the aquifer system beneath Long Island, New York to determine if the high density of stormwater infiltration facilities on the island were contaminating the groundwater. They concluded that many of the contaminants were filtered out in the soils beneath the recharge basin and therefore never reached the groundwater. This conclusion was in agreement with the results observed in Fresno, CA during a study associated with NURP (U. S. Environmental Protection Agency 1983b).

Pitt, *et al.* (1994 and 1996) conducted a study to review the groundwater contamination literature as it related to stormwater. They developed a methodology to evaluate the contamination potential of stormwater nutrients, pesticides, other organic compounds, pathogens, metals, salts and other dissolved minerals, suspended solids, and other contaminants. The potential for contamination was based on factors such as their mobility through the unsaturated zone above infiltration facilities, their abundance in stormwater, and their treatability. Conclusions from their study highlighted salts, some pathogens, 1,3-dichlorobenzene, pyrene, fluoranthene, and zinc as having high potential to contaminate groundwater under certain conditions.

The application and research of stormwater infiltration basins is more intense outside the United States. Studies have concentrated on the use of infiltration basins as CSO and stormwater runoff control strategies rather than simply groundwater recharge basins (Jacobsen 1991; Geldorf, *et al.* 1993; Jacobsen and Mikkelsen 1993; Mikkelsen, *et al.* 1994). The infiltration of polluted flows increases the contamination potential of the underlying aquifer. Therefore, more intensified research is required to investigate the contamination potential of groundwater from infiltrating polluted wet weather flows.

Mikkelsen, *et al.* (1994) state that although infiltration systems have several advantages they are rarely installed on a large-scale in urban areas because of the uncertainty associated with the risk for groundwater contamination. They offer recommendations that the most cost effective manner to prevent groundwater contamination is by controlling pollutants at the source. However, due to the short time-scale the environmental impacts of the pollutants must be assessed by documenting the potential contaminants in stormwater and their likely sources. Some of this need has been filled by Pitt, *et al.* (1996). Geldorf, *et al.* (1994) espoused the use of infiltration because of its positive impacts on the receiving water system. They stated that infiltration basins constructed correctly offer a design option that is environmentally sustainable.

Mikkelsen, *et al.* (1996a and 1996b) continued to be involved in a series of tests to examine the effects of stormwater infiltration on soil and groundwater quality. Their results indicate that pesticides and other highly mobile contaminants are of the greatest concern. On the other end of the spectrum, metals and PAHs present little concern for groundwater contamination during stormwater infiltration due to their high affinity for soils.

Urban Hydrology

The path of water in an urban environment follows the hydrologic cycle. An urban environment has, by definition, been altered such that many of the natural processes constituting the hydrologic cycle are altered. The management of the effects of these alterations on wet weather flows in newly urbanizing areas is part of the focus of this report. The need to address the topic is clear and one particular aspect that must be addressed is the changes to the hydrology in the urban area that must be reckoned prior to devising the management strategies. Within this section, some of the specific characteristics of urban hydrology, as presented in the literature, will be discussed.

Earlier in this section, the ancient strategies for urban drainage were discussed, from which it became apparent that the consideration of hydrology in the urban setting had an early beginning. However, despite the early beginning, urban hydrology is still lacking in refinement. Jones (1967) pointed out at that in the 1960s the rational method (Kuichling 1889) for drainage design had been the last major development in urban hydrology. It can still be argued today (thirty years later) that the rational method remains one of the last major developments in urban hydrology. Of course, computer models have developed markedly in that time and improved physically-based rainfall-runoff models exist, but all indications are that practitioners still predominantly utilize the rational method or similar techniques developed decades ago in one form or another.

A major economic consideration in drainage design is the mitigation of flood damages. To promote effective designs flood frequency analysis is needed. In an urban setting, the flood frequency characteristics will differ from those observed in a rural or natural setting. Numerous researchers have examined the flood frequency characteristics of urban settings. Some of the early urban hydrology work in the late 1950s and early 1960s addressed the effects of urbanization on the flood potential of small watersheds. The conclusions of this work were that urbanization had increased flood peaks by one and one-half to five times (Espey and Winslow 1974). Some of this early work included Ramey (1959) who determined that floods in the Chicago area had increased at least two and one-half times due to urban development. Wiitala (1961) found that the flood peaks in Michigan were approximately three times the peaks observed in undeveloped watersheds. Van Sickle (1962 and 1974) observed that urban development in Houston, Texas would increase peak discharge rates two to five times over those expected from the same watershed for undeveloped conditions. Savini and Kammerer (1961), Espey, *et al.* (1965 and 1969); and Espey and Winslow (1968) found similarly affected peak discharges, unit hydrograph shapes and other hydrologic characteristics in urban watersheds compared to undeveloped watersheds as previous research had observed. It should be noted, however, that numerous investigators pointed out that the dramatic increase in peak discharge becomes less significant for floods of increasing magnitude (Curtis, *et al.* 1964; Wilson 1967; Espey and Winslow 1974).

Espey and Winslow (1974) applied the Log-Pearson Type III distribution to 60 relatively small urban watersheds located throughout the United States. Applying the distribution to data indicated that the flood discharge would be significantly increased due to urbanization. An increase of 200% in some instances was predicted by the flood frequency analysis. They suggested that the flood frequency equations developed should be updated after the collection of more data.

Jones (1971) continued to stimulate urban hydrology in the engineering profession. It was anticipated that increased attention would act as a precursor to improved practice. In this paper he discussed urban drainage design, precipitation recording and analysis, runoff quantity estimations, as well as other aspects of urban hydrology and water quality. He discussed the current status of the subjects and then provided reasons for the problems and directions for advancement.

Starting in 1975 and continuing annually, for 10 years thereafter, a conference was held at the University of Kentucky addressing the topics of urban hydrology, hydraulics and sediment control. The contribution of these papers is too lengthy to discuss in detail, but it should be noted that the compiled papers of the conferences provide an excellent resource for urban hydrology. A list of all the papers is printed in *Current Practices in Modelling the Management of Stormwater Impacts* (James 1994). General topics covered at the conference included modeling, urban hydraulics, urban hydrology, stormwater management and many others. These conferences covered subjects related to many of the categories discussed in this report.

In terms of precipitation characteristics and analysis, major advancements and insights were provided from the late 1960s onward by the work of Keifer and Chu (1957), Huff (1967) and others. Keifer and Chu (1957) specifically investigated storm patterns for use in the design of drainage structures and systems. They realized that with the increased technical knowledge and computational capability, the only facet of drainage design that needed to be improved was precipitation and storm event analysis. Huff and others constructed a dense rain gage network in the Chicago for conducting comprehensive hydrometeorological research. Huff (1967) analyzed data from this network for heavy rainstorms and developed time distribution patterns. The network was updated for different projects throughout the 1970s trying to improve the utilization of meteorological data in drainage design (Huff 1969; Huff and Changnon 1977). Huff, *et al.* (1981) used the comprehensive rain gage network to develop and evaluate real-time monitoring-prediction system for facilitating and improving the operation of urban sewer systems.

The rational method is used for the design of some types of facilities in small drainage basins, where an estimate of only the peak rate of runoff is required. Rainfall information used with the rational method consists of intensity-duration-frequency (IDF) curves. The IDF curve concept was developed in the late 1800s in the United States in an era of intense precipitation analysis (Berwick, *et al.* 1980). IDF curves were eventually developed for most regions from recorded rainfall data. For use with the rational method, IDF curves are typically developed for a particular locality using the procedures set forth in TP 40 (Hershfield 1961) and HYDRO-35 (Frederick, *et al.* 1977). These two publications provide maps of the United States displaying rainfall data for different regions of the country in a graphical format.

More recent research into precipitation analysis has been conducted at the Danish Meteorological Institute (Mikkelsen, *et al.* 1996c and 1996d). This study began by changing the old rain gages for measuring extreme precipitation originally constructed as early as 1933 with modern systems of gages linked electronically to a central computer (Harremoës and Henze 1981). The data collected has revealed a geographic variability in rainfall patterns that calls for the revision of current engineering design uses of rainfall data (Harremoës and Mikkelsen 1995).

During the 1970s, the rainfall-runoff process was being studied with the intent of developing models. The EPA sponsored research to observe the process in both urban and rural settings. Brater and Sherril (1975) authored a report on the findings of this project. They discussed the rainfall-runoff process in the context of stormwater management and drainage design. Many others conducted research with the goal of describing the rainfall-runoff process. Sarma, *et al.* (1973) compared excess rainfall-direct runoff conceptual models at several urban watersheds. The instantaneous unit hydrograph (IUH) model performed the best of the conceptual models tested. Todini (1988) reviewed rainfall-runoff modeling of the past, evaluated the present models, and predicted the characteristics of rainfall-runoff modeling in the future.

With the proliferation of computer models in the 1970s came the need for large amounts of data for calibration and model process development. To answer this call, Huber and Heaney (1977) compiled a database of urban rainfall, runoff, and water quality data. Updates and additions to this database occurred later (Huber, *et al.*. 1979; Huber, *et al* 1981). The data in the database was from several catchments located in several cities. Many sources were reached during the accumulation of the data, which was eventually entered into a database. The collected data became part of the EPA STORET data retrieval system for increased accessibility.

The physical description of the rainfall-runoff process has been increasingly described in research projects as nonlinear. However, most of the traditional drainage design methods utilize linear runoff responses for modeling purposes. Improvements are needed in future research to provide methods that become implemented in design practice.

Summary of Literature

Granted, all the literature pertaining to wet weather management could not possibly be entered into the ProCite database. Moreover, the literature which is contained in the database could not possibly be exhaustively reviewed in the above discussion. However, more than enough of the literature has been reviewed and documented above to provide an accurate chronological development of wet weather management from ancient times to the present day. The purpose of this review, as stated earlier, was to determine past wet weather management strategies and to observe how they influenced the current strategies. The progression of wet weather management discussed above indicates decisions, ideas, and experiences in the past which resulted in the current state of wet weather management. This knowledge of past events provides insights into the future methodology which will enhance it. Another benefit of the literature review is the observance of research trends. The literature is an excellent reflection of the research that is being conducted. A review indicates areas that have been overwhelmed with research without much gain in knowledge and on the other hand areas that have been relatively neglected by research. This short summary describes some of the major trends in wet weather management as displayed in the literature as well as identifying areas that have been thoroughly researched or that have been neglected.

The history of wet weather management is indeed ancient. Strategies have developed from the elegant systems of the Romans to the pitiful systems of the middle ages to the advanced systems of today. Judging by this progression, the passage of time does not necessarily mean advancements of wet weather management strategies. In fact, engineers in London during the early eighteenth century tried to instill the same pride in drainage concerns as the Romans had displayed two thousand years before them, but many thought it was foolish to concern themselves with ancient concepts since civilization had advanced much since ancient times.

The methodology used in modern drainage design is approximately 150 years old and is now developing at a much faster rate than at any previous time. Ancient methods of design did not involve engineering calculations or experiments, but were based on judgment and trial and error. The 1800s are considered to be the beginning of modern drainage design. It was during this time period that experiments were conducted with the intent of deriving empirical relationships between design parameters (such as precipitation, watershed characteristics, etc.) and the size of drainage appurtenances.

Improved methods of planning sewerage systems were the next major step in the development. Lindley developed the first planned sewerage system for Hamburg in 1842, Bazalgette designed the Main Drainage of London in the 1850s, Chesbrough designed the first comprehensive sewerage system for Chicago in the 1850s, and many others also planned systems comprehensively during this time period (Metcalf and Eddy 1928). The comprehensive planning of sewerage systems ushered in the debate concerning combined versus separate systems of sewerage

(Hering 1881a). Reasons could be offered for use of either, but a definite choice was not discernible. Therefore, the debate over which type of sewerage system to utilize was argued in the technical literature and at technical gatherings.

Once drainage systems were being planned and designed comprehensively, improved empirical formula methods for sewer system design were instituted. In addition to the formula methods of design, the rational method for drainage design was being developed (Mulvaney 1851; Kuichling 1889). As mathematics improved, enhanced descriptions of the physical processes (rainfall, runoff, treatment, and others) inherent in wet weather management developed. These improvements resulted in equations describing infiltration and other abstractions as well as the rainfall-runoff process in general (Linsley and Ackerman 1942).

Research in developing mathematical descriptions of the physical processes continued to occur through the early to mid 1950s and became manifested in wet weather management through models, treatment techniques, and general understanding of underlying relationships. The computer age, which has developed over the last forty years has advanced the use of the physical descriptions of processes in certain aspects of wet weather management, especially models. Computer models have developed such that now they are required tools in the wet weather management profession.

In the same time that computers were improving wet weather management, water quality was becoming a concern. The knowledge that urban runoff was having severe impacts on receiving water quality completely altered the philosophy of wet weather management. Before this time the strategy was to remove stormwater as expeditiously as possible from the urban area. But more recently, the dual purposes of removing stormwater and promoting receiving water quality have led to more comprehensive management techniques. This has ultimately resulted in management techniques that address traditional quantity concerns and the newer water quality concerns. These dual purpose concerns were iterated in the literature throughout the past thirty years (Wanielista 1978; Geiger and Dorsch 1980). To further support the fusion of quantity and quality concerns in wet weather management evidence can be found in the technical conferences (Whipple 1975).

The advancement of technology in the previous thirty years is evident in the quantity of technical literature published in that time frame. However, although technology was advancing at a rapid rate, it was noticed that there existed a long lag between the significant developments and the applications in urban water resources practice. The slow “technology transfer” experienced in wet weather management was addressed by several individuals (McPherson 1975 and 1978b), but the problem persisted. Now it appears to be easier to advance technology and improve wet weather management on the research and development front, yet see years before these improvements are implemented in practice. The technology transfer phenomena is still in need of attention.

In addition to the technological advancements, such as with models, monitoring and controls, the improved technology has benefited the presentation, analysis, and other related aspects of wet weather management through instruments such as GIS, databases, word processors, and so on. These improvements have given researchers and engineers tools to make the more mundane tasks of engineering simpler and quicker, which facilitates the direction of time and energy toward implementation of the technological advancements.

It seems that as technology and understanding of the physical world has improved, there has been a corresponding advancement in wet weather management. It is anticipated that this correlation between technology and knowledge with wet weather management practices will continue in the future, albeit with a technology transfer time lag.

Future Outlook

The trends in wet weather management were generalized in the summary, and described in the literature review. This subsection considers these trends in the present day and attempts to forecast their future. Most of this section is based on material read or observed in the past few months and is an indication of topics currently gaining attention throughout the United States and the world. The topics mentioned are considered important factors to improving the wet weather management concepts.

This literature review has indicated that the technology has advanced many fold the last thirty years. However, problems still result from the lack of implementation of this technology. This was experienced for the 208 planning studies, in which many studies were conducted by regional planning boards, but few were actually implemented in their original form. Problems facing the wet weather management community in the future will not be entirely technical in nature. Technology is improving each year and providing for methods that are more than sufficient to produce excellent designs. However, the real problem lies with the implementation of this technology and methodology as was explained in the previous section. McPherson (1975 and 1978b) championed these concerns twenty years ago and offered suggestions to reduce the development to implementation lag time. Some of these suggestions and ones made since should be reevaluated and applied to today's circumstances. As mentioned in the introduction to this report, the goal of this project is to develop a design methodology that is effective yet simple to apply for a design engineer. This type of design philosophy will circumvent many of the detractors that usually impede the transfer of technology, thereby gaining implementation more swiftly.

Design engineers and planners will be forced to consider the environmental, socioeconomic, political, and legal ramifications associated with their plans and designs. These topics are the main inhibitors to the implementation of innovative technology and in the future must be addressed for progress to be made. Berwick (1980) and others have reviewed the reasons for lack of implementation and attribute it to a variety of problems. Some of the problems have been identified as the regulatory framework surrounding development, risks associated with development, public attitudes, and others. Problems also exist in the regulations and ordinances forcing design engineers to comply with standards that are either outdated or do not promote sustainability. Researchers and design engineers alike need to become more in tune with the political, socieconomic, and legal fabric of the urban community in order to better develop strategies that can be implemented.

History has displayed examples of the technology transfer time lag. Take the prediction of runoff from a watershed as an example. The formula methods, such as McMath, Roe, and Burkli-Ziegler, dominated sewer design of the 1800s. The rational method of determining stormwater runoff was introduced to the United States by Emil Kuichling in 1889, but it did not become a utilized method until much later. A paper by Charles Buerger (1915) states:

> "It (rational method) is not widely used, however, and the formula methods, of which the Burkli-Ziegler and the McMath are the most popular, are generally used, in spite of the common realization of the fact that the results given by them lack consistency, and are very erratic and unreliable."

This statement can be applied today, except now the rational method would be considered the method that engineers are continuing to embrace while the new technology that has been introduced recently is not being implemented. The reasoning Buerger offers for the lack of implementation is even more interesting. He states that the rational method has not received the widest use because it is relatively laborious, and requires a material exercise in judgment. This again is a popular reason expressed today for the lack of application of other techniques, but now the rational method is the popular method because of its simplicity and not the formula methods of Buerger's day.

The future is anticipated to be no different. If the trend of today mimics that of the past, it may be another twenty or more years before a method that has been introduced recently replaces an entrenched technique such as the rational method. Or, such as with the method Buerger was introducing in his paper, a new technique might never truly be implemented by practitioners regardless of the benefits and improvements that could be gained.

As one might conjecture from the above mention of the need for consideration of social, economic, and political concepts, the wet weather management field is also becoming increasingly multidisciplinary. It is not just a sanitary or civil engineer that is needed to design drainage structures. Disciplines that have become integral parts of the wet weather management field include biologists, ecologists, economists, computer scientists, geographers, geologists, sociologists, political scientists, and many others. Granted, an expert in each of these disciplines is not needed to design a wet weather system for a small-sized subdivision, but for the planning and design of a large urban region or the planning on a regional scale the input of experts in many of these fields might be required.

Although implementation of the technology is considered a major component for improving wet weather management, the improvement of technology cannot be entirely ignored. The future of modeling seems to be GIS and graphical pre- and post-processors. But the actual theory behind model applications needs to be addressed as well. In addition, the wet weather pollution problem is divided by models into several categories, e.g. sources, drainage system, receiving water, etc. Only recently have models begun to be integrated to better evaluate the system on a holistic scale. In the future models will need to continue to be developed in this fashion in order to advance wet weather management technology.

The use of the Internet will increase in the future. Already spatial data are being accumulated at certain sites in the forms of maps and databases that can be downloaded and used in wet weather management. The future direction of the Internet seems to be heading towards interactive applications in which users can perform functions remotely without actually having the data or necessary tools at their location. Examples of this include Intranet setups in large design firms in which information and tools are shared from a common server amongst engineers at several, sometimes remote locations. Along these same lines, interactive maps are now being implemented on the Internet for use at large. Future design, modeling, and management efforts could rely on such information being easily accessible.

The improvement in computer and modeling applications is definitely important for the advancement of wet weather management, but other aspects must also be addressed. For example, the methods utilized to control and treat stormwater discharges and CSOs are not perfect. How can these practices be better applied to newly urbanizing areas to enhance the development? How can the integration of these practices be improved to utilize the different techniques in a cost effective manner? These and other questions must be addressed.

Recently, a large number of papers and reports have been published related to the subject of sewer rehabilitation. It is no secret that the worlds', especially the United States' infrastructure is sorely in need of attention. As the historical portion of the literature review has noted, many of the wet weather systems in this country were developed in the early part of this century. Maintenance, retrofits, and rehabilitation since then have resulted in patchwork systems consisting of parts from different eras. The time is now and in the near future to develop cost effective methods to properly rehabilitate the wet weather flow systems to carry them far into the next century.

In the same vein as the rehabilitation concept, planners, designers, and constructors must provide infrastructure, specifically wet weather flow systems that will sustain themselves into the next century. The topic of sustainable development has been popular in the 1990s and will continue to be in the future. With the ever increasing population of the planet, it is becoming more difficult to provide infrastructure that meets the needs of humanity while concomitantly fusing harmoniously with the natural environment. To date, only a handful of case studies can boast of attaining short-term sustainable development. Developers must now start facing the reality that sustainable development must be a priority, otherwise in the future the engineering community will be faced with the problem of developing sustainable rehabilitation programs in which the systems that do not co-habitat with natural ecosystems will have to be retrofitted for that purpose most likely at a much greater expense.

Specific ideas being set forth recently concerning sustainable infrastructure approaches include the idea of integration (Zimmerman and Sparrow 1997). Integration is a term that can take on many different meanings depending on who is using it. One type of integration amounts to managing the entire urban water resources cycle comprehensively. In this type of arrangement wastewater, water supply, stormwater, and other water resources in an urban setting would be developed and managed comprehensively in a sustainable fashion. Another, broader perspective for integration involves the integration of infrastructure in general. This would amount to developing regions while considering infrastructure systems such as power, water, wastewater, stormwater, solid waste, transportation, communication, and others in an integrated manner. Possible ways to accomplish this would be to develop the infrastructure system comprehensively promoting cooperation in operation and management for the betterment of the community. Of course the ideas surrounding integration are in their infancy and therefore difficulty arises in locating examples and defining procedures of implementation.

Overall, wet weather management in newly urbanizing areas will be important in the future as water resources become more and more scarce. The planets population is growing at an incredible rate and the developing countries' urbanized areas require infrastructure to be constructed. Also the urbanized areas of the developed countries are continuing to expand. Some of the above topics mentioned relating to the future of wet weather management will need to be and possibly will be required to be incorporated into the development of newly urbanizing areas. This will promote the ideas of sustainability, cost effectiveness, comprehensive management that are being shown to be important aspects of wet weather management. The next section further reviews current wet weather flow design methods and also discusses future directions.

References

Accoustica Associates, Inc. *Demonstrate the feasibility of the use of ultrasonic filtration in treating the overflows from combined and/or storm sewers*. Report No. 11020---09/67, NTIS No. PB 201745, Washington, D.C., 1967.

Adams, B.J. and J.B. Bontje. "Microcomputer applications of analytical models for urban drainage design." *Proceedings of the Conference on Emerging Computer Techniques for Stormwater and Flood Management*, Edited by W. James, ASCE, 138-162, 1983.

Adeney, W.E. *The principles and practice of the dilution method of sewage disposal*. Cambridge University Press. New York, NY. 1928.

Agnew, R.W. *Biological treatment of combined sewer overflow at Kenosha, Wisconsin*. EPA-670/2-75-019, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1975.

Allen, D.M. *et al. Treatment of combined sewer overflows by high gradient magnetic separation*. EPA-600/2-77-015, NTIS No. PB 204935, U.S. Environmental Protection Agency, Washington, D.C., 1977.

Allen, D.M. *et al. Treatment of combined sewer overflows by high gradient magnetic separation*. EPA-600/2-78-209, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978.

Amy, G., R. Pitt, R. Singh, W. Bradford, and M. LaGraff. *Water quality management planning for urban runoff*. EPA-440/9-75-004, U.S. Environmental Protection Agency, Washington, D.C., 1974.

Anderson, J.J. "Real-time computer control of urban runoff." *Journal of the Hydraulics Division*, ASCE, 96(1), 153-164, 1970.

APWA (American Public Works Association). *Urban stormwater management*. APWA Special Report 49, Chicago, IL, 1981.

Ardis, C.V., K.J. Dueker, and A.T. Lenz. "Storm drainage practices of thirty-two cities." *Journal of the Hydraulics Division*, ASCE, 95(1), 383-408, 1969.

Baily, R. "Using automatic samplers to comply with stormwater regulations." *Water Engineering and Management*, 140(11), 23-25, 1993.

Bannerman, R.T., A.D. Legg, S.R. Greb. *Quality of Wisconsin stormwater*. USGS Open-File Report 96-458, U.S. Geological Survey and Wisconsin Department of Natural Resources, Madison, WI, 1996.

Bazalgette, J., *Proceedings Institute of Civil Engineers (London)*, 24, 292.

Beard, L.R. and S. Chang. "Urbanization impact on streamflow." *Journal of the Hydraulics Division*, ASCE, 105(6), 647-659, 1979.

Berwick, R., M. Shapiro, J. Kuhner, D. Luecke, and J.J. Wineman. *Select topics in stormwater management planning for new residential developments*. EPA-600/2-80-013, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980.

Betson, R. *Urban hydrology: A systems study in Knoxville, Tennessee*. Tennessee Valley Authority, 1976.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, A.S. Donigian, Jr., and R.C. Johanson. *Hydrological Simulation Program FORTRAN (HSPF): User's Manual for Release 10*. EPA-600/R-93-174, U.S. Environmental Protection Agency, Athens, GA, 1993.

Black, Crow & Edisness, Inc. and Jordan, Jones & Goulding, Inc. *Non point pollution evaluation Atlanta urban area*. Contract No. DACW 21-74-C-0107, U.S. Environmental Protection Agency, 1975.

Bourne, J. *Engineering*, 2, 267, 1866.

Boyce, E. "Engineering planning of sewage collection and treatment." *Sewage Works Journal*, 20, 502, 1949.

Brandstetter, A.B. *Assessment of mathematical models for storm and combined sewer management*. EPA-600/2-76-175a, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1976.

Bras, R.L. and F.E. Perkins. "Effects of urbanization on catchment response." *Journal of the Hydraulics Division*, ASCE, 101(3), 451-466, 1975.
Brater, E.F. "The unit hydrograph principle applied to small water-sheds." *Transactions of the American Society of Civil Engineers*, 105, 1154-1178, 1939.
Brater, E.F. *Rainfall-runoff relations on urban and rural areas*. EPA-670/2-75-046, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1975.
Brune, G.M. "Trap efficiency of reservoirs." *Transactions, American Geophysical Union*, 34(3), 407-418, 1953.
Brunner, P.G. *The pollution of storm water runoff in separate sewer systems: Studies with special reference to precipitation conditions in the lower Alp region*. Water Resources and Sanitary Engineering Department of Munich Technical University. (German Translation), 1975.
Buerger, C. "A method of determining storm-water run-off." *Transactions of the American Society of Civil Engineers*, 78, 1139-1205, 1915.
Burton, G.A. Jr. "Assessing stormwater impacts." *Hydraulic Engineering '94, Conference Proceedings, Volume 2*, Edited by G.V. Cotroneo and R.R. Rumer, ASCE, New York, 1198-1200, 1994.
Carson, R. *Silent Spring*. Houghton Mifflin Company, New York, NY, 1962.
Cave, K.A. and L.A. Roesner. "Overview of stormwater monitoring needs." *Stormwater NPDES related monitoring needs. Proceedings of the Engineering Foundation Conference*, Mt. Crested Butte, Colorado, August 7-12, 1994, Edited by H.C. Torno, ASCE, New York, 28-38, 1995.
Cermola *et al.* "SWMM application to combined sewerage in New Haven." *Journal of the Environmental Engineering Division*, ASCE, 105(6), 1035-1048, 1979.
Charalambous, C. and A.A. Elimam. "Heuristic design of sewer networks." *Journal of Environmental Engineering*, ASCE, 116(6), 1181-1199, 1990.
Chittenden, H.M. "Detention reservoirs with spillway outlets as an agency in flood control." *Transactions of the American Society of Civil Engineers*, 82, 1473-1540, 1918.
City of Chippewa Falls. *Storage and treatment of combined sewer overflows*. EPA-R2-72-070, Office of Research and Monitoring, U.S. Environmental Protection Agency, Washington, D.C., 1972.
City of Portland, Department of Public Works. *Demonstration of rotary screening for combined sewer overflows*. Report No. 11023FDD07/71, NTIS No. PB 206814, Portland, OR, 1971.
Clark, C.O. "Storage and the unit hydrograph." *Transactions of the American Society of Civil Engineers*, 110, 1419-1488, 1945.
Claytor, R.A. "An introduction to stormwater indicators: an urban runoff assessment tool." *Watershed Protection Techniques*, 2(2), 321-328, 1996a.
Claytor, R.A. "Habitat and biological monitoring reveals headwater stream impairment in Delaware's Piedmont." *Watershed Protection Techniques*, 2(2), 358-360, 1996b.
Claytor, R.A. W. and Brown. *Environmental indicators to assess the effectiveness of municipal and industrial stormwater control programs*. Prepared for the U.S. Environmental Protection Agency, Office of Wastewater Management, Center for Watershed Protection, Silver Spring, MD, 1996.
Cochrane Division, Crane Company. *Microstraining and disinfection of combined sewer overflows*. Report No. 11023EVO06/70, NTIS No. PB 195674/BA, U.S. Environmental Protection Agency, King of Prussia, PA, 1970.
Coffee, H.C. *et al. Demonstration of real time automatic control of combined sewer systems*. EPA-600/S2-83-084, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1983.
Colston, N.V. Jr. *Characterization and treatment of urban land runoff*. EPA-670/2-74-096, NTIS No. PB 240978, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1974.
Connick, D.J. *et al. Evaluation of a treatment lagoon for combined sewer overflow*. EPA-600/2-81-196, NTIS No. PB 82-105214, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1981.
Consoer, Townsend, and Associates. *Detention tank for combined sewer overflows: Milwaukee, Wisconsin demonstration project*. EPA-600/2-75-071, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1975.
Cornell, Howland, Hayes and Merryfield. *Rotary vibratory fine screening of combined sewer overflows*. Report No. 11023FDD03/70, NTIS No. PB 195168, U.S. Environmental Protection Agency, Corvallis, OR, 1970.
Crawford, N.H. and R.K. Linsley. Digital simulation in hydrology; Stanford Watershed Model IV. Technical Report No. 39, Department of Civil Engineering, Stanford University, 1966.
Curtis, L.W., G.P. Lee, and R.F. Thomas. *Report of study of the Wolf Creek channel and flood plain*. The Miami Conservancy District, Ohio, 1964.

Davis, P.L. and F. Borchardt. Combined sewer overflow abatement plan, Des Moines, Iowa. EPA-R2-73-170, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1974.

Dawdy, D.R. and T. O'Donnell. "Mathematical models of catchment behavior." *Journal of the Hydraulics Division*, ASCE, 91(4), 123-137, 1965.

Debo, T.N. and A.J. Reese. *Municipal storm water management*. Lewis Publishers, Boca Raton, FL, 1995.

DeGroot, W. (editor). *Proceedings of the Conference on stormwater detention facilities: planning, design, operation, and maintenance*. ASCE, New York, NY, 1982.

Deininger, R.A. "Systems analysis for water supply and pollution control." *National Resource System Models in Decision Making*, Edited by Toebes, G.H., Water Resources Center, Purdue University, Lafayette, IN, 1969.

Dendrou, S.A., J.W. Delleur, and J.J. Talavage. "Optimal planning for urban storm drainage systems." *Journal of the Water Resources Planning and Management Division*, ASCE, 104(1), 17-33, 1978a.

Dendrou, S.A., J.W. Delleur, and J.J. Talavage. "Planning storm-drainage systems for urban growth." *Journal of the Water Resources Planning and Management Division*, ASCE, 104(1), 1-16, 1978b.

Dendrou, S.A., J.W. Delleur, and J.J. Talavage. "Systematic planning of urban storm-drainage utilities." *International Symposium on Urban Hydrology, Hydraulics and Sediment Control*, OES Publishers, Lexington, KY, 229-234, 1978c.

DiToro, D.M. and M.J. Small. "Stormwater interception and storage." *Journal of the Environmental Engineering Division*, ASCE, 105(1), 43-54, 1979.

Dodson, R.D. *Storm water pollution control: industry and construction NPDES compliance*. McGraw-Hill, Inc., New York, NY, 1995.

Dowling, S.J. and B.W. Mar. "Culvert composite sampler: a cost effective stormwater monitoring device." *Journal of Water Resources Planning and Management*, ASCE, 122(4), 280-286, 1996.

Drehwing, F.J., A.J. Oliver, D.A. MacArthur, and P.E. Moffa. *Disinfection/treatment of combined sewer overflows*. EPA-600/2-79-134, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1979.

Drooker, P.B. *Application of the Stanford Watershed Model to a small New England watershed*. Master's thesis, Department of Soil and Water Science, Stanford University, 1968.

Dudley, L.A. "Low cost automatic sampler." *Stormwater NPDES related monitoring needs. Proceedings of the Engineering Foundation Conference*, Mt. Crested Butte, Colorado, August 7-12, 1994, Edited by H. C. Torno, ASCE, New York, 599-608, 1995.

Dunbar, D.D. and J.G.F. Henry. "Pollution control measures for stormwater and combined sewer overflows." *Journal Water Pollution Control Federation*, 38(1), 9, 1966.

Eagleson, P.S. "Unit hydrograph characteristics for sewered areas." *Journal of the Hydraulics Division*, ASCE, 88(2), 1-25, 1962.

Eisen, C. and M.P. Anderson. "The effects of urbanization on ground-water quality - a case study." *Groundwater*, 17(5), 456-462, 1979.

Elimam, A.A., C. Charalambous, and F.H. Ghobrial. "Optimum design of large sewer networks." *Journal of Environmental Engineering*, ASCE, 115(6), 1171-1190, 1989.

Elliot, W.J. "Chapter 2: Precipitation." *Environmental Hydrology*, Edited by A.D. Ward and W.J. Elliot, CRC/Lewis Publishers, Boca Raton, FL 19-50, 1995.

Ellis, J.B. "The characterisation of particulate solids and quality of water discharged from an urban catchment." *Effects of Urbanisation and Industrialisation on the Hydrological Regime and Water Quality*, Publication No. 123, IASH-AISH, Amsterdam, 283, 1977.

Ellis, J.B. "The nature and source of urban sediment and relation to water quality." *Man's Impact on the Hydrologic Cycle in the U.K.*, Edited by G.E. Hollis, Geobooks, Norwich, U.K., 199-216, 1979.

Ellis, J.B. "Benefits and blights of urban stormwater quality control." *Urban Drainage Systems*, Edited by R.E. Featherstone and A. James, Pitmans Press, London, U.K, 39-51, 1982.

Ellis, J.B. and D.M. Revitt. "Incidence of heavy metals in street surface sediments." *Water, Air & Soil Pollution*, 17, 87-100, 1982.

Ellis, J.B. "Urban runoff quality and control." *Advances in Water Engineering*, Edited by T.H.Y. Tebbutt, Elsevier Applied Science Publishers, New York, 234-240, 1985a.

Ellis, J.B. "The management and control of urban runoff quality." *Pollution in the Urban Environment,* Edited by M.W.H. Chan, R.W.M. Hoare, P.R. Holmes, R.J.S. Law and S.B. Reed, Elsevier Applied Science Publishers, New York, 606-614, 1985b.

Ellis, J.B. and W. Yu. “Bacteriology of urban runoff: the combined sewer as a bacterial reactor.” *Water Science and Technology*, 31(7), 303, 1995.
Envirogenics Company. *In-sewer fixed screening of combined sewer overflows*. Report No. 11024FKJ10/70, NTIS No. PB 213118, Division of Aerojet General Corporation, El Monte, CA, 1970.
EPA (U.S. Environmental Protection Agency). *Hypochlorite generator for treatment of combined sewer overflows*. Report No. 11023 DAA, Washington, D.C., 1972.
EPA (U.S. Environmental Protection Agency). *Areawide assessment procedures manual*, volumes I-III. EPA-600/9-76-014, Municipal Environmental Research Laboratory, Cincinnati, Ohio, 1976.
EPA (U.S. Environmental Protection Agency). *Proceedings stormwater management model (SWMM) users group meeting January 10-11, 1980*. EPA-600/9-80-017, Washington, D.C., 1980a.
EPA (U.S. Environmental Protection Agency). *Proceedings stormwater management model (SWMM) users group meeting June 19-20, 1980*. EPA-600/9-80-064, Washington, D.C., 1980b.
EPA (U.S. Environmental Protection Agency). *Results of the nationwide urban runoff program-executive summary*. Water Planning Division, Washington, D.C., 1983a.
EPA (U.S. Environmental Protection Agency). *Results of the nationwide urban runoff program, volume I - final report.* Water Planning Division, Washington, D.C., 1983b.
EPA (U.S. Environmental Protection Agency). *NPDES storm water sampling guidance document.* EPA-833/B-92-001, Cincinnati, Ohio, 1992.
EPA (U.S. Environmental Protection Agency). *NPDES storm water sampling and guidance manual*. C. K. Smoley, CRC Press, Inc., Boca Raton, FL, 1993.
EPA (U.S. Environmental Protection Agency). “Draft TMDL program implementation strategy.” *http://www.epa.gov.OWOW/tmdl/strategy*, June 1, 1997.
Espey, W.H. Jr., C.W. Morgan, and F.D. Masch. *A study of some effects of urbanization on storm runoff from a small watershed*. Center for Research in Water Resources, University of Texas, Austin, TX, 1965.
Espey, W.H. Jr. and D.E. Winslow. *The effects of urbanization in unit hydrographs for small watersheds, Houston, Texas, 1964-1967*. TRACOR Document Nos. 68-975-U and 68-1006-U, Office of Water Resources Research, 1968.
Espey, W.H. Jr., D.E. Winslow, and C.W. Morgan. “The effects of urbanization on peak discharge.” Paper presented at the Water Resources Symposium No. 2 on the Effects of Watershed Changes on Streamflow, University of Texas, Austin, TX, 1969.
Espey, W.H. Jr. and D.E. Winslow. “Urban flood frequency characteristics.” *Journal of the Hydraulics Division*, ASCE, 100(2), 279-293, 1974.
Everhart, R.C. "New town planned around environmental aspects." *Civil Engineering*, 43(9), 69-73, 1973.
Field, R. and E.J. Struzeski, Jr. "Management and control of combined sewer overflows." *Journal Water Pollution Control Federation*, 44, 1393, 1972.
Field, R. *The dual functioning swirl combined sewer overflow regulator/concentrator*. EPA-670/2-73-059, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1973.
Field, R. *et al. Water pollution and associated effects from street salting*. EPA-R2-73-257, NTIS No. PB 222795, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1973.
Field, R. and J.A. Lager. *Countermeasures for pollution from overflows*. EPA-670/2-74-090, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1974.
Field, R. and J.A. Lager. "Urban runoff pollution control - state-of-the-art." *Journal of the Environmental Engineering Division*, ASCE, 101(1), 107-125, 1975.
Field, R. and H.E. Masters. *Swirl device for regulating and treating combined sewer overflows*. EPA-625/2-77-012, NTIS No. PB 299571, EPA Technology Transfer Capsule Report, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.
Field, R., A.N. Tafuri, and H.E. Masters. *Urban runoff pollution control technology overview*. EPA-600/2-77-047, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.
Field, R. and R. Turkeltaub. "Urban runoff receiving water impacts: program overview." *Journal of the Environmental Engineering Division*, ASCE, 107(1), 83-100, 1981.
Field, R. “Combined sewer overflows: control and treatment.” *Control and Treatment of Combined Sewer Overflows*, Edited by P.E. Moffa, Environmental Engineering Series, Van Nostrand Reinhold, New York, NY, 1990.

Field, R. *et al.* “Storage of combined sewage in a marine water body.” *Proceedings of an Engineering Foundation Conference: Urban Stormwater Quality Enhancement - Source Control, Retrofitting, and Combined Sewer Technology*, Davos Platz, Switzerland, October 1989, EPA-600/A-92-060, NTIS No. PB 92-158567, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1992.

Field, R. “Storm and combined sewer overflow: An overview of EPA’s research program.” *Integrated Stormwater Management*, Edited by R. Field, M.L. O’Shea, and K.K. Chin, Lewis Publishers, Boca Raton, FL, 3-43, 1993.

Field, R., T. O’Conner, and R. Pitt. “Optimization of CSO storage and treatment systems.” *Proceedings of Water Environment Federations Specialty Conference on Reducing CSOs, Balancing Technologies, Costs and Water Quality*, Louisville, KY, 11-33, 1994.

Field, R. *Bibliography of storm and combined sewer pollution control R & D program documents*. EPA-600/9-90-032, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1995.

Field, R. and T.P. O’Conner. “Swirl technology: proper design, application and evaluation.” *Proceedings, WEFTEC ’95, 68th Annual Conference and Exposition*, Miami Beach, FL, WEF, 3-75, 1995.

Field, R. and T.P. O’Conner. "Swirl technology: enhancement of design, evaluation, and application." *Journal of Environmental Engineering*, ASCE, 122(8), 741-748, 1996.

Field, R. and T.P. O’Conner. “Optimization of CSO storage and treatment systems.” *Journal of Environmental Engineering*, ASCE, 123(3), 269-274, 1997.

Finnemore, E.J. “Stormwater pollution control: best management practices.” *Journal of the Environmental Engineering Division*, ASCE, 108(5), 835-851, 1982.

Flatt, P.E. and C.D.D. Howard. “Preliminary screening procedure for economic storage-treatment trade-offs in storm water control.” *International Symposium on Urban Hydrology, Hydraulics and Sediment Control*, Edited by W. James, OES Publishers, Lexington, KY, 219-228, 1978.

Foreman, K. *A passive flow measurement system for storm and combined sewer*. EPA-600/2-76-115, NTIS No. PB 253383, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1976.

Foreman, K. *Field testing of prototype acoustic emission sewer flowmeter*. EPA-600/2-79-084, NTIS No. PB 80-121544, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1979.

Forndran, A., R. Field, K. Dunkers, and D. Moran. “Combined sewer overflow - balancing flow for CSO abatement.” *Water Environment and Technology*, 3(5), 54-58, 1991.

Fram Corporation. *Strainer/filter treatment of combined sewer overflows*. Report No. 11020EXV07/69, NTIS No. PB 185949, East Providence, RI, 1969.

Frederick, R.H., V.A. Myers, and E.P. Auciello. *Five- to 60-Minute Precipitation Frequency for the Eastern and Central United States*. NOAA Technical Memorandum NWS HYDRO-35, National Oceanic and Atmospheric Administration (NOAA), Silver Spring, MD, 1977.

Froise, S. and S.J. Burges. "Least-cost design of urban-drainage networks." *Journal of the Water Resources Planning and Management Division*, ASCE, 104(1), 75-92, 1978.

Fulton, R.L. “Water resources planning in urban areas.” *Journal of the Hydraulics Division*, ASCE, 101(9), 1249-1255, 1974.

Garrison, E. *A history of engineering and technology: artful methods*. CRC Press, Boca Raton, FL, 175-191, 1991.

Gayman, M. “A glimpse into London’s early sewers.” Reprinted from *Cleaner Magazine*, http://klingon.util.utexas.edu, January 13, 1997.

Geiger, W.F. and H.R. Dorsch. *Quantity-Quality Simulation (QQS): A detailed continuous planning model for urban runoff control, volume I, model description, testing and applications*. EPA-600/2-80-011, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980.

Geldorf, G., P. Jacobsen, and S. Fujita. “Urban stormwater infiltration perspectives.” *Water Science and Technology*, 29(1-2), 245-254, 1994.

General Accounting Office (GAO). *Large construction projects to correct combined sewer overflows are too costly*. Report by the Comptroller General of the United States, December 28, 1979.

Gest, A.P. “Engineering.” In: *Our debt to Greece and Rome*, Edited by G.D. Hadzsits and D.M. Robinson, Cooper Square Publishers, Inc., New York, 1963.

Giessner, W.R., R.T. Cockburn, F.H. Moss, Jr., and M.E. Noonan. *San Francisco, Master Plan for Wastewater Management*. Preliminary Comprehensive Report, 1971.

Giessner, W.R., R.T. Cockburn, F.H. Moss, Jr., and M.E. Noonan. “Planning and control of combined sewerage systems.” *Journal of the Environmental Engineering Division*, ASCE, 100(4), 1013-1032, 1974.

Glover, G.E. and G.R. Herbert. *Microstraining and disinfection of combined sewer overflows-phase II*. EPA-R2-73-124, NTIS No. PB 219879, U.S. Environmental Protection Agency, Washington, D.C., 1973.

Graf, W.L. “The impact of suburbanization on fluvial geomorphology.” *Water Resources Research*, 11(5), 690-692, 1975.

Gregory, C.E. “Rainfall, and run-off in storm sewers.” *Transactions of the American Society of Civil Engineers*, 58, 458-510, 1907.

Gregory, C.E. "Intercepting sewers and storm stand-by tanks at Columbus, Ohio." *Transactions of the American Society of Civil Engineers*, 99, 1295-1342, 1934.

Grigg, N.S. *Water resources planning*. McGraw-Hill, Inc., New York, NY, 1985.

Grigg, N.S. and W. Schilling. “Automating stormwater and combined sewer systems: the possibilities.” *Water Engineering Management*, 133(5), 33, 1986.

Griggey, M.D. and W.G. Smith. "National needs for combined sewer overflow control." *Journal of the Environmental Engineering Division*, ASCE, 104(2), 351-366, 1978.

Grunsky, C.E. "Rain and run-off near San Francisco, California." *Transactions of the American Society of Civil Engineers*, 61, 496-543, 1908.

Grunsky, C.E. "Rainfall and runoff studies." *Transactions of the American Society of Civil Engineers*, 85, 66-136, 1922.

Guo, Y. and B.J. Adams. “Chapter 7: Long term performance modelling of stormwater quality ponds.” In: *Current Practices in Modelling the Management of Stormwater Impacts*, Edited by W. James, Lewis Publishers, Boca Raton, FL, 99-119, 1994.

Gupta, M.K. *et al. Screening/flotation treatment of combined sewer overflow-Volume I: bench-scale and pilot plant investigations*. EPA-600/2-77-069a, NTIS No. PB 272834, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.

Harremoës, P. and A. Henze. “This century’s shower in Denmark, registered by a new rain gauge system.” *Vannet Norden*, 14(2), 43-56, 1981.

Harremoës, P. and P.S. Mikkelsen. “Properties of extreme point rainfall I: results from a rain gauge system in Denmark.” *Atmospheric Research*, 37, 277-286, 1995.

Harremoës, P. and W. Rauch. “Integrated design and analysis of drainage systems, treatment plant and receiving waters.” *Journal of Hydraulic Research*, 34(6), 815-826, 1996.

Harvey, P.J. and C. Fan. *High-rate filtration of combined sewer overflows*. Report No. 11023EYI04/72, NTIS No. PB 211144, U.S. Environmental Protection Agency, Washington, D.C., 1972.

Heaney, J.P. *et al. Storm Water Management Model: refinement, testing, and decision making*. 11023 GSC, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1973.

Heaney, J.P., W.C. Huber, and S.J. Nix. *Storm Water Management Model, level 1, preliminary screening procedures*. EPA-600/2-76-275, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1976.

Heaney, J.P. and S.J. Nix. *Stormwater Management Model, level 1, comparative evaluation of storage-treatment and other management practices*. EPA-600/2-77-083, NTIS No. PB 265671, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.

Heaney, J.P., W.C. Huber, M.A. Medina, Jr., M.P. Murphy, S.J. Nix, and S.M. Hasan. *Nationwide evaluation of combined sewer overflows and urban storm water discharges, volume 2, cost assessments and impacts*. EPA-600/2-77-064b, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.

Heaney, J.P., S.J. Nix, and M.P. Murphy. “Storage-treatment mixes for stormwater control.” *Journal of the Environmental Engineering Division*, ASCE, 104(4), 581-592, 1978.

Heaney, J.P. *Economic/financial analysis of urban water quality management problems*. EPA Grant No. R 802411, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1979.

Heaney, J.P., W.C. Huber, and M.E. Lehman. *Nationwide assessment of receiving water impacts from urban stormwater pollution, volumes I and II*. EPA-600/S2-81-025, Cincinnati, Ohio, 1981.

Heaney, J.P. and W.C. Huber. "Nationwide assessment of urban runoff impact on receiving water quality." *Water Resources Bulletin*, 20(1), 35-42, 1984.

Heinking, G. and N. Wilcoxon. "Use of a swirl concentrator for combined sewer overflow." *Journal Water Pollution Control Federation*, 57(5), 398, 1985.

Hering, R. *Report to the U.S. National Board of Health*, 1881a.

Hering, R. “Sewerage systems.” *Transactions of the American Society of Civil Engineers*, 10, 361-386, 1881b.

Herricks, E.E., I. Milne, and I. Johnson. “Time-scale toxic effects in aquatic ecosystems.” In: *Stormwater NPDES related monitoring needs. Proceedings of the Engineering Foundation Conference*, Mt. Crested Butte, Colorado, August 7-12, 1994, Edited by H.C. Torno, ASCE, New York, 353-374, 1995.

Herricks, E.E., I. Milne, and I. Johnson. “A protocol for wet weather discharge toxicity assessment.” In: *WEFTEC ’96: Proceedings of the 69th Annual Conference and Exposition, Volume 4*, Dallas, TX, 13-24, 1996.

Hershfield, D.M. *Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods of 2 to 100 Years*. Technical Paper No. 40, U.S. National Weather Service, Silver Spring, MD, 1961.

Hess, S.G. and F.G. Manning. "A rational determination of storm overflows from intercepting sewers." *Sewage and Industrial Wastes*, 22, 145, 1950.

Hicks, W.I. “A method of computing urban runoff.” *Transactions of the American Society of Civil Engineers*, 109, 1217, 1944.

Hill, D. *A history of engineering in classical and medieval times*. Croom Helm Ltd., London, 1984.

Hodge, A.T. *Roman aqueducts & water supply*. Gerald Duckworth & Co. Ltd., London, 1992.

Hollang, M.G. *Computer models of wastewater collection systems*. PhD dissertation, Harvard University, Cambridge, MA, 1966.

Homack, P. *et al. Utilization of trickling filters for dual-treatment of dry- and wet-weather flows*. EPA-670/2-73-071, NTIS No. PB 231251, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1973.

Horner, W.W. and F.L. Flynt. “Relations between rainfall from small urban areas.” *Transactions of the American Society of Civil Engineers*, 101, 140, 1936.

Horner, W.W. and S.W. Jens. "Surface runoff determination from rainfall without using coefficients." *Transactions of the American Society of Civil Engineers*, 107, 1039-1117, 1942.

Howard, C.D.D. “Theory of storage and treatment-plant overflows.” *Journal of the Environmental Engineering Division*, ASCE, 105(1), 709-722, 1976.

Howard, C.D.D., P.E. Flatt, and U. Shamir. *Storm and combined sewer storage treatment theory compared to computer simulation*. EPA-600/2-81-125, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1981.

Howell, C.L. “The problem of interception and treatment of sewage at Buffalo, NY.” *Sewage Works Journal*, 2(1), 71-76, 1930.

Hoxie, R.L. “Excessive rain-falls considered with special reference to their occurrence in populous districts.” *Transactions of the American Society of Civil Engineers*, 25, 70-118, 1891.

Hoyt, J.C. “Comparison between rainfall and runoff in the Northeastern United States.” *Transactions of the American Society of Civil Engineers*, 59, 431-520, 1907.

Huber, W.C., J.P. Heaney, M.A. Medina, Jr., W.A. Peltz, H. Sheikh, and G.F. Smith. *Storm Water Management Model User’s Manual—Version II*. EPA-670/2-75-017, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1975.

Huber, W.C. and J.P. Heaney. *Urban rainfall-runoff-quality data base*. EPA-600/8-77-009, NTIS No. PB 270065, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.

Huber, W.C., J.P. Heaney, K.J. Smolenyak, and D.A. Aggidis. *Urban rainfall-runoff-quality data base: update with statistical analysis*. EPA-600/8-79-004, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1979.

Huber, W.C. *et al. Urban rainfall-runoff-quality data base: addendum I: statistical analysis and additional data*. EPA-600/2-81-238, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1981.

Huber, W.C., J.P. Heaney, S.J. Nix, R.E. Dickinson, and D.J. Polman. *Storm Water Management Model user's manual, version III*. EPA-600/S2-84-109a, NTIS No. PB 84-198423, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1984.

Huber, W.C. “Deterministic modeling of urban runoff quality.” In: *Urban Runoff Pollution*, Edited by H.C. Torno, J. Marsalek, and M. Desbordes, NATO ASI Series, Series G: Ecological Sciences, Vol. 10, Springer-Verlag, Berlin, 166-242, 1986.

Huber, W.C. and R.E. Dickinson. *Storm Water Management Model, Version 4, User's Manual*. EPA-600/3-88-001a, U.S. Environmental Protection Agency, Athens, Georgia, 1988.

Huff, F.A. “Time distribution of rainfall in heavy storms.” *Water Resources Research*, 3(4), 1007-1019, 1967.

Huff, F.A. “Precipitation detection by fixed sampling densities.” *Journal of Applied Meteorology*, 8, 834-837, 1969.

Huff, F.A. and S.A. Changnon. “A hydrometeorological research program.” *Water Resources Bulletin*, 13, 573-581, 1977.

Huff, F.A., J.L. Vogel, and S.A. Changnon. “Real-time rainfall monitoring-prediction system.” *Journal of the Water Resources Planning and Management Division*, ASCE, 107(2), 419-435, 1981.

Hydroscience, Inc. *A statistical method for the assessment of urban storm water*. EPA-440/3-79-023, U.S. Environmental Protection Agency, Washington, D.C., 1979.

Jacobsen, P. “Improvement of combined sewer systems by stormwater infiltration.” In: *Proceedings Second European Junior Scientist Workshop on Hydrological and Pollutional Aspects of Stormwater Infiltration*, Kastaniënbaum/Luzern, Switzerland, April 4-7, 1991, 1-10, 1991.

Jacobsen, P. and P.S. Mikkelsen. “Combined sewer overflow abatement by means of detention basins and stormwater infiltration.” In: *Proceedings ASCE International Symposium on Engineering Hydrology*, San Francisco, CA, July 25-30, 1993.

James, L.D. “Using a digital computer to estimate the effects of urban development on flood peaks.” *Water Resources Research*, 1(2), 223-234, 1965.

James, W. and M.A. Robinson. “Continuous modeling essential for detention design.” In: *Proceedings of the ASCE Conference on Stormwater Detention Facilities*, Henniker, New Hampshire, ASCE, New York, 163-175, 1982.

James, W. *Current practices in modelling the management of stormwater impacts*. CRC Press/Lewis Publishers, Boca Raton, FL, 1994.

James, W. “Why design storm methods have become unethical.” In: *Hydraulic Engineering ’94, Conference Proceedings*, Edited by G.V. Cotroneo and R.R. Rumer, ASCE, New York, 1203-1207, 1994.

James, W. “How to monitor *only* the important parameters.” In: *Stormwater NPDES related monitoring needs. Proceedings of the Engineering Foundation Conference*, Mt. Crested Butte, Colorado, August 7-12, 1994, Edited by H.C. Torno, ASCE, New York, 39-58, 1995.

James, W. “On reasons why traditional single-valued, single-event hydrology (typical design storm methodology) has become simple-minded, dishonest and unethical.” Internet site: *http://www.soe.uoguelph.ca/webfiles/james/c137a.html*, downloaded March 4, 1997.

Janson, L.E. *et al.* "Equalization of flow variations in combined sewers." *Journal of the Environmental Engineering Division*, ASCE, 102(6), 1139-1149, 1976.

Johanson, R.C., J.C. Imhoff, and H.H. Davis. *Users manual for Hydrological Simulation Program - Fortran (HSPF)*. EPA-600/9-80-015, U.S. Environmental Protection Agency, Athens, GA, 1980.

Johanson, R.C., J.C. Imhoff, and H.H. Davis. *Users manual for Hydrological Simulation Program - Fortran (HSPF): Users Manual for Release 8.0*. EPA-600/3-84-066, U.S. Environmental Protection Agency, Athens, GA, 1984.

Johnson, I., E.E. Herricks, and I. Milne. “Application of a test battery for wet weather discharge toxicity analyses.” In: *WEFTEC ’96: Proceedings of the 69th Annual Conference and Exposition, Volume 4*, Dallas, TX, 219-229, 1996.

Jones, D.E. Jr. “Urban hydrology - a redirection.” *Civil Engineering*, 37(8), 58-62, 1967.

Jones, D.E. Jr. “Where is urban hydrology practice today?” *Journal of the Hydraulics Division*, ASCE, 97(2), 257-264, 1971.

Jones, J.E. “Multipurpose stormwater detention ponds.” *Public Works*, 121(13), 52-53, 1990.

Justin, J.D. "Derivation of run-off from rainfall data." *Transactions of the American Society of Civil Engineers*, 77, 346-384, 1914.

Karl R. Rohrer Associates, Inc. *Underwater storage of combined sewer overflows*. Report No. 11022ECV09/71, NTIS No. PB 208346, U.S. Environmental Protection Agency, Washington, D.C., 1971.

Keefer, T.N. *et al. Dissolved oxygen impact from urban storm runoff*. EPA-600/2-79-156, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1979.

Ketchum, L.H. Jr. *Dissolved oxygen measurement in Indiana streams during urban runoff*. EPA-600/2-87-135, NTIS No. PB 284871, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978.

Kieth, L.H. *Environmental sampling and analysis: a practical guide*. Lewis Publishers, Inc., Chelsea, MI, 1991.

Kieth, L.H. (editor). *Compilation of EPA’s sampling and analysis methods*. Lewis Publishers, Inc., Chelsea, MI, 1992.

Kieth, L.H. (editor). *Compilation of EPA’s sampling and analysis methods, 2nd edition*. CRC/Lewis Publishers, Boca Raton, FL, 1996.

Kieth, L.H. (editor). *Principles of environmental sampling, 2nd edition*. American Chemical Society, Washington, D.C., (1996).

Kirby, R.S. and P.G. Laurson. *The early years of modern civil engineering*. Yale University Press, New Haven, CT, 227-239, 1932.

Klemes, V. “Empirical and causal models in hydrologic reliability analysis.” In: *Proceedings of the NATO Institute on Engineering Reliability and Risk in Water Resources*, Tucson, AZ, May 19-June 2, 1985, 391-403, 1987.

Ku, H.F.H. and D.L. Simmons. *Effects of urban runoff on groundwater beneath recharge basins on Long Island, New York*. Water Resources Investigations Report 85-4088, U.S. Geological Survey, New York, NY, 1986.

Kuichling, E. “The relation between the rainfall and the discharge of sewers in populous districts.” *Transactions of the American Society of Civil Engineers*, 20, 1-60, 1889.

Labadie, J.W., N.S. Grigg, and B.H. Bradford. "Automatic control of large-scale combined sewer systems." *Journal of the Environmental Engineering Division*, ASCE, 101(1), 27-39, 1975.

Lager, J.A. and W.G. Smith. *Urban stormwater management and technology: an assessment*. EPA-670/2-74-040, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1974.

Lager, J.A., W.G. Smith, W.G. Lynard, R.M. Finn, and E.J. Finnemore. *Urban stormwater management and technology: update and users’ guide*. EPA-600/8-77-014, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.

Lalor, M., R. Pitt, R. Field, and E. Thackston. “Locating inappropriate discharges to storm drains.” In: *Stormwater NPDES related monitoring needs. Proceedings of the Engineering Foundation Conference*, Mt. Crested Butte, Colorado, August 7-12, 1994, Edited by H.C. Torno, ASCE, New York, 63-80, 1995.

Larson, K.E. "Calculating overflows from combined sewer systems." *Journal of the Environmental Engineering Division*, ASCE, 105(5), 829-842, 1979.

Lee, J.A. *et al.* "Filtering combined sewer overflows." *Journal Water Pollution Control Federation*, 44, 1317, 1972.

Li, J.Y. *Comprehensive urban runoff control planning*. PhD dissertation, University of Toronto, Canada, 1991.

Li, J.Y. and B.J. Adams. “Chapter 7: Comprehensive urban runoff quantity and quality management modelling.” In: *New Techniques for Modelling the Management of Stormwater Quality Impacts*, Edited by W. James, Lewis Publishers, Boca Raton, FL, 151-176, 1993.

Lichty, T.W., D.R. Dawdy, and J.M. Bergmann. “Rainfall-runoff model for small basin flood hydrograph simulation.” *IAHS Publication No. 81*, 356-367, 1968.

Ligon, J.T., A.G. Law, and D.H. Higgins. *Evaluation and application of a digital hydrologic simulation model*. Report No. 12, Water Resources Research Institute, Clemson University, 1969.

Lindholm, O.G. "Pollutional analysis of combined sewer systems." *Journal of the Environmental Engineering Division*, ASCE, 102(2), 301-312, 1976.

Linsley, R.K. and W.C. Ackerman. "Method of predicting the runoff from rainfall." *Transactions of the American Society of Civil Engineers*, 107, 825-846, 1942.

Linsley, R.K. and N. Crawford. “Computation of a synthetic streamflow record on a digital computer.” *Publication No. 51*, International Association of Scientific Hydrology, 526-538, 1960.

Linsley, R.K. and N. Crawford. “Continuous simulation models in urban hydrology.” *Geophysical Research Letters*, 1(1), 59-62, 1974.

Lloyd-Davies, D.E. “The elimination of storm water from sewerage systems.” *Minutes of Proceedings, Institution of Civil Engineers* (London), 164, 41-67, 1906.

Loganathan, G.V., J.W. Delleur, and R.I. Segarra. “Planning detention storage for stormwater management.” *Journal of Water Resources Planning and Management*, ASCE, 111(4), 382-398, 1985.

Lorch, B. *Effects of highway traction sand and salt near Vail Pass, Colorado*. MS Poster Presentation, Hydrology Days Conference, Colorado State University, Fort Collins, CO, April 14-18, 1997.

Maher, M. *Microstraining and disinfection of combined sewer overflows-phase III*. EPA-670/2-74-049, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1974.

Mahida, V.U. *et al. Multi-purpose combined sewer overflow treatment facility, Mount Clemens, Michigan*. EPA-670/2-75-010, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1975.

Maner, A.W. “Public works in ancient Mesopotamia.” *Civil Engineering*, 36(7), 50-51, 1966.

Mason, D.G. *et al. Screening/flotation treatment of combined sewer overflows. Volume I: Bench scale and pilot plant investigations*. EPA-600/2-77-069a, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.

Mays, L.W. and B.C. Yen. "Optimal cost design of branched sewer systems." *Water Resources Research*, 11(1), 37, 1975.

Mays, L.W. and P.B. Bedient. “Model for optimal size and location of detention.” *Journal of the Water Resources Planning and Management Division*, ASCE, 108(3), 270-285, 1982.
McConnell, J.B. *Impact of urban storm runoff on stream quality near Atlanta, Georgia*. EPA-600/2-80-094, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980.
McHarg, I. *Design with nature*. Doubleday Natural History Press, New York, NY, 1969.
McHarg, I. “Ecological values and regional planning.” *Civil Engineering*, 40(8), 40-44, 1970.
McMath, R.E. “Determination of the size of sewers.” *Transactions of the American Society of Civil Engineers*, 16, 179-190, 1887.
McPherson, M.B. *Urban runoff*. Technical Memorandum No. 18, ASCE Urban Water Resources Research Program, New York, NY, 1972.
McPherson, M.B. “Translation of research results to users.” In: *Urban Runoff Quantity & Quality, Conference Proceedings*, August 11-16, 1974, New Hampshire, ASCE, New York, NY, 4-8, 1975.
McPherson, M.B. “Urban runoff control master planning.” *Journal of the Water Resources Planning and Management Division*, ASCE, 104(1), 223-234, 1978a.
McPherson, M.B. *Urban runoff control planning*. EPA-600/9-78-035, U.S. Environmental Protection Agency, Washington, D.C., 1978b.
Medina, M.A. Jr. *Interaction of urban storm water runoff, control measures and receiving water response*. PhD dissertation, University of Florida, Gainesville, FL, 1976.
Medina, M.A. Jr. *Level III: receiving water quality modeling for urban stormwater management*. EPA-600/2-79-100, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1979.
Medina, M.A. Jr., W.C. Huber. and J.P. Heaney. “Modeling stormwater storage/treatment transients: applications.” *Journal of the Environmental Engineering Division*, ASCE, 107(4), 799-816, 1981a.
Medina, M.A. Jr., W.C. Huber, and J.P. Heaney. “Modeling stormwater storage/treatment transient: theory.” *Journal of the Environmental Engineering Division*, ASCE, 107(4), 781-797, 1981b.
Meinholz, T.L. *Screening/flotation treatment of combined sewer overflows-Volume II: full-scale operation, Racine, WI*. EPA-600/2-79-106a, NTIS No. PB 80-130693, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1979.
Meinholz, T.L., W.A. Kreutzberger, M.E. Harper, and K.J. Fay. *Verification of the water quality impacts of combined sewer overflows*. EPA-600/2-79-155, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1979.
Melpar. *Combined sewer temporary underwater storage facility*. Report No. 11022DPP10/70, NTIS No. PB 197669, Falls Church, VA, 1970.
Metcalf & Eddy Engineers, University of Florida and Water Resources Engineers, Inc. *Storm Water Management Model, volume I, final report*. Report No. 11024EQG03/71, NTIS No. PB 208815, U.S. Environmental Protection Agency, Washington, D.C., 1971.
Metcalf, L. and H.P. Eddy. *American sewerage practice, volume I: design of sewers*. McGraw-Hill Book Company, Inc., New York, NY, 1-33, 1928.
Metcalf, L. and H.P. Eddy. *Sewerage and sewage disposal, a textbook*. McGraw-Hill Book Company, Inc., New York, NY, 1930.
Meyer, A.F. "Computing run-off from rainfall and other physical data." *Transactions of the American Society of Civil Engineers*, 79, 1056-1224, 1915.
Mikkelsen, P.S., G. Weyer, C. Berry, Y. Walden, V. Colandini, S. Poulsen, D. Grotehusmann, and R. Rohlfing. “Pollution from urban stormwater infiltration.” *Water Science and Technology*, 29(1-2), 293-302, 1994.
Mikkelsen, P.S., M. Häfliger, M. Ochs, J.C. Tjell, M. Jacobsen, and M. Boller. “Experimental assessment of soil and groundwater contamination from two old infiltration systems for road runoff in Switzerland.” In: *Proceedings, 7th International Conference on Urban Storm Drainage*, Hannover, Germany, September 9-13, 1996a.
Mikkelsen, P.S., M. Jacobsen, and M. Boller. “Pollution of soil and groundwater from infiltration of highly contaminated stormwater - a case study.” In: *Proceedings, 7th International Conference on Urban Storm Drainage*, Hannover, Germany, September 9-13, 1996b.
Mikkelsen, P.S., H. Madsen, H. Rosgjerg, and P. Harremoës. “Properties of extreme point rainfall III: identification of spatial inter-site correlation structure.” *Atmospheric Research*, 40, 77-98, 1996c.

Mikkelsen, P.S., K. Arngjerg-Nielsen, and P. Harremoës. “Consequences for established design practice from geographical variation of historical rainfall data.” In: *Proceedings, 7th International Conference on Urban Storm Drainage*, Hannover, Germany, September 9-13, 1996d.

Miles, S.W. and J.P. Heaney. "Better than "optimal" method for designing drainage systems." *Journal of Water Resources Planning and Management*, ASCE, 114(5), 477-499, 1988.

Miller, J.F. and J.L.H. Paulhus. “Rainfall-runoff relation for small basins.” *Transactions*, American Geophysical Union, 38(2), 216-218, 1957.

Minor, J.D. “Finding illicit connections and discharges with P^{2}IL.” In: *Stormwater NPDES related monitoring needs. Proceedings of the Engineering Foundation Conference*, Mt. Crested Butte, Colorado, August 7-12, 1994, Edited by H.C. Torno, ASCE, New York, 81-91, 1995.

Moffa, P.E. *et al. Bench-scale high rate disinfection of combined sewer overflows with chlorine and chlorine dioxide*. EPA-670/2-75-021, NTIS No. PB 242296, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1975.

Moffa, P.E., J.C. Byron, S.D. Freedman, J.M. Karanik, and R. Ott. *User’s guide: methodology for evaluating the impact and abatement of combined sewer overflows: a case study of Onondaga Lake, New York*. EPA-600/8-80-048, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980.

Moutal, H. *et al.* “Alternative vortex technology demonstration project.” In: *Proceedings Global Perspectives on Reducing CSOs*, WEF, 7-51, 1994.

Mulvaney, T.J. “On the use of self-registering rain and flood gages, in making observations of the relation of rainfall and flood discharges in a given catchment.” *Proceedings of the Institute of Civil Engineering of Ireland*, 4, 18-31, 1851.

Mumford, L. *The city in history: its origins, its transformations, and its prospects*. Harcourt, Brace & World, New York, NY, 1961.

Nielsen, J.B., S. Lindberg, and P. Harremoës. “Model based on-line control of sewer systems.” *Water Science and Technology*, 28(11-12), 87-98, 1994.

Nightingale, H.I. “Lead, zinc, and copper in soils of urban storm-runoff retention basins.” *American Water Works Association Journal*, 67, 443-446, 1975.

Nightingale, H.I. and W.C. Bianchi. “Ground-water chemical quality management by artificial recharge.” *Groundwater*, 15(1), 15-22, 1977a.

Nightingale, H.I. and W.C. Bianchi. “Ground-water turbidity resulting from artificial recharge.” *Groundwater*, 15(2), 146-152, 1977b.

Nightingale, H.I. “Water quality beneath urban runoff water management basins.” *Water Resources Bulletin*, 23(2), 197-205, 1987.

Nix, S.J. *Preliminary analysis of urban storm water management alternatives*. MS thesis, University of Florida, Gainesville, FL, 1976.

Nix, S.J. Analysis of storage/release systems in urban stormwater quality management. PhD dissertation, University of Florida, Gainesville, FL, 1982.

Nix, S.J., J.P. Heaney, and W.C. Huber. “Analysis of storage/release systems in urban storm water quality management: a methodology.” In: *Proceedings of the International Symposium on Urban Hydrology, Hydraulics, and Sediment Control*, University of Kentucky, Lexington, KY, 1983.

Nix, S.J. and J.P. Heaney. "Optimization of storm water storage-release strategies." *Water Resources Research*, 24(11), 1831-1838, 1988.

Nix , S.J. “Mathematical modeling of the combined sewer system.” In: *Control and Treatment of Combined Sewer Overflows*, Edited by P.E. Moffa, Environmental Engineering Series, Van Nostrand Reinhold, New York, NY, 1990.

Nix, S.J., P.E. Moffa, and D.P. Davis. “The practice of combined sewer system modeling.” *Water Resources Bulletin*, 27(2), 1-12, 1991.

Nix, S.J. *Urban stormwater modeling and simulation*, Lewis Publishers, Boca Raton, FL, 1994.

Nix, S.J. and S.R. Durrans. “Off-line stormwater detention systems.” *Water Resources Bulletin*, 32(6), 1329-1340, 1996.

Novotny, V. and H. Olem. *Water quality: prevention, identification, and management of diffuse pollution*. Van Nostrand Reinhold, New York, 85-99, 1994.

Odell, F.S. “The sewerage of Memphis.” *Transactions of the American Society of Civil Engineers*, 10, 23-52, 1881.

Olivieri, V.P., C.W. Kruse, K. Kawata, and J.E. Smith. *Microorganisms in urban stormwater*. EPA-600/2-77-087, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.

Ormsbee, L.E. *Systematic planning of dual purpose detention basins in urban watersheds*. PhD dissertation, Purdue University, 1983.

Ormsbee, L.E. “Detention basin design using continuous simulation.” In: *Engineering Hydrology, Conference Proceedings*, Edited by A.D. Feldman, Williamsburg, VA, ASCE, New York, 376-381, 1987.

O’Shea, M.L. and R. Field. “The detection and disinfection of pathogens in storm-generated flows.” In: *Integrated Stormwater Management*, Edited by R. Field, M.L. O’Shea, and K.K. Chin, Lewis Publishers, Boca Raton, FL, 225-244, 1993.

Palmer, C.L. "The pollutional effects of storm-water overflows from combined sewers." *Sewage and Industrial Wastes*, 22(2), 154, 1950.

Parks, J.W. *et al. An evaluation of three combined sewer overflow treatment alternatives*. EPA-670/2-74-079, NTIS No. PB 239115, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1974.

Personal Bibliographic Software, Inc. *ProCite for Windows, Version 3.0*, Ann Arbor, MI, 1995.

Pettis, C.R. "Appraisal of Unit-Graph method of flood estimation." *Civil Engineering*, 8(2), 114-115, 1938.

Pisano, W.C. *Swirl and helical bend regulator/concentrator for storm and combined sewer overflow control*. EPA-600/S2-84-151, NTIS No. PB 85-102523, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1984.

Pitt, R. and G. Amy. *Toxic materials analysis of street surface contaminants*. EPA-R2-73-283, U.S. Environmental Protection Agency, Washington, D.C., 1973.

Pitt, R. and M. Bozeman. *Water quality and biological effects of urban runoff on Coyote Creek: phase I-preliminary survey*. EPA-600/2-80-104, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980.

Pitt, R. and M. Bozeman. *Sources of urban runoff pollution and its effects on an urban creek*. EPA-600/S2-82-090, NTIS No. PB 83-111021, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1982.

Pitt, R., S. Clark, and K. Parmer. *Potential groundwater contamination from intentional and nonintentional stormwater infiltration*. EPA-600/SR-94-051, U.S. Environmental Protection Agency, Washington, D.C., 1994.

Pitt, R. “Effects of urban runoff on aquatic biota.” In: *Handbook of Ecotoxicology*, Edited by D. Hoffman *et al.*, Lewis Publishers, Boca Raton, FL, 609-630, 1995.

Pitt, R., R. Field, M. Lalor, and M. Brown. “Urban stormwater toxic pollutants: assessments, sources, and treatability.” *Water Environment Research*, 67(3), 260-275, 1995.

Pitt, R. “Urban stormwater toxic pollutant assessment, sources, and treatability-closure.” *Water Environment Research*, 68(5), 953-955, 1996.

Pitt, R. and J. Voorhees. *SLAMM, Version 6.4, Source Loading and Management Model for Stormwater Control*, 1996.

Pitt, R., S. Clark, K. Parmer, and R. Field. *Groundwater contamination from stormwater infiltration*. Ann Arbor Press, Inc., Chelsea, MI, 1996.

Poertner, H.G. *Stormwater management in the United States*. U.S. Office of Water Research and Technology Report, Washington, D.C., 1980.

Porcella, D.B. and D.L. Sorensen. *Characteristics of nonpoint source urban runoff and its effects on stream ecosystems*. EPA-600/3-80-032, Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency, Corvallis, OR, 1980.

Preul, H.C. and C.N. Papadakis. *Urban runoff characteristics - volume I - analytical studies*. EPA-600/2-76-217a, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1976a.

Preul, H.C. and C.N. Papadakis. *Urban runoff characteristics - volume II - field investigations*. EPA-600/2-76-217b, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1976b.

Qureshi, A.A. *Microbiological characteristics of stormwater runoffs at East York (Toronto) and Guelph separate storm sewers*. Report No. AQ 7501, MICRO 7717, Microbiology Section, Laboratory Services Branch, Ontario Ministry of the Environment, Toronto, Canada, 1977.

Rafter, G.W. *The relation between rainfall and run-off*. Water Supply Paper No. 80, U.S. Geological Survey, 1903.

Ramey, H.P. “Storm water drainage in the Chicago area.” *Journal of the Hydraulics Division*, ASCE, 85(4), 11-37, 1959.

Rand Development Corporation. *Rapid-flow filter for sewer overflows*. Report No. 11023DPI08/69, NTIS No. PB 194032, Cleveland, Ohio, 1969.

Rao, G.V.V. “Methods for sizing storm water detention basins - a designers evaluation.” In: *International Symposium on Urban Hydrology, Hydraulics and Sediment Control*, OES Publishers, Lexington, KY, 91-100, 1975.
Rauch, W. and P. Harremoës. “Optimal control of integrated urban drainage systems.” In: *Proceedings of the 7th International Conference on Urban Storm Drainage*, Hannover, Germany, September 9-13, 1996.
Reid, D. *Paris sewers and sewermen*. Harvard University Press, Cambridge, MA, 1991.
Reinelt, L.E., R.R. Horner, and B.W. Mar. “Nonpoint source pollution monitoring program design.” *Journal of Water Resources Planning and Management*, ASCE, 114(3), 335-352, 1988.
Renard, K.G. and R.H. Hawkins. “A historical perspective of ASCE’s approach to watershed management.” In: *Proceedings of the Symposium Watershed Management: Planning for the 21st Century*, ASCE, San Antonio, TX, 195-207, 1995.
Rex Chainbelt, Inc., Ecology Division. “Screening/flotation treatment of combined sewer overflows.” *Report No. 11020FDC01/72*, U.S. Environmental Protection Agency, 1972.
Robinson, R. “The tunnel that cleaned up Chicago.” *Civil Engineering*, 56(7), 34-37, 1986.
Roesner, L.A. “Real-time automatic control of San Francisco’s combined wastewater collection system.” In: *Proceedings of the USEPA SWMM Users Group Meeting*, October 26, 1976, Toronto, Canada, 1976.
Roesner, L.A., J.S. Aldrich, and R.E. Dickinson. *Storm Water Management Model User's Manual, Version 4: Addendum I, EXTRAN*. EPA-600/3-88-001b, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1988.
Roy F. Weston, Inc. *Combined sewer overflow abatement alternatives*. Report No. 11024EXF08/70, NTIS No. PB 203680, West Chester, PA, 1970.
Sarma, P.B.S., J.W. Delleur, and A.R. Rao. “Comparison of rainfall-runoff models for urban areas.” *Journal of Hydrology*, 18, 329-347, 1973.
Sartor, J.D. and G.B. Boyd. *Water pollution aspects of street surface contaminants*. EPA-R2-72-081, NTIS No. PB 214408, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1972.
Savini, J. and J.C. Kammerer. *Urban growth and the water regime*. U.S. Geological Survey Water-Supply Paper 1591-A, U.S. Geological Survey, Department of the Interior, Washington, D.C., 1961.
Scheible, O.K. and A. Forndran. *Ultraviolet disinfection of wastewaters from secondary effluent and combined sewer overflows*. EPA-600/2-86-005, NTIS No. PB 86-145182, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1986.
Scheible, O.K., R. Smith, and W. Cairns. *The application of ultraviolet disinfection to combined sewer overflows.* prepared for the New York City Department of Environmental Protection, 1991.
Schueler, T. “Stream channel geometry used to assess land use impacts in the Pacific Northwest.” *Watershed Protection Techniques*, 2(2), 345-348, 1996.
Segarra, R.I. and G.V. Loganathan. *Planning model for the control and treatment of stormwater runoff through detention storage*. U.S. Geological Survey Water-Resources Investigations Report G-1041-03, Geological Survey, Reston, VA, 1989.
Segarra, R.I. and G.V. Loganathan. “A stochastic pollutant load model for the design of stormwater detention facilities.” *Water Science and Technology*, 29(1-2), 327-335, 1994.
Segarra-Garcia, R. and M. El Basha-Rivera. “Optimal estimation of storage-release alternatives for storm-water detention systems.” *Journal of Water Resources Planning and Management*, ASCE, 122(6), 428-436, 1996.
Shelley, P.E. *Design and testing of a prototype automatic sewer sampling system*. EPA-600/2-76-006, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1975.
Sherman, L.K. "Streamflow from rainfall by Unit-Graph Method." *Engineering News - Record*, 108, 501-505, 1932.
Shuckrow, A.J. *et al. Physical-chemical treatment of combined and municipal sewage*. 11020 DSQ, EPA-R2-73-149, U.S. Environmental Protection Agency, Washington, D.C., 1973.
Shutes, R.B.E. “The influence of surface runoff on the macro-invertebrate fauna of an urban stream.” *The Science of the Total Environment*, 33, 271, 1984.
Small, M.J. and D.M. DiToro. “Stormwater treatment systems.” *Journal of the Environmental Engineering Division*, ASCE, 105(3), 557-569, 1979.
Smisson, B. “Design, construction, and performance of vortex overflow.” In: *Symposium on Storm Sewage Overflows*, Institute of Civil Engineers, 1967.
Smith, R. and R.G. Eilers. *Stream models for calculating pollutional effects of stormwater runoff*. EPA-600/2-78-148, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978.

Snyder, F.F. "Synthetic Unit-Graphs." *Transactions, American Geophysical Union*, 725-738, 1938.
Spooner, C.S. *et al. A demonstration of areawide water resources planning*. EPA-600/5-78-006a, U.S. Environmental Protection Agency, Washington, D.C., 1978.
Springfield Sanitary District. *Retention basin control of combined sewer overflows*. Report No. 11023---08/70, NTIS No. PB 200828, Springfield, IL, 1970.
Stall, J.B. and M.L. Terstriep. *Storm sewer design--an evaluation of the RRL method*. EPA-R2-72-068, NTIS No. PB 214134, U.S. Environmental Protection Agency, Washington, D.C., 1972.
Standard methods for the examination of water and wastewater. Edited by A.E. Greenburg, L.S. Clesceri, and A.D. Eaton, American Public Health Association, American Water Works Association, and Water Environment Federation, Washington, D.C., 1992.
Stanley, W.E. and W.J. Kaufman. "Sewer capacity design practice." *Journal Boston Society of Civil Engineers*, 40(4), 312, 1953.
Steel, E.W. *Water supply and sewerage*. McGraw-Hill Book Company, Inc., New York, NY, 1938.
Stegmaier, R.B. Jr. "Storm water overflows." *Sewage Works Journal*, 14(6), 1264-1273, 1942.
Stephenson, D. "Evaluation of effects of urbanization on storm runoff." In: *Proceedings, 7th International Conference on Urban Storm Drainage*, Hannover, Germany, September 9-13, 1996, 31-36, 1996.
Stiefel, R.C. *Dissolved oxygen measurements in Ohio streams following urban runoff*. EPA-600/2-80-092, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980.
Storm and Combined Sewer Pollution Control Branch. *Combined sewer overflow abatement technology*. Report No. 11024---06/70, NTIS No. PB 193939, Division of Applied Science and Technology, FWQA, Washington, D.C., 1970.
Strecker, E.W. "The use of wetlands for stormwater pollution control." In: *Seminar Publication - National Conference on Urban Runoff Management: Enhancing Urban Watershed Management at the Local, County, and State Levels, EPA-625/R-95-003*, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1995.
Sullivan, R.H., M.M. Cohn, J.E. Ure, F.E. Parkinson, and G. Galiana. *The swirl concentrator as a combined sewer overflow regulator facility*. EPA-R2-72-008, NTIS No. PB 214687, U.S. Environmental Protection Agency, Edison, NJ, 1972.
Sullivan, R.H. *et al. Relationship between diameter and height for design of a swirl concentrator as a combined sewer overflow regulator*. EPA-670/2-74-039, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1974.
Sullivan, R.H. *et al. The swirl concentrator for erosion runoff treatment*. EPA-600/2-76-271, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1976.
Sullivan, R.H. *et al. Field prototype demonstration of the swirl degritter*. EPA-600/2-77-185, NTIS No. PB 272668, U.S. Environmental Protection Agency, Washington, D.C., 1977.
Sullivan, R.H. *et al. The swirl primary separator: development and pilot demonstration*. EPA-600/2-78-122, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978.
Sullivan, R.H. *et al. Design manual: swirl and helical bend pollution control devices*. EPA-600/8-82-013, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1982.
Tang, W.H., L.W. Mays, and B.C. Yen. "Optimal risk-based design of storm sewer networks." *Journal of the Environmental Engineering Division*, ASCE, 101(3), 381-398, 1975.
Task Committee on the Effects of Urbanization on Low Flow, Total Runoff, Infiltration, and Ground-Water Recharge of the Committee on Surface-Water Hydrology of the Hydraulics Division, ASCE. "Aspects of hydrological effects of urbanization." *Journal of the Hydraulics Division*, ASCE, 101(5), 449-468, 1975.
Terstriep, M.L. and J.B. Stall. "Urban runoff by road research laboratory method." *Journal of the Hydraulics Division*, ASCE, 95(6), 1809-1834, 1969.
Terstriep, M.L. and J.B. Stall. *The Illinois Urban Drainage Area Simulator, ILLUDAS.* Bulletin 58, Illinois State Water Survey, Urbana, IL, 1974.
Thelen, E. *et al. Investigation of porous pavements for urban runoff control*. EPA Report No. 11034DUY03/720, NTIS No. PB 227516, U.S. Environmental Protection Agency, Washington, D.C., 1972.
Tholin, A.L. and C.J. Keifer. "Hydrology of urban runoff." *Transactions of the American Society of Civil Engineers*, 125, 1308, 1960.
Todini, E. "Rainfall-runoff modeling: past, present and future." *Journal of Hydrology*, 100(1-3), 341, 1988.
Tomlinson, R.D. *et al. Fate and effects of particulates discharged by combined sewers and storm drains*. EPA-600/2-80-111, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980.

Torno, H.C. *Stormwater NPDES related monitoring needs. Proceedings of the Engineering Foundation Conference*. Mt. Crested Butte, Colorado, August 7-12, 1994, ASCE, New York, NY, 1995.

Urbonas, B. and P. Stahre. *Stormwater: best management practices and detention for water quality, drainage, and CSO management*. PTR Prentice-Hall, Inc., Englewood Cliffs, NJ, 1993.

Urbonas, B., J. Carlson, and L.S. Tucker. “Survey of stormwater detention state of practice.” In: *Proceedings of the 21st Annual Conference, Water Policy Management. Solving Problems*, ASCE, New York, 873, 1994.

U.S. Army Corps of Engineers. *Urban Runoff: Storage, Treatment, and Overflow Model STORM*. Program No. 723-58-22520, Hydrologic Engineering Center, 1973.

U.S. Army Corps of Engineers. *Urban storm water runoff: STORM*. Generalized Computer Program 723-58-L2520, Hydrologic Engineering Center, Davis, CA, 1975.

U.S. Army Corps of Engineers. *Storage, Treatment, Overflow, Runoff Model: STORM*. Generalized Computer Program 723-S8-L2520, Hydrologic Engineering Center, Davis, CA, 1977.

U.S. Department of Agriculture, Soil Conservation Service. *Urban hydrology for small watersheds*. Technical Release No. 55, 1986.

Van Sickle, D. “The effects of urban development on flood runoff.” *Texas Engineer*, 32(12), 1962.

Van Sickle, D. “Storm drainage planning for growth areas.” In: *Urban Runoff Quantity and Quality, Conference Proceedings*, August 11-16, 1974, New Hampshire, Edited by W. Whipple Jr., ASCE, New York, 1975.

Walesh, S.G. "Simulation in watershed planning." *Journal of the Hydraulics Division*, ASCE, 99 (9), 1383-1399, 1973.

Walesh, S.G. and R.M. Videkovich. “Urbanization: hydrologic-hydraulic-damage effects.” *Journal of the Hydraulics Division*, ASCE, 104(2), 141-155, 1978.

Wanielista, M.P. *Stormwater Management Quantity and Quality*. Ann Arbor Science Publishers, Inc., Ann Arbor, MI, 1978.

Wanielista, M.P. *et al. Stormwater management to improve lake water quality*. EPA-600/2-82-048, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1982.

Ward, A.J.C., C.T. Haan, and B.J. Barfield. *Simulation of the sedimentology of sediment detention basins*. Research Report 103, Water Resources Research Institute, University of Kentucky, Lexington, KY, 1977.

Waring, G.E. *The sanitary drainage of houses and towns*, 1878.

Waring, G.E. “Separate systems of sewerage.” *Atlantic Monthly*, 61, July 1879.

Webster, C. “The sewers of Mohenjo-Daro.” *Journal Water Pollution Control Federation*, 34(2), 116-123, 1962.

Webster, G.S. “Municipal Engineering.” *Transactions of the American Society of Civil Engineers*, 84, 516-526, 1921.

Welch, F.L. and D.J. Stucky. *Combined sewer overflow treatment by the rotating biological contactor process*. Autotrol Corp., Milwaukee, WI, EPA-670/2-74-050, NTIS No. PB-231892, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1974.

Wenzel, H.G., J.W. Labadie, and N.S. Grigg. “Detention storage control strategy development.” *Journal of the Water Resources Planning and Management Division*, ASCE, 102(1), 117-135, 1976.

Wet Weather Advisory Committee. “Status Summary: Wet Weather Advisory Committee Efforts.” *ftp://pipes.ehsg.saic.com/s/bbs/wetlib/wetweat.txt*, location: http://pipes.ehsg.saic.com/wetlib.htm, January 1997, written in 1995.

Whipple, G.C. *et al.* “Discussion on the advances in sewage disposal.” *Transactions of the American Society of Civil Engineers*, 57, 91-140, 1906.

Whipple, W.W. Jr. (editor). *Urban runoff quantity & quality, conference proceedings*. August 11-16, 1974, New Hampshire, ASCE, New York, NY, 1975.

Whipple, W.W. Jr. “Dual-purpose detention basins.” *Journal of the Water Resources Planning and Management Division*, ASCE, 105(2), 403-412, 1979.

Whipple, W.W. Jr. "Urban runoff pollution and water quality planning." *Journal of the Technical Councils*, ASCE, 106(1), 101-115, 1980.

Whipple, W., N.S. Grigg, T. Grizzard, C.W. Randall, R.P. Shubinski, and L.S. Tucker. *Stormwater Management in Urbanizing Areas*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1983.

White, W.H. “European sewage and garbage removal.” *Transactions of the American Society of Civil Engineers*, 15, 849-872, 1886.

Wigington, P.J. Jr., C.W. Randall, and T.J. Grizzard. “Accumulation of selected trace elements on soils of urban runoff retention basins.” *Water Resources Bulletin*, 19(5), 709-718, 1983.
Wiitala, S.W. *Some aspects of the effect of urban and suburban development upon runoff*. Open File Report, U.S. Geological Survey, Lansing, MI, 1961.
Wildbore, P. “Optimizing the location and sizing of CSO storage and control structures.” In: *Proceedings, A Global Perspective for Reducing CSOs: Balancing Technologies, Costs, and Water Quality*, July 10-13, 1994, Louisville, KY, WEF and The CSO Partnership, 3-71, 1994.
Williams, T.I. (Editor). *A history of technology, volume VII. The twentieth century c. 1900 to c. 1950 part II*. Clarendon Press, Oxford, 1382-1398, 1978.
Wilson, K.V. *A preliminary study of the effect of urbanization on floods in Jackson, Mississippi*. Professional Paper 575-D, D259-D261, U.S. Geological Survey, Department of the Interior, Washington, D.C., 1967.
WP Software and XP Software, Inc. *XP-SWMM, StormWater Management Model with XP Graphical Interface, Users Manual*, Tampa, FL, 1993.
Wright-McLaughlin Inc. and Wright Water Engineers, Inc. *Urban storm drainage criteria manual*. Denver, CO, 1969.
Xie, J.D.M. *Modelling solar thermal enrichment of streams due to urban storm water*. Master’s thesis, University of Guelph, Canada, 1994.
Yen, B.C. *et al.* "Designing storm sewers using the rational method." *Water & Sewage Works*, 121(10), 92, 1974.
Yen, B.C. and A.S. Sevuk. "Design of storm sewer networks." *Journal of the Environmental Engineering Division*, ASCE, 101(4), 535-553, 1975.
Yousef, Y.A., M.P. Wanielista, W.M. McClellon, and J.S. Taylor. *Urban stormwater and combined sewer overflow impact on receiving water bodies, proceedings of national conference, Orlando, FL, Nov. 26-28, 1979*. EPA-600/9-80-056, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1980.
Zimmerman, R. and R. Sparrow. *Final report based on the workshop on integrated research for civil infrastructure. July 15-17, 1996, Washington, D.C.* National Science Foundation and Robert F. Wagner Graduate School of Public Service, New York University, February 1997.

Section 4
Current and Future Design Practices

Current Storm Drainage Design Practices

Past Surveys

In 1967, researchers at the University of Wisconsin distributed a survey to engineers in the state of Wisconsin to determine the level of service considered adequate (Ardis, *et al.* 1969). Questions on this past survey explored design procedures and policies. This survey was divided into two parts. The initial part of the survey collected background information on procedures, site information, and system requirements. The second portion of the survey required the respondent to design a stormwater system for a specified area based on the procedures and practices they regularly applied. It is interesting to note that although this survey only collected information within a single state, the variation in responses was significant.

Present Survey

Through examination of the past survey conducted by Ardis, *et al.* (1969) it was determined that a similar nationwide effort had the ability to produce a considerable amount of useful information for current storm drainage design practices. The types of questions asked in this current survey also pertained to methods of design, types of existing conditions considered, and regional site information incorporated into design. This knowledge was collected to provide insight into predominant design practices utilized. By doing this, we anticipated we could identify the most commonly used practices and to identify tools needed to facilitate their correct use. The survey was developed and sent to civil and environmental engineering firms across the nation in order to gather diverse data. The compilation of the information from this survey provides an overview of current drainage design practices. A copy of the survey is included as Figure 4-1.

Surveys were sent via e-mail and postal mail. Electronic versions of the surveys were sent to list servers, including NPSINFO, DIALOG-AGUA, ca-water, SEWER-LIST, water-distrib-systems, hydrology, and several others. To eliminate possible bias incurred through surveying only those engineers utilizing computers and e-mail, the survey was also distributed through postal mail. The survey was mailed to over 350 recipients in engineering firms and municipal water authorities across the nation. Some difficulty was encountered in acquiring sufficient mailing lists within reasonable costs. Therefore, this mailing was only sent to addressees on currently available mailing lists.

Survey Responses

Response to the survey has been satisfactory, with 100 responses received. Electronic responses were not as numerous as expected. It had been hypothesized that the ease of response provided by e-mail would elicit much greater participation. However, only 17 of the 100 surveys received were collected in this manner. The response from the postal mailing lists used was much better, with about 21% of those receiving the survey by mail completed and returned the survey.

Fifteen of the 100 surveys received were not applicable as these were completed by individuals who were not actively involved in drainage design. A breakdown of final 85 survey participants, by state, is shown below:

State	Responses	% of Total	State	Responses	% of Total
Minnesota	15	17.6	Indiana	2	2.4
Ohio	10	11.8	Massachusetts	2	2.4
New York	7	8.2	Oregon	2	2.4
Florida	6	7.1	Washington	2	2.4

California	5	5.9	Georgia	1	1.2
Kentucky	5	5.9	Maine	1	1.2
Michigan	4	4.7	Maryland	1	1.2
Missouri	4	4.7	Rhode Island	1	1.2
Pennsylvania	4	4.7	South Carolina	1	1.2
Virginia	4	4.7	Texas	1	1.2
Tennessee	3	3.5	Utah	1	1.2
Illinois	2	2.4	Wisconsin	1	1.2
			Total	85	100

Survey Questions

Questions in the survey were designed to facilitate simple answers in hopes to encourage a larger number of replies. In all possible cases, choices of answers were provided. This served both to make the questions easier to answer and also to simplify the analysis of the responses. The questions posed in the survey are as follows:

Figure 4-1. Survey on Storm Drainage Design Procedures.

We are conducting an EPA sponsored research project intended to develop and test a methodology for the design of storm drainage with respect to water quantity and quality. As part of this project, an effort is being made to summarize current practices used for storm drainage design. Please respond to the survey as it pertains to engineering practice your immediate area. The survey should take just a few minutes to complete. The reverse side of the survey is addressed and stamped for easy return (or it has been sent via email). If you feel any colleagues would be interested in completing the survey, please forward a copy to them. Thank you for your assistance, it is greatly appreciated.

Please give as much information as you can (at least identify your state or country):

Name: ____

Position: ____

Company: ____

Location (city, state/providence, and country): ____________________

1. Who determines acceptable design methods and level of service for your projects?

Clients _______

Regulations, established by: ___________________________________

2. What level of service do you provide in your storm drainage designs ("design storm frequency")

low density residential: ______ medium density resid.: ______

high density resid.: _____ strip commercial: ____

shopping centers/malls: _____ downtown commercial: _____

industrial: _____ institutional: _______

3. What design method do you most commonly use to design storm sewers?

Rational Method ______ NRCS (SCS) procedures ________

Regional method (please specify) ___________________________

Other (please specify): ___________________________________

4. Do you use a computer-assisted storm drainage design model? Product: ______

5. How is the time of concentration estimated?

Local engineering practice ("rules of thumb") ______

Time of concentration formulas (e.g., Kirpich, Izzard, FAA, etc.) ______

Field testing and local measurements ______

6. Which of the following occurrences indicate storm sewer system failure for your area? Please indicate the frequency that these events must occur, and/or the duration of the event, for the system to be considered inadequate.

Water ponding in yards ____ Water rising above curb ____

Water ponding at inlets ____ Combined sewer overflows ___

Water covering streets ____ Water entering basements ____

Manhole covers popping off ____

7. What water quality concerns do you associate with storm runoff? ___________

____

____

Please provide your postal or e-mail address if you would like to receive a copy of the results:

____

Also if you would like to describe any uncommon or new procedure you have developed and found to be effective, please do so, as we are interested in any innovations in the field. Please add any additional information as you think appropriate. Thank you for your time.

Robert Pitt, P.E., Ph.D. Associate Professor, Department of Civil and Environmental Engineering
University of Alabama at Birmingham, Birmingham, AL 35294. RPITT@ENG.UAB.EDU

Respondent Identification

The respondent was first asked to provide their name and position. The most surveys were completed by consultants at private engineering firms. Other respondents were affiliated with water boards and other government entities. Survey participants were classified by job description as shown below:

Job Title	Responses	% of Total
Consultant	45	54.9
Municipal position	34	41.5
State Dept. of Transportation	3	3.7
Totals	82	100

Design Authority

The first question on the survey inquired as to who establishes acceptable design methods and levels of service. Two choices are given, clients or regulations. It would be expected that most of the participants are governed by some regulations, but asking this question allows us to quantify the percentage of responding designers that are under specific regulations. Inferences can be drawn from this information concerning stormwater regulations, such as; are they as prevalent as they are perceived to be, what areas of the country are more likely to have regulations, and what areas have few regulations governing storm drainage design. It was determined that regulations govern acceptable design methods and levels of service for most projects. About 75% of those responding indicated that regulations dictated their designs, with these regulations being established by local and state agencies. Few of the respondents indicated that federal regulations were applicable. Most prevalent were regulations established by local or county authorities, indicating a regional focus for this issue. A regional focus may be positive, in the respect that municipalities recognize that the problem of stormwater is unique in each area. On the other hand, too local of a focus on stormwater eliminates the probable hydraulic interactions within and between watersheds. Only 8% of those answering this question indicated that clients dictated the levels of service and 15.5% stated that both clients and regulations made the necessary decisions. A breakup of the determining agency is shown below:

Determining Factor	Responses	% of Total
Regulations	63	75
Clients	8	8
Both	13	15.5

Design Storm Use

Question two investigated design storm frequencies used in various situations. The objective was to determine what levels of service are used in different land use situations. The land use categories were; low density residential, medium density residential, high density residential, strip commercial, shopping centers/malls, downtown commercial, industrial, and institutional. For each of these categories, the respondent identifies the level of service provided in design of stormwater drainage systems. Answers provided to this question were more difficult to interpret, there was increased variation in the answers and fewer participants responded with adequate information to the question. The survey was designed for the respondent to identify the design storm frequencies used in each land use area. However, many of the survey participants did not provide complete information in this section. Of the quantifiable answers, it appeared that most participants (42.4%) used a 10-year storm for drainage design in almost all cases. Several of the engineers who indicated the use of 10-year storms stated that most structures were also checked for flooding with respect to the 100-year storm. About 10% of the participants indicated the use of a 5-year design storm, 8.5% indicated the use of a 100-year storm, and 6.8% indicated the use of a 25-year storm for all land use areas. Most other answers were combinations of storms, for example, the use of a 2-year and 10-year, or a 5-year and 10-year design storm was common. Some participants indicated that they used a 2-year, a 10-year and a 100-year design storm for all land use areas and structures. Those who used different storms for different land use areas designed with storms ranging from 2 to 100 years. These were divided with the smaller storms being used in the less dense areas, and larger storms used in the more urbanized areas. One survey participant mentioned that one storm was used for drainage design while another, more frequently occurring storm, was used for water quality concerns.

Design Methods

Next, the respondents were asked to describe the overall design method used most often in drainage design for their area. The most popular methods are listed as choices: the Rational Method and the NRCS (SCS) procedures. The respondent can also indicate any regional method used, or additional methods not listed. The design method most commonly used to design storm sewers is the rational method, with 40.7% of those responding to this question indicating this is the method of choice. Others (31.4%) used a combination of the rational and NRCS (SCS) methods. Among those using both methods, the size of the area determined which method was appropriate, the rational method was used to design smaller areas, while the NRCS procedures were used for larger areas. About 14% of the survey participants indicated that they used only NRCS methods, 12.8% used regional methods, and 1.2% used other methods. The regional methods varied from procedures designed with the specific area in mind, to others who used only computer design packages in their design. The following list summarizes these responses:

Design Method	Responses	% of Total
Rational Method	35	40.7
NRCS (SCS)	12	14
NRCS & Rational	27	31.4
Regional	11	12.8
Other	1	1.2

Computer Model Use

Question four inquired about the use of computer-assisted storm drainage models. Computer programs and models have become an important tool used in storm drainage design. Use of computer models and applications greatly facilitates design work, however the correct use of programs is not always given the necessary consideration. Some form of a computer-assisted design model was used by 85.5% of the respondents. Of the 14.5% who reported they did not currently use computer design models, several plan to in the future. The choice of models in use was also broken down, with the most people using SWMM (24.8%). HEC-1 was the second most popular model, in use by 16.8% of those using models. Other packages with significant numbers of users were TR-55 and TR-20 programs, and various Haestad programs. Custom programs, designed in-house or for a specific region, were used by 7.9%. These are indicated in the following list:

Computer Model Use	Responses	% of Total
Yes	71	85.5
No	12	14.5

Computer Package	Responses	% of Total
SWMM	26	24.8
HEC-1	17	16.8
TR-55	13	12.9
Custom	8	7.9

Time of Concentration

Next, the respondent was asked to identify how time of concentration was determined in drainage areas. Again, choices were provided for the most common methods: local engineering practice, time of concentration formulas (Kirpich, Izzard, FAA, etc.), and field testing and local measurements. Time of concentration formulas, for example the Kirpich equation, Izzard and TR-55 equations, were used to determine the times of concentration by 64.5% of those responding to the survey. Local engineering practice was used by 29% of the participants, this being rules of thumb used by engineers when dealing with areas with shared characteristics. Only 6.5% used field testing and local measurements to determine times of concentration. Use of field testing and local measurements provides the most accurate, but most expensive, means for establishing time of concentration. Time of concentration methods and their frequency of use are shown below:

Method to determine Tc	Responses	% of Total
Tc formulas	60	64.5
Local engineering practice	27	29
Field testing/local measurements	6	6.5

Failure Criteria

Failure of stormwater drainage systems was covered in the next portion of the survey. A list of occurrences that commonly indicate system failure was provided. For each of these occurrences, the respondent was asked to identify the frequency and/or the duration of the particular event necessary for the system to be considered inadequate. The most common indication of recognized system failures was manhole covers popping off. Water entering basements and rising above curbs and streets were also widespread indicators. Usually, these situations occurring during less than a 10-year design storm were considered system failure. A low number of participants reported the occurrence of combined sewer overflows as indicating system failure. With respect to occurrences in general, it appeared that designers took these occurrences as evidence of the need for system maintenance and investigated them on a complaint driven basis.

Stormwater Quality Concerns

Finally, the respondent was asked to identify water quality concerns they associated with storm runoff. This question is left open-ended in order for a wide range of concerns to be mentioned. Most of the 80 answers here recognized the most broadly found concerns in stormwater pollution. Of the most widespread concern were sediments, with 62.5% of the participants mentioning this as a pollutant of concern. Nutrients and metals were the other most common answers, listed by 35% and 33.8% of the respondents respectively. Other frequent answers were oils and grease, bacteria, toxicants, CSOs, floatables, and salts. A few survey participants answered the question from a different angle and stated their main water quality concerns with stormwater pollution dealt with permit and discharge limits. Their focus was simply to remain within these regulated limits. The following lists these answers:

Stormwater Pollutant Concerns	Responses	% of Total
Sediment	50	62.5
Nutrients	28	35
Metals	27	33.8
Oils/Grease	24	30
Bacteria	18	22.5
Toxicants	14	17.5
CSOs	10	12.5

Innovations in Design

The survey ended with a request for any new or uncommon storm drainage methods or procedures to be described. Ideally, this would provide an indication of the direction designers are taking to improve the techniques available in implementing management strategies. Suggestions made in this area were offered by manufactures of BMP's for information or details about specific systems they had designed. There were no responses from design engineers. Drawing generalized conclusions from the lack of response here would be unwise, it is likely that those completing the survey simply did not have time to elaborate.

Survey Comparisons and Conclusions

Several interesting correlations can be made in comparing answers obtained in our current survey with those gathered in the previous University of Wisconsin survey conducted in 1967 (Ardis, *et al.* 1969). Of particular notice, in the 1967 survey, 70% of the reporting cities supported the use of 5- to 10-year design storms. Those cities with significantly different responses used smaller, rather than larger, storms. In the 1997 survey, the majority of participants used storms in approximately the same range, most stated they used a 10-year storm. Presently, there are more areas that adjust their designs to the less frequent larger storms, but essentially, the design criteria with respect to design storm frequency has not, according to our results, changed in the past thirty years.

The survey distributed earlier by UW demonstrated that "practically all" cities responding to the survey used the rational method for design. (Ardis, *et al*. 1969). There were problems reported in its use in this early survey however. Most cities using this procedure were not using it correctly, either the runoff coefficient or the rainfall intensity were determined incorrectly. The most significant problem was the use of the 24-hr average storm rain intensity instead of the rain intensity associated with the drainage area time of concentration. This error can cause gross under-designs of drainage systems. In our 1997 survey, it was established that a majority of engineers still employ the rational method for design. Unfortunately, we were not able to include any measure to detect the correctness of its use. Newer methods, such as those promoted by NRCS, are beginning to be used more in design practices. These methods found significant use in larger watershed, which is a positive indication of the realization of the limitations of the rational method by engineers.

System failure indicators were another factor examined in both surveys. In the earlier UW survey, it was determined that the most common indicator of system failure was water ponding at inlets. Although this was a concern of engineers in the present survey, it was not as prevalent. It appears to be the case that this is a much more common occurrence now and not as significant an indicator of system failure. The second leading sign of system failure in the 1967 survey was water ponding in back yards. Again this was not a priority for design engineers today.

Answers obtained in the two surveys give a similar picture of stormwater pollution. The same constituents were mentioned in both groups of responses. Reoccurring answers included sediment, oil and grease, salts, and fertilizers. It appears that the same body of common knowledge concerning stormwater pollution was present thirty years ago as it is today. However, there has been little use of stormwater pollution control measures during the past 30 years, even though recognition of the problem was common. The integration of SWMM with SLAMM will provide a means for addressing water quality concerns within a framework that many engineers are familiar with. Information obtained from this survey has provided us with a great deal of information about the design of sewer systems in the United States. Methods being used seem to be those which engineers feel the most comfortable with, that is, the ones that have been around the longest. However, these methods are sometimes being used in situations where they are not appropriate.

Wet Weather Flow Management: Lessons Learned from the Past

Much can be learned from observing past WWF management practices. Indeed, the review of the literature has provided helpful insights that should prove useful in developing future WWF management strategies. The following characteristics were often observed in successful strategies or were conspicuously missing from unsuccessful strategies. The list provided below indicates considerations that should be incorporated into future WWF management strategies:

- technology transfer
- user friendly design methods and tools
- political, social, and economic ramifications
- sustainability of design
- goal of wet weather system should be to mitigate impacts on the environment
- designs should be optimized in terms of pollutant control, receiving water impacts, and cost

McPherson (1975; 1978) voiced concerns 20 years ago and offered suggestions to reduce the technology transfer (development to implementation) lag time. Professional societies have published monographs with the purpose of bridging the gap between research and practice (Kibler 1982). History has displayed examples of the technology transfer time lag. Take the prediction of runoff from a watershed as an example. The formula methods, such as McMath, Roe, and Burkli-Ziegler, dominated sewer design in the late 1800s. The rational method of determining stormwater runoff was introduced to the United States by Emil Kuichling in 1889, but it did not become a widely utilized method until much later. A paper by Charles Buerger (1915) states:

> It [the rational method] is not widely used, however, and the formula methods, of which the Burkli-Ziegler and the McMath are the most popular, are generally used, in spite of the common realization of the fact that the results given by them lack consistency, and are very erratic and unreliable.

This statement can be applied today, except now the rational method might be considered the method that engineers are continuing to embrace while the new technology that has been introduced recently is not being implemented. The reasoning Buerger offered in 1915 for the lack of implementation is even more interesting. He stated that the rational method had not received the widest use because it was relatively laborious, and required a material exercise in judgment. This again is a popular reason expressed today for the lack of application of other techniques.

An advantage of developing user friendly design methods and tools is the reduction in the time lag between development and implementation. Practitioners generally embrace technology that is simple to understand while still providing the means to perform the job in the most cost effective manner possible. The methods and tools that have gained application through history have been simple to implement and easy to understand, although not necessarily the most accurate or appropriate.

Another consideration noticed during the review of the literature is that past design engineers and planners were forced to consider the socioeconomic, political, and legal ramifications associated with their plans and designs. These topics can be the primary inhibitors to the implementation of innovative technology and in the future must be addressed for progress to be made (Berwick, *et al.* 1980). Berwick, *et al.* (1980) and others have reviewed the reasons for lack of implementation and attribute it to a variety of problems. Some of the problems have been identified as the regulatory framework surrounding development, risks associated with development, public attitudes, and others. A future design methodology for WWF management will have an advantage if it considers the socioeconomic, political, and legal implications of system implementation.

Considering the other points listed above, sustainable development will have the benefit of significantly reducing the environmental impacts over time associated with a project; while promoting economic stability as well. The literature is replete with examples of entire systems (Paris in the middle ages) or parts of systems that were designed without considering the long-term sustainability of the project. The systems performed poorly and resulted in additional money being contributed to rehabilitate and maintain the design.

Insuring that a design is optimal in terms of pollutant control, receiving water impacts, and cost will eliminate many characteristics of a design that may lead to unsustainable development. Mathematical optimization is a relatively recent addition to WWF management, but variations have existed in the past. Essentially, the selection of a “best” method has always occurred, but it did not involve mathematical algorithms considering a range of possible alternatives. For example, the design of Hamburg’s sewerage in 1842 was based on providing a comprehensive system that took advantage of the situation to provide a low-cost, effective design. This and other comprehensive designs of that era involved the designers deciding between several possible alternatives. The implementation of mathematical optimization would have made that decision more objective and efficient.

Use of Combined Sewers in Newly Developing Areas

Even though domestic sewage collection systems are not a major topic for this research, the topic cannot be ignored when addressing wet weather flow. The continued use of combined sewer systems is common in many parts of the world, and the U.S. has many existing combined systems still in use. In addition, separate sewer overflows (SSOs) are also common in many urban areas that only have separate systems. Overflows of raw sewage during wet weather is therefore unfortunately common in many areas of the U.S. Overlooking these wet weather problems can badly distort efforts in stormwater management. In addition, there is renewed interest in the use of combined sewer systems in the U.S. under specific conditions, where their use (in conjunction with improved treatment facilities) may result in reduced, and more cost-effective, WWF discharges. Heaney, *et al.* (1997) for example, found that combined systems may discharge a smaller pollutant load to a receiving water than separate systems in cases where the stormwater is discharged untreated and where the sanitary wastewater is well treated. They present an example in southern Germany where combined sewer systems are being designed with extensive infiltration components to reduce the inflow of stormwater to the drainage system, reducing the frequency and magnitude of CSO events. Similar systems are also used in Switzerland and in Japan with comparable results.

Some of the important issues facing the use of combined sewers in the future include:

- the use of separate versus combined sewers and under what watershed/demographic conditions and

  characteristics warrant separate versus combined systems;

- the concept of larger size combined sewers providing for inline storage and flushing cells with or without steeper slopes and bottom shapes to alleviate antecedent dry-weather flow solids deposition; and
- taking advantage of new construction for larger capacity of dry-weather flow treatment and sludge handling facilities to accommodate additional flow during wet weather conditions.
- solids deposition in sewerage and prevention of solids from entering sewerage

These issues are discussed in the following parts of this section.

Conditions for the use of Combined Sewers

The debate on the use of combined sewers has been long. As noted above, Hering (1881) visited Europe and made recommendations to the U.S. National Board of Health concerning the use of combined sewers. He recommended that combined sewers be used in extensive and closely built-up districts (generally large or rapidly growing cities), while using separate systems for areas where rainwater did not need to be removed in underground drainage conveyance systems. His recommendations were largely ignored. Combined sewers were extensively used in many of the older U.S. cities because of perceived cost savings. Of course, the existing combined sewer systems in the U.S. are now mostly located in the most dense portions of central cities, along with some of the older residential areas. Many newer separate sanitary sewer systems also connect to downstream combined systems. In addition, current separate sewer systems actually may operate as combined systems due to excessive infiltration of sewage into stormwater systems, or by direct connections of sewage into stormwater systems.

Current Separate Systems that are actually Combined Systems. Unfortunately, many separate sanitary sewage collection systems in the U.S. are in poor repair, resulting in inappropriate discharges of sewage into receiving waters. Pitt, *et al.* (1994) developed a method for cities to identify and correct inappropriate discharges. The following discussion is from this user guide.

Current interest in illicit or inappropriate connections to storm drainage systems is an outgrowth of investigations into the larger problem of determining the role urban stormwater runoff plays as a contributor to receiving water quality problems. Urban stormwater runoff is traditionally defined as that portion of precipitation which drains from city surfaces exposed to precipitation and flows via natural or man-made drainage systems into receiving waters. Urban stormwater runoff also includes waters from many other sources which find their way into storm drainage systems. For example, Montoya (1987) found that slightly less than half the water discharged from Sacramento's stormwater drainage system was not directly attributable to precipitation. Sources of some of this water can be identified and accounted for by examining current NPDES (National Pollutant Discharge Elimination System) permit records, for permitted industrial wastewaters that can be discharged to the storm drainage system. However, most of the water comes from other sources, including illicit and/or inappropriate entries to the storm drainage system. These entries can account for a significant amount of the pollutants discharged from storm sewerage systems (Pitt and McLean 1986).

Three categories of non-stormwater outfall discharges were identified by Pitt, *et al.* (1994): pathogenic/toxicant, nuisance and aquatic life threatening, and clean water. The most important category is for stormwater outfalls contributing pathogens or toxicants. The most likely sources for this category are sanitary or industrial wastewaters. Section 402 (p)(3)(B)(ii) of the 1987 reenactment of the federal Clean Water Act (CWA) requires that National Pollutant Discharge Elimination System (NPDES) permits for municipal separate storm sewers shall include a requirement to effectively prohibit problematic non-stormwater discharges into storm sewers. Pitt, *et al.* (1994) developed a scheme to identify and correct problem outfalls to allow compliance with these CWA requirements. Outfall analysis surveys should have a high probability of identifying all of the outfalls in this most critical category. High probabilities of detection of other contaminated outfalls are also likely when using these procedures. After identification of the contaminated outfalls, their associated drainage areas are then subjected to a detailed source identification investigation. The identified pollutant sources are then corrected.

Sanitary sewage finds its way into separate storm sewers in a number of ways. Direct cross-connections may tie sanitary lines directly to storm drains (relatively rare), or seepage from leaking joints and cracked pipes in the sanitary collection system can infiltrate storm sewers (much more common). Surface malfunctions and insufficiently treated wastewater from septic tanks may contribute pollutants to separate storm sewers directly or by way of contaminated groundwater infiltration. Seepage of sewage or septic tank effluent (septage) into underground portions of buildings may be pumped into separate storm sewers by sump pumps (EPA 1989).

Due to indifference, ignorance, poor enforcement of ordinances, or other reasons, a stormwater drainage system may have sanitary wastewater sewerage direct connections. Obviously, the sanitary wastewater entering the storm drain will not receive any treatment and will pollute a large flow of stormwater, in addition to the receiving water. If the storm drain has a low dry-weather flow rate, the presence of sanitary wastewater may be obvious due to toilet paper, feces, and odors. In cases of high dry-weather flows, it may be more difficult to obviously detect raw sanitary wastewaters due to the low percentage of sanitary wastewater in the mixture. Even though the sanitary wastewater fraction may be low, the pathogenic microorganism counts may be exceedingly high.

Corrective measures involve undertaking a program of disconnecting the sanitary sewer connections to the storm drainage system and reconnecting them to a proper sanitary wastewater sewerage system. The storm drainage system then has to be repaired so that the holes left by the disconnected sanitary sewer entrances do not become a location for dirt and groundwater to enter. However, there are situations in which the sanitary system is so connected to the stormwater system that good intentions, vigilance, and reasonable remedial actions will not be sufficient to solve the problems. In an extreme case, it may be that while it was thought that a community had a separate sanitary sewer system and a separate storm drainage system, in reality the storm drainage system is acting as a combined sewer system. When recognized for what it really is, the alternatives for the future become clearer: undertake the considerable investment and commitment to rebuild the system as a truly separate system, or recognize the system as a combined sewer system, and operate it as such, without the disillusionment that it is a problem-plagued storm drainage system which can be rehabilitated.

It would be best to correct at least the sanitary sewer if only one drainage system can be corrected. This would have the dual advantage of preventing infiltration of high or percolating groundwaters into the sanitary sewerage and preventing pollution of stormwater with exfiltrating sanitary wastewater. Rehabilitation of either drainage systems by use of inserted liners, or otherwise patching leaking areas, are possible corrective measures. It is important that all drains with infiltration problems be corrected for this corrective action to be effective. This would also include repairing house lateral sanitary wastewater lines, as well as the main drainage runs. However, these corrective measures are more likely to be cost effective when only a relatively small part of the complete drainage systems require rehabilitation.

Normally, widespread failure of septic tank systems might necessitate the construction of a sanitary sewer to replace the septic tanks. Also, identifying and disconnecting sanitary sewers from the storm drainage system is usually undertaken. Connections (whether directly by piping or indirectly by exfiltration or infiltration) of sanitary sewers to the storm drainage system may be so widespread that the storm drainage system has to be recognized as a combined sewer system. This could also be the case when the prevalence of septic tank failures leads to widespread sanitary wastewater runoff to the storm drainage system. One usually thinks of a combined sewer system as having all of the sanitary sewer connections to the same sewers that carry stormwater, but, there are degrees of a storm drainage system becoming a combined sewer system. Prior to these actions taking place, the storm drainage system operates to some degree as a combined sewer system. It may be that the sanitary sewerage system is not capable of handling the load that would be imposed on it if a complete sewer separation program were undertaken. Or, in an extreme case, no sanitary sewer system may exist.

By recognizing that a combined sewer system does in fact exist may help to focus attention on appropriate remedial measures. The resources may not be available to undertake construction of a separate sanitary wastewater drainage system. One should then focus on how to manage the combined sewer system that is in place. Conventional CSO end-of-pipe storage/treatment needs to be investigated, in addition to methods to reduce the entry of stormwater into the drainage system (through upland infiltration, for example). Also, the combined sewer system may be tied into other combined sewers so that more centralized treatment and storage can be applied. While operation of a combined sewer system is not a desirable option, it may be preferable to having the stormwater and the large number of sanitary entries receive no treatment.

An early identification and decision to designate a storm drainage system a combined sewer system, will prevent abortive time and costs being spent on further investigations. These resources can then be more effectively used to treat the newly designated combined sewer system. In essence, recognition of a system as being a combined sewer system provides a focus in the regulatory community so that it may be possible to operate the system so as to minimize the damage to the environment. Plans can then be developed to provide the resources to separate the system.

Conditions where New Combined Systems may be Appropriate. As noted above, it may be more cost-effective and result in the least pollutant discharges to operate separate drainage systems that are badly in need of repair as actual combined sewer systems, compared to costly and ineffective repairs to the separate systems. However, proposed construction of new combined sewer systems would be very controversial in the U.S. and it would be very difficult to overcome resistance to their construction. The main areas of resistance relate to the massive efforts expended in the last several decades in reducing the number and severity of combined sewer overflows (CSOs), usually under court order. In addition, current interest and massive correction efforts to control separate sewer overflows (SSOs) in many cities would also result in a great deal of resistance from engineers, municipalities, regulatory agencies and environmental groups to the construction of new combined sewer systems. The political resistance to the construction of new combined sewer systems in the U.S. is therefore considered almost insurmountable. However, it may be interesting to note where they may be appropriate from a technical viewpoint.

As pointed out by Hering in 1881, combined sewer systems may be suitable in dense urban areas, where the sanitary sewage flow is relatively high per area. Of course, any use of a combined sewer must be accompanied with provisions to reduce any untreated overflows to almost zero. In reality, the current level of untreated sanitary sewage discharges in urban areas from badly functioning separate systems is likely much higher than anyone acknowledges or considers when conducting wet weather flow management projects. The major concern with combined sewer systems is the overflow discharges of dangerous levels of pathogenic microorganisms, and nuisance conditions associated with floatable debris and noxious sediment accumulations. Discharges of potentially dangerous medical wastes and drug paraphernalia is also of great concern. However, it may be possible to construct a new combined sewer system that would operate with fewer annual untreated discharges of sewage than many currently separate systems, plus provide treatment of stormwater. The following attributes would be helpful for any new sewerage system, especially a combined system:

- The major goal of any new WWF collection system should be the minimization of stormwater runoff and sanitary wastewater entering the system. As noted previously, there are many beneficial uses of stormwater that could account for substantial fractions of the annual runoff. Similarly, household water conservation (especially low-flow toilets and reduced flow showerheads, etc.) can also substantially reduce wastewater flows to the sewerage.

• The conveyance system could be either a conventional combined system, or one of two possible new scenarios that would reduce the flows in the sewerage that could cause CSOs or SSOs. These new options include: 1) utilize a flow storage tank at each household to retain sanitary wastewater during wet weather, or 2) prohibit the entry of stormwater into the sewerage at a level that would cause overflows. The effective use of an existing conventional combined sewer system would require extensive modifications to provide adequate storage and increased treatment capacity to reduce overflows. These new options are briefly described below:

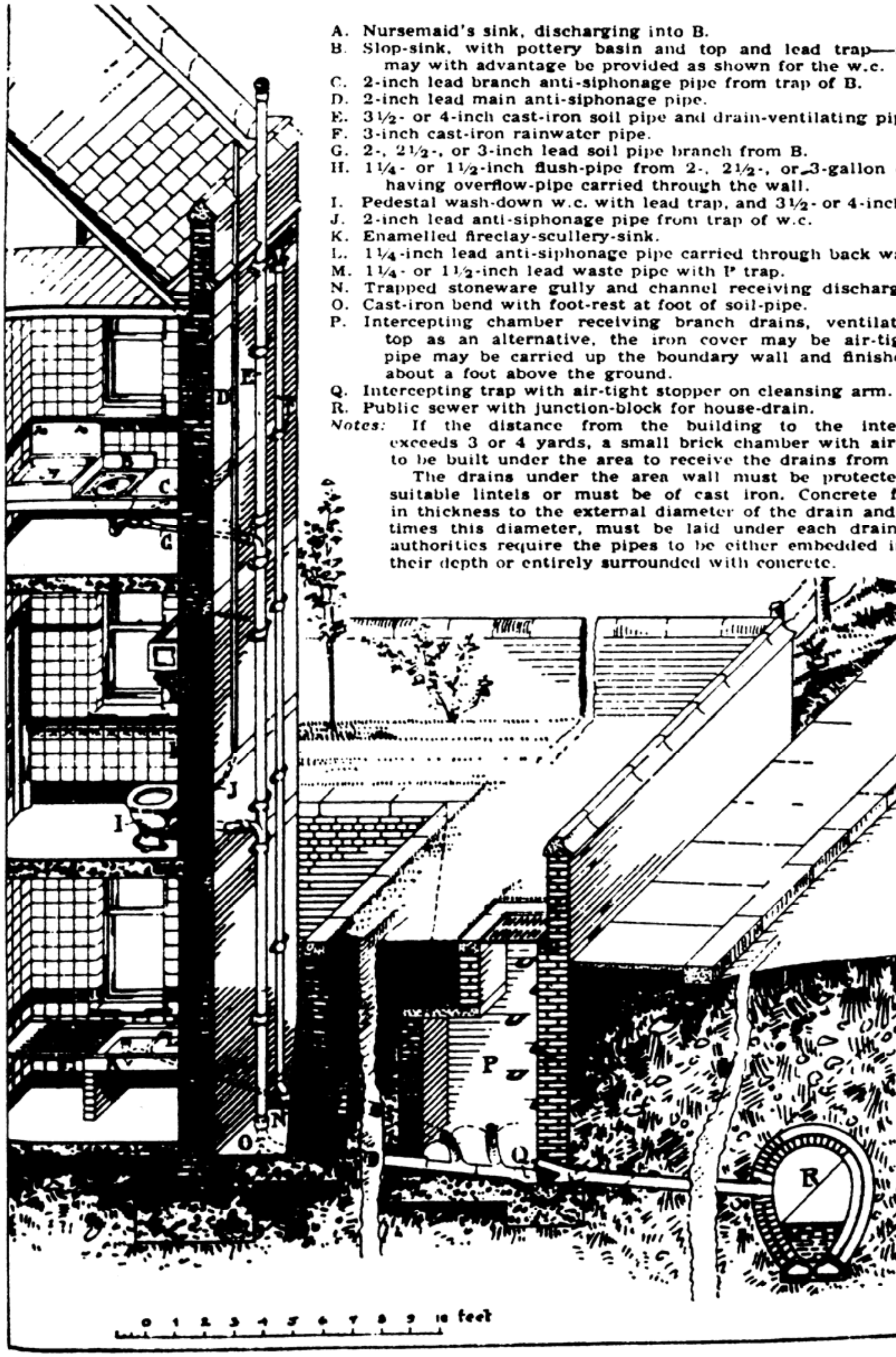
The first option may be termed a shared sewer system as the two flows (stormwater and sanitary wastewater) are not co-mingled at the same time in the single drainage system, but are kept separate as much as possible. This option, commonly used in England in the later part of the last century, and recently re-introduced by Pruel (1996) would require an adequately sized storage tank that could hold household wastewater for specific periods of time (depending on rain durations, conveyance capabilities, and treatment rate available). Figure 4-2 (Reyburn 1989) shows a old drawing of sanitary fittings and drains from a catalogue from Thos. Crapper & Co., Ltd., Sanitary Engineers, Chelsea, England. The house connections are all directed to an intercepting chamber which receives the branch drains from the house. This chamber is vented and is fitted with a trap. The large intercepting chamber is connected to the public sewer. In this drawing, the roof runoff is also directly connected to the intercepting chamber, possibly as an aid in flushing the chamber.

The intercepting chamber would normally be empty, with the wastewater flowing across the bottom of the tank in a small-flow channel (for an in-line installation), or the tank could be off-line. During wet weather, a flapper valve or other fitting at the connection to the full-flowing sewer would prevent additional water from entering the drainage, causing wastewater to back up into the intercepting chamber. When the wet weather flow subsided, the tank would empty into the sewerage. In a modern application, tank flushing could be accomplished (possibly using captured stormwater) with a tipping bucket or sprays to remove any settled solids in the tank. The flushing mechanisms would not need to be very complex. The initial higher flows (less than the capacity of the treatment facility) in the sewerage would therefore be mostly stormwater and would be used to flush solids, that accumulated during the low-flow sanitary wastewater flow conditions, to the treatment facility. This "first flush" would therefore be captured, along with a sizeable amount of stormwater, for treatment. As the WWF exceeded the capacity of the treatment facility, overflows of stormwater, with little sanitary sewage, would occur. There are many options available that can be used to temporarily increase the capacity of the treatment facility, or to provide temporary storage before treatment. In addition, many end-of-pipe stormwater treatment options are available to treat the smaller quantities of stormwater that would be discharged through the overflows.

Preul (1996) calculated the needed on-site storage volumes for this "shared sewer" concept. His "combined sewer prevention system" (CSPS) was investigated for locations in Cincinnati, Ohio, and in Toronto, Ontario. He found that storage tanks capable of detaining household sanitary wastewater on-site for 6 hours in Cincinnati would prevent about 90% of the CSO occurrences. The Toronto location would only require on-site detention capabilities of 3 hours for similar benefits. He has predicted an expected domestic wastewater production of about 60 to 80 liters per person per day in the future, with the required use of low water use plumbing fixtures. For a typical 2.8 person household, the daily sanitary wastewater flow in Cincinnati would be about 170 to 220 L per day per household. Therefore, a household storage volume of 55 L would provide 6 hours of average storage and 90% control of CSO occurrences. A 220 L storage capacity per household would virtually eliminate all CSOs in Cincinnati. Required household storage capacities in Toronto would be even less, with 30L storage tanks providing almost complete control. These are all relatively small volumes and would cost only a very modest amount, if designed and constructed at the time the housing units are built.

Another option is basically a separate sanitary sewerage system that is constructed to be very water-tight. This would be a less complex option than above, in some ways, but does require very good construction and maintenance practices. The sanitary sewerage system may be best a vacuum or small diameter pressurized system, both having been used for many years at numerous locations throughout the U.S. The stormwater would be conveyed separately, emphasizing on-site reuse and infiltration, through either open channels if compatible with the land use, or through a separate drainage system. Critical source area controls would be utilized, along with end-of-pipe treatment, as appropriate. With a tight conveyance system, no extra stormwater could enter the sanitary sewerage, greatly lessening the threat of overflows during wet weather.

Use of Larger, Steeper, and More Efficient Cross-Sections for Combined Sewers
According to Field, *et al*. (1994), new urban areas or upstream additions to older combined sewer systems should use advanced combined sewer designs requiring larger diameter sewers having steeper slopes and more effective bottom cross-sections to add storage capacity to the system and eliminate antecedent dry weather flow pollutant deposition and resulting pollutant concentrated storm flushes (Field 1975, 1980, and 1990b; Kaufman and Lai 1978; Sonnen 1977). The additional capital cost of an advanced combined sewer system would be incrementally small,



A. Nursemaid's sink, discharging into B.
B. Slop-sink, with pottery basin and top and lead trap—a flushing cistern may with advantage be provided as shown for the w.c.
C. 2-inch lead branch anti-siphonage pipe from trap of B.
D. 2-inch lead main anti-siphonage pipe.
E. 3½- or 4-inch cast-iron soil pipe and drain-ventilating pipe.
F. 3-inch cast-iron rainwater pipe.
G. 2-, 2½-, or 3-inch lead soil pipe branch from B.
H. 1¼- or 1½-inch flush-pipe from 2-, 2½-, or 3-gallon cistern; the latter having overflow-pipe carried through the wall.
I. Pedestal wash-down w.c. with lead trap, and 3½- or 4-inch branch soil-pipe.
J. 2-inch lead anti-siphonage pipe from trap of w.c.
K. Enamelled fireclay-scullery-sink.
L. 1¼-inch lead anti-siphonage pipe carried through back wall.
M. 1¼- or 1½-inch lead waste pipe with P trap.
N. Trapped stoneware gully and channel receiving discharge from M and F.
O. Cast-iron bend with foot-rest at foot of soil-pipe.
P. Intercepting chamber receiving branch drains, ventilated by grating at top as an alternative, the iron cover may be air-tight, and a 4-inch pipe may be carried up the boundary wall and finished with a grating about a foot above the ground.
Q. Intercepting trap with air-tight stopper on cleansing arm.
R. Public sewer with junction-block for house-drain.

Notes: If the distance from the building to the intercepting chamber exceeds 3 or 4 yards, a small brick chamber with air-tight cover ought to be built under the area to receive the drains from N and O.

The drains under the area wall must be protected from injury by suitable lintels or must be of cast iron. Concrete foundations, equal in thickness to the external diameter of the drain and in width to three times this diameter, must be laid under each drain, and some local authorities require the pipes to be either embedded in concrete to half their depth or entirely surrounded with concrete.

Figure 4-2. Nineteenth century English household holding tank located before sanitary sewerage (Reyburn 1989).

considering the overall cost of installing a conventional combined sewer system or a two-pipe separate (storm and sanitary) sewer system, and the cost effectiveness for storm-flow pollution control.

Larger combined sewers would provide in-system storage for short periods of excessive flows, and would allow larger flows to be conveyed to the treatment facility. Inflatable dams in the sewerage could be used to selectively back up water in the sewerage, reducing excessive flows. Upland detention can also be used to significantly reduce stormwater flows. Stormwater flows can be captured and detained at many locations before entering the drainage system. Temporary rooftop storage, parking lot storage, and even limited road flooding have been used to reduce stormwater flows into combined sewers. Conventional stormwater detention facilities are also available for storage of large volumes of stormwater. However, the use of extensive stormwater infiltration, as demonstrated in Germany, Switzerland, Canada, and in Tokyo in areas having combined sewerage appears to be very effective in reducing CSO volumes and frequency. The previously described household detention of sanitary wastewater should also be considered in conjunction with increased in-line storage and conveyance capacity. Of course, in order to be effective, treatment capacity would need to be increased to allow for a greater portion of the WWF to be treated. The following discussion presents several methods for increasing the treatment facility capacity for combined sewerage systems.

Solids in Sewers

Heaney, *et al.* (1997) stated that historically, sanitary sewers were designed primarily based on peak sewage flow rates, assuming that solids would be carried with the sewage if simple guidelines were followed. Generally, these guidelines require sewage flow rates of between 0.6 and 3.5 m/sec. Much more can be done to more effectively accommodate solids in sewers, however. Knowledge about solids in sewers and their associated pollutants is extensive after more than a decade of detailed research in Europe and Scandinavia, and elsewhere (USA and Japan in particular) prior to that, but little of this work has been incorporated in modern sewerage design. However, there are still significant outstanding uncertainties and research is continuing worldwide. The sewer sediments working group (SSWG) of the Joint Committee on Urban Storm Drainage of IAWQ/IAHR is producing a Scientific and Technical Report entitled *Solids in Sewers: state of the art*, and subtitled *Characteristics, effects and control of sewer solids and associated pollutants* which will summarize the available knowledge, and recommend future research directions (Ashley, *et al.* 1996). The following briefly summarizes these solids in sewers issues covered in this special report that have dramatic effects on combined sewer and separate sanitary sewer design and maintenance.

Origins, occurrence, nature and transport of solids in sewers. The emerging importance of sewers as a part of the treatment process and interaction with treatment plants has recently led to the concept of the "sewer as a reactor" (Hvitved-Jacobsen, *et al*. 1995). In-sewer processes are perhaps the least understood aspect of sewer solids. The transport and movement processes and mechanisms, together with aggregation and disaggregation effects, sediment deposition, change in nature and subsequent erosion and transport are all important processes. There are particular problems which differentiate sewers from fluvial sediment transport systems, such as source limitation, rigid non-erodible boundaries and organic effects.

Effects sewer solids have on the performance of wastewater systems. Problems caused by sewer solids relate to physical effects, such as blockages, conveyance constraints, and overall effects on the hydraulics. These all affect the relative roughness of the boundary between the flowing wastewater and the pipe material. The quality and potential pollution problems of erosion and sediment flushes and associated shock loads on treatment plants are significant and control rules are as yet poorly developed. Sewer corrosion and other gas related problems are also important, especially for H_2S, VOCs and odors.

Sediment management options. *It is important to integrate watershed source management opportunities with in-sewer control and treatment plant and CSO operation. Source controls can be applies prior to and at entry to sewerage systems. These include best management practices (BMPs), problems of sanitary wastes and cultural habits which may be difficult to change. For example, reductions in water usage for the promoted of conservation* *and/or alternative options for sanitary waste disposal may lead to inadequate flows within sewers for traditional assumptions about self-cleansing performance.*

There are new ideas for the structural design of sewers and ancillary components for the minimization of sediment problems. The use of recent research results in developing controlled sedimenting sewer designs (May 1995) is considered to be a major new design option. New research is needed in this area if design guidelines are to be developed (Bertrand-Krajewski, *et al.* 1995). Settling basins, varieties of tanks and overflow structures and innovatory screening systems are also available to minimize the introduction of solids into sewers. Operational measures such as flushing systems, balls, vane wagons and other cleaning methods are also available for flushing solids through the sewerage.

Future requirements and research needs. Ashley, *et al.* (1996) identified notable new developments in sewerage design, in addition to major research needs. These include:

- the concept of sewers as reactors,
- the interaction of solids with treatment plants,
- disposal of sewer solids,
- the interaction between gross solids and other sediments and options for their control,
- physical factors such as bed-forms in sewers and their effects,
- the ideal sewer shape, and
- proper determinations of particle settling velocity and particle size.

Increasing Capacity of Treatment and Sludge Handling Facilities

The design of new POTW should include treatment of CSO and not just treatment for peak dry weather flow conditions. Larger interceptors, higher treatment flowrates, and alternative highrate treatment methods should be used in new POTW designs (Field, *et al*. 1994). During construction of new facilities, many new opportunities are available, compared to retrofitting modifications to existing and outdated facilities. Some of these include specialized treatment unit operations that are capable of handling a wide range of flows, utilizing parallel processes to optimize treatment for widely varying flows, and using specialized high-rate processes for polishing effluent during high flow periods. There are many possible options for enhanced wet weather flow treatment at POTWs. Some of these are listed below (from Field, *et al.* 1994):

- POTW operational changes. Directing increased flows through primary settling tanks is usually the cheapest option for operating a treatment facility during increased wet weather flows. Generally, increased flows would decrease the performance of the settling tanks. However, when the normally untreated CSO is considered, significant improvements in pollutant discharges can usually be achieved, especially when considering the settling characteristics of wet weather flows that enable more effective settling compared to dry weather sanitary flows.

- Numerous modifications to settling tanks are also available to enhance wet weather performance. These include the use of dissolved air floatation, the use of lamella plates, and the possible use of chemical coagulants and polyelectrolytes.

- High-rate physical/chemical processes can also be used at POTWs during wet weather flows for enhanced treatment. These could be used as polishing units that would not normally be used during dry weather. Microscreens, polymer additions, coagulants with microsand and plate separators, plus deep-bed filters have all been shown to be highly effective when treating CSOs.

- Swirl degritters and deflection separators are also useful unit processes for combined sewage treatment that have not been used in separate sanitary sewage treatment.

- The production of solids in the treatment of combined sewage would be greater than typical for separate sanitary sewage. Much of the increased solids would be relatively gritty from the stormwater component, plus substantial litter may reach the POTW. These solids may have to be handled differently than conventional sanitary sewage solids.

Stormwater Drainage Design Objectives

An idealized WWF management system would include several attributes affecting the conveyance of the stormwater. Basic to these is an understanding of the different objectives of stormwater drainage systems, and the associated rainfall and runoff conditions. There are four major aspects of the drainage system, each reflecting distinct portions of the long-term rainfall record. Figure 4-3 is an example of observed rainfall and runoff observed at Milwaukee, WI, (Bannerman, *et al.* 1983) as monitored during the Nationwide Urban Runoff Program (EPA 1983). This observed distribution is interesting because of the unusually large rains that occurred twice during the monitoring program. This figure shows the accumulative rain count and the associated accumulative runoff volume for a medium density residential area. This figure shows that the median rain, by count, was about 0.3 inches, while the rain associated with the median runoff quantity is about 0.75 inches. Therefore, more than half of the runoff from this common medium density residential area was associated with rain events that were smaller that 0.75 inches. These rains included two very large storms which are also shown on this figure. These large storms (about 3 and 5 inches in depth) distort this figure because, on average, the Milwaukee area only can expect one 3.5 inch storm every five years. If these large rains did not occur, such as for most years, then the significance of the small rains would be even greater. Figure 4-4 shows the accumulative loadings of different pollutants (suspended solids, COD, phosphates, and lead) also monitored during the Milwaukee NURP monitoring activities. When these figures are compared, it is seen that the runoff and discharge distributions are very similar and that runoff volume is the most import factor affecting pollutant discharges.

As noted, these example rainfall and runoff distributions for Milwaukee can be divided into four regions:

• <0.5 inch. These rains account for most of the events, but little of the runoff volume, and are therefore easiest to control. They produce much less pollutant mass discharges and probably have less receiving water effects than other rains. However, the runoff pollutant concentrations likely exceed regulatory standards for several categories of critical pollutants, especially bacteria and some total recoverable heavy metals. They also cause large numbers of overflow events in uncontrolled combined sewers. These rains are very common, occurring once or twice a week (accounting for about 60% of the total rainfall events and about 45% of the total runoff events that occurred), but they only account for about 20% of the annual runoff and pollutant discharges. Rains less than about 0.05 inches did not produce noticeable runoff. In most areas, runoff from these rains should be totally captured and either re-used for on-site beneficial uses or infiltrated in upland areas. These rains should be removed from the surface drainage system.

• 0.5 to 1.5 inches. These rains account for the majority of the runoff volume (about 50% of the annual volume for this Milwaukee example) and produce moderate to high flows. They account for about 35% of the annual rain events, and about 20% of the annual runoff events. These rains occur on the average about every two weeks during the spring to fall seasons and subject the receiving waters to frequent high pollutant loads and moderate to high flows. The small rains in this category should also be removed from the drainage system and the runoff re-used on site for beneficial uses or infiltrated to replenish the lost groundwater infiltration associated with urbanization. The runoff from the larger rains should be treated to prevent pollutant discharges from entering the receiving waters.

• 1.5 to 3 inches. These rains produce the most damaging flows, from a habitat destruction standpoint, and occur every several months (at least once or twice a year). These recurring high flows, which were historically associated with much less frequent rains, establish the energy gradient of the stream and cause unstable streambanks. Only about 2 percent of the rains are in this category and they are responsible for about 10 percent of the annual runoff and pollutant discharges. Typical storm drainage design events fall in the upper portion of this category. Extensive pollution control designed for these events would be very costly, especially considering the relatively small portion of the annual runoff associated with the events. However, discharge rate reductions are important to reduce habitat problems in the receiving waters. The infiltration and other treatment controls used to handle the smaller storms in the above categories would have some benefit in reducing pollutant discharges during these larger, rare storms.

- >3 inches. The smallest rains in this category are included in design storms used for drainage systems in Milwaukee. These rains occur only rarely (once every several years to once every several decades, or less

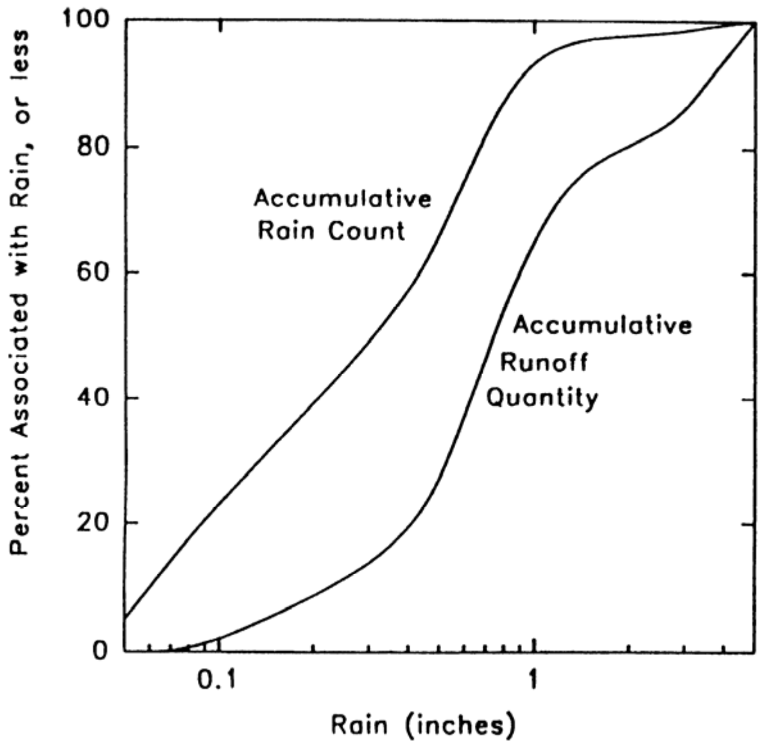


Figure 4-3. Milwaukee rainfall and runoff probability distributions.

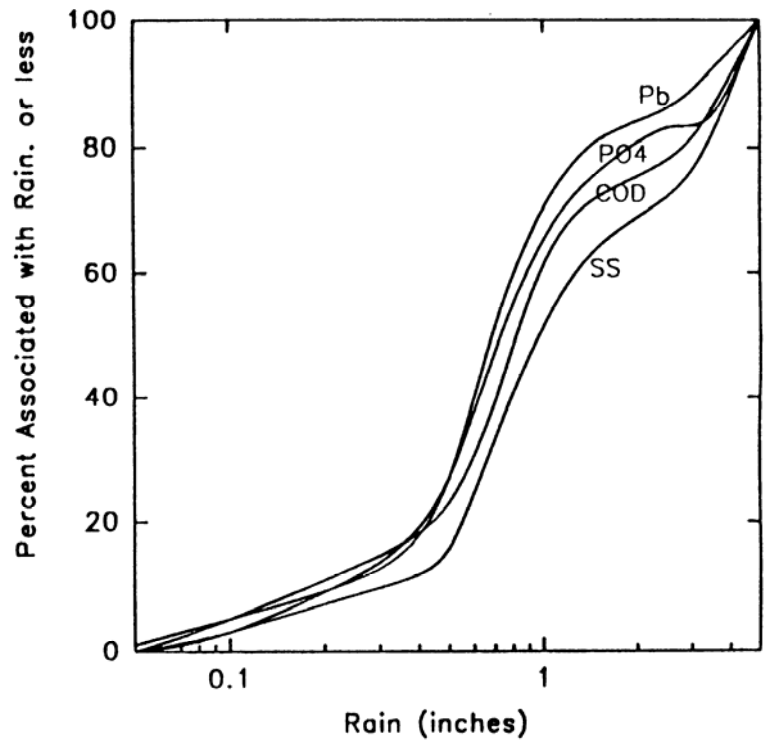


Figure 4-4. Milwaukee pollutant probability distributions.

frequently) and produce extremely large flows. The monitoring period during the Milwaukee NURP program was unusual in that two of these events occurred. Less than 2 percent of the rains were in this category (typically <<1% would be), and they produced about 15% of the annual runoff quantity and pollutant discharges. During a "normal" period, these rains would only produce a very small fraction of the annual average discharges. However, when they do occur, great property and receiving water damage results. The receiving water damage (mostly associated with habitat destruction, sediment scouring, and the flushing of organisms great distances downstream and out of the system) can conceivably naturally recover to before-storm conditions within a few years. These storms, while very destructive, are sufficiently rare that the resulting environmental problems do not justify the massive controls that would be necessary for their reduction. The problem during these events is massive property damage and possible loss of life. These rains typically greatly exceed the capacities of the storm drainage systems, causing extensive flooding. It is critical that these excessive flows be conveyed in "secondary" drainage systems. These secondary systems would normally be graded large depressions between buildings that would direct the water away from the buildings and critical transportation routes and to possible infrequent/temporary detention areas (such as large playing fields or parking lots). Because these events are so rare, institutional memory often fails and development is allowed in areas that are not indicated on conventional flood maps, but would suffer critical flood damage.

The above specific values are given for Milwaukee, WI, selected because of the occurrence of two very rare rains during an actual monitoring period. Obviously, the critical values defining the design storm regions would be highly dependent on local rain and development conditions. Computer modeling analyses from about 20 urban locations from throughout the U.S. were also conducted as part of this research and is reported in Appendix A. These modeled plots indicate how these rainfall and runoff probability distributions can be used for more effective storm drainage design in the future. In all cases, better integration of stormwater quality and drainage design objectives will require the use of long-term continuous simulations of alternative drainage designs in conjunction with upland and end-of-pipe stormwater quality controls. The complexity of most receiving water quality problems prevents a simple analysis. The use of simple design storms, which was a major breakthrough in effective drainage design more than 100 years ago, is not adequate when receiving water quality issues must also be addressed.

Design of Wet Weather Flow Systems in the Future

There are many questions that remain concerning the "best" wet weather flow drainage and treatment systems that should be used in newly developing areas. Of course, there is no one "best" answer for all areas and conditions. A wide variety of options exist and an engineer must select from these depending on numerous site specific situations. In most cases, conventional separate sanitary wastewater and stormwater drainage systems would seem most appropriate. However, these systems have shown to be of reduced value in many cases. The most significant problems relate to the large amount of inflow and infiltration (I/I) occurring in separate sanitary wastewater systems and the lack of stormwater pollution controls in separate stormwater systems. Pertroff (1996) estimated that more than half of the annual flows treated by municipal wastewater treatment plants are from I/I. In addition, I/I is likely the major cause of SSOs in separate sanitary wastewater collection systems. Therefore, in order for separate sanitary wastewater collection systems to be effective in the future, they must be constructed to eliminate almost all I/I contributions. This is possible, as demonstrated by current vacuum and pressurized sanitary wastewater collection systems.

Several discussion groups were held concerning future drainage design as part of the Engineering Foundation/ASCE conference *Sustaining Urban Water Resources in the 21st Century* held in Malmo, Sweden, on Sept. 7 – 12, 1997. Conference participants (mostly from western Europe, plus some from North America, Asia and eastern Europe) were separated into municipal, regulator, planner, and researcher/consultants groups to highlight their specific areas of concern. These concerns and suggestions for future drainage systems are summarized below.

Municipal Representatives (owners and operators of systems)

The municipal representatives are the real experts of the current systems and present conservative viewpoints because they will most likely be responsible for operations of drainage systems in the future. The following are some of their concerns and predictions for the future concerning urban drainage issues:

- We must start with existing systems and make slow and gradual changes.
- Future citizens will be better educated and will be willing to make life style changes that will reduce wastewater discharges.
- We will still have centralized wastewater treatment systems in the future because of better hygienic, health, energy, and environmental benefits, compared to de-centralized systems.
- Stormwater will be eliminated from sewerage in the future, increasing capacity for sanitary wastewater.
- I/I will be reduced considerably due to new methods of detection and prevention.
- There will be more rigid restrictions on the use of materials to prevent corrosion problems.
- Multi-disciplinary/integrated planning in urban areas will be more widespread, with clear strategies for operations. Relationships between precipitation, sewerage, treatment facilities, and receiving waters will be better considered.
- Urban drainage will become better integrated with other technical aspects of the infrastructure.
- Reuse of stormwater and treated wastewaters should be promoted where necessary (dual water systems, with degraded water available for less critical uses for example). Don't rely on highly purified domestic water for all uses.
- There was no consensus for the uniform use of either combined or separate systems in the future.

Representatives of Regulatory Agencies

Regulators stressed the need to live within the carrying capacity of the planet (water, food, housing, and industry). The central focus here was on water quantity and quality and the need to enhance water resources in the broadest context, such as at planet, country, catchment, community, and citizen levels. The principles of ideal regulations for urban drainage include the following:

- Self regulation is preferred. Too much regulation stifles innovation.
- Regulations must be balanced against risk.
- Only regulate that which is not managed in other ways.
- Good legislation is the least amount. Financial support and positive enforcement is needed most. However, effective punishment is also needed.
- Related resources (air, land, and water) should be regulated in one agency.
- Regulatory consistency, not uniformity, is needed most.
- Must have appropriate time scales for action considering needed planning.
- Education is the key component of what regulators should do. Designers are a key group for education. They should be linked with citizens for political and financial support. Politicians are short-term and typically have few long-term goals. Polluters need to know the objectives and problems.
- Prevention (polluter pays) is better than cure (where all pay).

Planners

The planners felt there must be a better agreement between all parties on the definition of sustainability. Planners encouraged the need to move away from urban stormwater management by drains and towards urban waterways. They also felt there are better ways to manage stormwater pollutants besides transport of the pollutants by water. Other issues that the planners brought up included:

- Much more effort should be spent on source control (prevention) than on treatment (cure).
- Emphasis should be placed on keeping stormwater on site instead of transporting it downstream.
- Soil characteristics need just as much consideration as transportation elements when selecting sites for

new development.

- The planning for urban development should be holistic by integrating water supply and drainage, for example. Currently, the developer does the planning.
- Only a small portion of the total domestic water needs require the highest quality water. Reuse of gray water on site, plus storage of stormwater for use on site needs to be considered.
- Greater emphasis should be placed on increasing density of urban development and making high density areas more comfortable, in order to preserve more open space.
- A multi-disciplinary approach in planning is critically needed. Developers and citizens should be brought together to examine new development scenarios.
- Better communication is needed between planners, developers, citizens, and politicians.
- Improved building techniques and materials are needed.
- Must convince politicians of the importance of long-term goals.
- Catchment planning is needed to increase building density in order to decrease impervious density.
- Water can give more identity in urban areas and should receive more attention in planning efforts.

Researchers and Consultants

The lack of a universal definition for sustainability was recognized by the researchers and consultants. Many local considerations make a universal definition impractical. However, there are many acceptable criteria for sustainability; the most basic being that sustainable actions would be acceptable over long periods of time. The urban area needs to consider both the built-up area plus the surrounding natural area. Similarly, the urban water cycle needs to consider water supply, stormwater, and sanitary wastewater together. Guiding principles of sustainable urban water resources include the following:

- Water is renewable on a large scale. We can have sustainable use of water if we are careful.
- We must accept multiple objectives and use a multi-disciplinary approach.
- Source control (especially pollution prevention) should be a top priority.
- We must not transport our problems downstream.

Technological aspects of the sustainability of urban stormwater resources include:

- "Best management practices" (BMPs) are not yet proven to be sustainable (functionally or economically).
- BMPs are more sustainable in new growth areas.
- It is barely possible to counterbalance new problems related to new growth if we impose high levels of effective controls in areas of new development, and simultaneously use high levels of retro-fitted controls in existing areas. It will be difficult to improve or fix existing problems with existing resources.
- Retro-fitting is possible, but much less effective and much more expensive than using controls in new development.
- Combined sewers will eventually function adequately.
- Future urban drainage approaches are not likely to change radically or quickly.
- Urbanization will continue in a manner similar to recent trends.
- There will be a gradual acceptance of source control of stormwater pollution.
- The urban water cycle may eventually include: bottled water for all consumptive uses, piped water for cooking and water contact, and recycled graywater and stormwater for other uses (such as irrigation and toilet flushing).

• There will be eventual optimization of combined and separate sewer systems.

Candidate Scenarios for Urban Drainage for the Future

The following list indicates some likely effective wastewater collection scenarios for several different conditions for the future:

• low and very low density residential developments (<2 acre lot sizes). Sanitary wastewater should be treated on site using septic tanks and advanced on-site treatment options. Domestic water conservation to reduce sanitary wastewater flows should be an important component of these systems. Most stormwater should be infiltrated on site by directing runoff from paved and roof areas to small bio-retention areas. Disturbed soil areas should use compost-amended soils and should otherwise be constructed to minimize soil compaction. Roads should have grass swale drainage to accommodate moderate to large storms.

• medium density developments (¼ to 2 acre lot sizes). Separate sanitary wastewater and stormwater drainage systems should be used. Sanitary wastewater collection systems must be constructed and maintained to eliminate I/I, or use vacuum or pressurized conveyance systems. Again, most stormwater should be infiltrated on site by directing runoff from paved and roof areas to small bio-retention areas. Paved areas should be minimized and the use of porous pavements and paver blocks should be used for walkways, driveways, overflow parking areas, etc. Disturbed soil areas should use compost-amended soils and should otherwise be constructed to minimize soil compaction. Grass swale drainages should be encouraged to accommodate moderate to large storms for the excess runoff in residential areas, depending on slope, soil types, and other features affecting swale stability. Commercial and industrial areas should also use grass swales, depending on groundwater contamination potential and available space. Wet detention ponds should be used for controlling runoff from commercial and industrial areas. Special controls should be used at critical source areas that have excessive pollution generating potential.

• high density developments. Combined sewer systems could be effectively used in these areas. On-site infiltration of the least contaminated stormwater (such as from roofs and landscaped areas) is needed to minimize wet weather flows. On-site storage of sanitary wastewaters during wet weather (using Preul's CSPS), plus extensive use of in-line and off-line storage, and the use of effective high-rate treatment systems would minimize the damage associated with any CSOs. The treatment of the wet weather flows at the wastewater treatment facility would likely result in less pollutant discharges in these areas than if conventional separate wastewater collection systems were used.

References

Ashley, R., M.Verbanck, J-L Bertrand-Krajewski, T. Hvitved-Jacobsen, C. Nalluri, G. Perrusquia, R. Pitt, E. Ristenpart, and A. Saul. "Solids In Sewers - The State of the Art." *7th International Conference on Urban Storm Drainage.* Hannover, Germany, 1996.

Bertrand-Krajewski J-L., H. Madiec, and O. Moine. "Study of two experimental sediment traps: operation and solids characteristics." *Proc. Int. Conf. Sewer Solids*. Dundee, Scotland. Sept. 1995. *Wat.Sci.Tech.* 1996.

Berwick, R., Shapiro, M., Kuhner, J., Luecke, D., and Wineman, J. J. "Select topics in stormwater management planning for new residential development." *EPA-600/2-80-013*, U.S. Environmental Protection Agency (EPA), Cincinnati, Ohio. 1980.

Bourne, J. *Engineering*, 2, 267. 1866.

Brater, E. F. "The unit hydrograph principle applied to small water-sheds." *Transactions of the American Society of Civil Engineers*, 105, 1154-1178. 1939.

Buerger, C. "A method of determining storm-water run-off." *Transactions of the American Society of Civil Engineers*, 78, 1139-1205. 1915.

Clark, C. O. "Storage and the unit hydrograph." *Transactions of the American Society of Civil Engineers*, 110, 1419-1488. 1945.

Dendrou, S. A., Delleur, J. W., and Talavage, J. J. "Optimal planning for urban storm drainage systems." *Journal of the Water Resources Planning and Management Division*, ASCE, 104(1), 17-33. 1978.

Deininger, R. A. "Systems analysis for water supply and pollution control." *National Resource System Models in Decision Making*, G. H. Toebes, ed., Water Resources Center, Purdue University, Lafayette, IN. 1969.

Di Toro, D. M. and Small, M. J. “Stormwater interception and storage.” *Journal of the Environmental Engineering Division*, ASCE, 105(1) 43-54. 1979.
Eagleson, P. S. “Unit hydrograph characteristics for sewered areas.” *Journal of the Hydraulics Division*, ASCE, 88(2), 1-25. 1962.
Eagleson, P. S. and March, F. “Approaches to the linear synthesis of urban runoff systems.” *Report 85*, Hydrodynamics Lab., Massachusetts Institute of Technology, Cambridge, MA. 1965.
EPA (U.S. Environmental Protection Agency). *Results of the nationwide urban runoff program, volume I - Final report*. Water Planning Division, Washington, D.C. 1983.
Field, R. “Urban runoff pollution control-state of-the-art.” *J. Environ. Eng. Div.*, 101, (EE1), 107. 1975.
Field, R. “EPA research in urban stormwater pollution control.” *J. Hyd. Div.* 106 (HY5), 819. 1980.
Field, R. and Turkeltaub, R. “Urban runoff receiving water impacts: program overview.” *Journal of the Environmental Engineering Division*, ASCE, 107(1), 83-100. 1981.
Field, R. *Storm and combined sewer overflow: an overview of EPA’s research program*. Rep. No. EPA-600/8-89/054 (NTIS PB90-187006), U.S. Environmental Protection Agency, Cincinnati, Ohio. 1990b.
Field, R. T. O'Connor, and R. Pitt. “Optimization of CSO storage and treatment systems.” Proceedings: *A Global Perspective for Reducing CSOs: Balancing Technologies, Costs, and Water Quality*. July 10 to 13, 1994, Louisville, Kentucky. Water Environment Federation. Fairfax, VA. 1994.
Gayman, M. “A glimpse into London’s early sewers, parts 1-3.” Reprinted from *Cleaner Magazine*, URL http://klingon.util.utexas.edu, downloaded January 13, 1997.
Gest, A. P. “Engineering.” *Our Debt to Greece and Rome*, G. D. Hadzsits and D. M. Robinson, eds., Cooper Square Publishers, Inc., New York, NY. 1963.
Gray, H. F. “Sewerage in ancient and mediaeval times.” *Sewage Works Journal*, 12, 939-946. 1940.
Gregory, C. E. “Rainfall, and run-off in storm sewers.” *Transactions of the American Society of Civil Engineers*, 58, 458-510. 1907.
Grunsky, C. E. “Rainfall and runoff studies.” *Transactions of the American Society of Civil Engineers*, 85, 66-136. 1922.
Heaney, J. P. and Huber, W. C. “Nationwide assessment of urban runoff impact on receiving water quality.” *Water Resources Bulletin*, 20(1), 35-42. 1984.
Heaney, J.P., L. Wright, D. Sample, R. Pitt, R. Field, and C-Y Fan. “Innovative wet-weather flow collection/control/treatment systems for newly urbanizing areas in the 21st century.” Proceedings of: *Sustaining Urban Water Resources in the 21st Century*. Edited by A.C. Rowney, P. Stahre, and L.A. Roesner. Malmo, Sweden. Sept. 7 – 12, 1997. An Engineering Foundation/ASCE Conference. To be published by ASCE in 1998.
HEC (Hydrologic Engineering Center). “Urban runoff, storage, treatment, and overflow model: STORM.” *Program No. 723-58-22520*, U.S. Army Corps of Engineers, Davis, CA. 1973.
HEC (Hydrologic Engineering Center). “Urban storm water runoff: STORM.” *Generalized Computer Program 723-58-L2520*, U.S. Army Corps of Engineers, Davis, CA. 1975.
Hering, R. “Sewerage systems.” *Transactions of the American Society of Civil Engineers*, 10, 361-386. 1881.
Hill, D. *A history of engineering in classical and medieval times*. Croom Helm Ltd., London. 1984.
Hodge, A. T. *Roman aqueducts & water supply*. Gerald Duckworth & Co. Ltd., London. 1992.
Horner, W. W. and Flynt, F. L. “Relations between rainfall and runoff from small urban areas.” *Transactions of the American Society of Civil Engineers*, 101, 140. 1936.
Horner, W. W. and Jens, S. W. “Surface runoff determination from rainfall without using coefficients.” *Transactions of the American Society of Civil Engineers*, 107, 1039-1117. 1942.
Howard, C. D. D. “Theory of storage and treatment-plant overflows.” *Journal of the Environmental Engineering Division*, ASCE, 105(1), 709-722. 1976.
Huber, W. C., Heaney, J. P., Medina, M. A., Jr., Peltz, W. A., Sheikh, H., and Smith, G. F. “Storm water management model user’s manual - Version II.” *EPA-670/2-75-017*, U.S. Environmental Protection Agency (EPA), Cincinnati, Ohio. 1975.
Huber, W. C., Heaney, J. P., Nix, S. J., Dickinson, R. E., and Polman, D. J. “Storm water management model user’s manual - Version III.” *EPA-600/S2-84-109a*, U.S. Environmental Protection Agency (EPA), Cincinnati, Ohio. 1984.
Huber, W. C. and Dickinson, R. E. “Storm water management model - Version 4, user’s manual.” *EPA-600/3-88-001a*, U.S. Environmental Protection Agency (EPA), Athens, GA. 1988.

Hvitved-Jacobsen T., P. H.Nielsen, T.Larsen, N. A.Jensen (Eds.) “The sewer as a physical, chemical and biological reactor.” *Wat.Sci.Tech*. Vol. 31 No. 7. 1996.

Hydroscience, Inc. “A statistical method for the assessment of urban storm water.” *EPA-440/3-79-023*, U.S. Environmental Protection Agency (EPA), Washington, D.C. 1979.

Jones, D. E., Jr. “Urban hydrology - a redirection.” *Civil Engineering*, 37(8), 58-62. 1967.

Justin, J. D. “Derivation of run-off from rainfall data.” *Transactions of the American Society of Civil Engineers*, 77, 346-384. 1914.

Kaufman, H. L. and Lai, F. H. *Conventional and Advanced Sewer Design Concepts for Dual Purpose Flood and Pollution Control - A Preliminary Case Study, Elizabeth, NJ*. Rep. No. EPA-600/2-78-90 (NTIS PB 285 663), U.S. Environmental Protection Agency, Cincinnati, Ohio. 1978.

Kibler, D. F., ed. *Urban stormwater hydrology*. Water Resources Monograph 7, American Geophysical Union, Washington, DC. 1982.

Kirby, R. S. and Laurson, P. G. *The early years of modern civil engineering*. Yale University Press, New Haven, CT, 227-239. 1932.

Kirby, R. S., Withington, S., Darling, A. B., and Kilgour, F. G. *Engineering in history*. Originally published in 1956, Dover Publications, Inc., New York, NY. 1990.

Kuichling, E. “The relation between the rainfall and the discharge of sewers in populous districts.” *Transactions of the American Society of Civil Engineers*, 20, 1-60. 1889.

Linsley, R. K. and Ackerman, W. C. “Method of predicting the runoff from rainfall.” *Transactions of the American Society of Civil Engineers*, 107, 825-846. 1942.

Maner, A. W. “Public works in ancient Mesopotamia.” *Civil Engineering*, 36(7), 50-51. 1966.

May R.W. P. (1995): Development of design methodology for self-cleansing sewers. *Proc. Int. Conf. Sewer Solids*. Dundee, Scotland. Sept. 1995. *Wat.Sci.Tech.* 1996.

Mays, L. W. and Yen, B. C. “Optimal cost design of branched sewer systems.” *Water Resources Research*, 11(1), 37. 1975.

McMath, R. E. “Determination of the size of sewers.” *Transactions of the American Society of Civil Engineers*, 16, 179-190. 1887.

Metcalf & Eddy Engineers, University of Florida, and Water Resources Engineers, Inc. “Storm water management model, volume I - Final report.” *Report No. 11024EQG03/71*, U.S. Environmental Protection Agency (EPA), Washington, D.C. 1971.

Metcalf, L. and Eddy, H. P. *American sewerage practice, volume I: Design of sewers*. McGraw-Hill Book Company, Inc., New York, NY, 1-33. 1928.

Mulvaney, T. J. “On the use of self-registering rain and flood gages, in making observations of the relation of rainfall and flood discharges in a given catchment.” *Proceedings of the Institute of Civil Engineers of Ireland*, 4, 18-31. 1851.

Mumford, L. *The city in history: Its origins, its transformations, and its prospects*. Harcourt, Brace & World, New York, NY. 1961.

McPherson, M. B. “Translation of research results to users.” *Urban Runoff Quantity and Quality, Conference Proceedings*, August 11-16, 1974, New Hampshire, ASCE, New York, NY, 4-8. 1975.

McPherson, M. B. “Urban runoff planning and control.” *EPA-600/9-78-035*, U.S. Environmental Protection Agency (EPA), Washington, D.C. 1978.

Odell, F. S. “The sewerage of Memphis.” *Transactions of the American Society of Civil Engineers*, 10, 23-52. 1881.

Personal Bibliographic Software, Inc. *ProCite for Windows, Version 3.0*, Ann Arbor, MI. 1995.

Petroff, R.G. “An analysis of the root causes of SSOs.” In: *National Conference on Sanitary Sewer Overflows (SSOs).* EPA/625/R-96/007. U.S. Environmental Protection Agency. Office of Water. Washington, D.C. 1996.

Pettis, C. R. “Appraisal of unit-graph method of flood estimation.” *Civil Engineering*, 8(2), 114-115. 1938.

Pitt, R.E. and Bozeman, M. “Sources of urban runoff pollution and its effects on an urban creek.” *EPA-600/S2-82-090*, U.S. Environmental Protection Agency (EPA), Cincinnati, Ohio. 1982.

Porcella, D. B. and Sorenson, D. L. “Characteristics of nonpoint source urban runoff and its effects on stream ecosystems.” *EPA-600/3-80-032*, Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency (EPA), Corvallis, OR. 1980.

Preul, H.C. “Combined sewage prevention system (CSCP) for domestic wastewater control.” Presented at the *7th International Conference on Urban Storm Drainage,* Hannover, Germany, 1996. pp. 193 – 198. 1996.

Rafter, G. W. “The relation between rainfall and run-off.” *Water Supply Paper No. 80*, U.S. Geological Survey. 1903.

Rao, R. A., Delleur, J. W., and Sarma, P. B. S. “Conceptual hydrologic models for urbanizing areas.” *Journal of the Hydraulics Division*, ASCE, 98(7), 1205-1220. 1972.

Reid, D. *Paris sewers and sewermen*. Harvard University Press, Cambridge, MA. 1991.

Reyburn, W. *Flushed with Pride, the Story of Thomas Crapper*. Pavilion Books, Ltd. London. 1989.

Sherman, L. K. “Streamflow from rainfall by unit-graph method.” *Engineering News - Record*, 108, 501-505. 1932.

Snyder, F. F. “Synthetic unit-graphs.” *Transactions, American Geophysical Union*, 725-738. 1938.

Sonnen, M. *Abatement of Deposition and Scours in Sewers*. Rep. No. EPA/6002-77-212 (NTIS PB 276 585), U.S. Environmental Protection Agency, Cincinnati, Ohio. 1977.

Tang, W. H., Mays, L. W., and Yen, B. C. “Optimal risk-based design of storm sewer networks.” *Journal of the Environmental Engineering Division*, ASCE, 101(3), 381-398. 1975.

Tarr, J. A. and McMichael, F. C. “Historic turning points in municipal water supply and wastewater disposal, 1850-1932.” *Civil Engineering*, ASCE, October, 82-86. 1977.

Viessman, W., Jr. “Runoff estimation for very small drainage areas.” *Water Resources Research*, 4(1), 87-93. 1968.

Waring, G. E. “Separate systems of sewerage.” *Atlantic Monthly*, 61, July 1879.

Webster, C. “The sewers of Mohenjo-Daro.” *Journal Water Pollution Control Federation*, 34(2), 116-123. 1962.

Webster, G. S. “Municipal engineering.” *Transactions of the American Society of Civil Engineers*, 84, 516-526. 1921.

Whipple, G. C., *et al.* “Discussion on the advances in sewage disposal.” *Transactions of the American Society of Civil Engineers*, 57, 91-140. 1906.

Section 5
The Integration of SWMM and SLAMM

Introduction

The use of computers has become common in many aspects of engineering practice, including wet weather management. In fact, no reasonable methodology can be conducted without the analytical and modeling capabilities of a computer. Unfortunately, no currently available software package adequately integrates wet weather quantity and quality objectives. This project will, however, develop such a package with the integration of two currently used computer models -- the EPA's Storm Water Management Model (SWMM) (Huber, *et al.* 1988) and the Source Loading and Management Model (SLAMM) (Pitt and Voorhees 1995). These two popular models have unique characteristics that when merged will create the kind of tool needed for effective wet weather management. *The integrated model will form the principal analytical tool used in the design methodology.*

SWMM (The Storm Water Management Model)

The U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) is a large and relatively complex software package capable of simulating the movement of precipitation and pollutants from the ground surface, through pipe/channel networks and storage/treatment facilities, and finally to receiving waters. The model can be used to simulate a single event or a long, continuous period.

SWMM is probably the most popular of all urban runoff models. Unfortunately, it has a reputation for being a difficult model to use. This is not necessarily the case if one knows the fundamentals of how it works and if the parts of the model not needed in a particular application are simply not used. SWMM uses well-known hydrologic and hydraulic concepts to simulate the urban drainage system. Its reputation for sophistication (and difficulty) derives more from the numerical algorithms necessary to solve the rather straightforward governing equations that are trying to simulate a complex system (i.e., the urban stormwater drainage system) driven by a highly dynamic input (i.e., precipitation).

SWMM is divided into several "blocks". The major blocks, i.e., RUNOFF, TRANSPORT, EXTRAN, and STORAGE/REATMENT are computational blocks responsible for the hydrologic, pollutant generation and transport, and hydraulic calculations. Others, *i.e*., EXECUTIVE, STATISTICAL, RAIN, TEMP, GRAPH, and COMBINE, perform various auxiliary functions, and are known as service blocks. The ability of SWMM to route flows and pollutants through a drainage and/or sewer system is its strength. While not very user friendly, it is not overly difficult to manage and use. A few "preprocessing" packages are available to help prepare the input data.

SWMM is described later in this section, although because of the great deal of technical literature available for SWMM, the description is brief.

SLAMM (The Source Loading and Management Model)

SLAMM was originally developed to better understand the relationships between sources of urban runoff pollutants and runoff quality. It has been continually expanded since the late 1970s and now includes a wide variety of source area and outfall control practices (infiltration practices, wet detention ponds, porous pavement, street cleaning, catchbasin cleaning, and grass swales). SLAMM is strongly based on actual field observations, with minimal reliance on theoretical processes that have not been adequately documented or confirmed in the field. SLAMM is mostly used as a planning tool, to better understand sources of urban runoff pollutants and their control. Special emphasis has been placed on small storm hydrology and particulate washoff in SLAMM. Many currently available urban runoff models have their roots in drainage design where the emphasis is with very large and rare rains. In contrast, many stormwater quality problems are mostly associated with common and relatively small rains. The assumptions and simplifications that are legitimately used with drainage design models are not appropriate for water quality models. SLAMM therefore incorporates unique process descriptions to more accurately predict the sources of runoff pollutants and flows for the storms of most interest in stormwater quality analyses. However, SLAMM can be effectively used in conjunction with hydraulic models (such as SWMM in this project) to incorporate the mutual benefits of water quality controls and drainage design. SLAMM has been used in many areas of North America and has been shown to accurately predict stormwater flows and pollutant characteristics for a broad range of rains, development characteristics, and control practices.

SLAMM is unique in many aspects. One of the most important aspects is its ability to consider many stormwater controls (affecting source areas, drainage systems, and outfalls) together, for a long series of rains. Another is its ability to accurately describe a drainage area in sufficient detail for water quality investigations, but without requiring a great deal of superfluous information that field studies have shown to be of little value in accurately predicting discharge results. SLAMM also applies stochastic analysis procedures to more accurately represent actual uncertainty in model input parameters in order to better predict the actual range of outfall conditions (especially pollutant concentrations). However, the main reason SLAMM was developed was because of errors contained in many existing urban runoff models. These errors were obvious when comparing actual field measurements to the solutions obtained from model algorithms.

SLAMM is described in more detail later in this section, and in the Appendices.

SLAMM/SWMM Interface

In this project, SLAMM is used in place of SWMM's RUNOFF Block to provide the runoff and pollutant loads for input into the TRANSPORT, EXTRAN, or STORAGE/TREATMENT Blocks of SWMM. This approach better accounts for small storm processes and adds greater flexibility in evaluating source area flow and pollutant controls. SWMM has a well-developed Windows-based interface. The output from SLAMM will be manipulated so that it is acceptable for SWMM. The principal manipulation is to convert the event volume and load into event hydrographs and pollutographs. Secondarily, the flows and loads must be assigned to various locations in the sewer system, or storage/treatment system, simulated by SWMM.

SLAMM currently provides the following output, in a one line per event format:

Event characteristic

1. Event number
2. Rain start date
3. Rain start time
4. Julian start date and time
5. Rain duration (hrs)
6. Rain interevent period (days)
7. Runoff duration (hrs)
8. Rain depth (in)
9. Runoff volume (ft^3)
10. Volumetric runoff coefficient (R_v)
11. Average flow (cfs)
12. Peak flow (cfs)
13. Suspended solids concentration (mg/L)
14. Suspended solids mass (pounds)

The interface package developed for SLAMM-SWMM will include the following capabilities:

- Ability to develop alternative hydrograph shapes for SLAMM runoff events.

- Assignment of source area hydrographs and pollutographs to specific locations on a sewer system or storage/treatment system simulated by SWMM.
- Ability to create a long time series of flows and loads from SLAMM (including dry periods) for effective long-term continuous simulation in SWMM.

The SLAMM/SWMM Interface program will be Windows-based, programmed using Visual Basic. The most current public domain versions of SLAMM (version 8.4) and SWMM (version 4.4) will be used.

SWMM, The EPA's Storm Water Management Model

The U.S. Environmental Protection Agency Storm Water Management Model - or SWMM - is a large, relatively complex software package capable of simulating the movement of precipitation and pollutants from the ground surface, through pipe/channel networks and storage/treatment facilities, and finally to receiving waters. The model is can be used to simulate a single event or a long, continuous period. This summary is taken from a book by Nix (1994).

SWMM has been released under several different "official" versions (Metcalf and Eddy, Inc., *et al*. 1971; Huber, *et al*. 1975, 1984; Huber and Dickinson, 1988; Roesner, *et al*. 1984, 1988) and there are many "unofficial" versions modified for specific purposes (some offered by private vendors). The original versions were designed for mainframe use, but the later versions can be executed on a personal computer. The current version of SWMM (Version 4.4; Huber and Dickinson, 1988 and Roesner, *et al*. 1988) may be obtained (along with the documentation) from the Center for Exposure Assessment Modeling (CEAM), U.S. Environmental Protection Agency, College Station Road, Athens, Georgia 30613. The web site, from which the SWMM package can be downloaded, is ftp://ftp.epa.gov/epa_ceam/wwwhtml/ceamhome.htm. The CEAM phone number is 1-706-546-3549.

SWMM is probably the most popular of all urban runoff models. Unfortunately, it has a reputation for being a difficult model to use. This is not necessarily the case if one knows the fundamentals of how it works and if the parts of the model not needed in a particular application are discarded. SWMM uses well-known hydrologic and hydraulic concepts to simulate the urban watershed. Its reputation for sophistication (and difficulty) derives more from the numerical algorithms necessary to solve the rather straightforward governing equations that are trying to simulate a complex system (i.e., the urban watershed) being driven by a highly dynamic input (i.e., precipitation).

There is an extensive body of literature describing SWMM and a wide range of applications. Interested readers should begin their review of this literature by referring to a document prepared by Huber, *et al.* (1985). This large body of experience is an advantage that SWMM probably enjoys over all other urban runoff models. The SWMM internet user's group, through the University of Guelph, also offers a great deal of SWMM support.

SWMM is divided into several "blocks". The major blocks - i.e., RUNOFF, TRANSPORT, STORAGE/TREATMENT, and EXTRAN - are *computational blocks* responsible for the hydrologic, pollutant generation and transport, and hydraulic calculations. Others blocks - i.e., EXECUTIVE, STATISTICAL, RAIN, TEMP, GRAPH, and COMBINE - perform various auxiliary functions, and are known as *service blocks*. A general operational schematic of SWMM is shown in Figure 5-1. The computational blocks, RUNOFF, TRANSPORT, EXTRAN, and STORAGE/TREATMENT are described below. The RUNOFF Block is only summarized here so as to provide a comparison with SLAMM, recalling that SLAMM is replacing the RUNOFF Block.

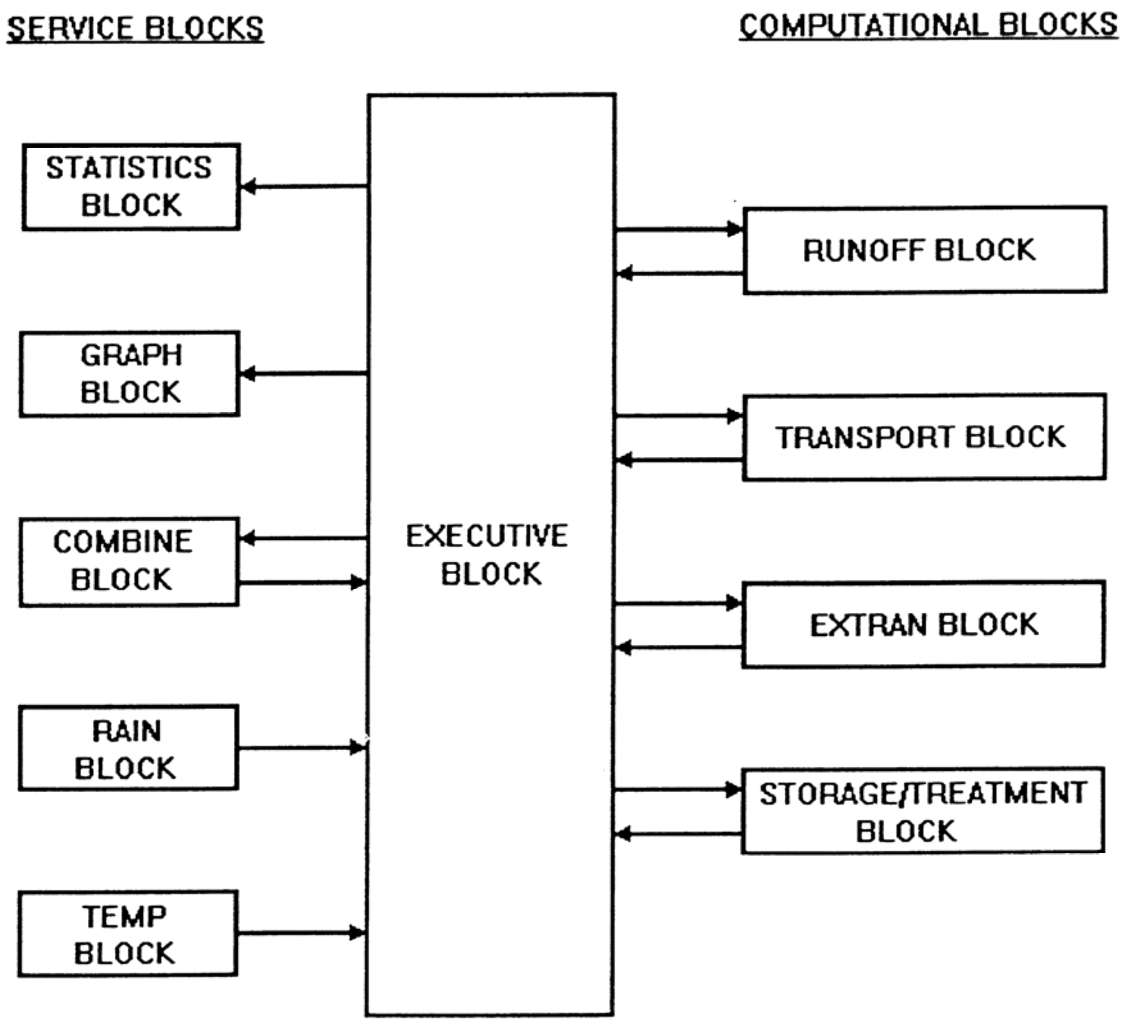


Figure 5-1. SWMM, the Storm Water Management Model, program configuration (after Huber and Dickinson 1988).

RUNOFF Block

The RUNOFF Block generates surface runoff and pollutant loads in response to precipitation and surface pollutant accumulations (Huber and Dickinson, 1988). The key to applying RUNOFF is the division of the watershed into a number of subwatersheds (or subcatchments). Each subwatershed should be relatively homogeneous (i.e., the physical characteristics should be consistent). Just how homogeneous each subwatershed should be depends on how finely characterized the watershed must be to meet the modeling objectives. Dividing the watershed into a large number of subwatersheds implies that each is probably very homogeneous; a smaller number implies less homogeneity.

<u>Runoff Simulation</u>. The conceptual view of surface runoff used by the RUNOFF Block is quite simple and is summarized in Figure 5-2. Essentially, each subwatershed surface is treated as a nonlinear reservoir with a single inflow – precipitation. There are several “discharges” including infiltration, evaporation, and surface runoff. The capacity of this “reservoir” is the maximum depression storage, which is the maximum surface

storage provided by ponding, surface wetting, and interception. Surface runoff occurs only when the depth of water in the "reservoir" exceeds the maximum depression storage.

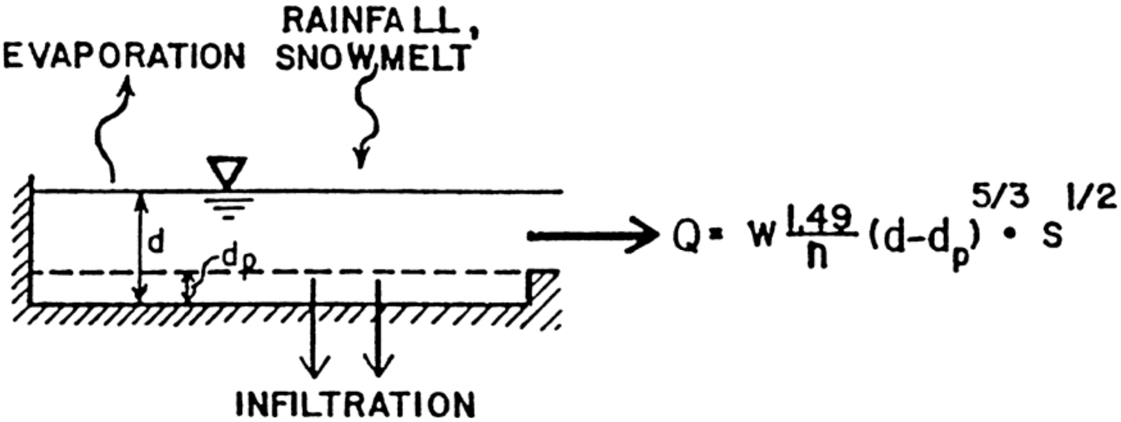


Figure 5-2. Nonlinear reservoir representation of a subwatershed, RUNOFF Block, SWMM (Huber and Dickinson 1988).

The water in storage is also being depleted by infiltration and evaporation. Infiltration occurs only if the ground surface is pervious (as opposed to an impervious surface, such as a paved parking lot, which by definition allows no infiltration). The infiltration process is modeled by one of two methods (Horton's equation or the Green-Ampt equation), which can be selected by the user. Infiltrated water is routed through upper and lower subsurface zones and may contribute to total runoff through ground water flow (this capability is a relatively new addition to SWMM). Monthly average evaporation rates (provided by the user) are directly employed to calculate the amount of water evaporated from the surface (and indirectly to calculate evapotranspiration from the subsurface zones). The precipitation intensity, less the rates of infiltration and evaporation, is known as the *rainfall excess*.

The entire process is repeated for each subwatershed (each having its own unique set of physical characteristics) and is modeled by two equations. One is the continuity of mass equation, which tracks the volume or depth of water on the surface of the subwatershed:

change in volume stored on the subwatershed per unit time		*rainfall excess(net inflow to the subwatershed)*	*Runoff (outflow from the subwatershed)*	
$dV/dt = d(A \cdot d)/dt$	=	$(A \cdot i_e)$	$-\ Q$	(5-1)

where $V = A \cdot d$ = volume of water on the subwatershed, $feet^3$ or $meters^3$;
A = area of the subwatershed, $feet^2$ or $meters^2$;
d = depth of water on the subwatershed, feet or meters;
t = time, seconds;
I_e = rainfall excess, which is the rainfall intensity less the evaporation/infiltration rate, feet/second or meters/second; and
Q = runoff flow rate from the subwatershed, $feet^3$/second or $meters^3$/second.

The second equation is based on Manning's equation and is used to model the rate of surface runoff (i.e., the outflow rate from the reservoir) as a function of the depth of flow above the maximum depression storage depth. Manning's equation can be stated as:

$$Q = A_c \cdot (\beta/n) \cdot R^{2/3} \cdot S_o^{1/2} \tag{5-2}$$

where A_c = cross-sectional area of flow over the subwatershed, feet^2 or meters^2;
n = Manning's roughness coefficient;
R = hydraulic radius of flow over the watershed, feet or meters;
S_o = slope of the subwatershed, feet/foot or meters/meter (which is assumed to equal the friction or energy slope); and
β = 1.49 if U.S. customary units are used or 1.0 if metric units are used.

The cross-sectional area of flow is:

$$A_c = W \cdot (d - d_p) \tag{5-3}$$

where W = width of flow over the subwatershed, or the width of overland flow, feet or meters; and
d_p = depth of maximum depression storage, feet or meters.

The hydraulic radius is the cross-sectional area of flow divided by the wetted perimeter. Since the depth of flow is very small, the wetted perimeter can be approximated by W. Thus, R can be calculated as:

$$R = [W \cdot (d - d_p)]/W = d - d_p \tag{5-4}$$

Substituting Equations 5-3 and 5-4 into Equation 5-2 yields:

$$Q = W \cdot (\beta/n) \cdot (d - d_p)^{5/3} \cdot S_o^{1/2} \tag{5-5}$$

Substituting Equation 5-5 into Equation 5-1 and dividing by A produces:

$$dd/dt = i_e - [(\beta \cdot W)/(A \cdot n)] \cdot (d - d_p)^{5/3} \cdot S_o^{1/2} \tag{5-6}$$

Equation 5-6 is the second governing equation used in RUNOFF.

The two governing equations are solved numerically as follows. Equation 5-1 can be approximated by:

$$(d_{n+1} - d_n)/dt = i_e - Q/A \tag{5-7}$$

where Δt = $t_{n+1} - t_n$, time step size, seconds;

$n, n+1$ = subscripts indicating conditions at the end of time step n (or start of time step n+1) and the end of time step n+1 (e.g., d_{n+1} is the depth at the end of time step n+1);
i_e = average precipitation intensity during time step n+1, feet/second or meters/second; and
Q = average runoff flow rate during time step n+1, feet^3/second or meters^3/second.

Equation 5-7 shows the differential term dd/dt approximated by a finite difference of values for depth at two points in time separated by Δt. The value of the differential term is then approximated by the average of the terms on the right-hand side evaluated at the beginning and end of Δt. If the average runoff flow rate is calculated as a function of the average depth of flow Equation 5-7 becomes:

$$(d_{n+1} - d_n)/dt = I_e - [(\beta \cdot W)/(A \cdot n)] \cdot (d - d_p)^{5/3} \cdot S_o^{1/2} \tag{5-8}$$

where d = $(d_n + d_{n+1})/2$, average depth of flow during time step n+1, feet or meters.

Equation 5-8 is a relatively simple nonlinear, algebraic relationship with one unknown at any time, d_{n+1}. (The value of d_n is, of course, known from the end of the previous time step.) The Newton-Raphson technique for numerically solving a nonlinear equation is used to solve for d_{n+1}. The calculated value of d_{n+1} is then used in Equation 5-5 to calculate the value of Q at the end of the time step. For all intents and purposes, Equation 5-8 is the core of the RUNOFF Block.

The most perplexing parameter in Equation 5-8 is the width of overland flow, W. Essentially, it is the width over which surface runoff occurs. Again, using the reservoir analogy, this width is similar to the length of a weir or spillway. An idealized view is shown in Figure 5-3. In this schematic, surface runoff is being discharged to a drainage channel running down the center of the subwatershed. In this situation, the two halves are symmetrical and, thus, the total length of overland flow is twice the length of the channel. Of course, this idealized case never occurs, but it demonstrates the concept.

The width of overland flow primarily affects the rapidity of runoff. Recall the weir analogy. In this case, though, when the weir width is enlarged, the length of the "reservoir" is shortened so that the surface area and depth of flow behind the weir remain constant for a given volume of water. As a result, a shorter width will delay runoff; a longer width will facilitate runoff.

The RUNOFF Block has a limited ability to route flows through simple gutter and pipes using the nonlinear reservoir technique. However, the more sophisticated routines in TRANSPORT and EXTRAN Blocks are almost always employed for this purpose.

The surface flows generated by the RUNOFF Block are concentrated at nodes. In other words, the flows are not distributed along gutters or pipes (as implied by Figure 5-3). The width of overland flow is used as a computational tool but the flow is not actually distributed over this distance.

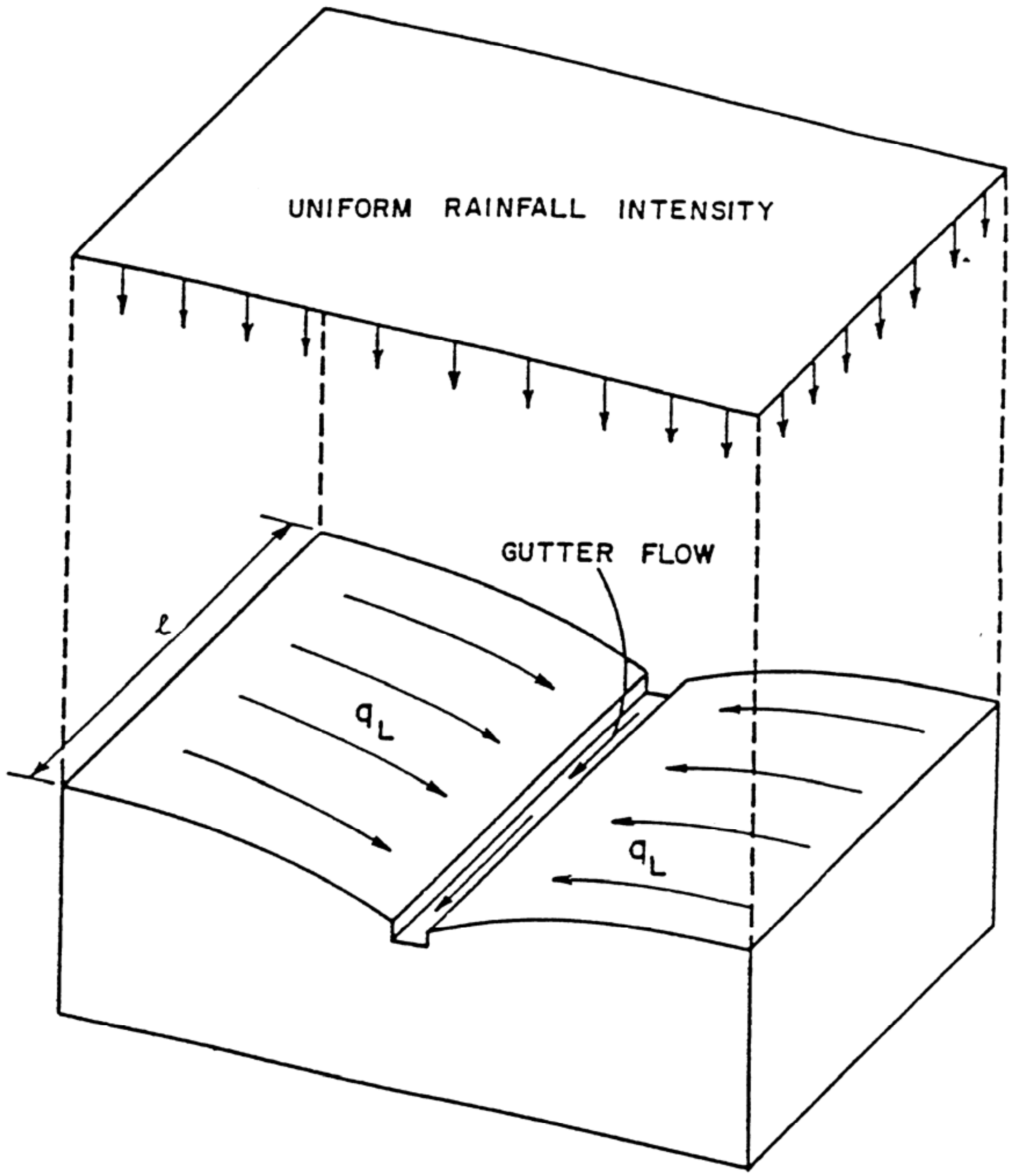
Pollutant Load Simulation

The accumulation of pollutants on the subwatershed surface is modeled in a number of ways. Pollutants can be accumulated as "dust and dirt" on streets or as a simple areal load. Loads may be accumulated in a linear or nonlinear fashion. The different methods (essentially four different equations) are summarized in Figure 5-4 along with a visualization of the accumulation modeled by each.

The washoff of accumulated pollutants is handled in one of two ways. One method applies the following "first-order" relationship to each subwatershed:

$$-P_{off} = dP_p/dt \quad = \quad -K \cdot P_p \qquad (5\text{-}9)$$

where P_{off} = rate at which pollutant is washed off the subwatershed at time t, quantity/second;
P_p = amount of pollutant p on the subwatershed surface at time t, quantity; and
K = coefficient, 1/second.



q_L = RATE OF OVERLAND FLOW/UNIT WIDTH.

W = 2ℓ = TOTAL WIDTH OF OVERLAND FLOW

Figure 5-3. Idealized subwatershed-gutter arrangement illustrating the subwatershed width of overland flow, RUNOFF Block, SWMM (Huber and Dickinson 1988).

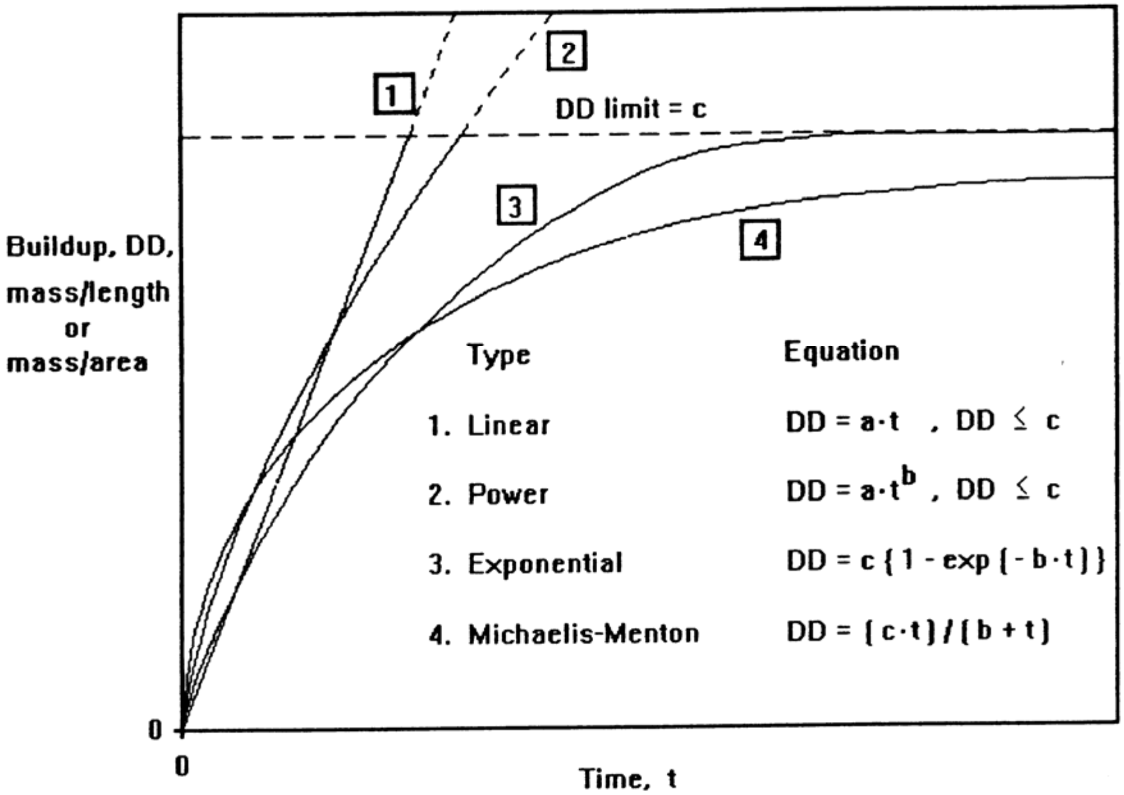


Figure 5-4. Buildup equations, RUNOFF Block, SWMM (after Huber and Dickinson 1988).

The term "quantity" is used in the definitions of P_{off} and P_p because the pollutants modeled by SWMM can be characterized with a variety of units (e.g. milligrams, MPN for coliform bacteria, NTU for turbidity, etc.). Equation 5-9 says that the rate at which a pollutant disappears from a subwatershed surface is proportional to the amount remaining on the subwatershed surface. The coefficient K is assumed to be proportional to the runoff rate:

$$K = R_c \cdot r \qquad (5\text{-}10)$$

where R_c = washoff coefficient, inches^{-1} or millimeters^{-1}; and
r = runoff rate over the subwatershed at time t, inches/second or millimeters/second (calculated from Q in Equation 5-5, r = Q/A).

Substituting Equation 5-10 into Equation 5-9 and multiplying by -1 yields:

$$P_{off} = -dP_p/dt = R_c \cdot r \cdot P_p \qquad (5\text{-}11)$$

A major deficiency of Equation 5-11 is that the runoff pollutant concentrations are forced to decrease over the course of a runoff event. Equation 5-11 shows the washoff rate increasing with runoff, but dividing Equation 5-11 by the runoff flow, Q, yields:

$$C = P_{off}/Q = \text{conv}(R_c \cdot r \cdot P_p)/(A \cdot r) = \text{conv}(R_c \cdot P_p)/A \qquad (5\text{-}12)$$

where C = concentration, quantity/volume;
Q = $A \cdot r$, runoff flow rate, feet^3/second or meters^3/second;
A = subwatershed area, acres or hectares; and
conv = a constant containing a number of conversion factors.

Note that the runoff rate, r, disappears in Equation 5-12. Thus, the concentration, C, become independent of the runoff rate and directly proportional to a decreasing amount of pollutant remaining on the watershed. A decreasing concentration, while fairly common, is certainly not the only possible trend. Concentrations can increase during a runoff event. To overcome this problem, an exponent other than one is allowed for r:

$$P_{off} = -dP_p/dt = R_c \cdot r^n \cdot P_p \quad (5\text{-}13)$$

where n = exponent for the runoff rate.

The load calculated by Equation 5-13 is combined with the runoff flow rate to calculate the concentration, i.e., $C = P_{off}/Q$. If $n = 1$, Equation 5-13 reverts to Equation 11 and the concentration will decrease over the course of an event. Otherwise, concentration is proportional to r^{n-1} (recall Equation 5-12) and as such it may increase if the runoff rate is large enough to offset the reduced value of P_p.

The solution to Equation 5-13 is determined from a finite difference approximation which produces:

$$P_p(t+\Delta t) = P_p(t) \cdot \exp\{-R_c \cdot 0.5 \cdot [r(t)^n + r(t+\Delta t)^n]\Delta t\} \quad (5\text{-}14)$$

where $0.5[r(t)^n + r(t+\Delta t)^n]$ = average runoff rate over Δt, inches/second or millimeters/second.

The second method allows the user to simulate the washoff as a simple function of the runoff rate:

$$P_{off} = R_c \cdot Q^n \quad (5\text{-}15)$$

where coefficients R_c and n are assigned particular values for each pollutant. In this method, the simulation of pollutant load washoff may be totally independent of the amount accumulated on the surface (i.e., the load is a function of the runoff flow rate only) or may be linked to the accumulated amount by not allowing the total load discharged during a particular storm to exceed the amount present on the surface at the beginning of the storm.

Other Capabilities and Summary

There are many other capabilities not discussed here, most notably snowmelt simulation. The RUNOFF Block consumes a considerable portion of the SWMM user’s manual, making it seem more profound and difficult than it is. Recall that the heart of the block is a very simple nonlinear reservoir representation of the surface runoff process, rudimentary nonlinear and linear buildup relationships, and a first-order washoff process.

Unfortunately, many users incorrectly use RUNOFF through misinterpretation of the early stormwater data that was used in its development, especially the washoff mechanisms and infiltration of water through compacted soils and infiltration through pavement. In addition, RUNOFF doesn’t allow direct application of many common stormwater control practices. For these reasons, SLAMM is used during this project to replace the RUNOFF block of SWMM.

TRANSPORT Block

The TRANSPORT Block routes flows and pollutant loads through a sewer system (Metcalf and Eddy, Inc., *et al.* 1971; Huber and Dickinson 1988). These flows and loads are generated by the RUNOFF Block (or some other program, e.g., SLAMM) and input to points throughout the system. TRANSPORT also has the ability to simulate dry-weather or sanitary sewage flows for routing through a sewer system. Hydrographs and pollutographs can also be manually introduced at various points in the system.

The sewer system is viewed as a series of “elements”. This is shown in Figure 5-5. Elements may be nodes or conduits. Nodes link conduits and include manholes, pump stations, storage units, and flow dividers (see Table 5-1). Inflows to the system, such as surface runoff, occur at the nodes and may be entered directly by the user or come from other programs such as the RUNOFF Block or SLAMM through an interface file. A conduit may have one of 15 different cross-sectional shapes supplied by the model or two supplied by the user (see Table 5-1). Simple flow diversion devices (e.g., overflow structures) are also allowed.

Each element is identified by a user-supplied number. The numbering scheme can be arbitrary, for the system elements are fashioned into a connected network by indicating which elements are upstream of each element. In other words, element 11 is not necessarily connected to element 12, nor is element 12 necessarily connected to element 13. But element 119 <u>can</u> be connected to element 1034 if the user specifies that element 1034 is one of the elements immediately upstream of element 119.

Flow Routing
Ideally, flow in sewers can be represented by two partial differential equations: the continuity and momentum equations or, as they are sometimes known, the Saint-Venant equations (Chow, *et al*. 1988):

Momentum:

pressure force	*Convective Acceleration*	*local acceleration*	*gravity force*	*friction force*	
$\delta h/\delta t$ +	$(v/g)\cdot\delta v/\delta x$ +	$(1/g)\cdot\delta v/\delta t$ =	S_o -	S_f	(5-16)

Continuity:

inflows and outflows to and from a control volume		*change in amount of water in control volume*			
$\delta Q/\delta x$	+	$\delta A/\delta t$	=	0	(5-17)

where
h = water depth, feet or meters;
v = average flow velocity, feet/second or meters/second;
x = distance along the conduit, feet or meters;
t = time, seconds;
g = acceleration due to gravity, 32.2 feet/second^2 or 9.8 meters/seconds^2;
S_o = invert slope (slope of the conduit), feet/foot or meters/meter;
S_f = friction (energy) slope, feet/foot or meters/meter;
Q = flow rate, feet^3/second or meters^3/second; and
A = cross-sectional area of flow, feet^2 or meters^2.

Unfortunately, the Saint-Venant equations are difficult to manipulate and simplifications are often desirable. TRANSPORT uses a simplified version of the momentum equation in which all terms on the left hand side are neglected, i.e.,

$$S_f = S_o \qquad (5\text{-}18)$$

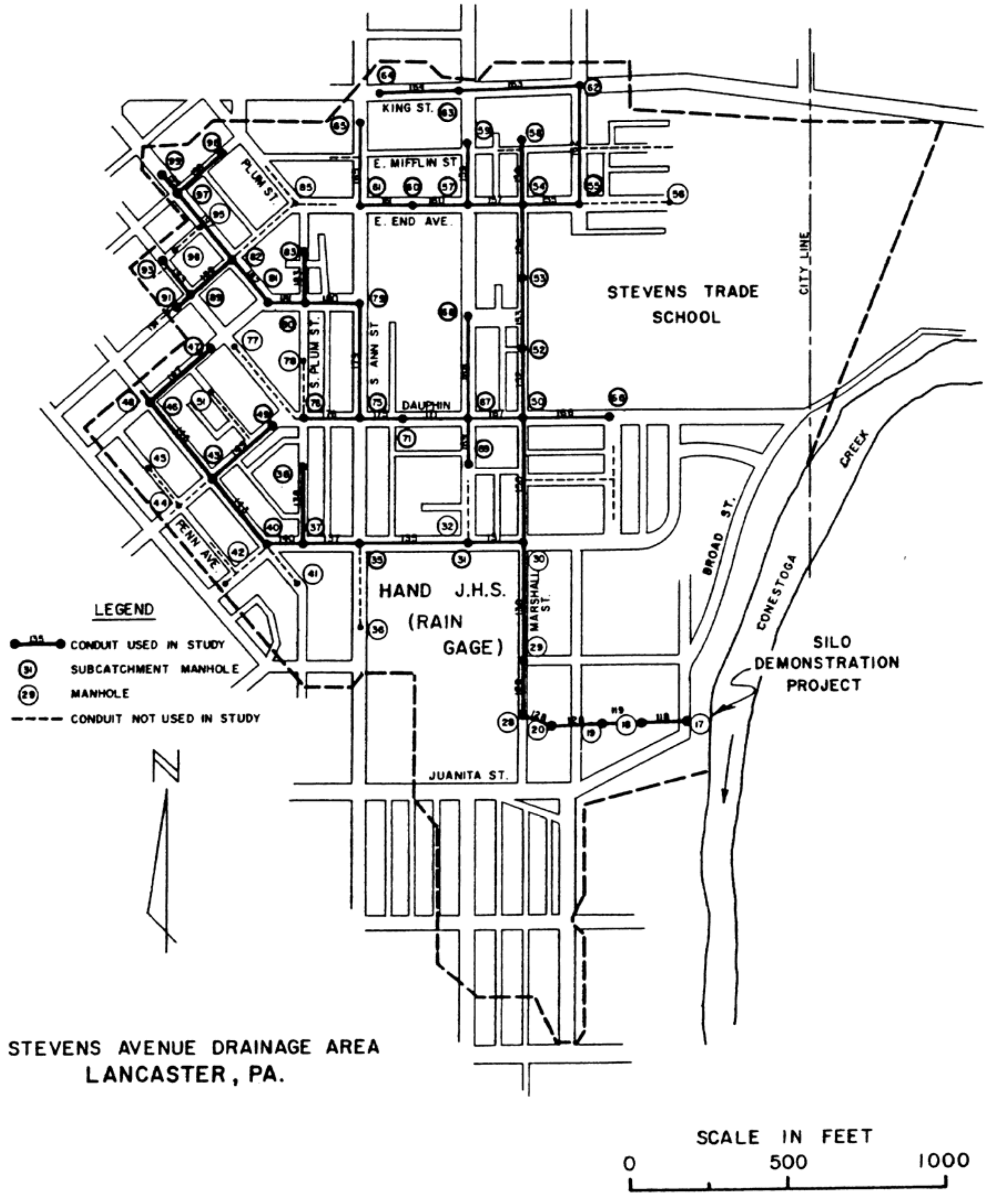


Figure 5-5. Node and conduit representation of a sewer system, TRANSPORT Block, SWMM (Heaney, *et al*. 1975).

Table 5-1. Elements in TRANSPORT Block, SWMM (Huber and Dickinson 1988)

Element Class	Types
Conduits/channels (links)	Circular
	Rectangular
	Phillips standard egg shape
	Boston horseshoe
	Gothic
	Catenary
	Louisville semielliptic
	Basket-handle
	Semicircular
	Modified basket-handle
	Rectangular, triangular bottom
	Rectangular, round bottom
	Trapezoid
	Parabolic
	Power Function
	HEC-2 Format — Natural Channel
	User supplied
Nonconduits (nodes)	
Manhole	Lift station
	Flow divider
	Storage unit
	Flow divider — weir
	Flow divider
	Backwater element

The friction slope, S_f, is estimated from Manning's equation:

$$S_f = Q^2/[(\beta/n)^2 \cdot A^2 \cdot R^{4/3}] \tag{5-19}$$

where n = Manning's roughness coefficient;
R = hydraulic radius, feet or meters; and
β = 1.49 when U.S. customary units are used or 1.0 when metric units are used.

From Equations 5-18 and 5-19,

$$Q = (k/n) \cdot A \cdot R^{2/3} \cdot S_o^{1/2} \tag{5-20}$$

Essentially the original momentum equation, Equation 5-16, is replaced with an equation where Q is a function of depth only (recall that the cross-sectional area, A, and the hydraulic radius, R, are functions of depth, h). This *kinematic wave approximation*, as it is commonly known, is what distinguishes the TRANSPORT Block from its more sophisticated cousin, the EXTRAN Block (see the next section). Since flow is a function of depth alone, "disturbances" or changes that occur at one point in a sewer system can only affect what happens at downstream points, not upstream points. The full momentum equation propagates the effects of disturbances in both directions since flow (or velocity) is also a function of local and convective acceleration and pressure. With hydraulic effects propagated in only the downstream direction, backwater conditions cannot be simulated. In addition, the fact that flow is treated as a function of only depth means that the TRANSPORT Block cannot simulate surcharge conditions (flow under pressure). In summary, the TRANSPORT Block views the system as a simple cascade of conduits with downstream conduits having no effect on upstream conduits.

It is especially important to understand how the TRANSPORT Block behaves when it encounters surcharge conditions. Flows exceeding the open-channel capacity of a conduit are stored at the upstream end of the conduit (at a node) and released when this capacity again becomes available. Hydrographs passing through such a conduit become "clipped" (as shown in Figure 5-6) and, as a result, potential surcharge problems at downstream conduits may be masked.

The continuity equation, Equation 5-17, is approximated by a finite difference relationship:

$$[(1-w_t)(A_{j,n+1} - A_{j,n}) + w_t(A_{j+1,n+1} - A_{j+1,n})]/\Delta t \quad + \quad [(1-w_x)(Q_{j+1,n} - Q_{j,n}) + w_x(Q_{j+1,n+1} - Q_{j,n+1})]/\Delta x = 0 \tag{5-21}$$

where Δt = $t_{n+1} - t_n$, time step size, seconds;
Δx = $x_{j+1} - x_j$, distance interval length (the conduit length), feet or meters;
$j, j+1$ = subscripts indicating conditions at the upstream end and the downstream end of conduit M, respectively;
$n, n+1$ = subscripts indicating conditions at the end of time step n (which is also the beginning of time step n+1) and the end of time step n+1, respectively; and
w_t, w_x = weights.

The weights w_x and w_t were both set to 0.55 after a series of tests to determine the best values for numerical stability. This numerical approximation and its application are illustrated in Figure 5-7.

Equations 5-20 and 5-21 are used together to route flows through a sewer system. At the end of any time step n+1, the unknown quantities are the flow and cross-sectional area of flow at the downstream end of conduit M, $Q_{j+1,n+1}$ and $A_{j+1,n+1}$. (The variables $Q_{j,n}$ and $A_{j,n}$ are known from the previous time step and conditions at the upstream end of the conduit). With only two unknowns, these two equations are sufficient to determine the

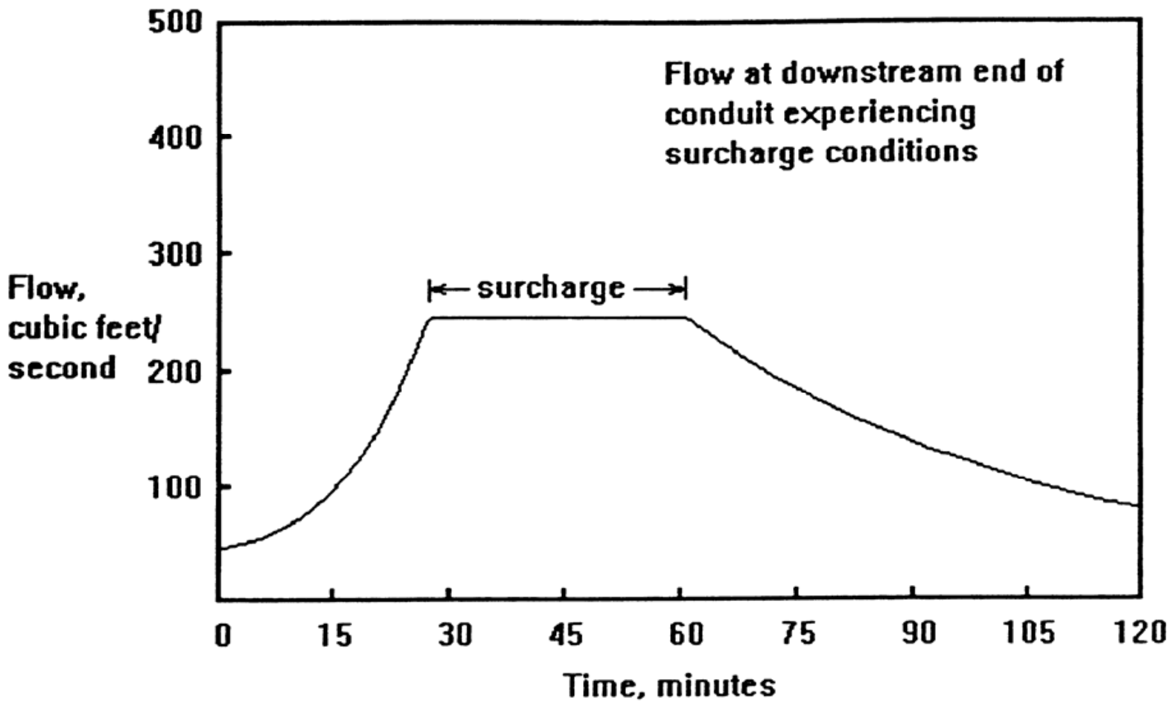


Figure 5-6. Effect of surcharging on downstream hydrograph, TRANSPORT Block, SWMM.

value of both. The calculations are carried out from the most upstream conduit to the most downstream conduit during each time step.

Nodes (e.g., manholes) are treated very simply in the TRANSPORT Block. Flow exiting a node is just the sum of all the flows entering the node.

Although the numbering scheme used to identify the various elements is arbitrary from the user's perspective, the program establishes a separate internal numbering scheme for the routing calculations. Again, this is possible because the user identifies the elements upstream of each element.

It should be noted that several modifications were made to Equations 5-20 and 5-21 to improve model accuracy. These will not be discussed here. It is sufficient to say that these two equations are the heart of the TRANSPORT Block.

Pollutant Routing

Pollutants are routed through the system by treating each conduit as a completely mixed reactor with first-order decay. The governing differential equation is shown below:

change in mass in conduit per unit time		*mass rate to conduit*		*mass rate from conduit*		*decay in conduit*		*mass source or sink*	
$d(V \cdot C)/dt = V \cdot dC/dt + C \cdot dV/dt$	=	$(Q_i \cdot C_i)$	-	$(Q \cdot C)$	-	$K \cdot C \cdot V$	±	L	(5-22)

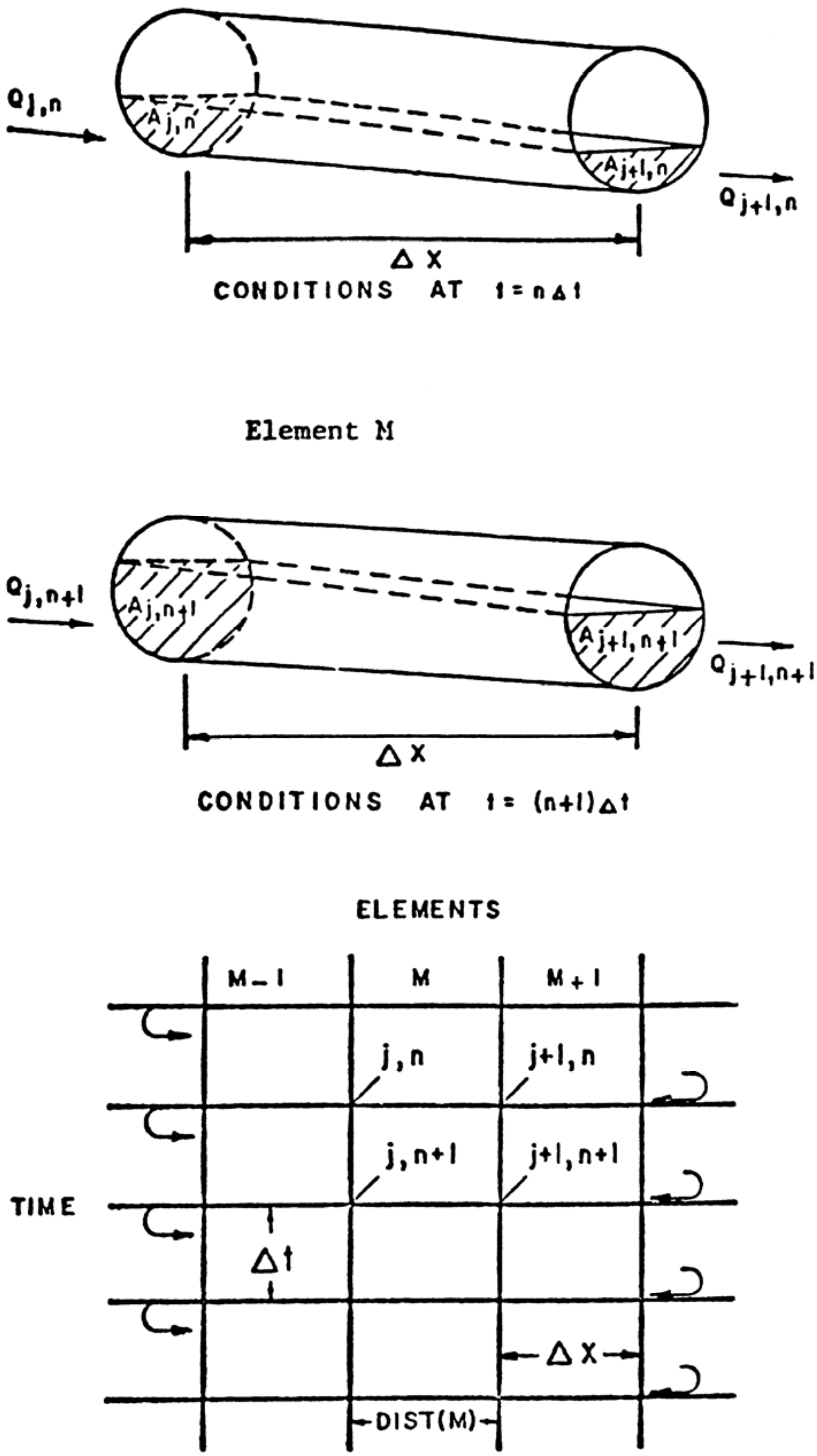


Figure 5-7. Numerical approximation definitions in TRANSPORT Block, SWMM (Metcalf and Eddy, Inc., *et al*. 1971).

where C = pollutant concentration in conduit and discharge from conduit, quantity/volume (e.g., milligrams/liter);
V = volume of water in conduit, $feet^3$ or $meters^3$;
Q_i = inflow rate to conduit, $feet^3$/second or $meters^3$/second;
C_i = pollutant concentration in inflow, quantity/volume;
Q = outflow rate from conduit, $feet^3$/second or $meters^3$/second;
K = first-order decay coefficient, $seconds^{-1}$; and
L = source (or sink) of pollutant to the conduit, quantity/time.

An integrated form of the solution to this differential equation is used with a simple numerical technique to carry out the estimates for concentration in each conduit.

Other Capabilities and Summary
The TRANSPORT Block has a very simple routine to estimate infiltration into the sewer system. The routine is not very useful and the user can just as easily enter infiltration flows at various nodes in the system. Unfortunately, there is no direct way to generate sewer infiltration from the subsurface flows simulated in the RUNOFF Block.

The TRANSPORT Block also contains a rather data-intensive routine for estimating dry-weather flows and pollutant loads (which would be useful in watersheds with combined sewer systems). The estimates are calculated as functions of land use, population, income levels, and a host of other factors.

In summary, the TRANSPORT Block effectively routes flows and pollutants through a simple sewer system, as long as surcharging is not encountered. Unlike its companion the EXTRAN Block, TRANSPORT is capable of routing pollutants. It is numerically stable and relatively easy to apply.

EXTRAN Block
The EXTRAN Block exceeds the hydraulic capabilities of the TRANSPORT Block, but omits pollutant routing (Roesner, *et al.* 1988). The block has a developmental history that is a little different from the rest of SWMM, joining the software bundle in the latter versions.

<u>Flow Routing</u>. Similar to the TRANSPORT Block, the sewer system is viewed as a network of links and nodes (or, collectively, elements). Inflows to the system occur at the nodes and may be entered directly by the user or come from the RUNOFF Block or other programs (e.g., SLAMM). The number of element types that can be modeled is not as extensive as that of the TRANSPORT Block and the method of linking the system together is slightly different (see Table 5-2). Because hydraulic “signals” are propagated in both directions, upstream <u>and</u> downstream nodes are identified for each link (or conduit).

The EXTRAN Block uses the complete Saint-Venant equations to model the routing of flows through a sewer system. However, the equations are expressed a little differently than in the previous section outlining the TRANSPORT Block (i.e., Equations 5-16 and 5-17):

Momentum:

pressure and gravity force		*convective acceleration*		*local acceleration*		*friction force*		
$g\cdot A\cdot(\delta H/\delta x)$	+	$\delta(Q^2/A)/\delta x$	+	$\delta Q/\delta t$	+	$g\cdot A\cdot S_f$	= 0	(5-23)

Table 5-2. Elements in EXTRAN Block, SWMM (Roesner, *et al*. 1988)

Element Class	Types
Conduits or links	Rectangular
	Circular
	Horseshoe
	Eggshape
	Baskethandle
	Trapezoid
	Power function
	Natural Channel (irregular cross section)
Junctions or nodes	Manholes
Diversion structures	Orifices
	Transverse weirs
	Side-flow weirs
Pump stations	On-line or off-line pump station
Storage basins	On-line, enlarged pipes or tunnels
	On-line or off-line, arbitrary stage-area relationship
Outfall structures	Transverse weir with tide gate
	Transverse weir without tide gate
	Side-flow weir with tide gate
	Side-flow weir without tide gate
	Outfall with tide gate
	Free outfall without tide gate

Continuity:

inflows and outflows to and from a control volume		*change in amount of water in control volume*		
$\delta Q/\delta x$	+	$\delta A/\delta t$	=	0

(5-24)

where H = z + h, hydraulic head, feet or meters;

z = conduit invert elevation, feet or meters;
h = water depth, feet or meters;
x = distance along the conduit, feet or meters;
t = time, seconds;
g = acceleration due to gravity, 32.2 feet/second^2 or 9.8 meters/seconds^2;
S_f = friction (energy) slope, feet/foot or meters/meter;
Q = flow rate, feet^3/second or meters^3/second; and
A = cross-sectional area of flow, feet^2 or meters^2.

Note that the gravity force term found in Equation 5-16 is incorporated in the first term of Equation 5-23. The friction force term is estimated by Manning's equation:

$$S_f = Q^2/[(\beta/n)^2 \cdot A^2 \cdot R^{4/3}] = Q \cdot |v|/[(\beta/n)^2 \cdot A^2 \cdot R^{4/3}] \quad (5\text{-}25)$$

where n = Manning's roughness coefficient;
R = hydraulic radius, feet or meters; and
β = 1.49 when U.S. customary units are used or 1.0 when metric units are used.

The absolute value sign on velocity, v, insures that the friction force, as expressed by S_f, opposes the direction of flow. For example, if flow is reversed (from the nominal direction of flow) both Q and v would be negative. Taking the absolute value of v allows S_f to become negative as well.

Equations 5-23 and 5-24 are combined through a few algebraic manipulations. These first of these relies on the identity

$$Q^2/A = v^2/A \quad (5\text{-}26)$$

where v = average flow velocity, feet/second or meters/second.

Substituting Equation 5-26 into the convective acceleration term of the momentum equation (Equation 5-23) yields:

$$g \cdot A \cdot (\delta H/\delta x) + 2A \cdot v \cdot (\delta v/\delta x) + v^2 \cdot (\delta A/\delta x) + \delta Q/\delta t + g \cdot A \cdot S_f = 0 \quad (5\text{-}27)$$

Noting that $Q = A \cdot v$, the continuity equation, Equation 5-24, can be written as:

$$A \cdot (\delta v/\delta x) + v \cdot (\delta A/\delta x) + \delta A/\delta t = 0 \quad (5\text{-}28)$$

Multiplying by velocity v and rearranging terms yields:

$$A \cdot v \cdot (\delta v/\delta x) = -v \cdot (\delta A/\delta t) - v^2 \cdot (\delta A/\delta x) \quad (5\text{-}29)$$

Substituting this result into the second term of the revised momentum equation (Equation 5-27) leads to the basic flow equation used in the EXTRAN Block:

$$g \cdot A \cdot (\delta H/\delta x) - 2v \cdot (\delta A/\delta t) - v^2 \cdot (\delta A/\delta x) + \delta Q/\delta t + g \cdot A \cdot S_f = 0 \quad (5\text{-}30)$$

Essentially, Equation 5-30 contains two variables, Q and H (v and A are related to Q and H). Therefore, the continuity equation (Equation 5-24) is used to provide a second equation relating Q and H at each node. Finite difference approximations are used to numerically solve the two partial differential equations. The details will not be discussed here. The numerical techniques used in the EXTRAN Block are somewhat unstable and some attention must be paid to the size of the time step and conduit lengths.

Other Capabilities and Summary. The routing of pollutant loads is not modeled. Nor are there routines for estimating sewer infiltration or dry-weather flows.

The EXTRAN Block should be used with care and not undertaken lightly. While hydraulically powerful, it has proven to be numerically "temperamental." Nevertheless, EXTRAN should be used if the sewer system to be modeled is complicated and subject to surcharging.

STORAGE/TREATMENT Block

The STORAGE/TREATMENT Block is designed to route flow and pollutant loads through a storage/treatment facility (Nix 1982; Huber and Dickinson 1988). These flows and loads may come from other blocks in SWMM or other sources. The user is given a great deal of flexibility by the block's ability to connect as many as five storage/treatment units together in a variety of networks. Each unit may be given detention (or storage) characteristics or be modeled as a simple flow-through device.

If a unit is modeled as a detention unit, as shown in Figure 5-8, flows are routed through the unit with a level-surface flow routing procedure (i.e., the modified Puls method). This method is based on yet another version of the continuity of mass equation (Viessman, *et al.* 1988):

change in volume of water in detention unit per unit time		*flow rate entering the detention unit*		*flow rate leaving the detention unit*	
dV/dt	$=$	I	$-$	Q	(5-31)

where V = volume of water in detention unit, feet^3 or meters^3;
I = inflow rate, feet^3/second or meters^3/second;
Q = outflow rate, feet^3/second or meters^3/second; and
t = time, seconds.

Equation 5-31 is approximated by the following finite difference relationship:

$$(V_{n+1} – V_n)/\Delta t = (I_n + I_{n+1})/2 + (Q_n + Q_{n+1})/2 \qquad (5\text{-}32)$$

where $n, n+1$ = subscripts indicating conditions at the end of time step n (or the beginning of time step n+1) and the end of time step n+1, respectively; and
Δt = $t_{n+1} – t_n$, time step size, seconds.

At the end of any time step, the values of V_{n+1} and Q_{n+1} are unknown. (The values for V_n and Q_n are known from the previous time step.) A second relationship between storage, V, and discharge, Q, is needed to determine their values. The program gives the user a two ways to provide this relationship. One uses a linear interpolation algorithm to approximate the relationship through a series of volume-discharge data pairs (each pair occurring at a particular depth). With two relationships (Equation 5-32 and the user-supplied volume-discharge information) it is possible to solve for V_{n+1} and Q_{n+1} at each time step.

Pollutants are routed through the detention unit in either a completely mixed or plug-flow manner. In the completely mixed case, all incoming material is instantly distributed throughout the detention unit and, thus, the pollutant concentration is uniform throughout the unit (see Figure 5-9). The following continuity of mass equation is used to simulate the fate of pollutants in the completely mixed detention unit:

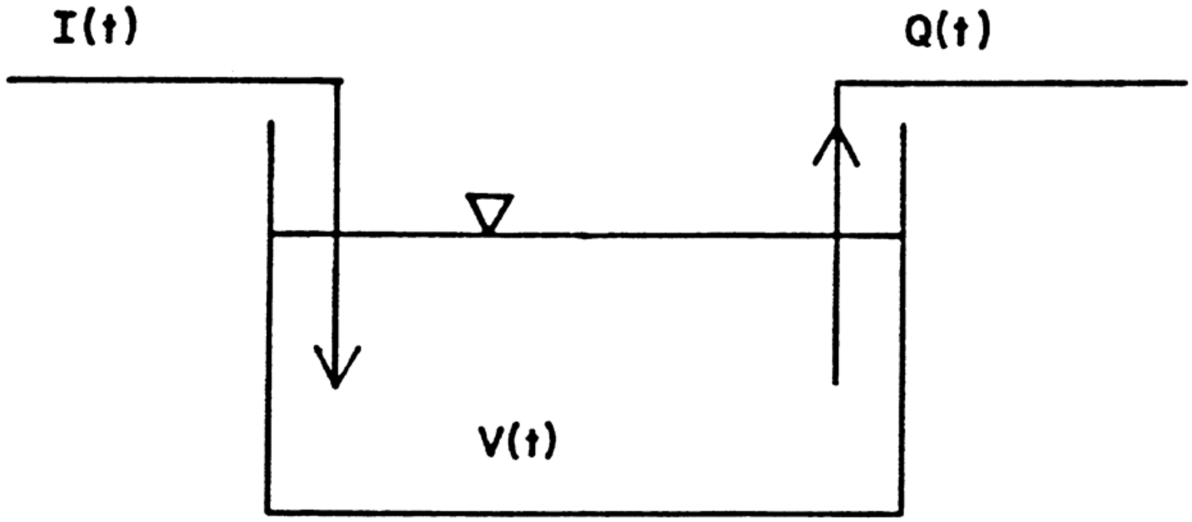


Figure 5-8. Level-surface reservoir, STORAGE/TREATMENT Block, SWMM (after Huber and Dickinson 1988).

change in mass in detention unit per unit time		*mass rate entering the detention unit*		*mass rate leaving the detention unit*		*"reaction" of pollutant by first-order decay*	
$d(CV)/dt$	=	$I \cdot C_I$	-	$Q \cdot C$	-	$K_c \cdot C \cdot V$	(5-33)

where C_I = influent pollutant concentration, quantity/volume (e.g., milligrams/liter);
C = effluent pollutant concentration, quantity/volume; and
K_c = decay coefficient, seconds^{-1}.

Equation 5-33 is approximated by a finite difference equation in a manner very similar to that done for Equation 5-31. The result is an algebraic solution for the effluent pollutant concentration at the end of every time step.

In the plug-flow case, the stormwater and pollutants entering the detention unit in a given time step forms a "plug" (see Figure 5-10). The number of plugs (and/or fraction of a plug) leaving the unit in any time step is, of course, directly related to the departing volume (as determined by the flow routing procedure).

Pollutant removal is modeled through the use of "removal equations" or through a set of relationships describing discrete particle settling. In the former the program provides several variables such as detention time, inflow rate, etc. around which the user can build a wide range of removal equations. This is done by providing a generic function that can be manipulated through the assignment of the program variables to the variables in the generic equation and the selection of appropriate values for the equation coefficients. The generic function is:

$$R = [a_{12} \cdot \exp(a_1 x_1) \cdot x_2^{a2} + a_{13} \cdot \exp(a_3 x_3) \cdot x_4^{a4} + a_{14} \cdot \exp(a_5 x_5) \cdot x_6^{a6} + a_{15} \cdot \exp(a_7 x_7 + a_8 x_8) \cdot x_9^{a9} \cdot x_{10}^{a10} \cdot x_{11}^{a11}]^{a16} \quad (5\text{-}34)$$

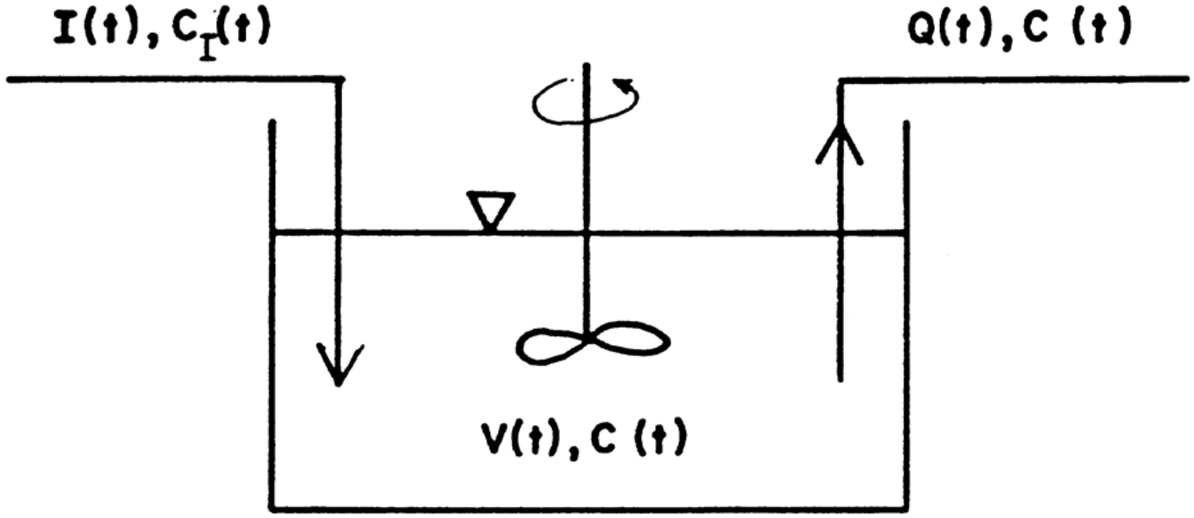


Figure 5-9. Completely mixed detention unit, STORAGE/TREATMENT Block, SWMM (Huber and Dickinson 1988).

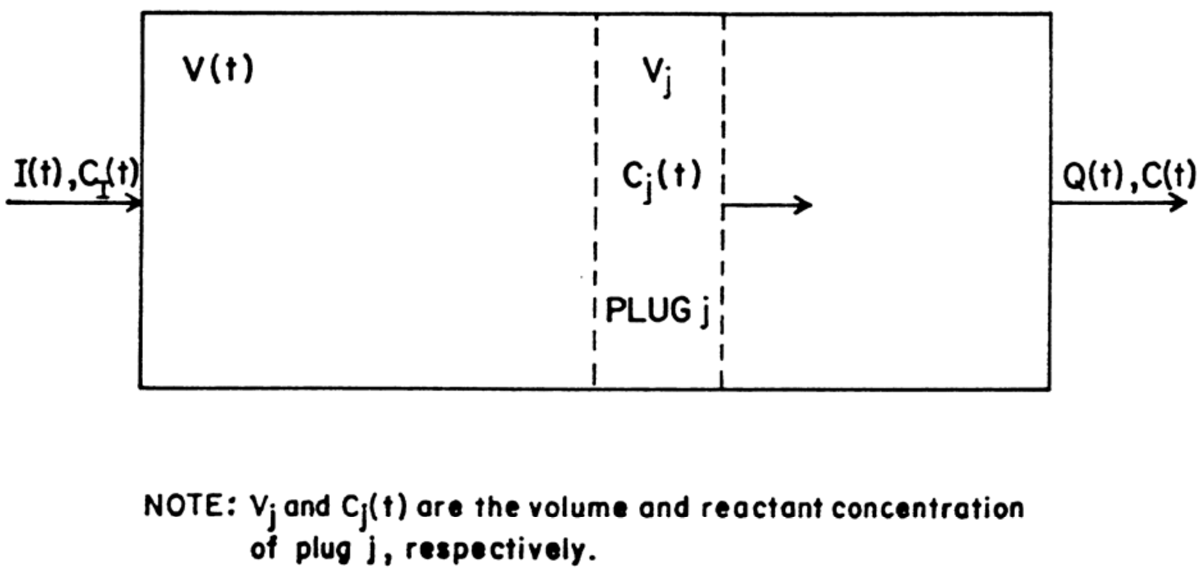


Figure 5-10. Plug-flow detention unit, STORAGE/TREATMENT Block, SWMM (Huber and Dickinson 1988).

where x_i = removal equation variable;

a_j = coefficients; and
R = removal fraction, $0 \le R \le 1.0$.

As mentioned above, each variable x_i can represent one of a number of variables in the storage/treatment algorithm. The selection varies depending on whether the detention basin is assumed to behave as a plug-flow reactor or a completely mixed reactor. In the completely mixed mode, Equation 5-34 is really only used to provide a value for K_c in Equation 5-33. In the plug-flow mode, the equation is applied to each plug and many more options are available.

The particle-settling algorithm can only be used in the plug-flow mode. The size distribution of particles entering the detention unit is assumed to remain constant for all incoming flows. The settling of particles is based on the theory of discrete particle settling modified for the effects of turbulence (Nix 1982). The outgoing size distribution changes over time as differences in flow conditions dictate. The removal (settling) of a particular pollutant is based on its association with particles of various settling velocities or sizes and specific gravities (e.g., 20% of the BOD load is associated with particles that have a given range of settling velocities). This association also remains constant for all incoming pollutant loads. This assumption, and that of a constant particle size distribution, is a major limitation. It should be said, however, that this limitation only exists because the RUNOFF Block does not predict the distribution of particle sizes carried along with stormwater runoff. The algorithms in the STORAGE/TREATMENT Block can handle time-varying distributions.

When a unit is defined as a simple flow-through or non-detention device, flow is routed without delay, i.e., inflow = outflow. Pollutant removal is simulated with Equation 5-34 (again, built by the user with variables provided by the program), or by assuming that all particles of a certain size or larger are removed.

The STORAGE/TREATMENT Block is not intended to be a sophisticated unit operations simulator. There are other models that simulate these processes in great detail. This block is designed to give the user a reasonable prediction of how a wet-weather facility will respond to dynamic stormwater flows and pollutant loads. In order to keep the model tractable, the representation of pollutant routing and removal is fairly simple.

SLAMM, the Source Loading and Management Model

Introduction

The Source Loading and Management Model (SLAMM) was originally developed to better understand the relationships between sources of urban runoff pollutants and runoff quality. It has been continually expanded since the late 1970s and now includes a wide variety of source area and outfall control practices (infiltration practices, wet detention ponds, porous pavement, street cleaning, catchbasin cleaning, and grass swales). SLAMM is strongly based on actual field observations, with minimal reliance on pure theoretical processes that have not been adequately documented or confirmed in the field. SLAMM is mostly used as a planning tool, to better understand sources of urban runoff pollutants and their control.

Special emphasis has been placed on small storm hydrology and particulate washoff in SLAMM, common areas of misuse in the SWMM RUNOFF block. Many currently available urban runoff models have their roots in drainage design where the emphasis is with very large and rare rains. In contrast, stormwater quality problems are mostly associated with common and relatively small rains. The assumptions and simplifications that are legitimately used with drainage design models are not appropriate for water quality models. SLAMM therefore incorporates unique process descriptions to more accurately predict the sources of runoff pollutants and flows for the storms of most interest in stormwater quality analyses. However, SLAMM can be effectively used in conjunction with drainage design models to incorporate the mutual benefits of water quality controls on drainage design.

SLAMM has been used in many areas of North America and has been shown to accurately predict stormwater flows and pollutant characteristics for a broad range of rains, development characteristics, and control practices. As with all stormwater models, SLAMM needs to be accurately calibrated and then tested (verified) as part of any local stormwater management effort.

SLAMM is unique in many aspects. One of the most important aspects is its ability to consider many stormwater controls (affecting source areas, drainage systems, and outfalls) together, for a long series of rains. Another is its ability to accurately describe a drainage area in sufficient detail for water quality investigations, but without requiring a great deal of superfluous information that field studies have shown to be of little value in accurately predicting discharge results. SLAMM also applies stochastic analysis procedures to more accurately represent actual uncertainty in model input parameters in order to better predict the actual range of outfall conditions (especially pollutant concentrations). However, the main reason SLAMM was developed was because of errors contained in many existing urban runoff models. These errors were obvious when comparing actual field measurements to the solutions obtained from model algorithms.

In addition to the material presented in this report section, Appendices A and B summarize the small storm hydrology features used in SLAMM (showing how drainage and water quality objectives can be both addressed with the model), Appendix C is a user's guide for using SLAMM, Appendix D describes the source area and outfall controls incorporated in SLAMM, and Appendix E contains the source code for SLAMM.

History of SLAMM and Typical Uses

The Source Loading and Management Model (SLAMM) was initially developed to more efficiently evaluate stormwater control practices. It soon became evident that in order to accurately evaluate the effectiveness of stormwater controls at an outfall, the sources of the pollutants or problem water flows must be known. SLAMM has evolved to include a variety of source area and end-of-pipe controls and the ability to predict the concentrations and loadings of many different pollutants from a large number of potential source areas. SLAMM calculates mass balances for both particulate and dissolved pollutants and runoff flow volumes for different development characteristics and rainfalls. It was designed to give relatively simple answers (pollutant mass discharges and control measure effects for a very large variety of potential conditions).

SLAMM was developed primarily as a planning level tool, such as to generate information needed to make planning level decisions, while not generating or requiring superfluous information. Its primary capabilities include predicting flow and pollutant discharges that reflect a broad variety of development conditions and the use of many combinations of common urban runoff control practices. Control practices evaluated by SLAMM include detention ponds, infiltration devices, porous pavements, grass swales, catchbasin cleaning, and street cleaning. These controls can be evaluated in many combinations and at many source areas as well as the outfall location. SLAMM also predicts the relative contributions of different source areas (roofs, streets, parking areas, landscaped areas, undeveloped areas, etc.) for each land use investigated. As an aid in designing urban drainage systems, SLAMM also calculates correct NRCS curve numbers that reflect specific development and control characteristics. These curve numbers can then be used in conjunction with available urban drainage procedures to reflect the water quantity reduction benefits of stormwater quality controls.

SLAMM is normally used to predict source area contributions and outfall discharges. However, SLAMM has been used in conjunction with a receiving water model (HSPF) to examine the ultimate receiving water effects of urban runoff (Ontario 1986).

The development of SLAMM began in the mid 1970s, primarily as a data reduction tool for use in early street cleaning and pollutant source identification projects sponsored by the EPA's Storm and Combined Sewer Pollution Control Program (Pitt 1979; Pitt and Bozeman 1982; Pitt 1984). Additional information contained in SLAMM was obtained during the EPA's Nationwide Urban Runoff Program (NURP) (EPA 1983), especially the early Alameda County, California (Pitt and Shawley 1982), and the Bellevue, Washington (Pitt and Bissonnette 1984) projects. The completion of the model was made possible by the remainder of the NURP projects and additional field studies and programming support sponsored by the Ontario Ministry of the Environment (Pitt and McLean 1986), the Wisconsin Department of Natural Resources (Pitt 1986), and Region V of the U.S. Environmental Protection Agency. Early users of SLAMM included the Ontario Ministry of the Environment's Toronto Area Watershed Management Strategy (TAWMS) study (Pitt and McLean 1986) and the Wisconsin Department of Natural

Resources' Priority Watershed Program (Pitt 1986). SLAMM can now be effectively used as a tool to enable watershed planners to obtain a better understanding of the effectiveness of different control practice programs.

A logical approach to stormwater management requires knowledge of the problems that are to be solved, the sources of the problem pollutants, and the effectiveness of stormwater management practices that can control the problem pollutants at their sources and at outfalls. SLAMM is designed to provide information on these last two aspects of this approach.

SLAMM Computational Processes

Figure 5-11 illustrates the wide variety of development characteristics that affect stormwater quality and quantity. This figure shows a variety of drainage systems from concrete curb and gutters to grass swales, along with directly connected roof drainage systems and drainage systems that drain to pervious areas. "Development characteristics" define the magnitude of these drainage efficiency attributes, along with the areas associated with each surface type (road surfaces, roofs, landscaped areas, etc.). The use of SLAMM shows that these characteristics greatly affect runoff quality and quantity. Land use alone is usually not sufficient to describe these characteristics. The types of the drainage system (curbs and gutters or grass swales) and roof connections (directly connected or draining to pervious area), are probably the most important attributes affecting runoff characteristics. These attributes are not directly related to land use, but some trends are obvious: most roofs in strip commercial and shopping center areas are directly connected, and the roadside is most likely drained by curbs and gutters, for example. Different land uses, of course, are also associated with different levels of pollutant generation. For example, industrial areas usually have the greatest pollutant accumulations due to material transfer and storage, and heavy truck traffic.

Figure 5-12 shows how SLAMM considers a variety of pollutant and flow routings that may occur in urban areas. SLAMM routes material from unconnected sources to the drainage system directly or to adjacent directly connected or pervious areas which in turn drain to the collection system. Each of these areas has pollutant deposition mechanisms in addition to removal mechanisms associated with them. As an example, unconnected sources, which may include rooftops draining to pervious areas or bare ground and landscaped areas, are affected by regional air pollutant deposition (from point source emissions or from fugitive dust) and other aspects that would affect all surfaces. Pollutant losses from these unconnected sources are caused by wind removal and by rain runoff washoff which flow directly to the drainage system, or to adjacent areas. The drainage system may include curbs and gutters where there is limited deposition, and catch basins and grass swales which may remove substantial participates that are transported in the drainage system. Directly connected impervious areas include paved surfaces that drain directly to the drainage system. These source areas are also affected by regional pollutant deposition, in addition to wind removal and controlled removal processes, such as street cleaning. On-site storage is also important on paved surfaces because of the large amount of participate pollutants that are not washed-off, blown-off, or removed by direct cleaning (Pitt 1979; Pitt and Shawley 1982; Pitt 1984).

Figure 5-13 shows how SLAMM proceeds through the major calculations. There is a double set of nested loops in the analyses where runoff volume and suspended solids (particulate residue) are calculated for each source area and then for each rain. These calculations consider the affects of each source area control, in addition to the runoff pattern between areas. Suspended solids washoff and runoff volume from each individual area for each rain are summed for the entire drainage system. The effects of the drainage system controls (catch basins or grass swales, for example) are then calculated. Finally, the effects of the outfall controls are calculated.

SLAMM uses the water volume and suspended solids concentrations at the outfall to calculate the other pollutant concentrations and loadings. SLAMM keeps track of the portion of the total outfall suspended solids loading and runoff volume that originated from each source area. The suspended solids fractions are then used to develop

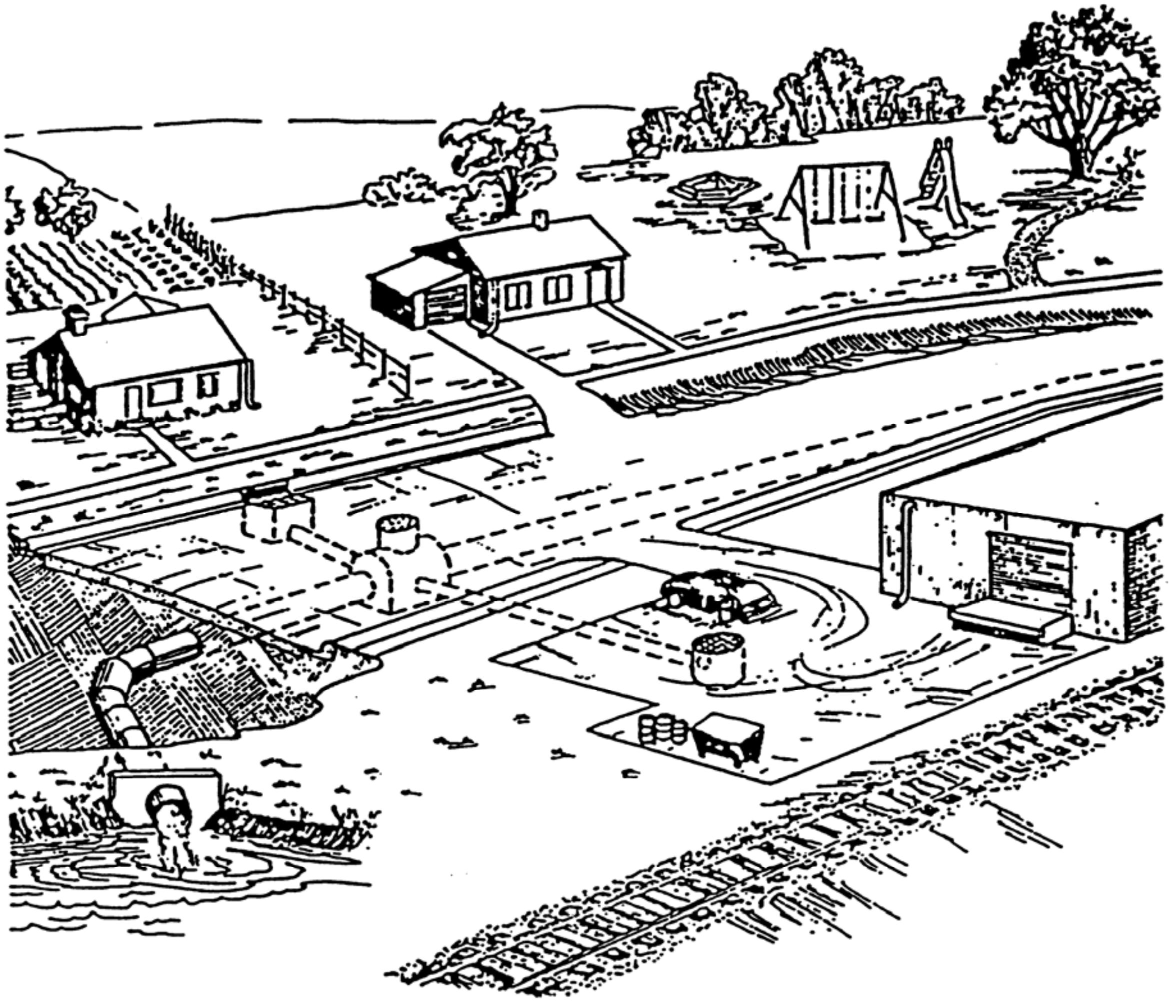


Figure 5-11. Urban runoff source areas and drainage alternatives (Pitt 1986).

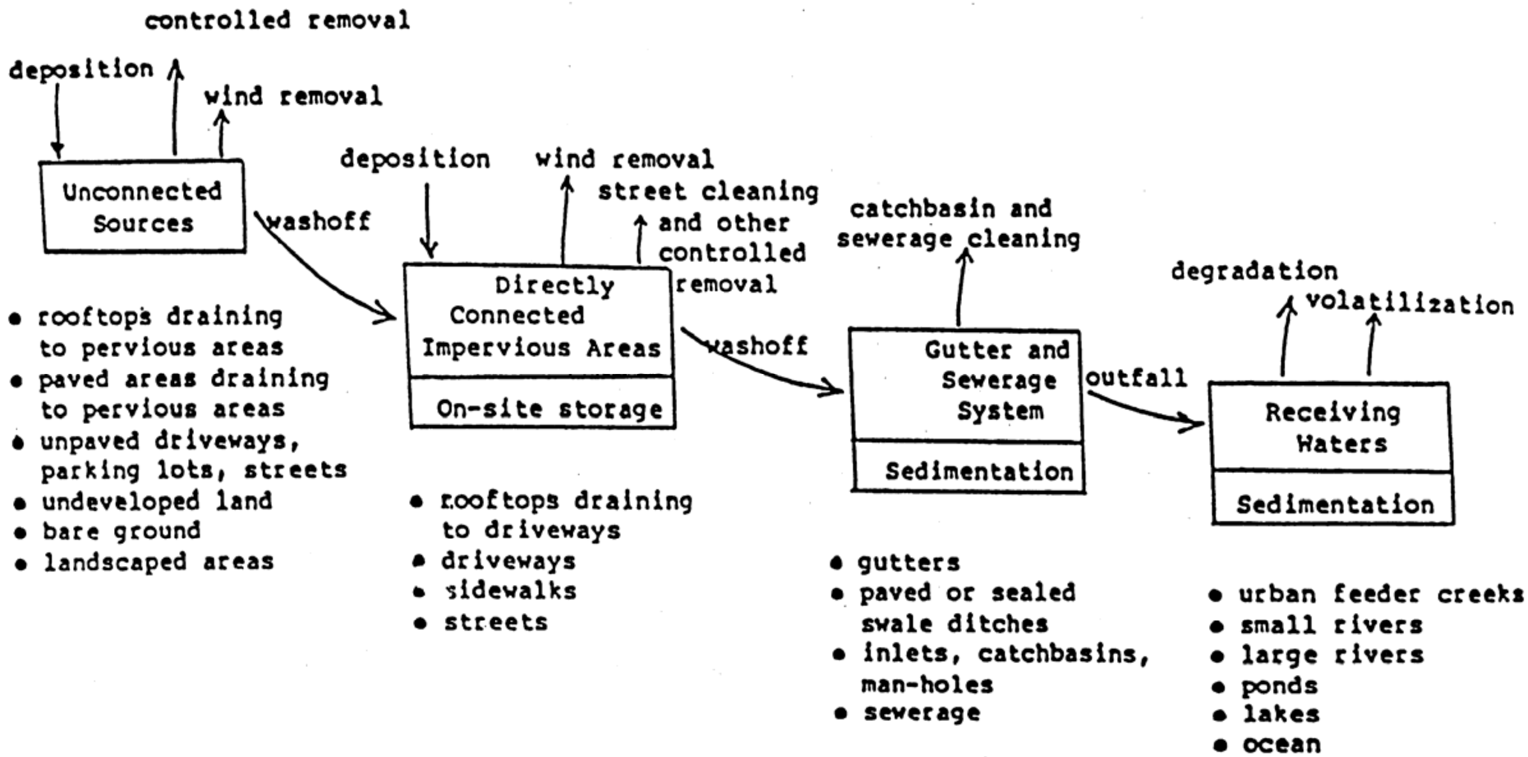


Figure 5-12. Pollutant deposition and removal at source areas (Pitt 1986).

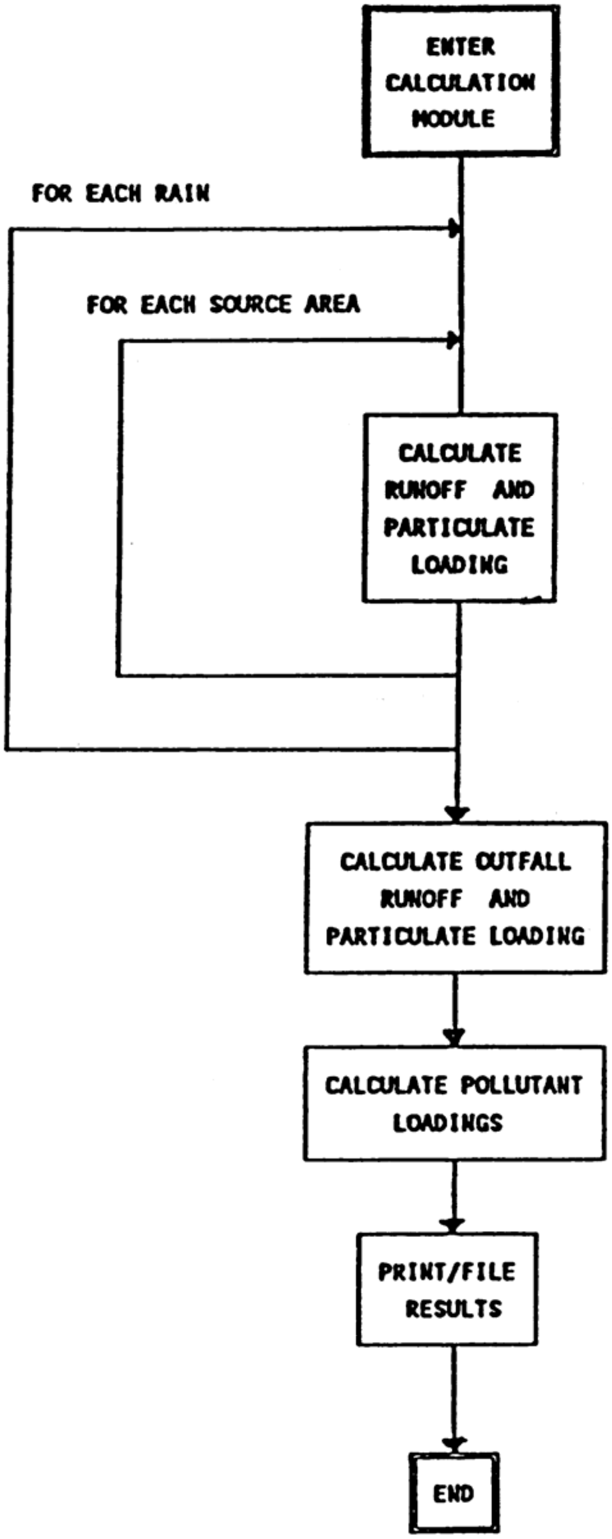


Figure 5-13. SLAMM calculation flow chart.

weighted loading factors associated with each pollutant. In a similar manner, dissolved pollutant concentrations and loadings are calculated based on the percentage of water volume that originates from each of the source areas within the drainage system.

SLAMM predicts urban runoff discharge parameters (total storm runoff flow volume, flow-weighted pollutant concentrations, and total storm pollutant yields) for many individual storms and for the complete study period. It has built-in Monte Carlo sampling procedures to consider many of the uncertainties common in model input values. This enables the model output to be expressed in probabilistic terms that more accurately represent the likely range of results expected.

Monte Carlo Simulation of Pollutants Strengths Associated with Runoff from Various Urban Source Areas

Initial versions of SLAMM only used average concentration factors for different land use areas and source areas. This was satisfactory for predicting the event mean concentrations (EMC, as used by NURP, EPA 1983) for an extended period of time and in calculating the unit area loadings for different land uses. Figure 5-14 is a plot of the event mean concentrations at a Toronto test sites (Pitt and McLean 1986). The observed concentrations are compared to the SLAMM predicted concentrations for a long term simulation. All of the predicted EMC values are very close to the observed EMC values. However, in order to predict the probability distributions of the concentrations, it was necessary to include probability information for the concentrations found in the different source areas. Statistical analyses of concentration data (attempting to relate concentration trends to rain depths and season, for example) from these different source areas have not been able to explain all of the variation in concentrations that have been observed. The statistical analyses also indicate that most pollutant concentration values from individual source areas are distributed log-normally. Therefore, log-normally distributed random concentration values are used in SLAMM for these different areas. The result is much more reasonable predictions for concentration distributions at the outfall when compared to actual observed conditions. This provides more accurate estimates of criteria violations for different stormwater pollutants at an outfall for long continuous simulations.

Use of SLAMM to Identify Pollutant Sources and to Evaluate Different Control Programs

Table 5-3 is a field sheet that has been developed to assist users of SLAMM describe test watershed areas. This sheet is mostly used to evaluate stormwater control retrofit practices in existing developed areas, and to examine how different new development standards effect runoff conditions. Much of the information on the sheet is not actually required to operate SLAMM, but is very important when considering additional control programs (such as public education and good housekeeping practices) that are not quantified by SLAMM. The most important information shown on this sheet is the land use, the type of the gutter or drainage system, and the method of drainage from roofs and large paved areas to the drainage system. The efficiency of drainage in an area, specifically if roof runoff or parking runoff drains across grass surfaces, can be very important when determining the amount of water and pollutants that enter the outfall system. Similarly, the presence of grass swales in an area may substantially reduce the amount of pollutants and water discharged. This information is therefore required to use SLAMM.

The areas of the different surfaces in each land use is also very important for SLAMM. Figure 5-15 is an example showing the areas of different surfaces for a medium density residential area in Milwaukee. As shown in this example, streets make up between 10 and 20 percent of the total area, while landscaped areas can make up about half of the drainage area. The variation of these different surfaces can be very large within a designated area. The analysis of many candidate areas may therefore be necessary to understand how effective or how consistent the model results may be for a general land use classification.

Tables 5-4 and Table 5-5 are coding sheets that have been prepared for SLAMM users. The information on these sheets is used by SLAMM to determine the concentrations and loadings from the different source areas and the effectiveness of different control practices. Table 5-4 shows general information describing the areas and the

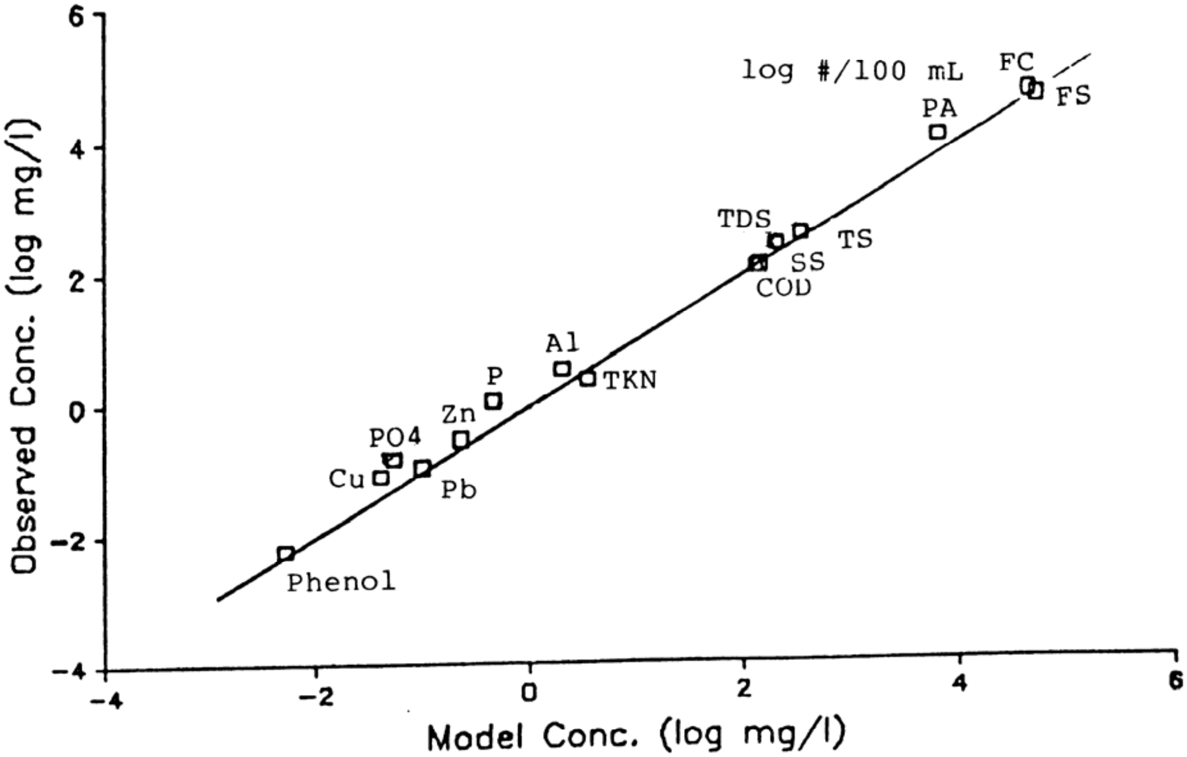


Figure 5-14. Observed and modeled outfall pollutant concentrations – Emery (industrial site) (Pitt 1987).

Table 5-3. Study Area Description Field Sheet

Location: Site number:
Date: Time:
Photo numbers: Roll number:
Land-use and industrial activity:
Residential: low medium high density single family
multiple family
trailer parks
high rise apartments
Income level: low medium high
Age of development: <1930 '30-'50 '51-'70 '71-'80 new
Institutional: school hospital other (type):
Commercial: strip shop. center downtown hotel offices
Industrial: light medium heavy(manufacturing) describe:
Open space: undeveloped park golf cemetery
Other: freeway utility ROW railroad ROW other:
Maintenance of building: excellent moderate poor
Heights of buildings: 1 2 3 4+ stories
Roof drains: underground gutter impervious pervious
Roof types: flat comp. shingle wood shingle other:
Sediment source nearby? No Yes (describe):
Treated wood near street? No telephone poles fence other:
Landscaping near road:
quantity: None some much
type: deciduous evergreen lawn
maintenance: excessive adequate poor
leafs on street: none some much
Topography:
street slope: flat (<2%) medium (2-5%) steep (>5%)
land slope: flat (<2%) medium (2-5%) steep (>5%)
Traffic speed: <25 mph 25-40 mph >40 mph
Traffic density: Light moderate heavy
Parking density: none light moderate heavy
Width of street: number of parking lanes:
number of driving lanes:
Condition of street: good fair poor
Texture of street: smooth intermediate rough
Pavement material: asphalt concrete unpaved
Driveways: paved unpaved
condition: good fair poor
texture: smooth intermediate rough
Gutter material: grass swale lined ditch concrete asphalt
condition: good fair poor
street/gutter interface: smooth fair uneven
Litter loadings near street: clean fair dirty
Parking/storage areas (describe):
condition of pavement: good fair poor
texture of pavement: smooth intermediate rough
unpaved
Other paved areas (such as alleys and playgrounds), describe:
condition: good fair poor
texture: smooth intermediate rough
Notes:

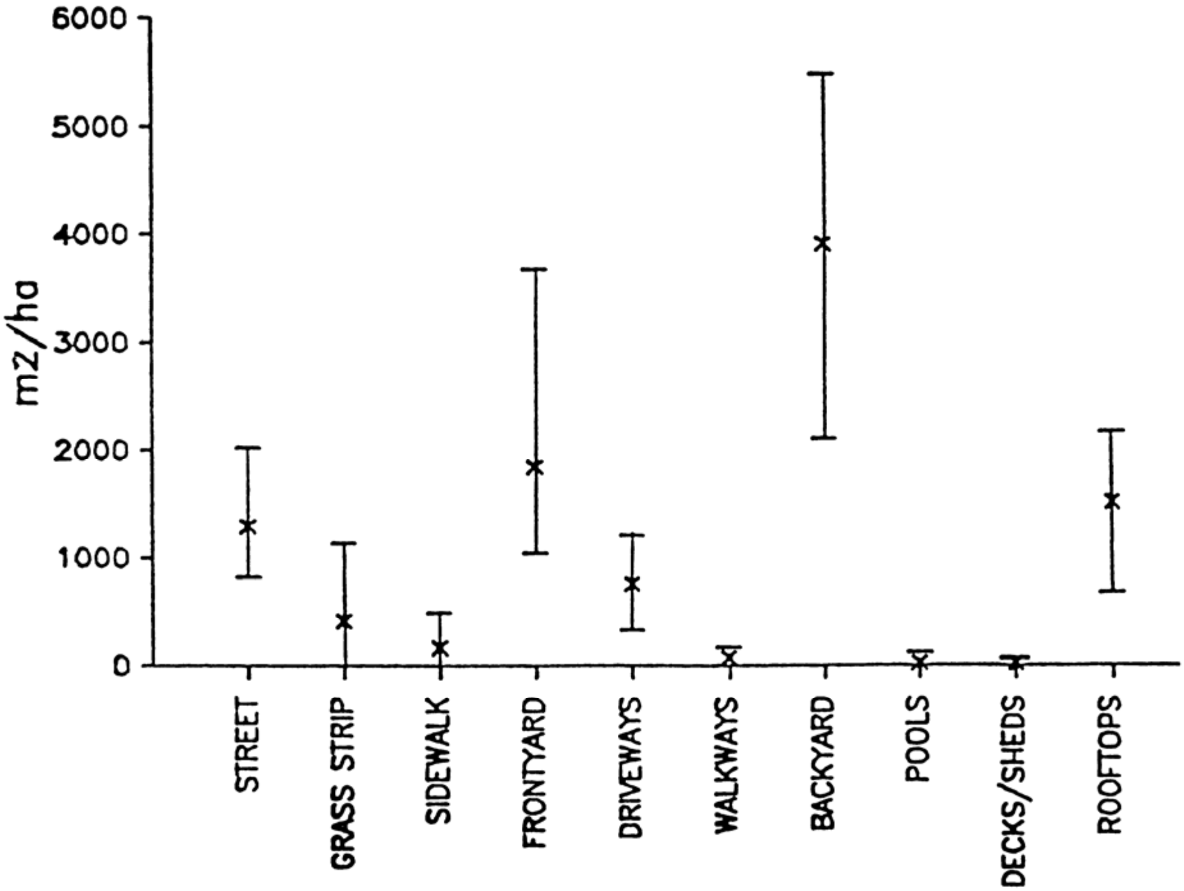


Figure 5-15. Source areas – Milwaukee medium density residential areas (without alleys) (Pitt 1987).

Table 5-4a. SLAMM Site Characterization Data Coding Sheet (Pitt and Voorhees 1995)

Newres.dat: Medium Density Residential, 1961–1980 development, curbs & gutters, clayeys

Land Use: Residential / Institutional / Commercial / Industrial / Open Space

Source Area	Area (ac)						
Roofs 1	2.60	Flat/Pitched	Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Roofs 2	6.05	Flat/Pitched	Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Roofs 3		Flat/Pitched	Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Roofs 4		Flat/Pitched	Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Roofs 5		Flat/Pitched	Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Paved Parking 1			Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Paved Parking 2			Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Paved Parking 3			Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Unpaved Parking 1			Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Unpaved Parking 2			Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Playground 1			Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Playground 2			Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Driveways 1	1.19		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Driveways 2	1.18		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Driveways 3			Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Sidewalks 1			Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Sidewalks 2			Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Strts/Alleys 1	6.58	2.73 curb-miles (40' wide)	Texture: Smth/Int/Rough/ V Rough		Accum: Default/A:__ B:__ C:__	Init Load: Default/ ___ lbs	S
Strts/Alleys 2	0.65	0.27 curb-miles (40' wide)	Texture: Smth/Int/Rough/ V Rough		Accum: Default/A:__ B:__ C:__	Init Load: Default/ ___ lbs	S
Strts/Alleys 3		curb-miles	Texture: Smth/Int/Rough/ V Rough		Accum: Default/A: B: C:	Init Load: Default/ lbs	S
Lrg Landscapes 1				Soil: Sandy/Clayey			IWO
Lrg Landscapes 2				Soil: Sandy/Clayey			IWO
Undvlpd Area	4.59			Soil: Sandy/Clayey			IWO
Sml Landscapes 1	50.94			Soil: Sandy/Clayey			IO
Sml Landscapes 2	26.22			Soil: Sandy/Clayey			IO
Sml Landscapes 3				Soil: Sandy/Clayey			IO
Isolated Area							
Other Pervious Area				Soil: Sandy/Clayey			IWO
Other Directly Conncted Area							IWPO
Other Disconnected Area				Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO

$\Sigma = 100.00$

Page 1 of 2

Table 5-4b. SLAMM Site Characterization Data Coding Sheet (Pitt and Voorhees 1995)

Land Use: Freeways

Source Area	Area (ac)						
Paved Lanes/Shoulders 1	______	Texture: Smth/Int/Rough/ V Rough	ADT: ______ veh/day	Highway Length: ____ miles	Init Load: Default/ ___ lbs		IWO
Paved Lanes/Shoulders 2	______	Texture: Smth/Int/Rough/ V Rough	ADT: ______ veh/day	Highway Length: ____ miles	Init Load: Default/ ___ lbs		IWO
Paved Lanes/Shoulders 3	______	Texture: Smth/Int/Rough/ V Rough	ADT: ______ veh/day	Highway Length: ____ miles	Init Load: Default/ ___ lbs		IWO
Paved Lanes/Shoulders 4	______	Texture: Smth/Int/Rough/ V Rough	ADT: ______ veh/day	Highway Length: ____ miles	Init Load: Default/ ___ lbs		IWO
Paved Lanes/Shoulders 5	______	Texture: Smth/Int/Rough/ V Rough	ADT: ______ veh/day	Highway Length: ____ miles	Init Load: Default/ ___ lbs		IWO
Large Turf Areas	______	Soil: Sandy/Clayey					IWO
Undeveloped Areas		Soil: Sandy/Clayey					IWO
Other Pervious Area	______	Soil: Sandy/Clayey					IWO
Other Directly Conncted Area	______						IWPO
Other Disconnected Area	______	Soil: Sandy/Clayey		Density: Low/Med or High		Alleys: Yes/No	IWPO

Model Run Starting Date : 01 / 01 / 76
Model Run Ending Date: 12 / 31 / 76

Parameter File Names:
Rain File: BHAM76 .RAN
Runoff Coefficient File: Runoff .RSV
Particulate Solids Concentration File: Part .PSC
Pollutant Relative Concentration File: Poll .PPD
Particulate Residue Delivery File: Delivery .PRR

Seed: 0 / 5

pollutants:
particulate residue (suspended solids)
filterable phosphate
total lead

Table 5-5a. SLAMM Control Device Data Sheet (Pitt and Voorhees 1995)

Control Device for Land Use : Medium Density Residential ; Source Area: ______________
File name: Newres .DAT

Infiltration Area or Trench: I

1. Water percolation rate (in/hr): __________
2. Area served by device (acres): __________
3. Surface area of the device (ft^2): __________
4. Width to Depth Ratio of the Device: __________

total rooftop leader disconnections: eliminate "roof 1" and increase "roof 2" to 8.65 acres

Street Cleaning S (same for both street types)

1. Number of Street Cleaning Schedule Changes: 0
2. Start Cleaning Date

	Start Cleaning Date	Cleaning Schedule No.
1	01 / 01 / 76	9 (every 4 weeks)
2	___/___/___	
3	___/___/___	
4	___/___/___	
5	___/___/___	
6	___/___/___	
7	___/___/___	
8	___/___/___	
9	___/___/___	
10	___/___/___	

Cleaning Schedule Code

1. None
2. 7 Passes/wk
3. All weekdays
4. 4 Passes/wk
5. 3 Passes/wk
6. 2 Passes/wk
7. 1 Pass/wk
8. Every two weeks
9. Every 4 weeks
10. Every 8 weeks
11. Every 12 weeks

3. Final Street Cleaning Date: 12 / 31 / 76
4. Overall Street Cleaning Productivity:

Default Cleaning Productivity:

1. Parking Density
   1. None
   2. Light
   3. Medium
   4. Extensive (short term)
   5. Extensive (long term)
2. Parking Controls: Yes / No

User Defined Cleaning Productivity:

m Slope (less than 1): ________

b Intercept (greater than or equal to 1): ________

Porous Pavement P

1. Infiltration rate of pavement, base, or soil, whichever is the least (in/hr): _______
2. Porous Pavement Area (acres): __________

Other Flow or Pollutant Reduction Control O

1. Pollutant concentration reduction (fraction): ______________
2. Water volume (flow) reduction (fraction): ______________
3. Area served by other control (acres): ______________

Table 5-5b. SLAMM Control Device Data Sheet (Pitt and Voorhees 1995)

Catchbasin Cleaning C

1. Total sump volume (ft^3): 950
2. Area served by other control (acres): 100
3. Percentage of sump volume which is full at beginning of study period (0 to 100): 30
4. Number of times catchbasin cleaned during study period (0 - 5 times): 2
5. Date each time catchbasin is cleaned:
   1. 02/ 15 / 76
   2. 08/ 15 / 76
   3. ___/___/___
   4. ___/___/___
   5. ___/___/___

Grass Swales G

1. Swale infiltration rate (in/hr): 0.5
2. Swale density (ft/acre): 350
3. Wetted swales width (ft): 3.5
4. Area served by swales (acres): 100

Other Flow or Pollutant Reduction Control at the Outfall O

1. Particulate Residue Reduction due to rainfall delivery (fraction)

Rain (mm)	Particulate Reduction	Rain (mm)	Particulate Reduction
1		25	
2		30	
3		40	
5		50	
10		60	
15		70	
20		80	

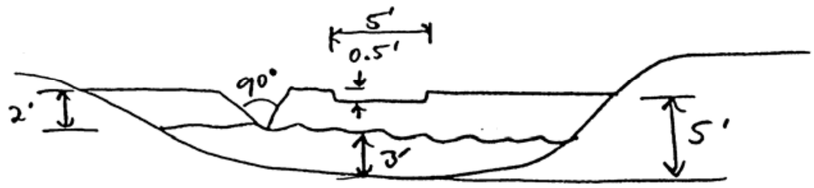
2. Water volume (flow) reduction (fraction): ______
3. Area served by other control (acres): ______

Drainage System Type	Fraction of Total Area
1. Grass Swales:	
2. Undeveloped roadside:	
3. Curbs and gutters in poor condition (or flat):	
4. Curbs and gutters in fair condition:	1 (except for grass swale test)
5. Curbs and gutters in good condition (or steep):	

Table 5-5c. SLAMM Control Device Data Sheet (Pitt and Voorhees 1995)

Wet Detention Ponds D

Diagram Outlet Structure in Space Below



100 acres served
Medium.cpz particle size distribution file

1. Initial Stage Elevation (feet) above datum: 3
2. Number of stage elevation increments required: 5
3. Total number of outlets (maximum: 10): 2
4. Stage, pond area, seepage, and other outlet information:

Entry Number	Stage (ft)	Pond Area (acres)	Natural Seepage (cfs)	Other Outflow (cfs)
0	0.0	0.0	0.0	0.0
1	1	0.1		
2	2	0.2		
3	3	0.5		
4	4	0.7		
5	5	0.9		
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				
25				
26				
27				
28				
29				
30				

Table 5-5d. SLAMM Control Device Data Sheet (Pitt and Voorhees 1995)

Wet Detention Ponds (continued)

5. Outlet Characteristics
   1. Rectangular Weir
      1. Weir length (ft): 5 ft
      2. Height from bottom of weir opening (invert) to top of weir: 0.5 ft
      3. Height from datum to bottom of weir opening (invert) (ft): 4.5 ft
   2. V-Notch Weir
      A) Weir angle
         1. 22.5 degrees
         2. 30 degrees
         3. 45 degrees
         4. 60 degrees
         5. 90 degrees
         6. 120 degrees

      B) Height from bottom of weir opening (invert) to top of weir: 2 ft

      C) Height from datum to bottom of weir opening (invert) (ft): 3 ft
   3. Orifice
      1. Orifice diameter (ft): ________
      2. Invert elevation above datum (ft): ________
   4. Seepage Basin characteristics
      1. Infiltration rate (in/hr): ________
      2. Width of device (ft): ________
      3. Length of device (ft): ________
      4. Invert elevation of seepage basin inlet above datum (ft): ________
   5. Monthly Evaporation Rate

Month Number	Month	Evaporation (in/day)
1	January	
2	February	
3	March	
4	April	
5	May	
6	June	
7	July	
8	August	
9	September	
10	October	
11	November	
12	December	

characteristics of source areas. More information is required for some source areas than others, based upon responses to questions. Table 5-5 contains the coding sheets to describe the types of control practices that are to be investigated using SLAMM in a specific watershed area. Control practices evaluated by SLAMM include infiltration trenches, seepage pits, disconnections of directly connected roofs and paved areas, percolation ponds, street cleaning, porous pavements, catchbasin cleaning, grass swales, and wet detention ponds. These devices can be used singly or in combination, at source areas or at the outfalls or, in the case of grass swales and catchbasins, within the drainage system. In addition, SLAMM provides a great deal of flexibility in describing the sizes and other design aspects for these different practices.

One of the first problems in evaluating an urban area for stormwater controls is the need to understand where the pollutants of concern are originating under different rain conditions. Figures 5-16 through 5-19 are examples for a typical medium density residential area (described in the previous coding sheets) showing the percentage of different pollutants originated from different major sources, as a function of rain depth. As an example, Figure 5-16 shows the areas where water is originating. For storms of up to about 0.1 inch in depth, street surfaces contribute about one-half to the total runoff to the outfall. This contribution decreased to about 20 percent for storms greater than about 0.25 inch in depth. This decrease in the significance of streets as a source of water is associated with an increase of water contributions from landscaped areas (which make up more than 75% of the area and have clayey soils). Similarly, the significance of runoff from driveways and roofs also starts off relatively high and then decreases with increasing storm depth. Figures 5-17, 5-18 and 5-19 are similar plots for suspended solids, phosphorus and lead. These show that streets contribute almost all of these pollutants for the smallest storms up to about 0.1 inch. The contributions from landscaped areas then become dominant. Figure 5-19 shows that the contributions of phosphates are more evenly distributed between streets, driveways, and rooftops for the small storms, but the contributions from landscaped areas completely dominate for storms greater than about 0.25 inch in depth. Obviously, these are just example plots and the source contributions would vary greatly for different land uses/development conditions, rainfall patterns, and the use of different source area controls.

A major use of SLAMM is to better understand the role of different sources of pollutants. As an example, to control suspended solids, street cleaning (or any other method to reduce the washoff of particulates from streets) may be very effective for the smallest storms, but would have very little benefit for storms greater than about 0.25 inches in depth. However, erosion control from landscaped surfaces may be effective over a wider range of storms. The following list shows the different control programs that were investigated in this hypothetical medium density residential area having clayey soils:

- Base level (as built in 1961-1980 with no additional controls)
- Catchbasin cleaning
- Street cleaning
- Grass swales
- Roof disconnections
- Wet detention pond
- Catchbasin and street cleaning combined
- Roof disconnections and grass swales combined
- All of the controls combined

This residential area, which was based upon actual Birmingham, Alabama, field observations for homes built between 1961 to 1980, has no controls, including no street cleaning or catchbasin cleaning. The use of catchbasin cleaning in the area, in addition to street cleaning was evaluated. Grass swale use was also evaluated, but swales are an unlikely retrofit option, and would only be appropriate for newly developing areas. However, it is possible to disconnect some of the roof drainages and divert the roof runoff away from the drainage system and onto grass surfaces for infiltration in existing developments. In addition, wet detention ponds can be retrofitted in different areas and at outfalls. Besides those controls examined individually, catchbasin and street cleaning controls

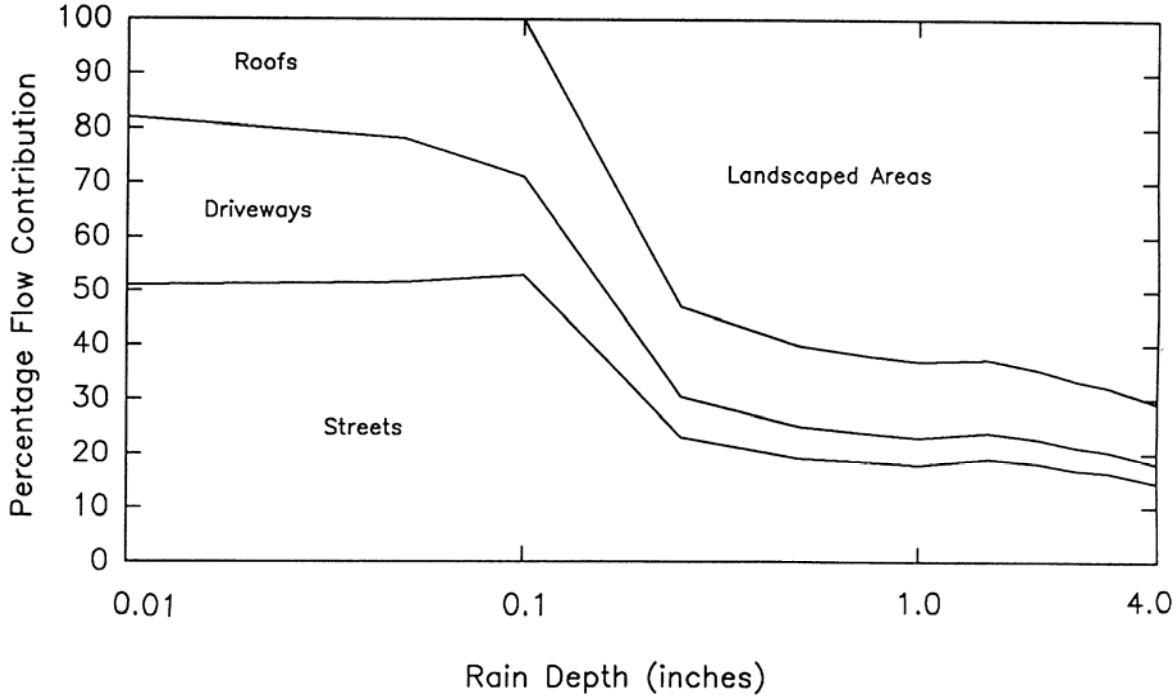


Figure 5-16. Flow sources for example medium density residential area having clayey soils (Pitt and Voorhees 1995).

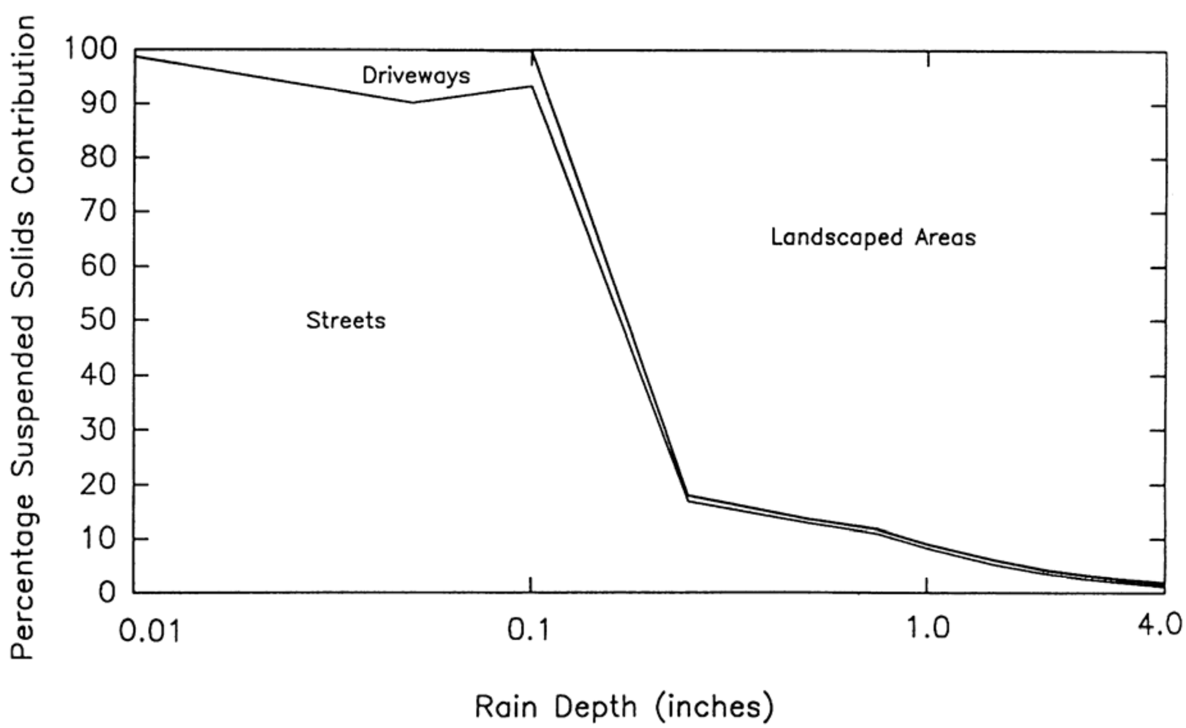


Figure 5-17 Suspended solids sources for example medium density residential area having clayey soils (Pitt and Voorhees 1995).

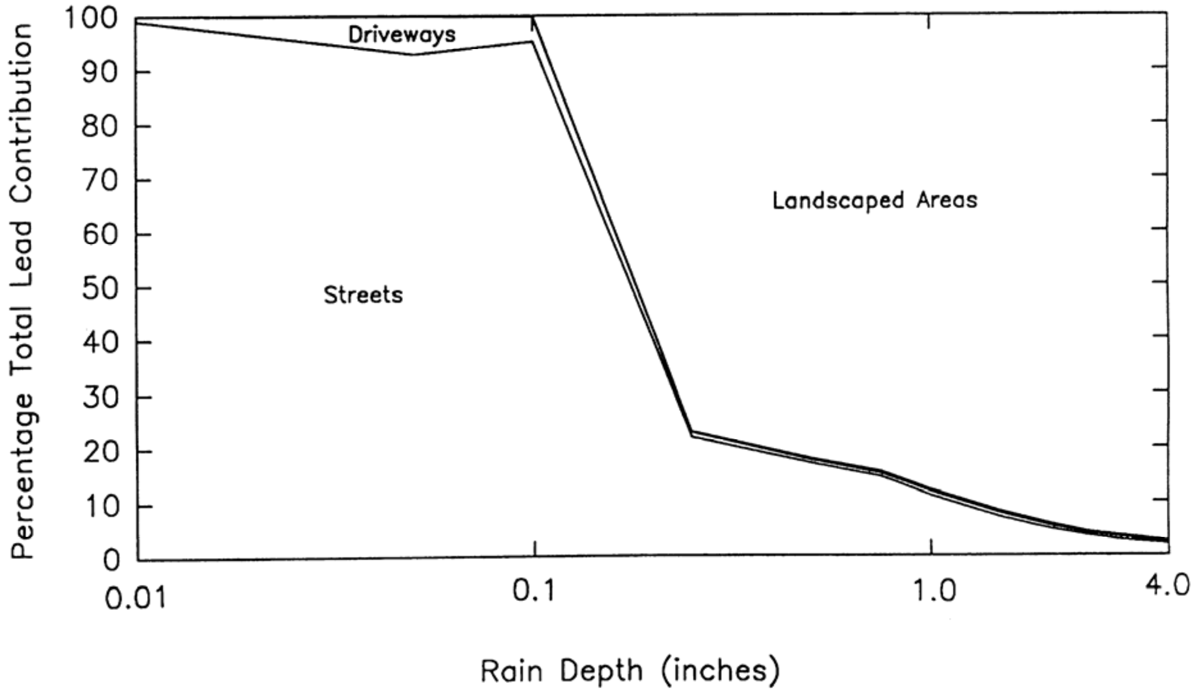


Figure 5-18 Total lead sources for example medium density residential area having clayey soils (Pitt and Voorhees 1995).

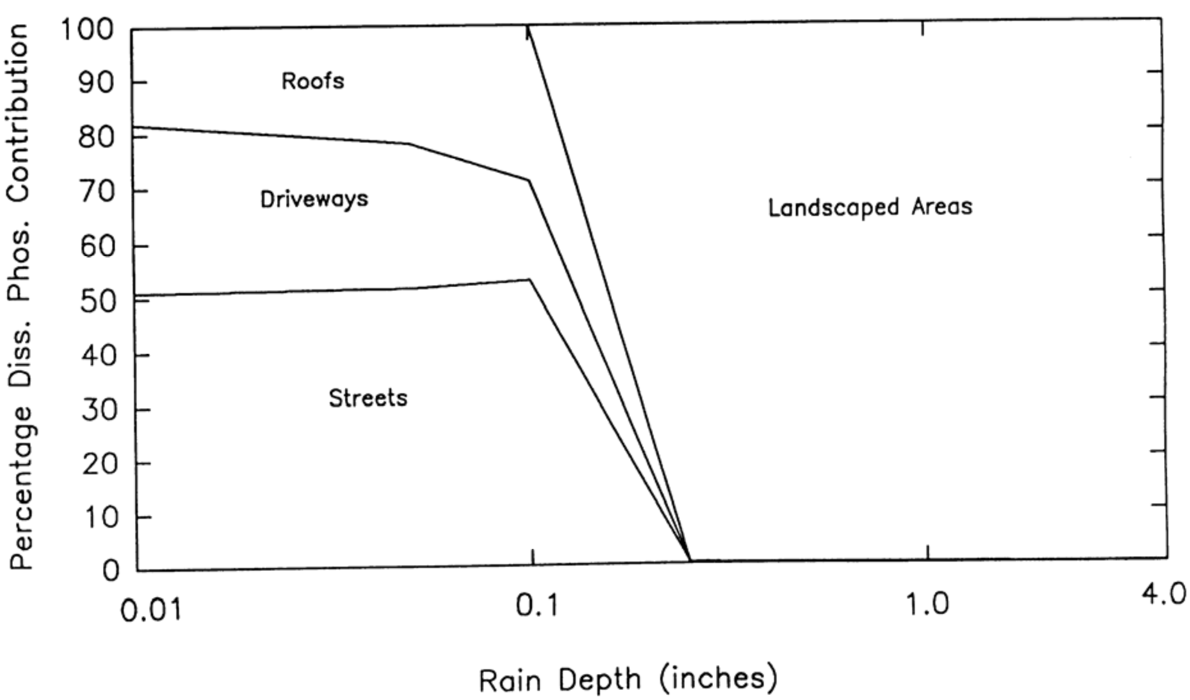


Figure 5-19 Dissolved phosphate sources for example medium density residential area having clayey soils (Pitt and Voorhees 1995).

combined were also evaluated, in addition to the combination of disconnecting some of the rooftops and the use of grass swales. Finally, all of the controls together were also examined.

The following list shows a general description of this hypothetical area:

- all curb and gutter drainage (in fair condition)
- 70% of roofs drain to landscaped areas
- 50% of driveways drain to lawns
- 90% of streets are intermediate texture (remaining are rough)
- no street cleaning
- no catchbasins

About one-half of the driveways currently drain to landscaped areas, while the other half drain directly to the pavement or the drainage system. Almost all of the streets are of intermediate texture, and about 10 percent are rough textured. As noted earlier, there currently is no street cleaning or catchbasin cleaning.

The level of catchbasin use that was investigated for this site included 950 ft^3 of total sump volume per 100 acres (typical for this land use), with a cost of about $50 per catchbasin cleaning. Typically, catch basins in this area could be cleaned about twice a year for a total annual cost of about $85 per acre of the watershed.

Street cleaning could also be used with a monthly cleaning effort for about $30 per year per watershed acre. Light parking and no parking restrictions during cleaning is assumed, and the cleaning cost is estimated to be $80 per curb mile.

Grass swale drainage was also investigated, assuming that swales could be used throughout the area, there could be 350 feet of swales per acre (typical for this land use), and the swales were 3.5 ft. wide. Because of the clayey soil conditions, an average infiltration rate of about 0.5 inch per hour was used in this analysis, based on many different double ring infiltrometer tests of typical soil conditions. Swales cost much less than conventional curb and gutter systems, but have an increased maintenance frequency. Again, the use of grass swales is appropriate for new development, but not for retrofitting in this area.

Roof disconnections could also be utilized as a control measure by directing all roof drains to landscaped areas. The objective would be to direct all the roof drains to landscaped areas. Since 70 percent of the roofs already drain to the landscaped areas, only 30 percent could be further disconnected, at a cost of about $125 per household. The estimated total annual cost would be about $10 per watershed acre.

An outfall wet detention pond suitable for 100 acres of this medium density residential area would have a wet pond surface of 0.5% of drainage area to provide about 90% suspended solids control. It would need 3 ft. of dead storage and live storage equal to runoff from 1.25” rain. A 90^{o} V notch weir and 5 ft. wide emergency spillway could be used. No seepage or evaporation was assumed. The total annual cost was estimated to be about $ 130 per watershed acre.

Table 5-6 summarizes the SLAMM results for runoff volume, suspended solids, filterable phosphate, and total lead for 100 acres of this medium density residential area. The only control practices evaluated that would reduce runoff volume are the grass swales and roof disconnections. All of the other control practices evaluated do not infiltrate stormwater. Table 5-6 also shows the total annual average volumetric runoff coefficient (Rv) for these different options. The base level of control has an annual flow-weighted Rv of about 0.3, while the use of swales would reduce the Rv to about 0.1. Only a small reduction of Rv (less than 10 percent) would be associated with complete roof disconnections compared to the existing situation because of the large amount of roof disconnections that already occur. The suspended solids analyses shows that catchbasin cleaning alone could result in about 14 percent suspended solids reductions. Street cleaning would have very little benefit, while the use of grass swales would reduce the suspended solids discharges by about 60 percent. Grass swales would have minimal effect on the

Table 5-6 SLAMM Predicted Runoff and Pollutant Discharge Conditions for Example[1] (Pitt and Voorhees 1995)

Birmingham 1976 rains: (112 rains, 55 in. total 0.01-3.84 in. each)	Runoff Volume annual ft3/acre	flow-wtg. Rv	CN range	Suspended Solids flow-wtg. mg/L	annual lbs/acre	Filterable Phosphate flow-wtg. µg/L	annual lbs/acre	Total Lead flow-wtg. µg/L	annual lbs/acre
Base (no controls)	59800	0.3	77-100	385	1430	157	0.58	543	2.0
Catchbasin cleaning	59800	0.3	77-100	331	1230	157	0.58	468	1.7
reduction (lbs or ft3)	0				200		0		0.29
reduction (%)	0			14	14	0	0	14	14
cost ($/lb or $/ft3)	N/A				0.43		N/A		293
($85/acre/yr)									
Street cleaning	59800	0.3	77-100	385	1430	157	0.58	543	2.0
reduction (lbs or ft3)	0				0		0		0.01
reduction (%)	0			0	0	0	0	0	0.49
cost ($/lb or $/ft3)	N/A				N/A		N/A		3000
($30/acre/yr)									
Grass swales	23300	0.12	63-100	380	554	151	0.22	513	0.75
reduction (lbs or ft3)	36500				876		0.36		1.28
reduction (%)	61			1	61	4	62	6	63
cost ($/lb or $/ft3)	minimal				minimal		minimal		minimal
($minimal/acre/yr)									
Roof disconnections	56000	0.28	76-100	410	1430	156	0.55	443	1.6
reduction (lbs or ft3)	3800				0		0.03		0.48
reduction (%)	6			-6	0	1	5	18	24
cost ($/lb or $/ft3)	0				N/A		333		21
($10/acre/yr)									
Wet detention pond	59800	0.3	77-100	49	185	157	0.58	69	0.26
reduction (lbs or ft3)	0				1250		0		1.8
reduction (%)	0			87	87	0	0	87	87
cost ($/lb or $/ft3)	N/A				0.10		N/A		73
($130/acre/yr)									
CB & street cleaning	59800	0.3	77-100	331	1230	157	0.58	468	1.7
reduction (lbs or ft3)	0				200		0		0.29
reduction (%)	0			14	14	0	0	14	14
cost ($/lb or $/ft3)	N/A				0.58		N/A		397
($115/acre/yr)									
Roof dis. & swales	20900	0.1	63-100	403	526	139	0.18	352	0.46
reduction (lbs or ft3)	38900				904		0.40		1.6
reduction (%)	65			-5	63	11	69	35	77
cost ($/lb or $/ft3)	0.00026				0.01		25		6.4
($10/acre/yr)									
All above controls	20900	0.1	63-100	42	55	139	0.18	36	0.05
reduction (lbs or ft3)	38900				1375		0.40		1.98
reduction (%)	65			89	96	11	69	93	97
cost ($/lb or $/ft3)	0.0066				0.19		638		129
($255/acre/yr)									

[1] Medium density residential area, developed in 1961-1980, with clayey soils (curbs & gutters); new development controls (not retro-fit)

reduction of suspended solids concentrations at the outfall (they are primarily an infiltration device, having very little filtering benefits). Wet detention ponds would remove about 90 percent of the mass and concentrations of suspended solids. Similar observations can be made for filterable phosphates and lead.

Figures 5-20 through 5-23 show the maximum percentage reductions in runoff volume and pollutants, along with associated unit removal costs. As an example, Figure 5-20 shows that roof disconnections would have a very small potential maximum benefit for runoff volume reduction and at a very high unit cost compared to the other practices. The use of grass swales could have about a 60 percent reduction at minimal cost. The use of roof disconnection plus swales would slightly increase the maximum benefit to about 65 percent, at a small unit cost. Obviously, the use of roof disconnections alone, or all controlled practices combined, are very inefficient for this example. For suspended solids control, catchbasin cleaning and street cleaning would have minimal benefit at high cost, while the use of grass swales would produce a substantial benefit at very small cost. However, if additional control is necessary, the use of wet detention ponds may be necessary at a higher cost. If close to 95 percent reduction of suspended solids were required, then all of the controls investigated could be used together, but at substantial cost.

SLAMM/SWMM Interface Program

Introduction

The purpose of the SLAMM-SWMM Interface Program (SSIP) is to allow the user to replace SWMM's RUNOFF Block with SLAMM. This allows SLAMM to provide the runoff and pollutant loads for input into the TRANSPORT or EXTRAN Blocks of SWMM, instead of using results from the RUNOFF Block. Using SLAMM better accounts for small storm processes and adds greater flexibility in evaluating source area flow and pollutant controls. The interface program manipulates the output from SLAMM so that it is acceptable for SWMM. The principal manipulation is to convert the event volumes and loads into event hydrographs and pollutographs.

The version of the SLAMM-SWMM Interface Program presented here is Version 1. 1. This version has not reached the full potential envisioned for the program. This is discussed later. It is assumed that the reader is familiar with both SLAMM and SWMM and has the appropriate documentation.

SSIP Version 1.0

An early version of the SLAMM-SWMM Integration Program was developed to work with SWMM Windows provided by the US Environmental Protection Agency (based on SWMM Version 4.3, USEPA, 1995). This was used to create SSIP Version 1.1, which is deigned for use with all SWMM 4 sub-versions.

SSIP Version 1.1

SSIP Version 1.1 takes hydrographs and pollutographs from SLAMM and partially prepares input hydrographs for use in the SWMM EXTRAN Block and input hydrographs and pollutographs for the SWMM TRANSPORT Block. *However, at this time SSIP has only been tested in the preparation of hydrographs for SWMM EXTRAN.*

SLAMM currently has the option of producing source area hydrographs and pollutographs over continuous periods. Each location is produced as a separate file. The format for these files is as follows:

- First Line = subcatchment number (defined in SLAMM)
- Second Line = labels for each column in "quotation marks", separated by commas
- Third Line = Values separated by commas, no spaces (e.g., time,flow,pollutant,pollutant,)
- NOTE: The time increments used in each file must be identical (e.g., 1, 1.5, 2, … must be the same for each file).

These files are converted into files appropriate for SWMM. However, at this time, the user must manually manipulate some of these converted files for actual use in SWMM. The SLAMM/SWMM Interface Program

Version 1.1 is Windows-based and is programmed in Visual Basic. A new version is currently being prepared that will further minimize the needed user manipulation.

How SSIP Works

1. SSIP goes through each SLAMM hydrograph/pollutograph file, one at a time, in the directory chosen by the user. These files have the extension *.hyd.

2. SSIP then creates the files for SWMM (*.hp1, *.hp2, and*.hp3 for TRANSPORT and *.hp4 for EXTRAN).

3. Next, it reads the second hydrograph/pollutograph file and appends the information to the first files that were created. This will be done for all files with the extension *.hyd. So it is important that only the files desired are located in the directory.

4. When there are no more SLAMM files left, the user gets a message that the file conversions are completed.

Interface Program Instructions

The instructions below are illustrated with a series of files provided with the disk that accompanies this report. These files are referred to throughout this section in order to illustrate the process for executing SSIP and creating useable hydrograph files for SWMM EXTRAN. (Recall that this is the only application of SSIP that has been tested to date.) All of the needed SLAMM and SSIE files are installed in a single directory when the files are installed (from the attached disks having zipped filed).

1 . The user begins by opening the file “Interface1.exe” provided on the disk. A series of dialog boxes will then appear. Instructions for each dialog box appear with that box. The dialog boxes are discussed below:

- A start-up box. This box starts the program.
- A file location box (to identify where the SLAMM files are and where the SWMM files are to be placed.) At this time, SSIP seems to work best if all file operations (including the execution of SIPP) are carried out under the same directory. Set the SLAMM file locator to the directory to which you placed the contents of the supplied disk (this is where the SLAMM files are located). For this application there are three files, associated with each of three locations for which SLAMM produced hydrographs and pollutographs. These three locations will be input to SWMM. Set the SWMM file locator to the same directory.
- A SWMM Block selection box (i.e. for which SWMM Block files are to be produced). The TRANSPORT option has not been tested. Use only the EXTRAN option at this time. Select the EXTRAN option.
- A “process complete” box informing the user that the SWMM files have been created.

2. Once the processing is complete, as many as four files (*.hp 1, *.hp2, and *.hp3 for TRANSPORT and *.hp4 for EXTRAN) will have been produced. These files need to be manually placed in a SWMM system input file produced by the user. (The term “system input file” is meant to describe the file that describes the drainage system.) An example system input file is included on the disk as “extrn001.run”. This file is associated with Example 1 in the SWMM EXTRAN Block users manual (Roesner, *et al*. 1988). Be sure it is on the directory you created on your hard drive.

The SWMM system input file will need to be modified before SWMM can be executed. For the most part, this requires the user to modify and then merge the file created by SSIP with the SWMM system input file. Open the file named “usehp001.hp4” with any text editor. (The “001” indicates that this is the first time a file was created. If you repeated this operation, a file called “usehp002.hp4” would be produced.) Then do the following:

- Remove the first line that simply says “3”.
- On the line labeled “K2”, replace the three alphanumeric labels (in quotes) with 82309, 80408, and 81009 (no quotes), respectively. These are the three locations in SWMM to which the SLAMM produced flows are being directed (see Example 1 in the SWMM EXTRAN users manual).

- Resave this file.

Open the example SWMM system input file “extrn001.run” with any text editor. Then do the following:

- Optional: change the value 1440 to some other appropriate value. This is the number of time steps. The number of time steps multiplied by the computational time step length (the value 20 to the right of the number of time steps), in seconds, must be equal to or shorter than the time represented by the flow history provided by SLAMM. In this case, the example SLAMM files covers 365 hours, or 1,314,000 seconds. The hydrograph time step is 2.5 minutes. (The computational time step and the flow time step do not have to be the same.)
- Replace the lines labeled “K3” with the file “usehp001.hp4”. Be sure that the “$ENDPROGRAM” line is the last line in the resulting file. The K3 lines in EXTRAN are the hydrographs to input to the sewer system, with each line representing a different point in time.
- Resave this file.

3. Execute SWMM with the modified “extrn001.run” file. You can follow this process with any sub-version of SWMM Version 4.

Limitations and Caveats
SSIP takes all the SLAMM files from the directory chosen by the user and converts them. If there are SLAMM files (i.e., those with the extension *.HYD) in the directory chosen by the user that are not to be included in the conversion, it is suggested that the user delete or move these files before running the Interface Program.

SSIP does not run on Windows NT because of file permissions. It is designed to run under Windows 95 or Windows 98. SSIP may work under other operating systems, but these have not been tested or supported.

Future Versions
Work is continuing on making SSIP much more user friendly and efficient. In its present form, the user is far too involved in file manipulation. Future versions will also transfer information through the more efficient and automated interface mechanisms found in SWMM (see Section 2 of the SWMM user's manual, Huber, *et al.* 1988) rather than through the user-prepared system input files. Location matching will also be part of SSIP (as opposed to the manual matching done now). These changes will make the interface effort much more seamless for the user.

References
Bachhuber, J.A. “A decision making approach for stormwater management measures: A case example in the City of Waukesha, Wisconsin.” *North American Water and Environment Congress*. American Society of Civil Engineers. Reston, VA. C-184-1. 1996.

Bannerman, R., K. Baun, M. Bohn, P.E. Hughes, and D.A. Graczyk. *Evaluation of Urban Nonpoint Source Pollution Management in Milwaukee County, Wisconsin*, Vol. I. Grant No. P005432-01-5, PB 84-114164. US Environmental Protection Agency, Water Planning Division, November 1983.

Bannerman, R.T., A.D. Legg, and S.R. Greb. *Quality of Wisconsin Stormwater, 1989-94*. U.S. Geological Survey. Open-file report 96-458. Madison, WI. 26 pgs. 1996.

Boehn, C.G. “The treatment train detention concept.” *North American Water and Environment Congress*. American Society of Civil Engineers. Reston, VA. C-111-2. 1996.

Chow, V.T., D.R. Maidment, and L.W. Mays, *Applied Hydrology,* McGraw-Hill, Inc., New York, 1989.

EPA (U.S. Environmental Protection Agency). *Final Report for the Nationwide Urban Runoff Program*. Water Planning Division, Washington, D.C., December 1983.

Haubner, S.M. and E.F. Joeres. “Using a GIS for estimating input parameters in urban stormwater quality modeling.” *Water Resources Bulletin*. Vol. 32, no. 6, pp. 1341 – 1351. December 1996.

Heaney, J.P., W.C. Huber, H. Sheikh, M.A. Medina, Jr., J.R. Doyle, W.A. Peltz, and J.E. Darling, *Urban Stormwater Management Modeling and Decision-Making*, EPA-670/2-75-022, U.S. Environmental Protection Agency, Cincinnati, Ohio, May, 1975.

Huber, W.C and R.E. Dickinson, *Storm Water Management Model, Version 4, User's Manual*, EPA-600/3-88-001a, U.S. Environmental Protection Agency, Athens, Georgia, 1988.
Huber W.C., J.P. Heaney, and B.A. Cunningham, *Storm Water Management Model (SWMM) Bibliography*, EPA-600/3-85-077, U.S. Environmental Protection Agency, Athens, Georgia, September, 1985.
Huber, W.C., J.P. Heaney, M.A. Medina, Jr., W.A. Peltz, H. Sheikh, and G.F. Smith, *Storm Water Management Model User's Manual--Version II*, EPA-670/2-75-017, U.S. Environmental Protection Agency, Cincinnati, Ohio, March, 1975.
Huber, W.C., J.P. Heaney, S.J. Nix, R.E. Dickinson, and D.J. Polmann, *Storm Water Management Model User's Manual, Version III*, EPA-600/2-84-109a, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1984.

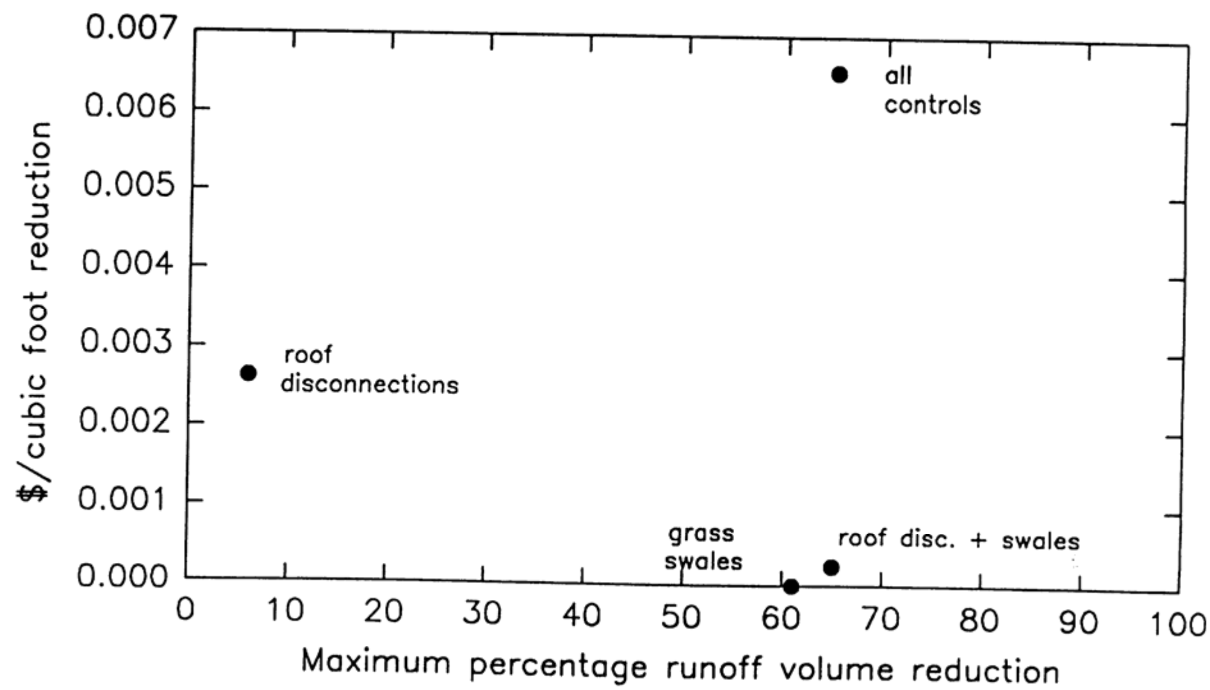


Figure 5-20. Cost-effectiveness data for runoff volume reduction benefits (Pitt and Voorhees 1995).

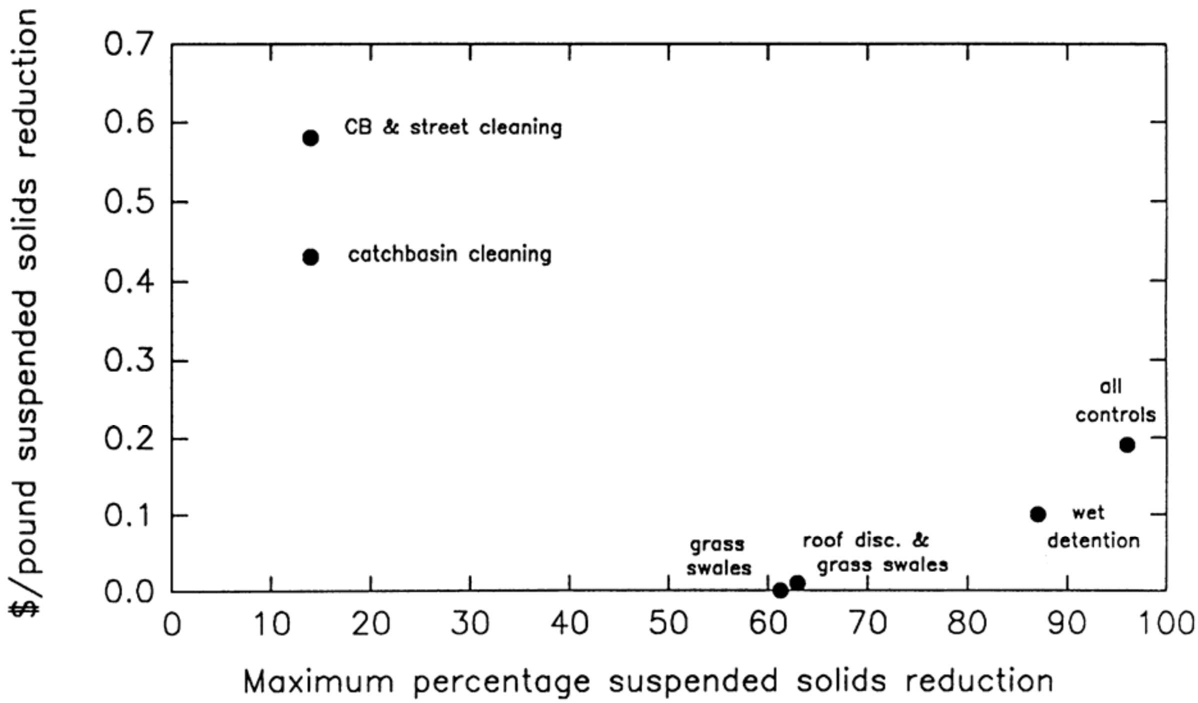


Figure 5-21. Cost-effectiveness data for suspended solids reduction benefits (Pitt and Voorhees 1995).

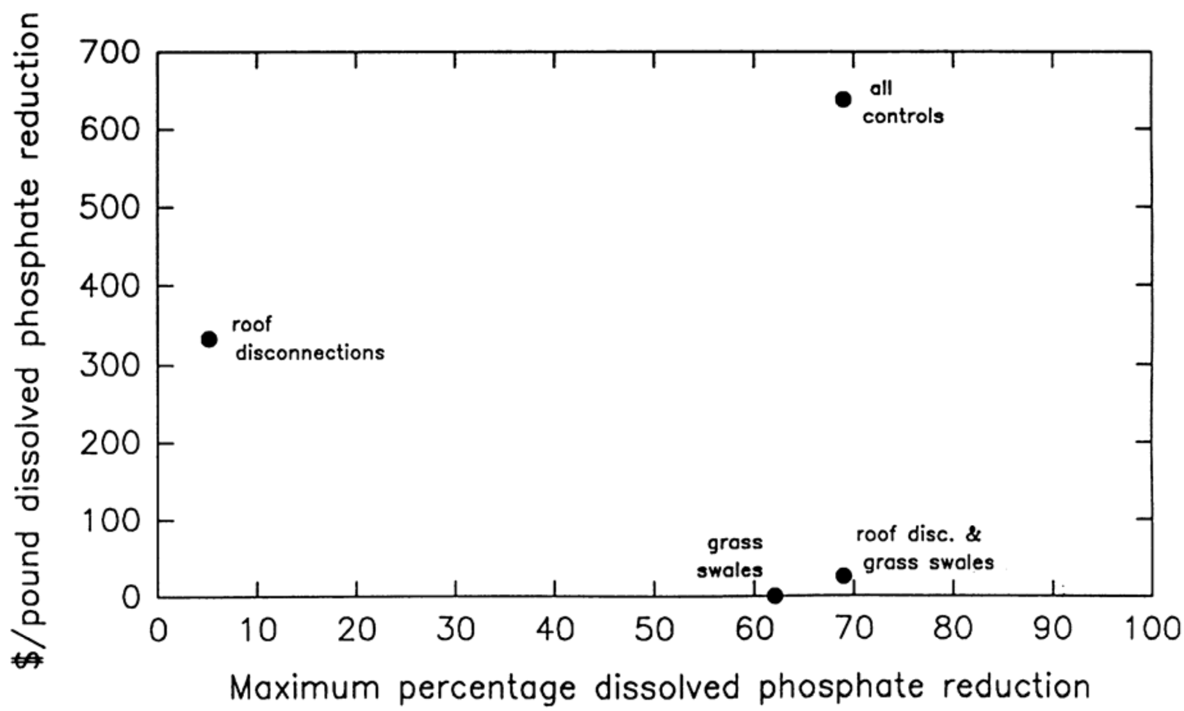


Figure 5-22. Cost-effectiveness data for dissolved phosphate reduction benefits (Pitt and Voorhees 1995).

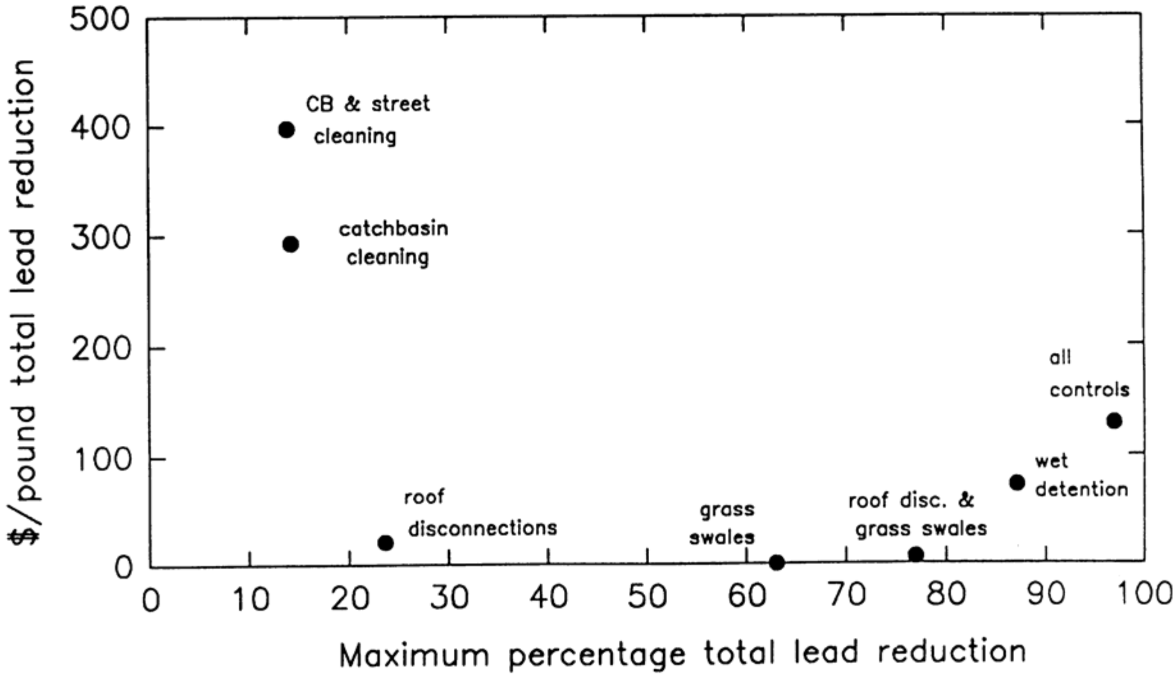


Figure 5-23. Cost-effectiveness data for total lead reduction benefits (Pitt and Voorhees 1995).

Kim, K., P.G. Thum, and J. Prey. “Urban non-point source pollution assessment using a geographical information system.” *Journal of Environmental Management*. Vol. 39., no. 39, pp. 157 – 170. 1993.

Kim, K. and S. Ventura. “Large-scale modeling of urban nonpoint source pollution using a geographical information system.” *Photogrammetric Engineering & Remote Sensing*. Vol. 59, no. 10, pp. 1539 – 1544. October 1993.

Legg, A.D., R.T. Bannerman, and J. Panuska. Variation in the Relation of Rainfall to Runoff from Residential Lawns in Madison, Wisconsin, July and August 1995. U.S. Geological Survey. Water-resources investigations report 96-4194. Madison, Wisconsin. 11 pgs. 1006.

McCuen, R.H. *Hydrologic Analysis and Design*. Prentice Hall. Englewood Cliffs, New Jersey. 1989.

Ontario Ministry of the Environment. *Humber River Water Quality Management Plan*, Toronto Area Watershed Management Strategy. Toronto, Ontario, 1986.

Metcalf and Eddy, Inc., University of Florida, and Water Resources Engineers, Inc., “Storm Water Management Model, Vols. I, II, III and IV,” EPA Reports 11024 DOC 07/71, 08/71, 09/71, 10/71, U.S. Environmental Protection Agency, Washington, D.C., 1971.

Nix, S.J., *Analysis of Storage/Release Systems in Urban Stormwater Quality Management*, Ph.D. Dissertation, University of Florida, Gainesville, Florida, 1982.

Nix, S.J., *Urban Stormwater Modeling and Simulation*, Lewis Publishers, Boca Raton, Florida, 1994.

Pitt, R. *Demonstration of Nonpoint Pollution Abatement Through Improved Street Cleaning Practices*. EPA-600/2-79-161, U.S. Environmental Protection Agency, Cincinnati, Ohio, August 1979.

Pitt, R. and M. Bozeman. *Sources of Urban Runoff Pollution and Its Effects on an Urban Creek*. EPA-600/S2-82-090, U.S. Environmental Protection Agency, Cincinnati, Ohio, December 1982.

Pitt, R. and G. Shawley. *A Demonstration of Non-Point Source Pollution Management on Castro Valley Creek*. Alameda County Flood Control and Water Conservation District (Hayward, CA) for the Nationwide Urban Runoff Program, U.S. Environmental Protection Agency, Water Planning Division, Washington, D.C., June 1982.

Pitt, R. Characterization, *Sources, and Control of Urban Runoff by Street and Sewerage Cleaning*. Contract No. R-80597012, U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, Ohio, 1984.

Pitt, R. and P. Bissonnette. *Bellevue Urban Runoff Program, Summary Report*. Storm and Surface Water Utility, Bellevue, Washington, November 1984.

Pitt, R. “Runoff controls in Wisconsin’s priority watersheds,” *Conference on Urban Runoff Quality - Impact and Quality Enhancement Technology*, Henniker, New Hampshire, Edited by B. Urbonas and L.A. Roesner, Proceedings published by the American Society of Civil Engineering, New York, June 1986.

Pitt, R. and J. McLean. *Toronto Area Watershed Management Strategy Study - Humber River Pilot Watershed Project*. Ontario Ministry of the Environment, Toronto, Ontario, June 1986.

Pitt, R. *Small Storm Flow and Particulate Washoff Contributions to Outfall Discharges*. Ph.D. dissertation, Department of Civil and Environmental Engineering, the University of Wisconsin - Madison, November 1987.

Pitt, R. “Effects of urban runoff on aquatic biota.” In: *Handbook of Ecotoxicology*. Edited by D. Hoffman. Lewis Publishers. 1984.

Pitt, R. and J. Voorhees. *DETPOND, A Water Quality Wet Detention Pond Program*. Dept. of Civil and Environmental Engineering. University of Alabama at Birmingham, Birmingham, Alabama. 1992.

Pitt, R. and J. Voorhees. “Source loading and management model (SLAMM).” *Seminar Publication: National Conference on Urban Runoff Management: Enhancing Urban Watershed Management at the Local, County, and State Levels*. March 30 – April 2, 1993. Center for Environmental Research Information, U.S. Environmental Protection Agency. EPA/625/R-95/003. Cincinnati. Ohio. pp. 225-243. April 1995.

Pitt, R. “Unique features of the Source Loading and Management Model (SLAMM).” In: *Advances in Stormwater and Water Quality Management Modeling*. Edited by William James. CHI publications, Ann Arbor Press. To be published in 1997.

Roesner, L.A., R.P. Shubinski, and J.A. Aldrich, *Storm Water Management Model User's Manual, Version III: Addendum I, EXTRAN*, EPA-600/2-84-109b, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1984.

Roesner, L.A., J.A. Aldrich, and R.E. Dickinson, *Storm Water Management Model, User's Manual, Version 4: Addendum I, EXTRAN*, EPA-600/3-88-001b, U.S. Environmental Protection Agency, Cincinnati, Ohio, August, 1988.

Sartor, J.D. and G.B. Boyd. *Water Pollution Aspects of Street Surface Contaminants*. EPA-R2-72-081, U.S. Environmental Protection Agency, November 1972.

SCS (U.S. Soil Conservation Service). *Urban Hydrology for Small Watersheds*. U.S. Dept. of Agriculture Tech. Release No. 55 (revised), June 1986.

Sutherland, R. *Portland Stormwater Quality using SIMPTM*. Draft report. OTAK, Inc. Lake Oswego, OR. 1993.

Thum, P.G., S.R. Pickett, B.J. Niemann, Jr., and S.J. Ventura. "LIS/GIS: Integrating nonpoint pollution assessment with land development planning." *Wisconsin Land Information Newsletter*. University of Wisconsin – Madison. Vol., no. 2, pp. 1 – 11. 1990.

Ventura, S.J. and K. Kim. "Modeling urban nonpoint source pollution with a geographical information system." *Water Resources Bulletin*. Vol. 29, no. 2, pp. 189 – 198. April 1993.

Viessman, Jr., W., G.L. Lewis, and J.W. Knapp, *Introduction to Hydrology*, Third Edition, Harper and Row, Publishers, Inc., New York, 1989.

Voorhees, J. *Stormwater Management Using Infiltrating Detention Ponds*. MSCE Thesis. Department of Civil and Environmental Engineering. Madison, Wisconsin. 1989.

Appendix A
The Integration of Water Quality and Drainage Design Objectives

Introduction

Different drainage design criteria and receiving water use objectives often require the examination of different types of rains for the design of urban drainage systems. These different (and often conflicting) objectives of a stormwater drainage system can be addressed by using distinct portions of the long-term rainfall record. Several historical examinations (including Heaney, *et al*. 1977) have also considered the need for the examination of a wide range of rain events for drainage design. However, the lack of efficient computer resources severely restricted long-term analyses in the past. Currently, computer resources are much more available and are capable of much more comprehensive investigations (Gregory and James 1996). In addition to having more efficient computational resources, it is also necessary to re-examine some of the fundamental urban hydrology modeling assumptions (Pitt 1987). Most of the urban hydrology methods currently used for drainage design have been successfully used for large "design" storms. Obviously, this approach (providing urban areas safe from excessive flooding and associated flood related damages) is the most critical objective of urban drainage. However, it is now possible (and legally required in many areas) to provide urban drainage systems that also minimizes other problems associated with urban stormwater. This broader set of urban drainage objectives requires a broader approach to drainage design, and the use of hydrology methods with different assumptions and simplifications.

Runoff volume is usually the most important hydrology parameter in water quality studies, while peak flow rate and time of concentration are usually the most important hydrologic parameters for flooding and drainage studies. The relationships between these different hydrologic parameters and rain parameters are significantly different for different classes of rains. Runoff models for water quality investigations should therefore be different than the runoff models for flooding and drainage investigations. Similarly, flooding and drainage investigations should normally not use a hydrology model developed for water quality investigations.

The importance of different areas in a watershed as pollutant sources is dependent on accurate hydrology predictions. One also need to know the variations of each source area's importance for different rains. Many control practice designs also depend on inflow hydrology. If one incorrectly predicts the sources of pollutants or flows, then one will not get expected stormwater control benefits. This appendix briefly describes a method to accurately predict the sources of urban runoff source flows during important small rains. This method is fundamental to the Source Loading and Management Model (SLAMM) that will be used in conjunction with the SWMM model.

Most existing stormwater models incorrectly predict flows associated with small rains in urban areas. This is important because common small storms are responsible for most of the annual urban runoff discharge quantities throughout North America (EPA 1983, Pitt 1987). Most existing urban runoff models originated from drainage and flooding evaluation procedures that emphasized very large rains (several inches in depth). These large storms only contribute very small portions of the annual average discharges. Obviously, the pollutant shock loadings and habitat destruction caused by a large storm may create significant receiving water use impairments, but a number of years will be available for recovery before another massive rain occurs. However, moderate storms, occurring several times a year, are responsible for the majority of the pollutant discharges. The effects caused by these frequent discharges are mostly chronic in nature (such as contaminated sediment and frequent high flow rates) and the interevent periods are not long enough to allow the receiving water conditions to recover (Pitt and Bozeman 1982).

Simplifying the assumptions concerning runoff losses for impervious and pervious areas for small rains has little significance on the accuracy of the predictions of runoff volumes for large rains. These same assumptions, however, cause dramatically large errors when predicting runoff associated with small rains, the rains of most importance for water pollutant discharges. The significance of small rains as important pollutant generators is then missed and controls are then designed for wrong storms and wrong source areas. The hydrology prediction method described here is a simplified procedure used to predict runoff volumes from individual homogeneous areas for a wide variety of rains. It requires knowledge of certain development characteristics of the urban area.

Rainfall and Runoff Characteristics for Urban Areas

Actual stormwater characteristics that can be used to evaluate design procedures are included in Appendix B. That appendix includes summaries of data obtained from the EPA's Nationwide Urban Runoff Program (EPA 1983), the EPA's Urban- Rainfall-Runoff-Quality Data Base (Heaney, *et al*. 1982), and from the Humber River portion of the Toronto Area Watershed Management Study (Pitt and McLean 1986). The Toronto area data were from two extensively monitored watersheds, a residential/commercial area and an industrial area. Most of the EPA's "Data Base" data presented in that appendix is from 2 locations in Broward County, FL; 1 site in Dade County, FL; 2 sites in Salt Lake City, UT; and 2 sites in Seattle, WA. Most of the data were obtained during the 1970s. These sites had the best representation of data of interest for these analyses and the sites were well described. Parameters examined included simultaneous rainfall and runoff depths, plus peak rain and flow rates. The following plots were prepared using this data:

- runoff depth versus rainfall,
- volumetric runoff coefficient (Rv) versus rainfall,
- NRCS curve number (CN) versus rainfall, and
- ratio of reported peak flow/peak rainfall versus rainfall.

In a similar manner, information from the EPA's NURP program (EPA 1983) was also investigated. A wider variety of information was collected during NURP, enabling additional relationships examining stormwater quality. That data is also presented in Appendix B and is a subset of data from the 28 cities involved in the NURP program. Most of the data is from 5 sites in Champaign, IL; 2 sites in Austin, TX; 5 sites in Irondequoit Bay, NY; 1 site in Rapid City, SD; plus additional observations from Tampa, FL, Winston Salem, NC, and Eugene and Springfield, OR. Most of this data were obtained during the early 1980s and was subjected to rigorous quality control. Besides the four plots listed above, the following plots were also constructed examining potential water quality concentration relationships:

- total suspended solids concentration versus rainfall,
- COD concentration versus rainfall,
- phosphorous concentration versus rainfall,
- lead concentration versus rainfall,
- peak flow/peak rain versus rainfall, and
- peak flow rate versus peak rain intensity.

These plots were constructed to examine stormwater design methods using actual monitored data. These data can be used to examine many typical assumptions concerning stormwater drainage design and stormwater quality. Figures A-1 through A-9 show example plots for the John South Basin, a single family residential area, monitored during the EPA's NURP project in Champaign-Urbana, IL. The basic rainfall versus runoff plots (Figure A-1) were made to indicate the smoothness of this basic relationship. A large scatter instead of a smooth curve may indicate measurement errors or uneven rainfalls over the catchment, or highly variable infiltration characteristics (due to changing soil moisture before the different rains). As shown on these plots, the runoff depth increases with increasing rain. However, several plots do show substantial scatter, mostly for sites having relatively small runoff yields. In addition, in some cases, more runoff was observed than could be accounted for by the rain. Errors in these measurements may be significant and would vary for the different sites. The senior authors of this report were involved in several of the monitoring projects that are included in these analyses, and also served on EPA technical committees overseeing others. In addition, we have many years experience in monitoring these parameters in many locations and recognize many of the past problems and current attempts to correct them. The following list therefore shows possible measurement errors that may have affected this data:

- variable rainfall over a large test catchment that was not well represented by enough rain gages (Although several of the test catchments had multiple rain gages, most did not, and few were probably frequently re-calibrated in the field.),
- poorly calibrated monitoring equipment (Many flow monitoring equipment relied on using the Manning's equation in pipes, with assumed roughness coefficients, without independent calibration, while other monitoring locations used calibrated insert weirs.)
- transcription errors (Many of these older monitoring activities required manual transfer from field equipment recorders to computers for analysis. In many cases, obvious "factor of ten" errors were made, for example.),
- newly developed equipment that has not been adequately tested, and
- difficult locations in the sewerage or streams that were monitored.

It is expected that the measurement errors were probably no less than about 25% during these monitoring activities. The effects of actual influencing factors can only be determined after the effects of these errors are considered.

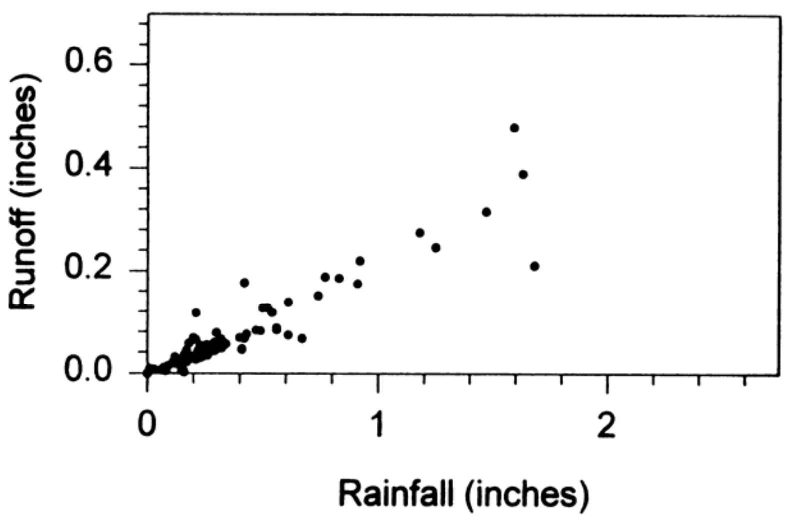


Figure A-1. Runoff vs. rainfall.

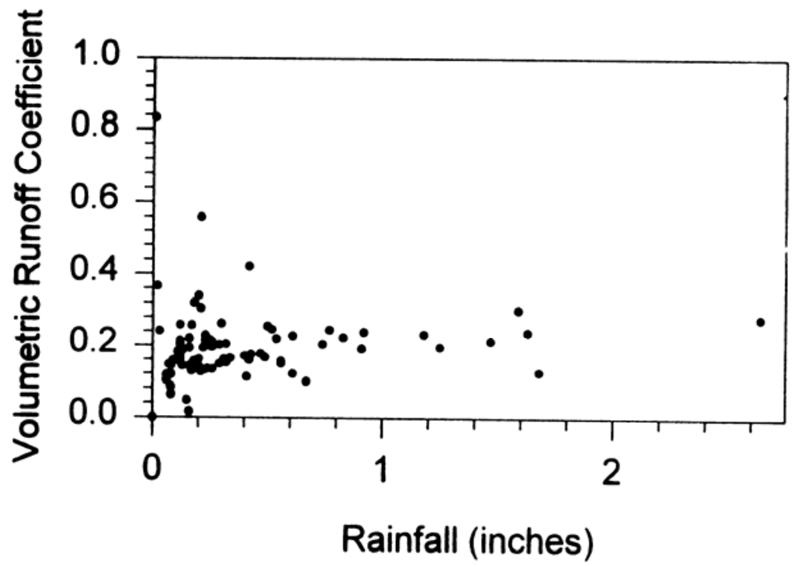


Figure A-2. Rv vs. rainfall.

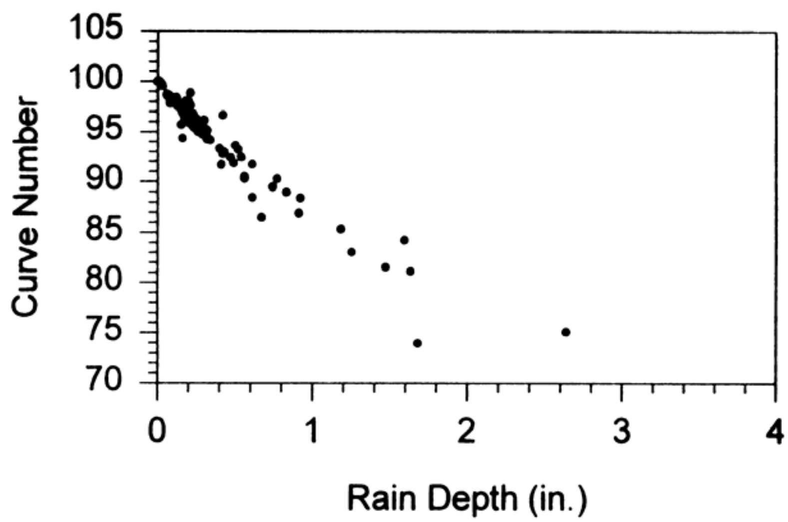


Figure A-3. Curve number vs. rain depth.

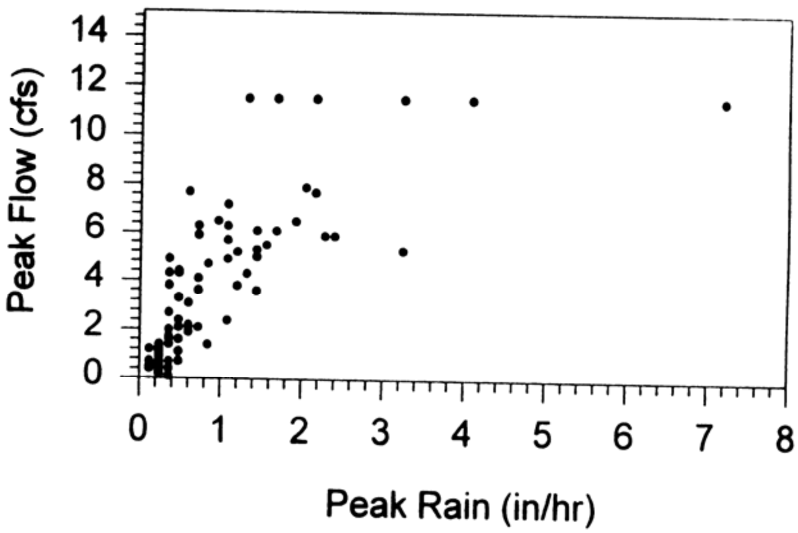


Figure A-4. Peak flow vs. peak rain.

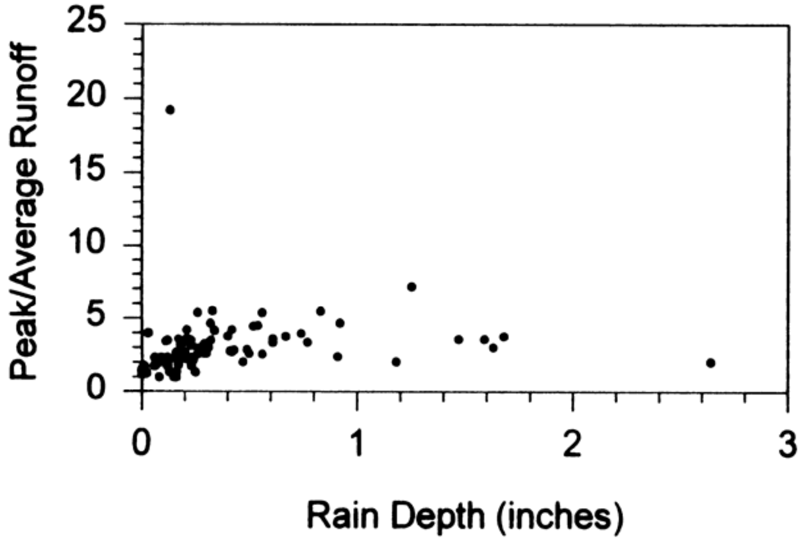


Figure A-5. Peak/avg. runoff vs. rain depth.

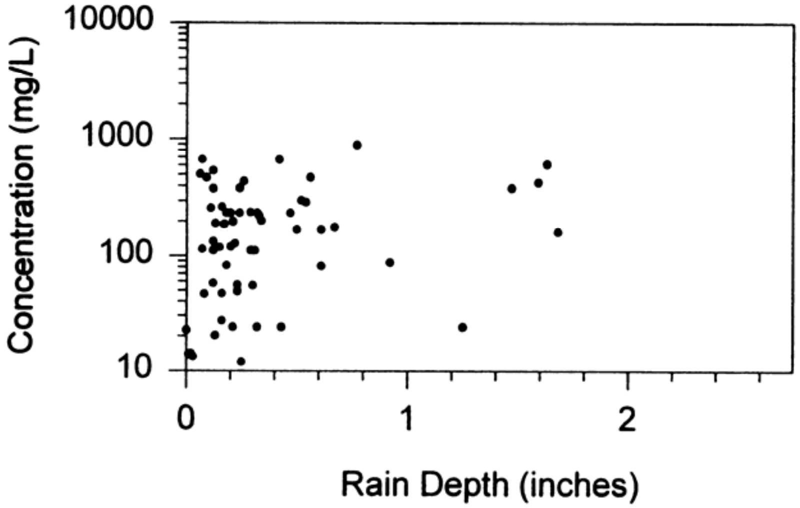


Figure A-6. SS vs. rain depth.

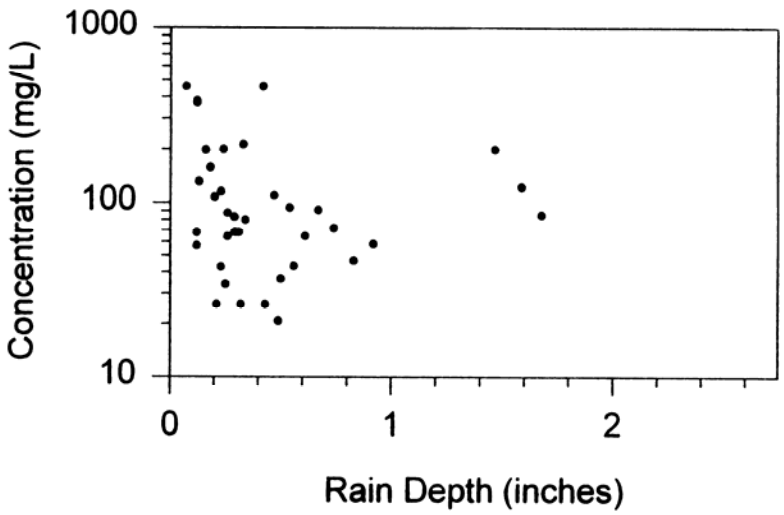


Figure A-7. COD vs. rain depth.

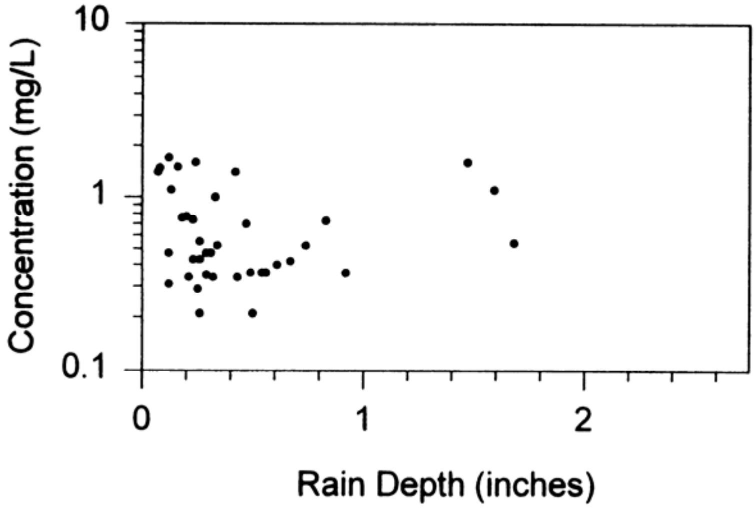


Figure A-8. Phosphorus vs. rain depth.

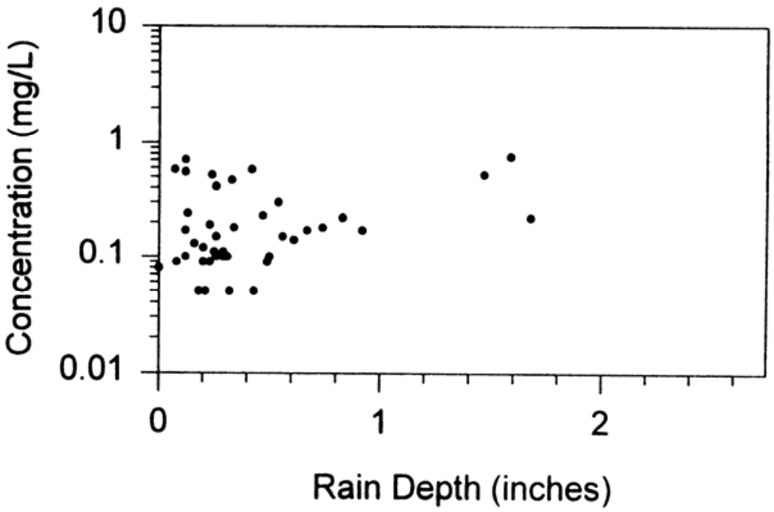


Figure A-9. Lead vs. rain depth.

The plots of rainfall versus the volumetric runoff coefficient plot (Figure A-2) shows the ratio of the runoff volume, expressed as depth for the watershed, to rain depth, or the Rv, for different rain depths. This is a related plot to the one described above. If the Rv ratio was constant for all events, the rainfall versus runoff depth plot described above, would indicate a straight diagonal line, with no scatter. It is typically assumed that the above described relationship would indicate increasing Rv values as the rain depth increased. Figure A-1 shows a slight upwards curve with increasing rain depths. This is due to the rainfall losses making up smaller and smaller portions of the total rainfall as the rainfall increases, with a larger fraction of the rainfall occurring as runoff. The plot of Rv versus rainfall (Figure A-2) would therefore show an increasing trend with increasing rain depth. In most cases, the plots of actual data indicate a large (random?) scatter, making the identification of a trend problematic. The use of a constant Rv for all rains may also be a problem because of the large scatter. In many cases, the long-term average Rv for a residential area may be close to the typically used value. In Figure A-2, the values appear to center about 0.2 (somewhat smaller than the typically used value of about 0.3 for medium density residential areas), but the observed Rv values may range from lows of less than 0.04 to highs of greater than 0.5, especially for the smallest rains. The small rains probably have the greatest measurement errors, as the rainfall is much more variable for small rains than for larger rains, plus very low flows are difficult to accurately measure. Obviously, understanding what may be causing this scatter is of great interest, but is difficult because of measurement errors masking trends that may be present. In many cases, using a probability distribution to describe this variation may be the best approach.

Figure A-3 is a plot of the NRCS curve number (CN) versus rainfall depth (SCS 1986). The NRCS assumes that the CN is constant for all rain depths for a specific site. However, they specify several limitations, including:

- the CN method is less accurate when the runoff is less than 0.5 inch. It is suggested that an independent procedure be used for confirmation,
- the CN needs to be modified according to antecedent conditions, especially soil moisture before an event, and
- the effects of impervious modifications (especially if they are not directly connected to the drainage path) needs to be reflected in the CN.

Few of these warnings are considered by most storm drainage designers, or by users of NRCS CN procedures for stormwater quality analyses. Figure A-3 shows the typical pattern obtained when plotting CN against rain depth. The CN for small rain depths is always very large (approaching 100), then it decreases as the rain depth increases. At some point, the observed CN values equal the NRCS published recommended CN. During rains smaller than this matching point, the actual CN is greater than the NRCS CN. Predicted runoff depths would therefore be much less than the observed depths during these rains. Very large differences in runoff depths are associated with small differences in CN values, making this variation very important.

One of the other plot types presented in Appendix B shows the observed peak runoff flow rate versus the peak rain intensity (Figure A-4). If the averaging period for the peak flows and peak rain intensities were close to the catchment time of concentration (t_c), the slope of this relationship would be comparable to the Rational coefficient (C). The averaging times for the peak values probably ranged from 5 minutes to 1 hour for the different projects. Unfortunately, this averaging time period was rarely specified in the data documentation. Most urban area t_c values probably range from about 5 to 15 minutes. As indicated in this figure, the relationship between these two parameters shows a general upward trend, but it would be difficult to fit a statistically valid straight line through the data. As noted above for the other two drainage design procedures, actual real-world variations (coupled to measurement errors) add a lot of variation to the predicted runoff flow and volume estimates. Most drainage designers do not consider the actual variations that may occur.

Figure A-5 shows an example plot of the ratio of the peak runoff flow rate to the average runoff flow rate versus rain depth. These values can be used to help describe the shape of simple urban area hydrographs. If the hydrograph can be represented by a simple triangular hydrograph, then the peak flow to average flow ratio must be close to 2. As shown on these figures, this ratio is typically substantially larger than 2 (it can never be less than 1 obviously), indicating the need to use a somewhat more sophisticated hydrograph shape (such as a double triangular hydrograph that can consider greater flows). These plots indicate if this ratio can be predicted as a function of rain depth. In most cases, values close to 2 are seen for the smallest rains, but they ratio increases to 5, or more, fairly quickly, but with much variability.

Appendix B also contains several plots for each NURP site showing stormwater concentrations versus rainfall depth. Example plots for total suspended solids, COD, phosphorous, and lead are shown on Figures A-6 through A-9. It is commonly assumed that runoff pollutant concentrations are high for small rains (and at the beginning of all rains) and then taper off (the “first-flush” effect). As indicated on these plots, concentration has a generally random pattern. In many cases, the highest concentrations observed will occur for small events, but there is a large variation in observed concentrations at all rain depths. The upper limits of observed concentrations may show a declining curve with increasing rain depths, but the concentrations may best be described with random probability distributions. Analyses of concentrations versus antecedent dry periods can reduce some of this variability, as can analyses of runoff concentrations from isolated source areas.

Small Storm Hydrology

Stormwater Receiving Water Problems

Reviews of numerous urban receiving water studies from throughout the U.S. have identified the following diverse list of receiving water problems that may be caused by stormwater (Pitt 1995):

- Sedimentation damage in stormwater conveyance systems and in receiving waters.
- Nuisance algae growths from nutrient discharges into quiescent waters.
- Inedible fish and undrinkable water caused by toxic pollutant discharges.
- Shifts to less sensitive aquatic organisms caused by contaminated sediments and habitat destruction.
- Property damage from increased drainage system failures.
- Swimming beach closures from pathogenic microorganisms.
- Water quality violations, especially for bacteria and total recoverable heavy metals.

The first four problem areas are mostly associated with slug (mass) discharges (not instantaneous concentrations or rates), while the last three are mostly associated with instantaneous concentrations and high flow rates.

In order to predict receiving water problems caused by stormwater, accurate flow estimates and pollutant mass discharges must be known. Knowing where the potentially problem pollutants originate in the watershed is also valuable in order to select appropriate stormwater control candidates. Accurate knowledge of runoff volumes during different storms has been shown to be necessary when predicting pollutant discharges.

Typical Problems with Assumptions Commonly Used in Urban Hydrology Analyses

Most of the Annual Rain is Associated With Many Small Individual Events

This discussion reviews actual monitored rainfall and runoff distributions for Milwaukee, WI (data from Bannerman, *et al*. 1983), and examines long-term rainfall histories and predicted runoff from 24 locations throughout the U.S. The Milwaukee observations show that southeastern Wisconsin rainfall distributions can be divided into the following categories, with possible management approaches relevant for each category of rain:

- Common rains having relatively low pollutant discharges are associated with rains less than about 0.5 in. (12 mm) in depth. These are key rains when runoff-associated water quality violations, such as for bacteria, are of concern. In most areas, runoff from these rains should be totally captured and either re-used for on-site beneficial uses or infiltrated in upland areas. For most areas, the runoff from these rains can be relatively easily removed from the surface drainage system.

- Rains between 0.5 and 1.5 in. (12 and 38 mm) are responsible for about 75% of the runoff pollutant discharges and are key rains when addressing mass pollutant discharges. The small rains in this category can also be removed from the drainage system and the runoff re-used on site for beneficial uses or infiltrated to replenish the lost groundwater infiltration associated with urbanization. The runoff from the larger rains should be treated to prevent pollutant discharges from entering the receiving waters.

- Rains greater than 1.5 in. (38 mm) are associated with drainage design and are only responsible for relatively small portions of the annual pollutant discharges. Typical storm drainage design events fall in the upper portion of this category. Extensive pollution control designed for these events would be very costly, especially considering the relatively small portion of the annual runoff associated with the events. However, discharge rate reductions are important to reduce habitat problems in the receiving waters. The infiltration and other treatment controls used to handle the smaller storms in the above categories would have some benefit in reducing pollutant discharges during these larger, rarer storms.

- In addition, extremely large rains also infrequently occur that exceed the capacity of the drainage system and cause local flooding. Two of these extreme events were monitored in Milwaukee during the Nationwide Urban Runoff Program (NURP) project (EPA 1983). These storms, while very destructive, are sufficiently rare that the resulting environmental problems do not justify the massive stormwater quality controls that would be necessary for their reduction. The problem during these events is massive property damage and possible loss of life. These rains typically greatly exceed the capacities of the storm drainage systems, causing extensive flooding. It is critical that these excessive flows be conveyed in “secondary” drainage systems. These secondary systems would normally be graded large depressions between buildings that would direct the water away from the buildings and critical transportation routes and to possible infrequent/temporary detention areas (such as large playing fields or parking lots). Because these events are so rare, institutional memory often fails and development is allowed in areas that are not indicated on conventional flood maps, but would suffer critical flood damage.

Obviously, the critical values defining these rain categories are highly dependent on local rain and development conditions. Computer modeling analyses from several representative urban locations from throughout the U.S. are presented in this paper. These modeled plots indicate how these rainfall and runoff probability distributions can be used for more effective storm drainage design in the future. In all cases, better integration of stormwater quality and drainage design objectives will require the use of long-term continuous simulations of alternative drainage designs in conjunction with upland and end-of-pipe stormwater quality controls. The complexity of most receiving water quality problems prevents a simple analysis. The use of simple design storms, which was a major breakthrough in effective drainage design more than 100 years ago, is not adequate when receiving water quality issues must also be addressed.

This discussion also reviews typical urban hydrology methods and discusses common problems in their use in predicting flows from these important small and moderate sized storms. A general model is then described, and validation data presented, showing better runoff volume predictions possible for a wide range of rain conditions.

Figure A-10 includes cumulative probability density functions (CDFs) of measured rain and runoff distributions for Milwaukee during the 1981 NURP monitored rain year (data from Bannerman, *et al*. 1983). CDFs are used for plotting because they clearly show the ranges of rain depths responsible for most of the runoff. Rains between 0.05 and 5 in. were monitored during this period, with two very large events (greater than 3 inches) occurred during this monitoring period which greatly distort these curves, compared to typical rain years. The following observations are evident:

- The median rain depth was about 0.3 in.
- 66% of all Milwaukee rains are less than 0.5 in. in depth.
- For medium density residential areas, 50% of runoff was associated with rains less than 0.75 in.
- A 100-yr., 24-hr rain of 5.6 in. for Milwaukee could produce about 15% of the typical annual runoff volume, but it only contributes about 0.15% of the average annual runoff volume, when amortized over 100 yrs.
- Similarly, a 25-yr., 24-hr rain of 4.4 in. for Milwaukee could produce about 12.5% of the typical annual runoff volume, but it only contributes about 0.5% of the average annual runoff volume, when amortized over 25 yrs.

Figure A-11 shows CDFs of measured Milwaukee pollutant loads associated with different rain depths for a medium density residential area. Suspended solids, COD, lead, and phosphate loads are seen to closely follow the runoff volume CDF shown in Figure A-10, as expected. Since load is the product of concentration and runoff volume, some of the high correlation shown between load and rain depth is obviously spurious. However, these overlays illustrate the range of rains associated with the greatest pollutant discharges.

The monitored rainfall and runoff distributions for Milwaukee show the following distinct rain categories:

• <0.5 inch. These rains account for most of the events, but little of the runoff volume, and are therefore easiest to control. They produce much less pollutant mass discharges and probably have less receiving water effects than other rains. However, the runoff pollutant concentrations likely exceed regulatory standards for several categories of critical pollutants, especially bacteria and some total recoverable metals. They also cause large numbers of overflow events in uncontrolled combined sewers. These rains are very common, occurring once or twice a week (accounting for about 60% of the total rainfall events and about 45% of the total runoff events that occurred), but they only account for about 20% of the annual runoff and pollutant discharges. Rains less than about 0.05 inches did not produce noticeable runoff.

• 0.5 to 1.5 inches. These rains account for the majority of the runoff volume (about 50% of the annual volume for this Milwaukee example) and produce moderate to high flows. They account for about 35% of the annual rain events, and about 20% of the annual runoff events. These rains occur on the average about every two weeks during the spring to fall seasons and subject the receiving waters to frequent high pollutant loads and moderate to high flows.

• 1.5 to 3 inches. These rains produce the most damaging flows, from a habitat destruction standpoint, and occur every several months (at least once or twice a year). These recurring high flows, which were historically associated with much less frequent rains, establish the energy gradient of the stream and cause unstable streambanks. Only about 2 percent of the rains are in this category and they are responsible for about 10 percent of the annual runoff and pollutant discharges.

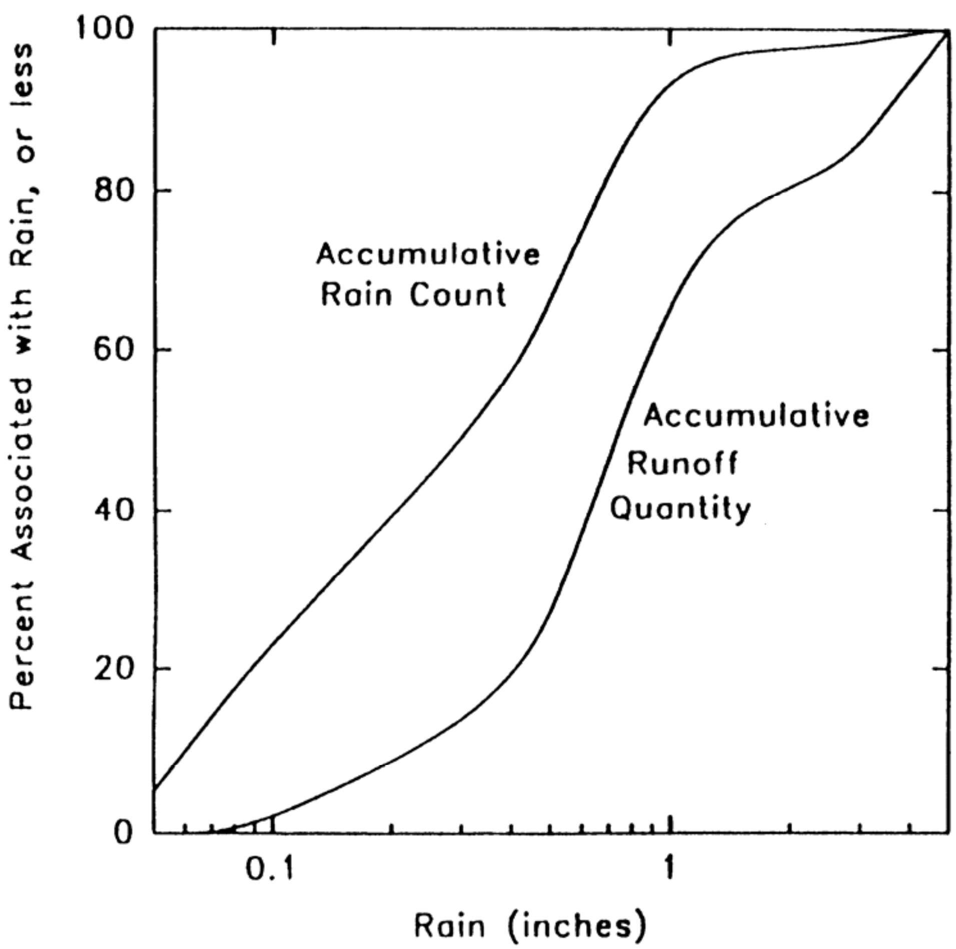


Figure A-10. Milwaukee rain and runoff distributions.

• >3 inches. This category is rarely represented in field studies due to the rarity of these large events and the typically short duration of most field observations. The smallest rains in this category are included in design storms used for drainage systems in Milwaukee. These rains occur only rarely (once every several years to once every several decades, or less frequently) and produce extremely large flows. The 3-year monitoring period during the Milwaukee NURP program (1980 through 1983) was unusual in that two of these events occurred. Less than 2 percent of the rains were in this category (typically <<1% would be), and they produced about 15% of the annual runoff quantity and pollutant discharges. During a "normal" period, these rains would only produce a very small fraction of the annual average discharges. However, when they do occur, great property and receiving water damage results. The receiving water damage (mostly associated with habitat destruction, sediment scouring, and the flushing of organisms great distances downstream and out of the system) can conceivably naturally recover to before-storm conditions within a few years.

These rainfall and pollutant mass distributions are not unique for Milwaukee. Appendix B of this report contains many examples of similar plots of monitored rainfall, runoff, and pollutant mass distributions for other NURP projects from throughout the country (including 5 sites in Champaign, IL; 2 sites in Austin, TX; 5 sites in Irondequoit Bay, NY; 1 site in Rapid City, SD; plus additional observations from Tampa, FL, Winston Salem, NC, and Eugene and Springfield, OR).

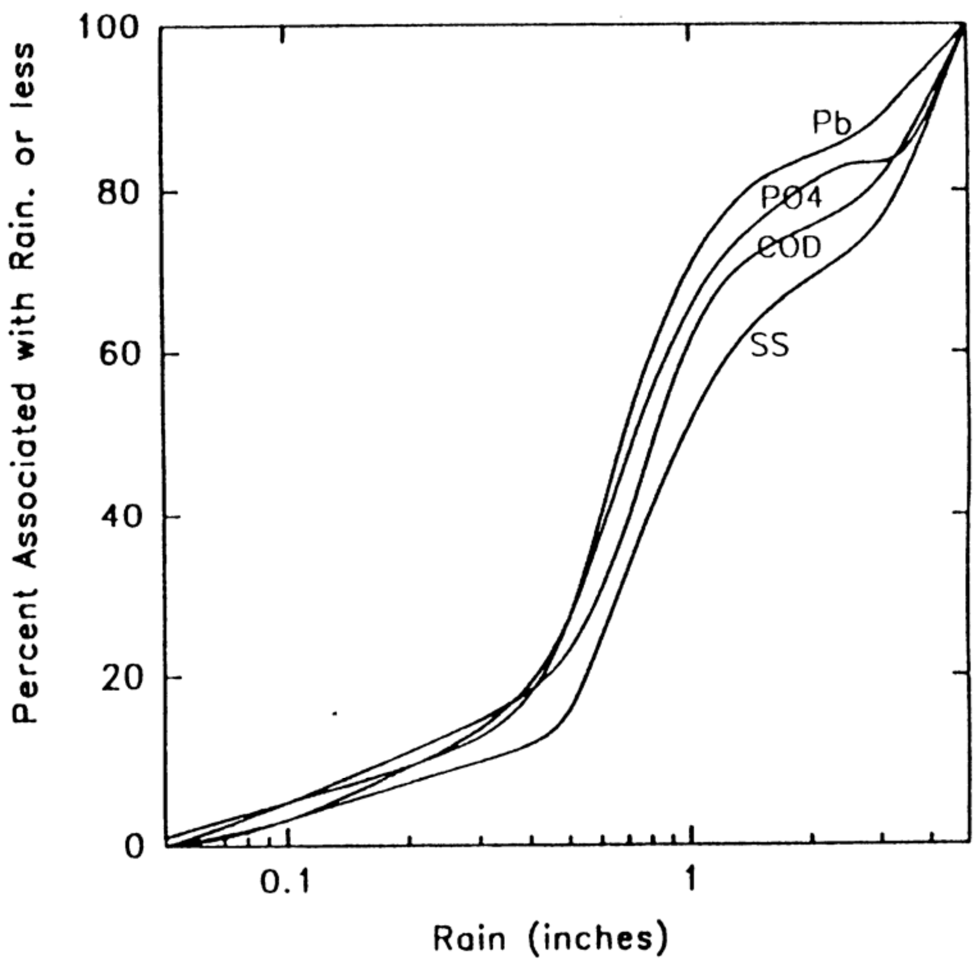


Figure A-11. Milwaukee pollutant discharge distributions.

In addition, long-term continuous simulations were made using SLAMM (incorporating the small storm hydrology components described in this report section) for 22 representative locations from throughout the U.S. (Figure A-12). These locations represent most of the major river basins and much of the rainfall variations in the country. These analyses are only intended to show the importance of these smaller rains for many different regions and conditions. They are not intended to be used for design purposes. As noted earlier, the recommended approach for design is to continuously model long rain records for site specific conditions. These locally derived runoff distributions, reflecting site conditions and actual rains, can then used for evaluating alternative drainage and water quality designs.

These simulations were based on 5 to 10 years of rainfall records, usually containing about 500 individual rains. The rainfall records were from certified NOAA weather stations and were obtained from CD-ROMs distributed by EarthInfo of Boulder, CO. Hourly rainfall depths for the indicated periods were downloaded from the CD-ROMs into an Excel spreadsheet. The files were slightly modified (by eliminating the daily total rainfall column) and saved as a comma delineated file. This file was then read by an utility program included in the SLAMM package. This rainfall file utility combined adjacent hourly rainfall values into individual rains, based on user selections (at least 6 hrs of no rain was used to separate adjacent rain events and all rain depths were used, with the exception of the “trace” values). These rain files for each city were then used in SLAMM for typical medium density and strip commercial developments. The outputs of these computer runs were then plotted as shown on Figure A-13.

Figure A-12. U.S. major river basins and modeled cities.

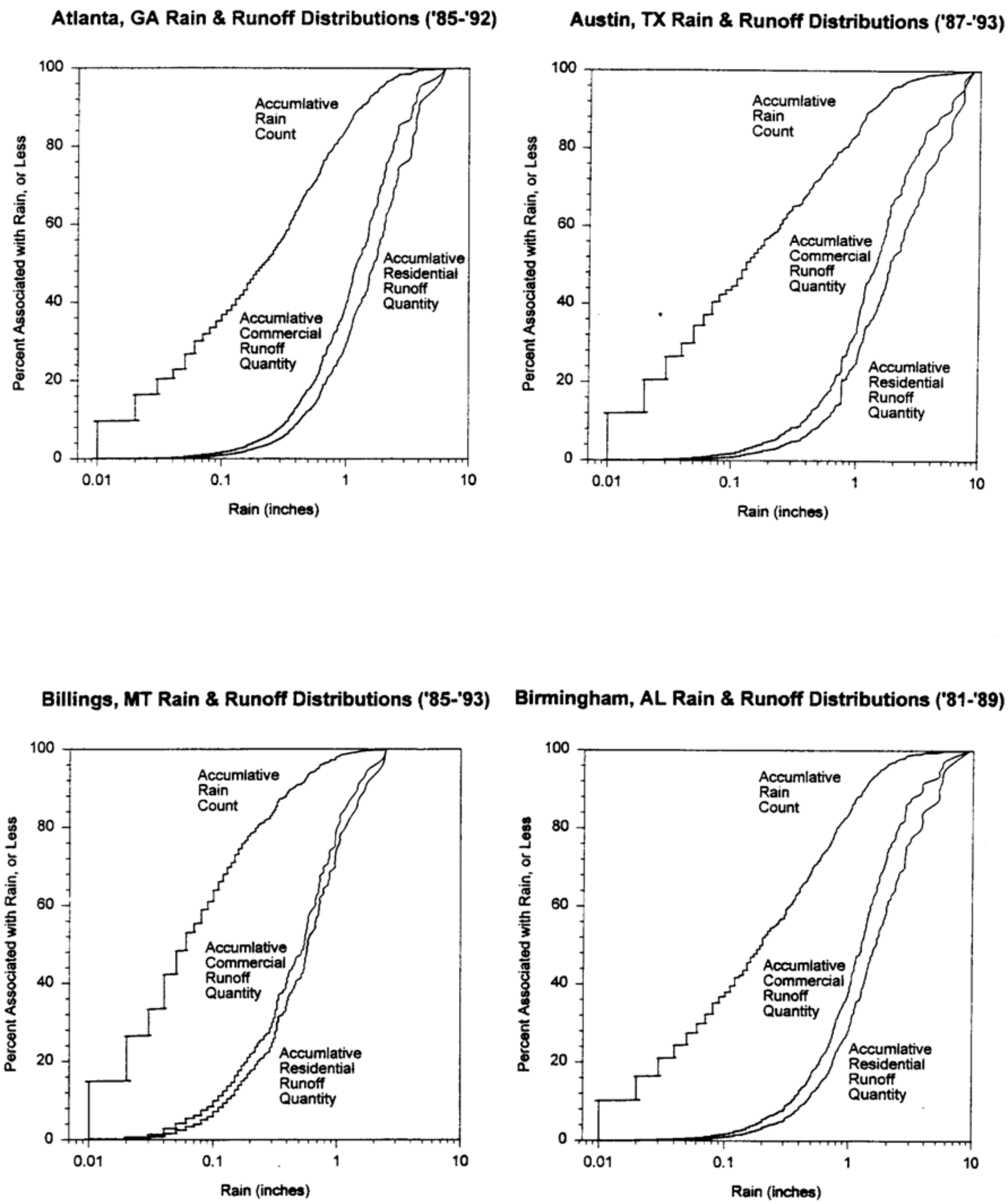


Figure A-13a. Modeled rain, runoff, and pollutant distributions.

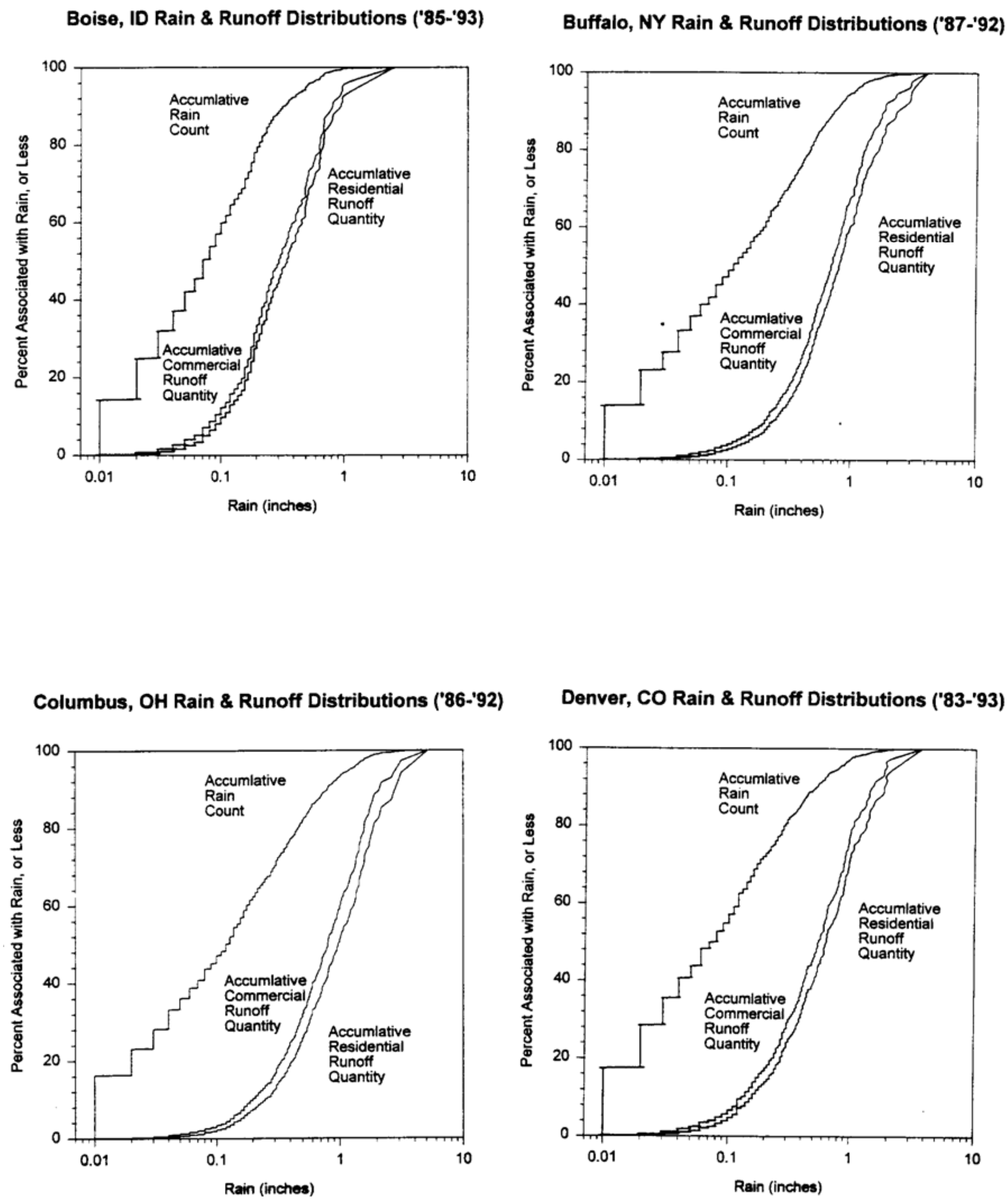
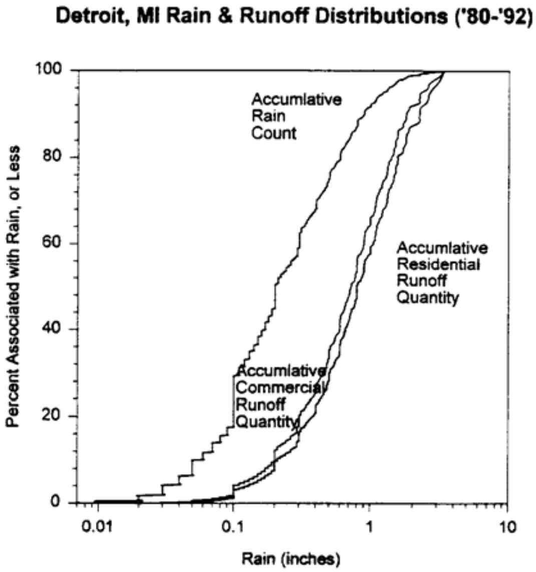
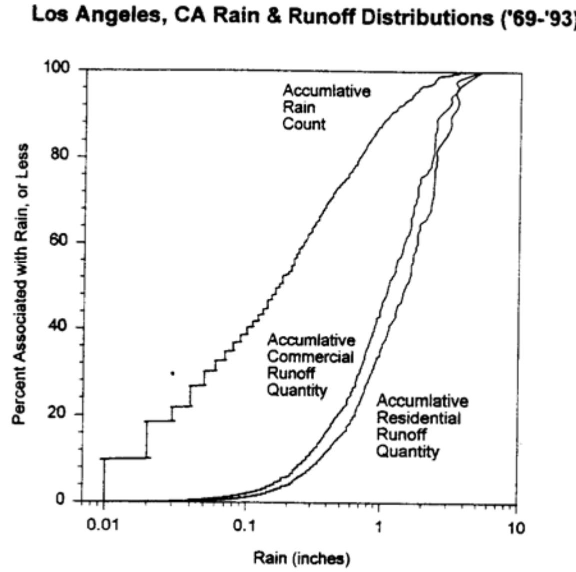
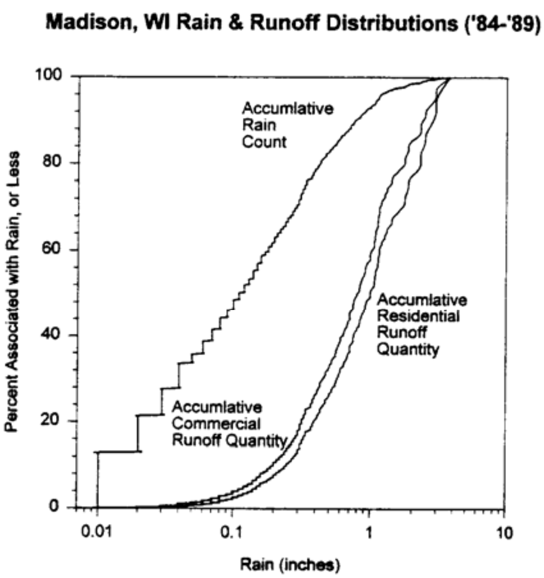


Figure A-13b. Modeled rain, runoff, and pollutant distributions (cont.).







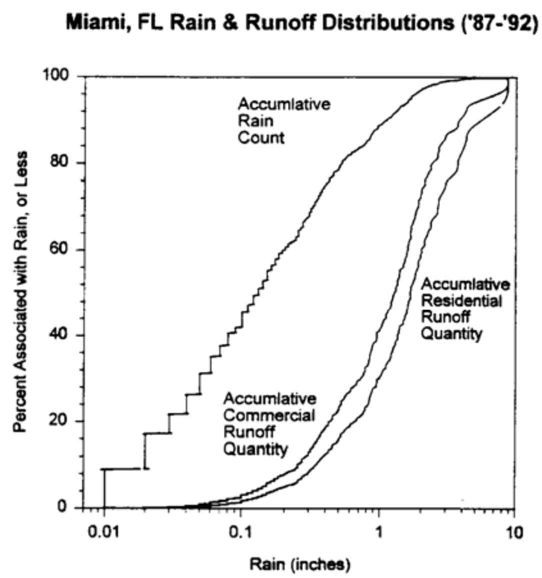


Figure A-13c. Modeled rain, runoff, and pollutant distributions (cont.).

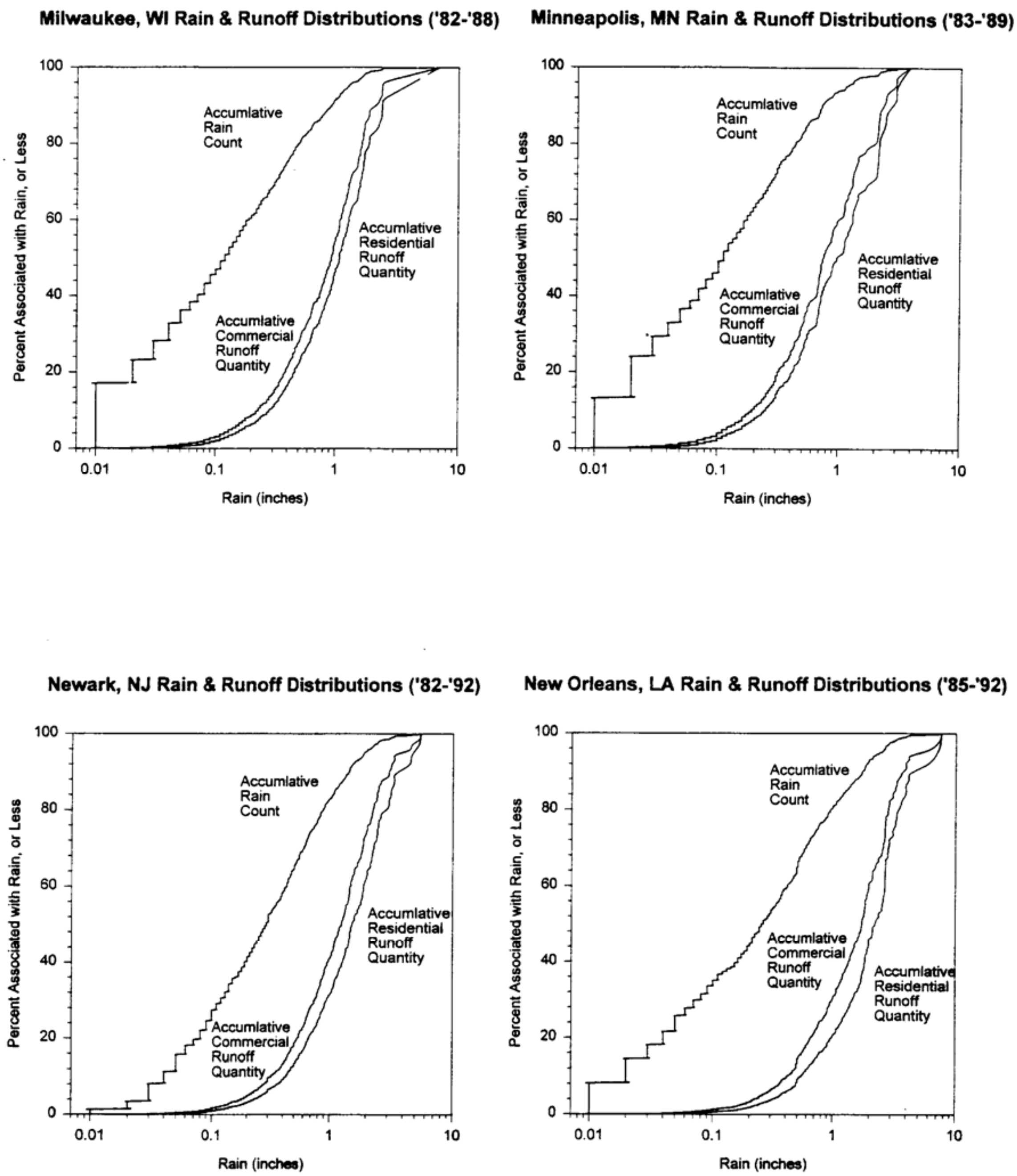


Figure A-13d. Modeled rain, runoff, and pollutant distributions (cont.).

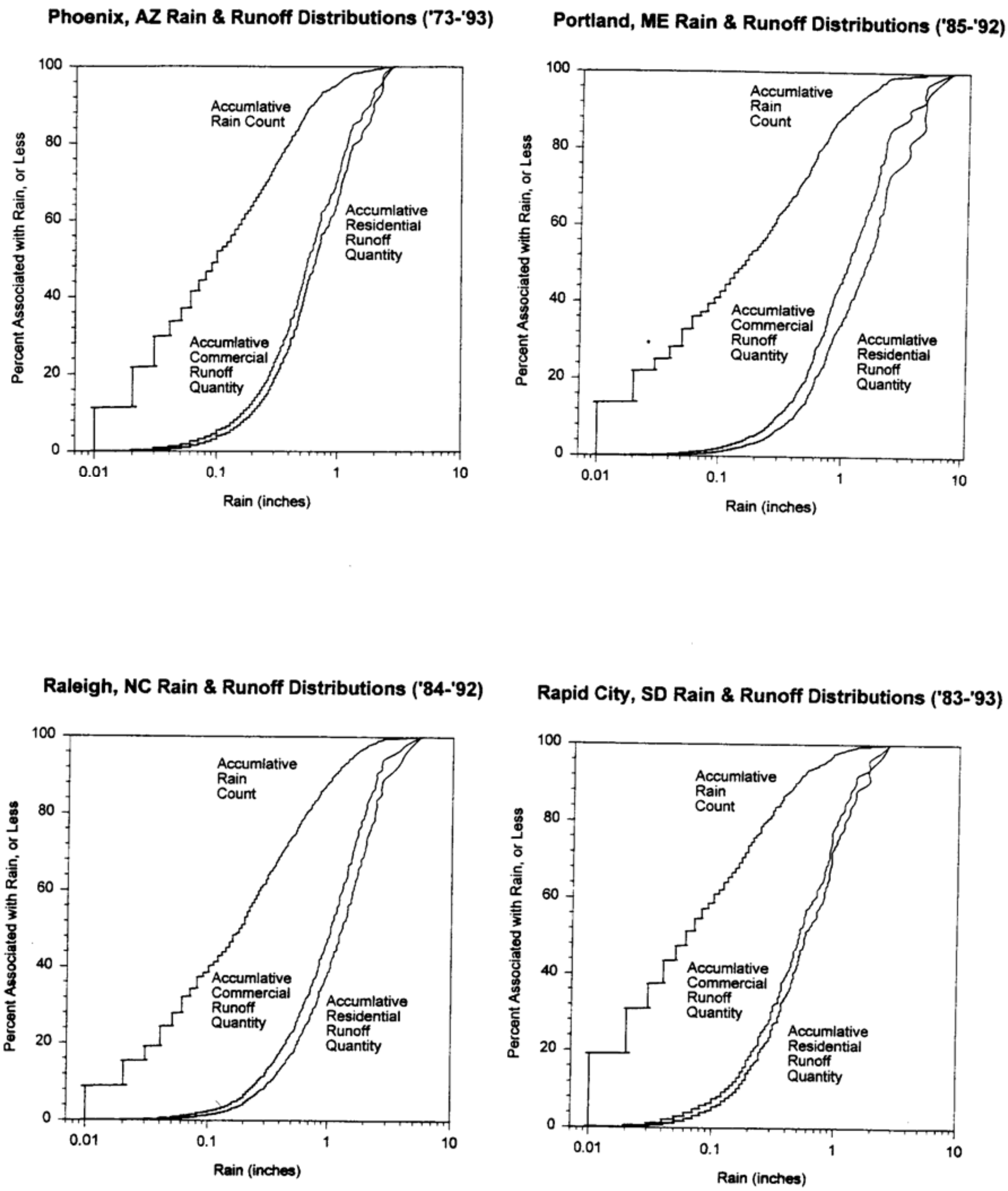


Figure A-13e. Modeled rain, runoff, and pollutant distributions (cont.).

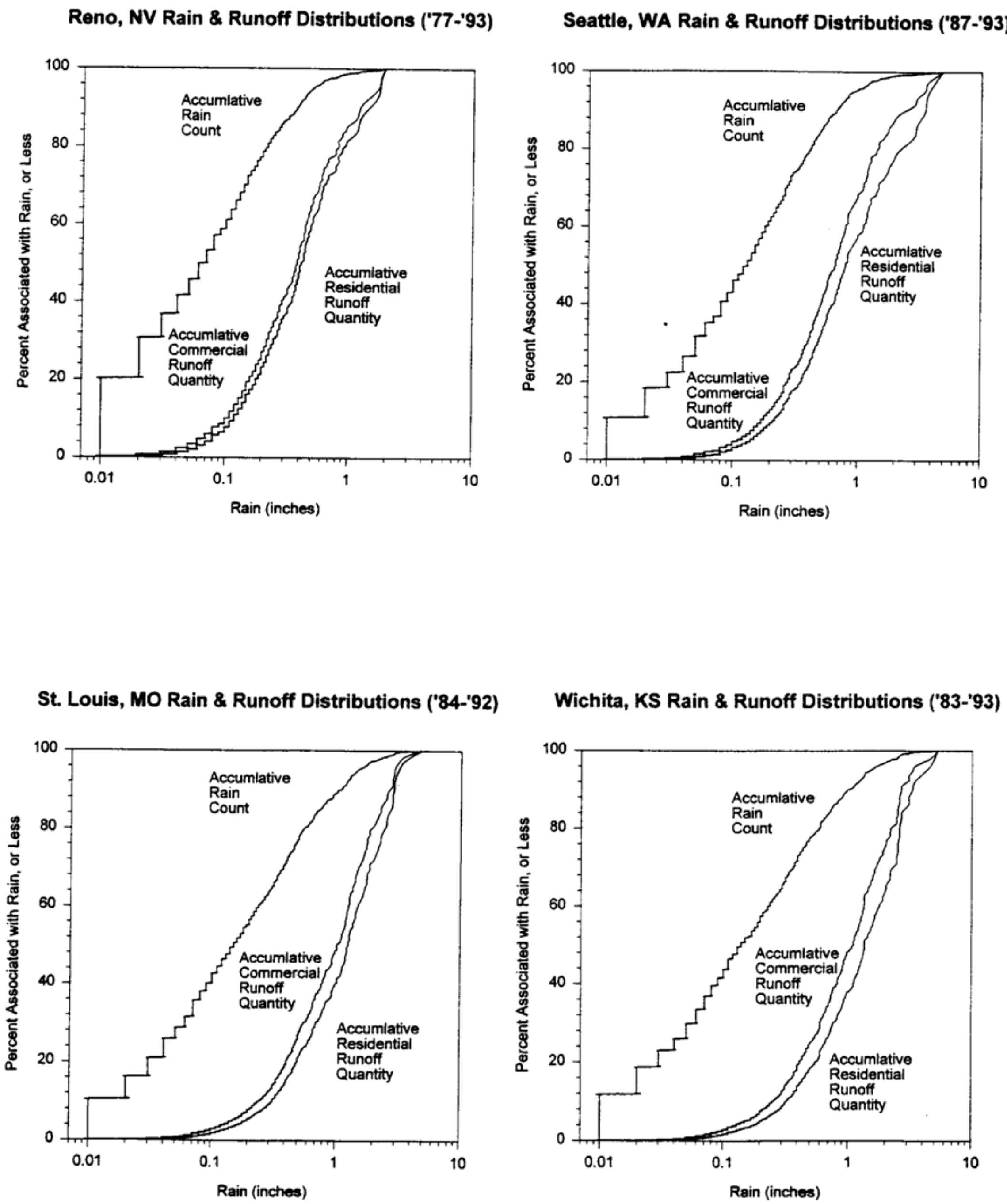


Figure A-13f. Modeled rain, runoff, and pollutant distributions (cont.).

Table A-1 summarizes these rain and runoff distributions for different U.S. locations, while Figures A-14 through A-19 plot some of the important values on a U.S. map. Lower and upper runoff distribution breakpoints were identified on all of the individual distributions. The breakpoints separate the distributions into the following three general categories:

• less than lower breakpoint: small, but frequent rains. These generally account for 50 to 70 percent of all rain events (by number), but only produce about 10 to 20 percent of the runoff volume. Figure A-15 shows that the rain depth for this breakpoint ranges from about 0.10 in. in the Southwest arid regions of the country, to about 0.5 in. in the wet Southeast. These events are most important because of their frequencies, not because of their mass discharges. These rains are therefore of great interest where water quality violations associated with urban stormwater occur. This would be most common for bacteria (especially fecal coliforms) and for total recoverable heavy metals which typically exceed receiving water numeric criteria during practically every rain event in heavily urbanized drainages having separate stormwater drainage systems.

• between the lower and upper breakpoint: moderate rains. These rains generally account for 30 to 50 percent of all rains events (by number), but produce 75 to 90 percent of all of the runoff volume (Figure A-19). Figure A-17 shows that the rain depths associated with the upper breakpoint range from about 1 to 2 in. in the arid parts of the U.S. to up to 5 or 6 in. in wetter areas. As shown earlier for actual monitored events in Milwaukee and elsewhere, as shown in Appendix B, these runoff volume distributions are approximately the same as the pollutant distributions. Therefore, these intermediate rains also account for most of the pollutant mass discharges and much of the actual receiving water problems associated with stormwater discharges.

• above the upper breakpoint: large, but rare rains. These rains include the typical drainage design events and are therefore quite rare. During the period analyzed, many of the sites only had one or two, if any, events above this breakpoint. These rare events do account for about 5 to 10 percent of the runoff on an annual basis, as shown on Figure A-18. Obviously, these events must be evaluated to ensure adequate drainage.

Because of the importance of these small and moderate rains, it is important to review typically used urban hydrology methods that have been commonly used to predict runoff from urban areas. These tools have been reasonably successful when evaluating drainage capacity for large “design storm” events. However, the following paragraphs will indicate their short-comings when used for evaluating the common smaller events. A general urban runoff model is also presented that has been shown to be useful to predict runoff volumes for a wide range of rain events, especially the small and moderate rains of greatest interest in water quality evaluations.

The Rainfall-Runoff Inter-Relationships for Different Urban Areas are Surprisingly Similar

Figure A-20 shows a dendogram from a cluster analysis (using SYSTAT) of rainfall and runoff data from two areas: an industrial area and a residential and commercial mixed land use area (Pitt 1987). Most of the variation in runoff volumes for different rains can be explained by rain volume variations alone. Rain intensity and antecedent periods are not very important when predicting runoff volumes. However, rain intensity information is very important for predicting runoff rates which are needed for drainage and flooding studies. It is also noted that the runoff duration is closely related to rain duration. A simple procedure for predicting runoff volume is possible using only total rain depth (and land development characteristics).

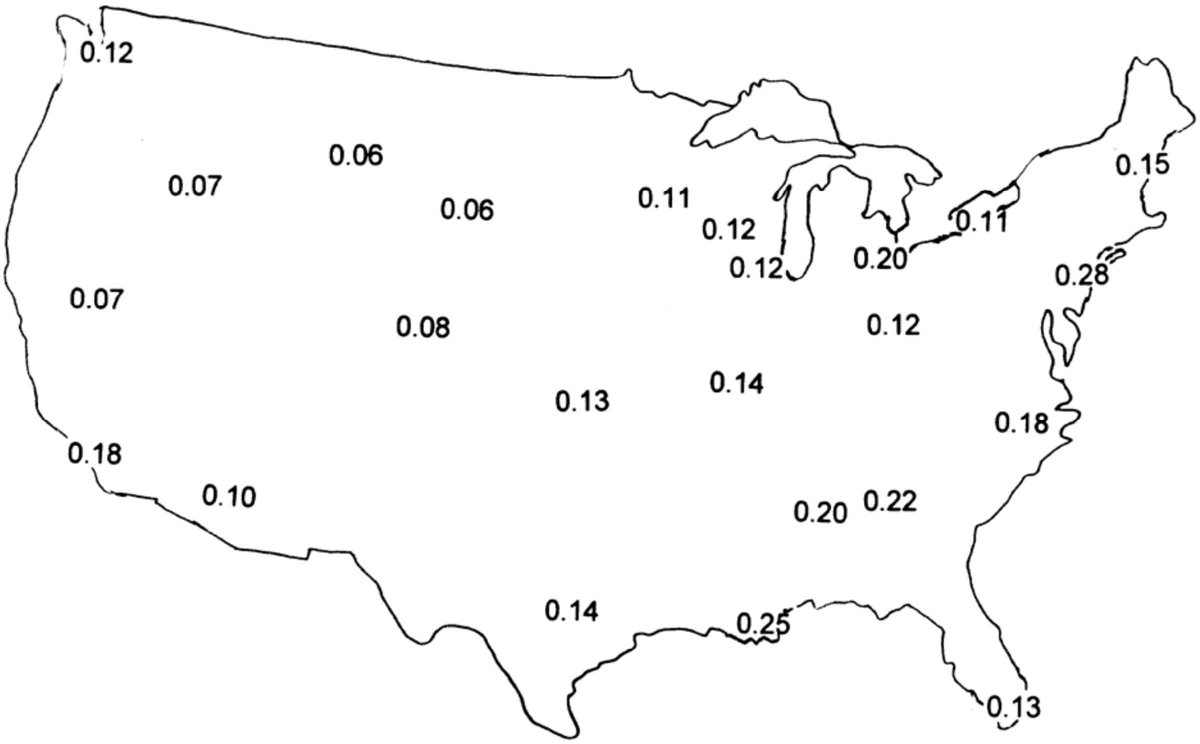


Figure A-14. Median rain depth (in.).

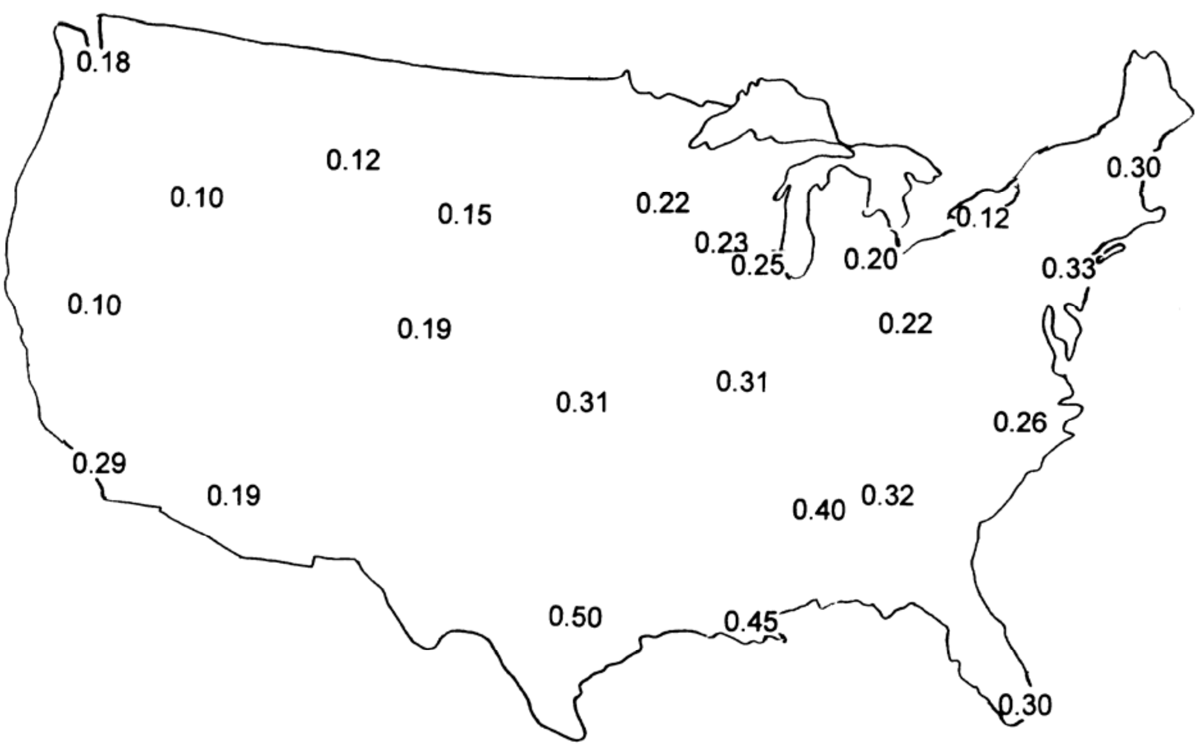


Figure A-15. Lower breakpoint rain depth (in.).

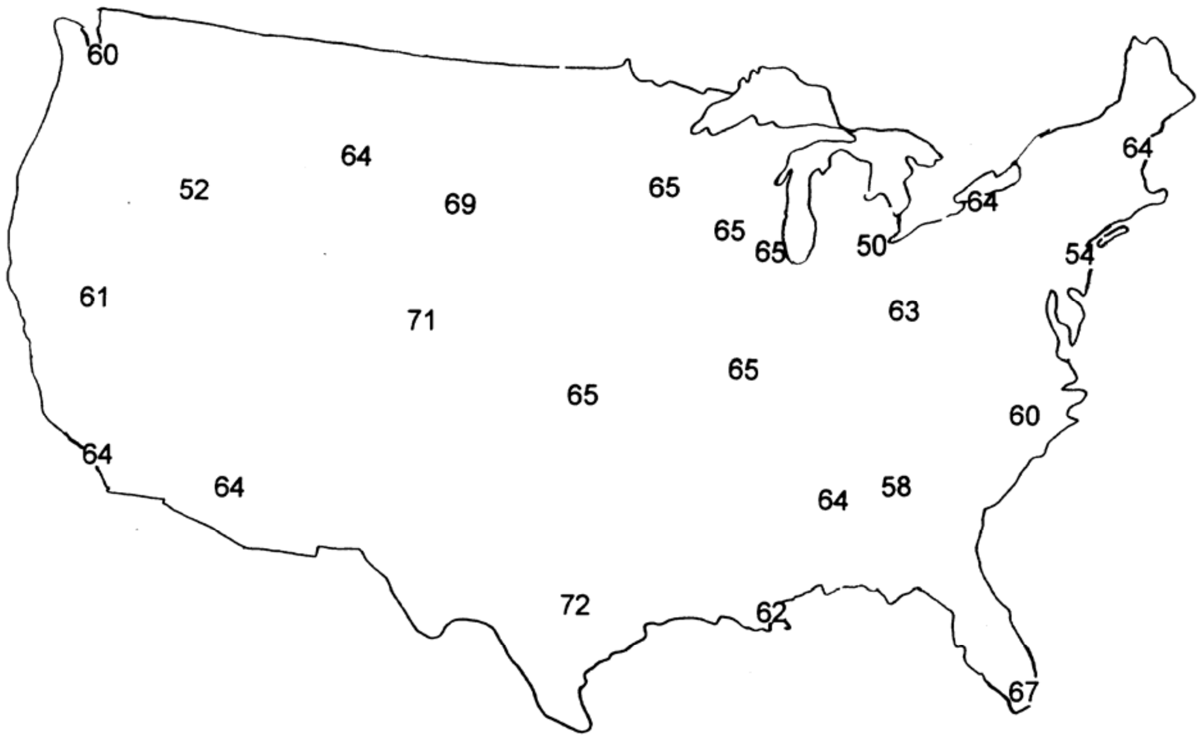


Figure A-16. Percentage of rain events less than lower breakpoint.

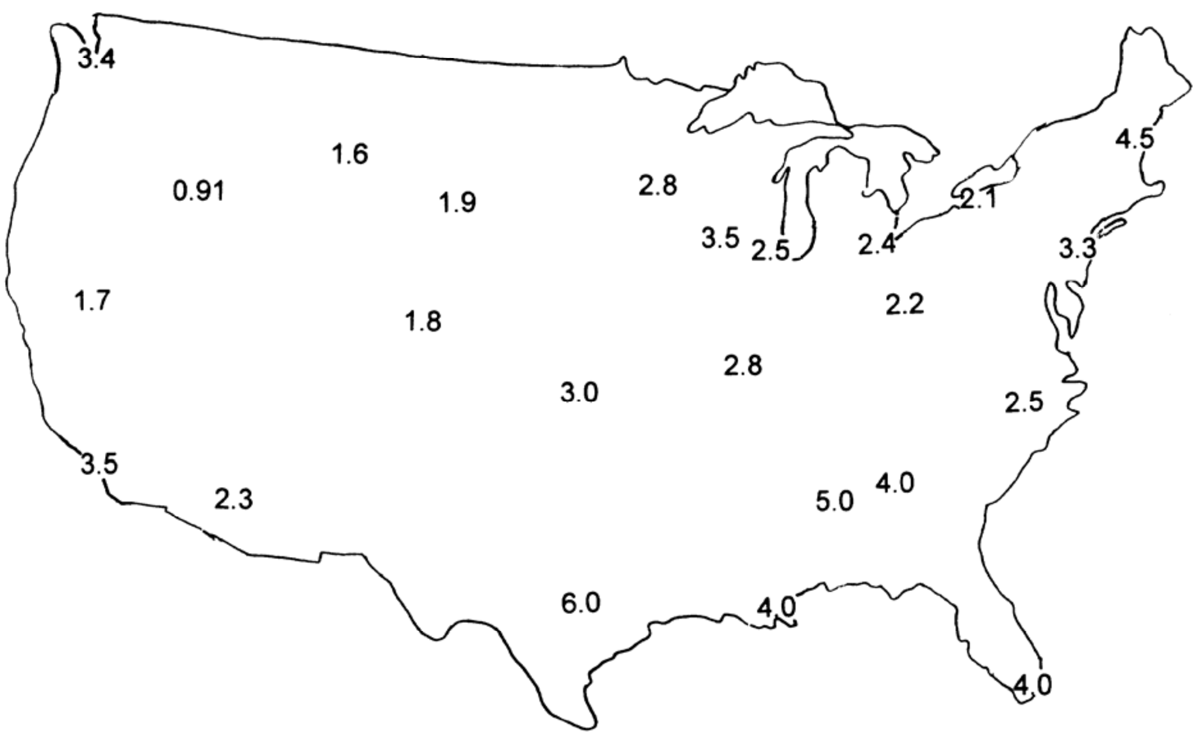


Figure A-17. Upper breakpoint rain depth (in.).

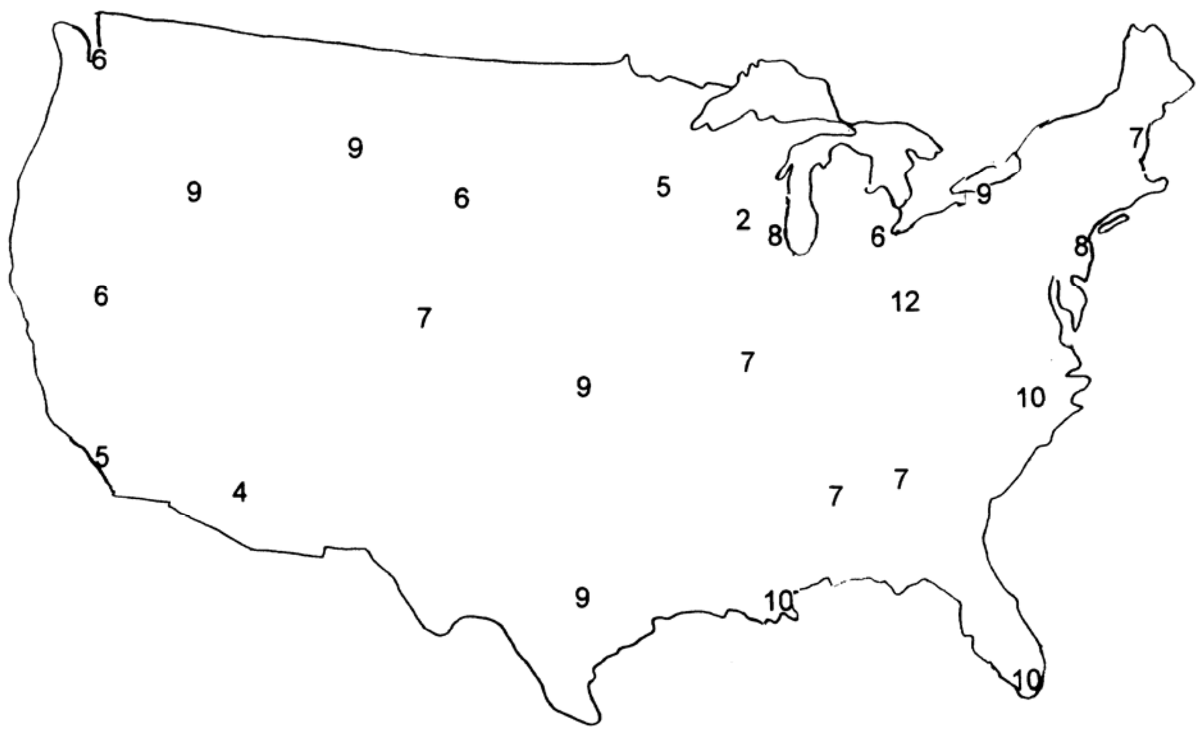


Figure A-18. Percentage of runoff volume greater than upper breakpoint.

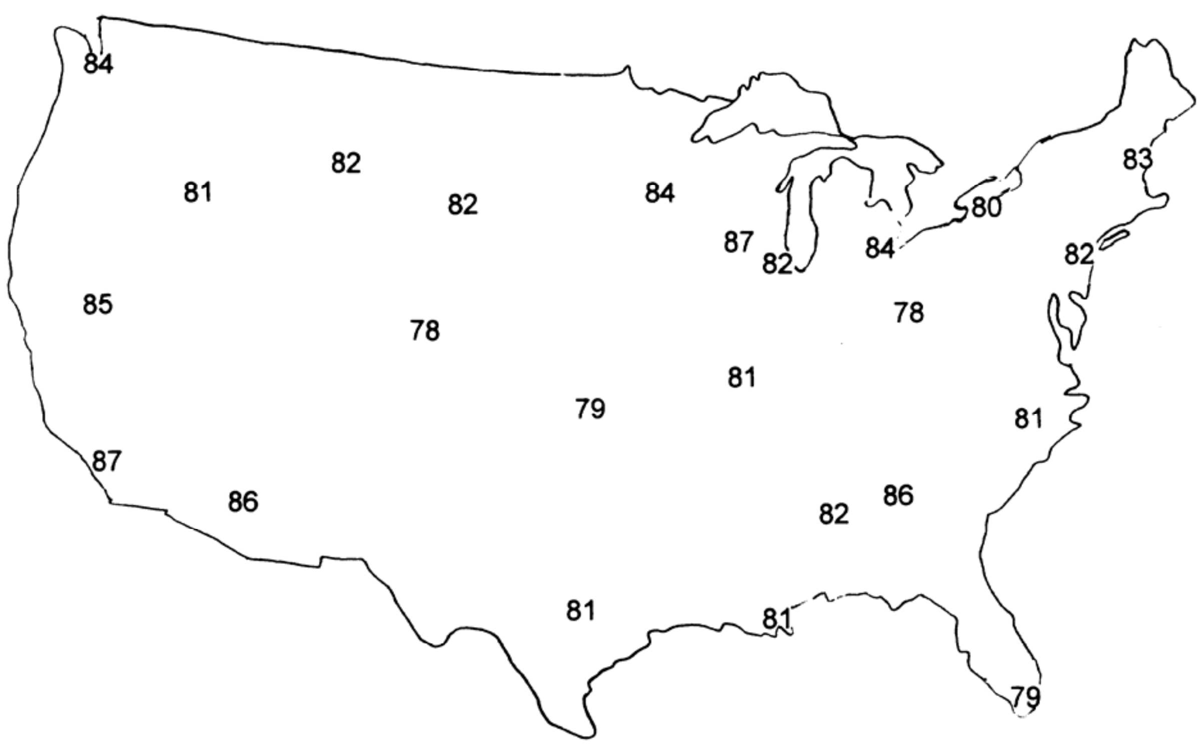


Figure A-19. Percentage of runoff volume between breakpoints.

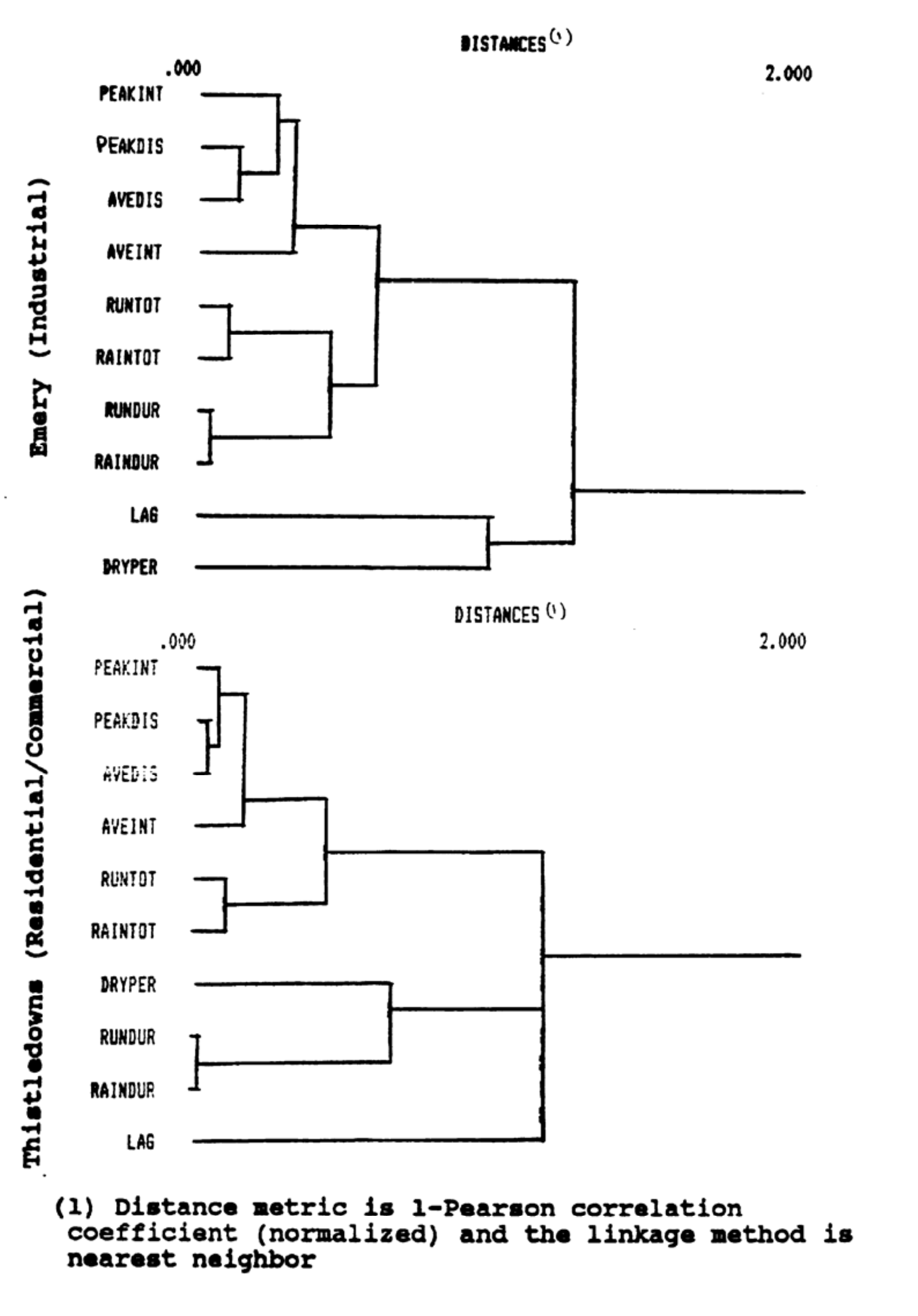


Figure A-20. Cluster analysis (dendogram) for basic urban hydrology structure (Pitt 1987).

Varying Contributing areas are Important in Urban Hydrology

Figure A-21 shows the components of a hypothetical hydrograph for an urban area. For small rains, most of the runoff observed at the outfall originates from street surfaces and other directly connected impervious areas. However, as the rain depth increases, runoff from pervious areas become important. The critical problem is being able to predict when these component areas contribute significant runoff volumes (and pollutants). SLAMM (Pitt 1986 and 1992) was developed to enable predictions of runoff contributions (and source area controls), using a simplified urban hydrology approach appropriate for important small rains.

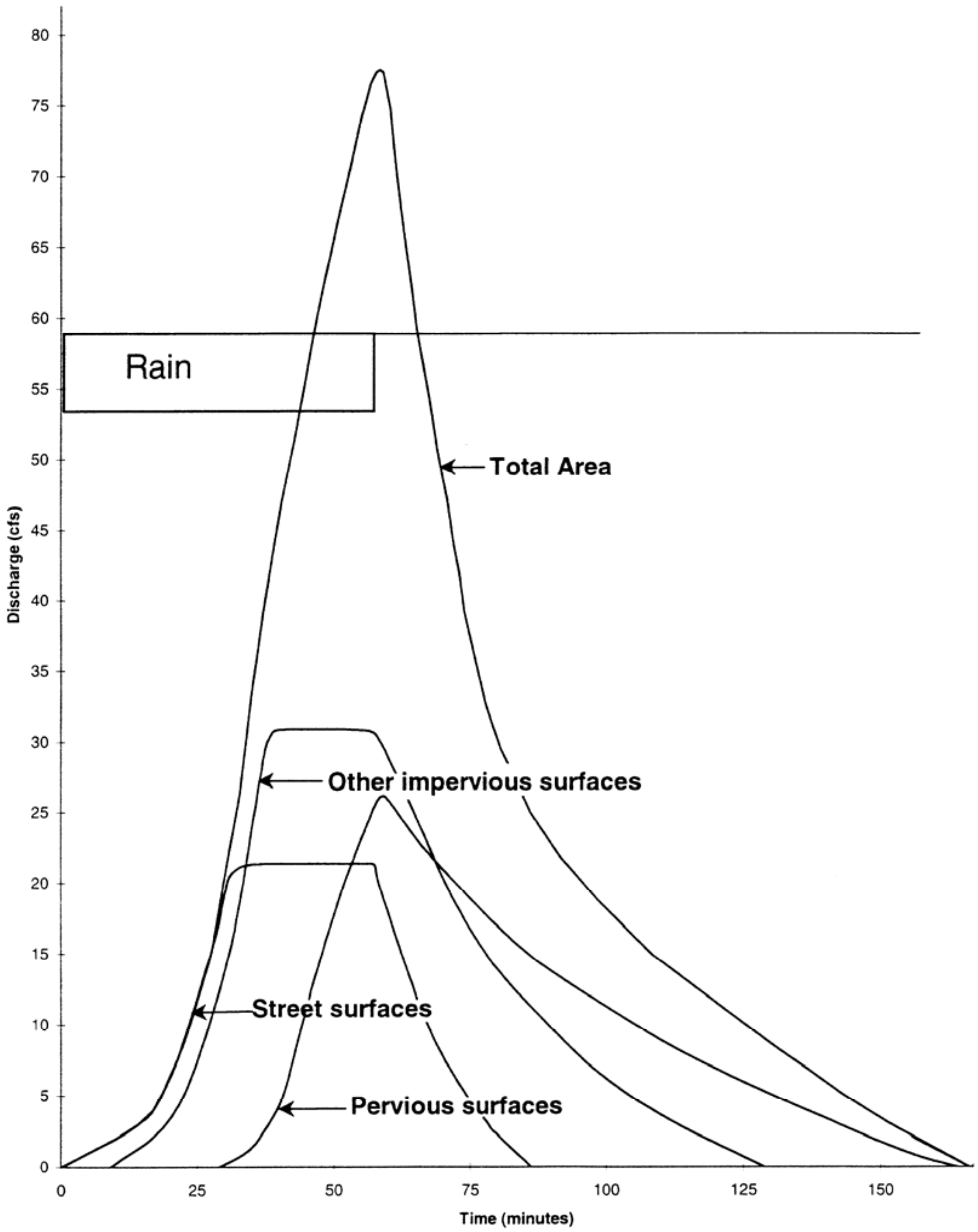


Figure A-21. Variable contributing area unit hydrographs for urban site.

Observed Runoff Volumes Do Not Compare Well With Commonly Used Urban Runoff Prediction Methods

Some of the most commonly used stormwater design methods utilizes the NRCS curve number (CN) method, especially TR-20 and TR-55 (SCS 1986). The NRCS recommends against the use of the curve number procedure for rains less than one-half inch. Unfortunately, this warning is ignored in many urban runoff models that have been developed. As shown previously, small rains are very significant when analyzing urban runoff. In addition, the NRCS recommends that the curve number method should be used for individual components of the drainage area, if CN values differ by more than 5, instead of using a composite CN for the complete area. Unfortunately, many users of the CN method ignore these two basic warnings, and many urban stormwater models use composite CN values for all storms. The CN method is a suitable tool if properly used, unfortunately, it is frequently used for small storms and for water quality evaluations, well beyond its intended use addressing drainage design for conveyance objectives for large rains.

Figure A-22a shows rainfall-runoff plots for eight monitored areas in Milwaukee. The curve is similar to the US. Natural Resources Conservation Service (NRCS) curve number (CN) rainfall-runoff plot contained in TR-55 (SCS 1986). This figure also shows the NRCS CN values calculated using actual P (precipitation) and Q (runoff quantity) data. CNs vary greatly with rain depth.

Figure A-22b shows that CNs at the Milwaukee NURP monitored sites did not approach the published CN values for typical medium density residential areas until the rains were much greater than five inches. The Milwaukee high density land use areas can use published CN values for rains as small as two inches, while the Milwaukee commercial area CNs are correct when close to one inch.

Appendix B shows numerous similar plots for other monitored locations from throughout the U.S., collected during the EPA's NURP projects in the early 1980s (EPA 1983), and from the EPA's rainfall-runoff-quality data base (Huber, *et al.* 1982). Figures A-23 through A-26 contain CN versus rain depth plots for many of these cities, including: 2 locations in Broward County, FL; 1 site in Dade County, FL; 2 sites in Salt Lake City, UT; and 2 sites in Seattle, WA (from the rainfall-runoff-quality data base), plus 4 sites in Champaign, IL; 5 sites in Irondequoit Bay, NY; 2 sites in Austin, TX; and 1 site in Rapid City, SD (from the NURP data). Figure A-23 contains plots for areas with little urbanization, Figure A-24 contains plots for medium density residential areas and mixed common urban areas, Figure A-25 contains plots for high density and commercial areas, and Figure A-26 contains plots for catchments having only major roadways. In all cases, the general pattern is the same: observed curve numbers are all very high for small rains, tapering off as the rains become large. All of the test watersheds are typical for these land uses and do not contain any unusual drainage designs or stormwater controls.

Table A-2 is a summary of these observed curve numbers at several different rain depths, compared to typical curve numbers presented by the NRCS (SCS 1986) for these land uses. Several of the sites had adequate descriptions to enable curve numbers to be estimated, based on their directly connected impervious areas and soil texture. The following list shows these sites, with the NRCS recommended curve numbers, and the approximate rain depth where these curve numbers were observed:

- Broward Co., FL, residential land use (40% imperv., with sandy soils). NRCS CN = 61, observed at about 3.5 in. of rain.
- Champaign-Urbana, IL, single family residential land use (18% imperv., with silty, poorly drained soils). NRCS CN = 84, observed at about 1.2 in. of rain.
- Champaign-Urbana, IL, single family residential land use (19% imperv., with silty, poorly drained soils). NRCS CN = 84, observed at about 1.2 in. of rain.
- Dade Co., FL, high density residential land use (almost all impervious, "D" soils). NRCS CN = 92, observed at about 1.3 in. of rain.

Table A-1. Rainfall and Runoff Distribution Characteristics for Different Locations from Throughout the U.S.

	Median rain depth, by count (in)	Corresponding percentage of runoff for the median rain depth	Rain depth associated with median runoff depth (in)	Lower breakpoint rain depth (in)	Percentage of rain events less than lower breakpoint	Percentage of runoff volume less than lower breakpoint	Upper breakpoint rain depth (in)	Percentage of rain events less than upper breakpoint	Percentage of runoff volume less than upper breakpoint	Percentage of runoff volume between breakpoints	Percentage of rain events between breakpoints
Columbia North Pacific											
Boise, ID	0.07	3 - 5	0.30 – 0.35	0.10	52	9 - 11	0.91	99	89 - 93	80 - 82	47
Seattle, WA	0.12	4 - 6	0.62 – 0.80	0.18	60	8 - 11	3.4	99	92 - 96	84 - 85	39
California											
Los Angeles, CA	0.18	3 - 5	1.2 – 1.5	0.29	64	7 - 10	3.5	99	92 - 98	85 - 88	35
Great Basin											
Reno, NV	0.07	3 - 5	0.35 – 0.41	0.10	61	8 - 10	1.7	99	93 - 95	85	38
Lower Colorado											
Phoenix, AZ	0.10	4 - 6	0.55 – 0.68	0.19	64	9 - 12	2.3	99	94 - 98	85 - 87	35
Missouri											
Billings, MT	0.06	2 - 4	0.55 – 0.60	0.12	64	8 - 10	1.6	99	89 - 93	81 - 83	35
Denver, CO	0.08	2 - 4	0.50 – 0.60	0.19	71	13 - 17	1.8	99	91 - 95	78	28
Rapid City, SD	0.06	2 - 4	0.50 – 0.55	0.15	69	10 - 13	1.9	99	92 - 96	82 - 83	30
Arkansas-White-Red											
Wichita, KS	0.13	2 - 5	1.1 – 1.4	0.31	65	10 - 13	3.0	99	88 - 93	78 - 80	34
Texas Gulf											
Austin, TX	0.14	2 – 3	1.4 – 1.8	0.50	72	8 - 12	6.0	99	88 - 94	80 - 82	27
Upper Mississippi											
Minneapolis, MN	0.11	3 - 5	0.73 – 1.0	0.22	65	9 - 13	2.8	99	94 - 96	83 - 85	34
Madison, WI	0.12	3 - 5	0.78 – 0.98	0.23	65	9 - 13	3.5	99	97 - 99	86 - 88	34
Milwaukee, WI	0.12	2 - 4	0.9 – 1.1	0.25	65	9 - 12	2.5	99	89 - 95	80 - 83	34
St. Louis, MO	0.14	4 - 6	1.0 – 1.2	0.31	65	10 - 13	2.8	99	90 - 95	80 - 82	34
Great Lakes											
Detroit, MI	0.20	7 - 11	0.72 – 0.81	0.20	50	7 - 11	2.4	99	92 - 95	85 - 84	49
Buffalo, NY	0.11	2 - 4	0.61 – 0.72	0.12	64	8 - 12	2.1	99	88 - 93	80 - 81	35
Ohio											
Columbus, OH	0.12	3 - 5	0.80 – 1.0	0.22	63	8 - 12	2.2	99	85 - 91	77 - 79	36
North Atlantic											
Portland, ME	0.15	2 - 4	1.1 – 1.5	0.30	64	8 - 12	4.5	99	90 - 96	82 - 84	35
Newark, NJ	0.28	6 - 12	1.2 – 1.5	0.33	54	8 - 12	3.3	99	89 - 94	81 - 82	45
Lower Mississippi											
New Orleans, LA	0.25	3 - 5	1.7 – 2.2	0.45	62	7 - 11	4.0	99	88 - 93	81 - 82	37
South Atlantic Gulf											
Atlanta, GA	0.22	3 – 5	1.2 – 1.7	0.32	58	5 – 9	4.0	99	91 – 95	86	41
Birmingham, AL	0.20	3 - 5	1.2 – 1.5	0.40	64	8 - 13	5.0	99	90 - 96	82 - 83	35
Raleigh, NC	0.18	4 - 6	1.0 – 1.2	0.26	60	7 - 11	2.5	99	87 - 93	80 - 82	39

Miami, FL	0.13	3 - 5	1.2 – 1.6	0.30	67	9 - 13	4.0	99	87 - 93	78 - 80	32

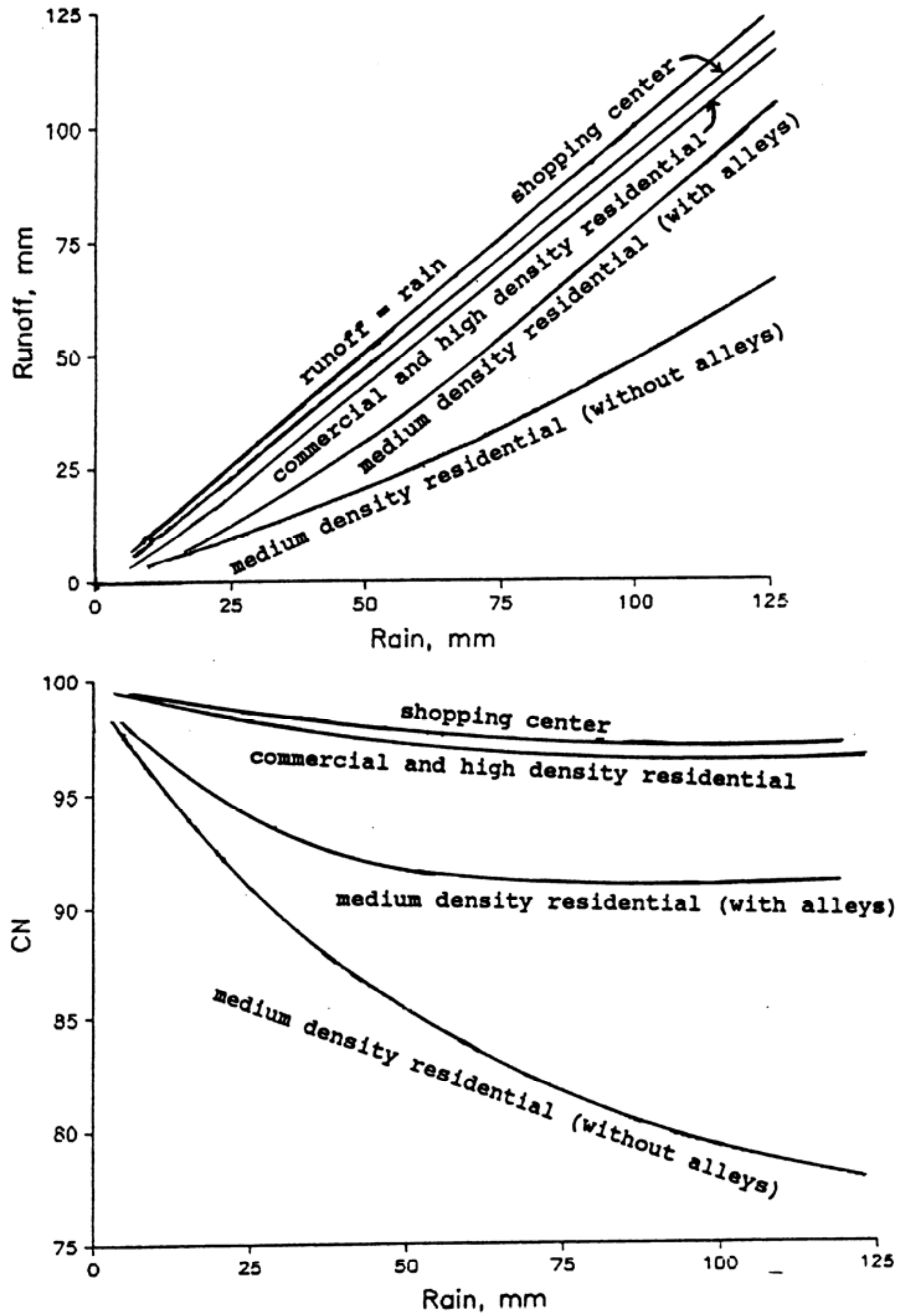


Figure A-22. Observed rainfall-runoff and curve numbers for Milwaukee (Pitt 1987).

- Champaign-Urbana, IL, commercial land use (40% imperv., with silty and poorly drained soils). NRCS CN = 87, observed at about 1.1 in. of rain.

- Champaign-Urbana, IL, commercial land use (55% imperv., with silty and poorly drained soils). NRCS CN = 91, observed at about 0.8 in. of rain.

- Broward Co., FL, transportation catchment (54% imperv., with sandy soils). NRCS CN = 73, observed at about 1.7 in. of rain.

- Salt Lake City, UT, roadway land use (mostly paved, sandy loam). NRCS CN = 89, observed at about 0.3 in. of rain.

- Salt Lake City, UT, transportation catchment (imperv. Raods, clay loam). NRCS CN = 95, observed at about 0.15 in. of rain.

For the rains less than the matching point (rain depth where the NRCS recommended CN was observed), the actual CN is larger than the recommended CN and the predicted runoff using the NRCS methods would be less than actually occurred. Similarly, for rains larger than the matching point, the actual CN is smaller than the recommended CN and the predicted runoff using the NRCS CN method would be greater than actually occurred. The magnitude of the runoff differences varies greatly, depending on the CN values and the rain depth. As an example, if the recommended NRCS CN was 84, but the actual CN was really 98 for a 0.2 in. rain (similar to the Champaign, IL, medium density residential sites), the percentage error is infinite. For a 1 in. rain, the actual CN at this site was about 86 and the recommended NRCS value remains at 84. The difference now is much smaller, as the rain depth being examined is close to the matching point depth of 1.2 inches. If the rain depth of concern was much larger, say 3 inches, the errors would be in the other direction, as summarized below:

	0.2 in. rain (matching point of 1.2 in)	1 in. rain (matching point of 1.2 in)	3 in. rain (matching point of 1.2 in)
CN of 84 (recommended by NRCS)	0 in. of runoff predicted by NRCS	0.15 in. of runoff predicted by NRCS	1.52 in. of runoff predicted by NRCS
Actual CN and predicted runoff	0.10 in. of runoff observed (actual CN of 98)	0.20 in. of runoff observed (actual CN of 86)	0.91 in. of runoff observed (actual CN of 74)
	Actual is infinitely larger, predicted is infinitely less.	Actual is larger, predicted is less. Error of 25%.	Actual is less, predicted is larger. Error of –67%.

The overall annual runoff depth error associated with using the NRCS recommended CN method depends on the frequency of rains having the different errors. Because the matching point rainfall depths are close to the rain depth associated with the median runoff depth, as shown previously on A-1, the annual errors may be within reason. However, the errors associated with individual events, and for the three classes of rain depths described earlier, are likely very large. This is a significant problem with stormwater quality management where accurate representations of the sources of the runoff are needed in order to evaluate control practices and development options. If the relative sources of the runoff flows are in great error, inappropriate and wasteful expenditures are likely.

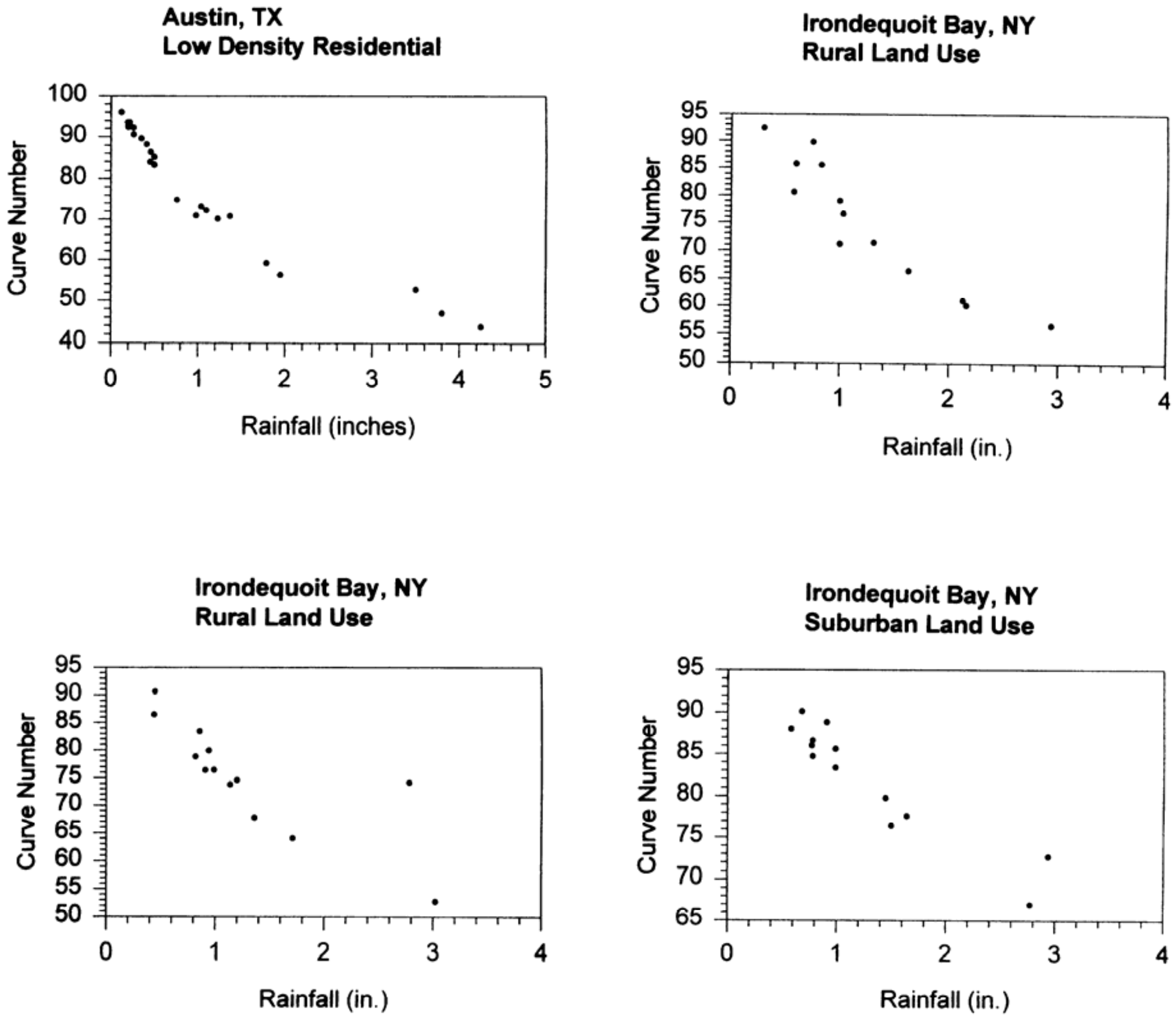


Figure A-23. Low density development observed CN vs. rain depth plots.

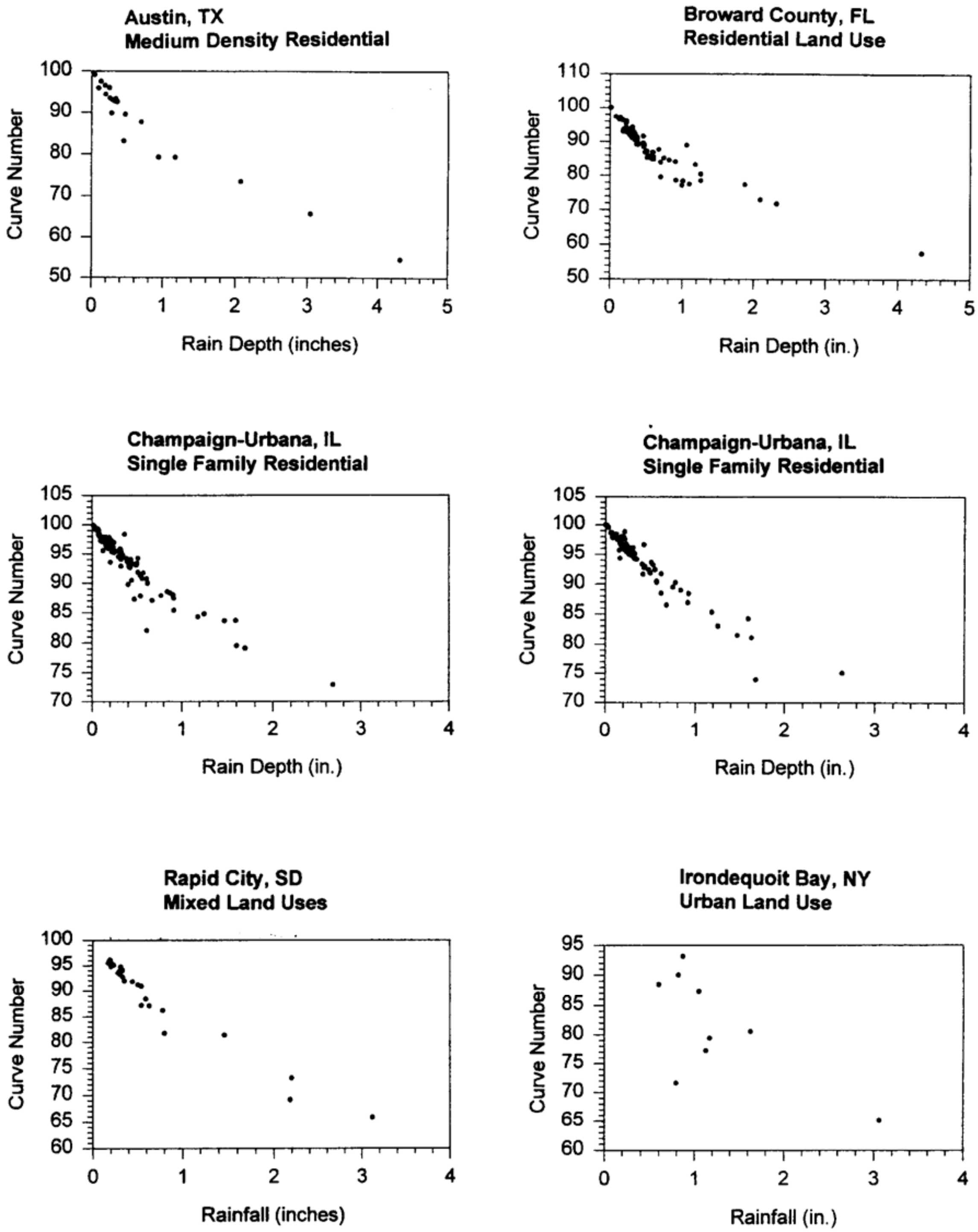


Figure A-24. Medium density land use area observed CN vs. rain depth plots.

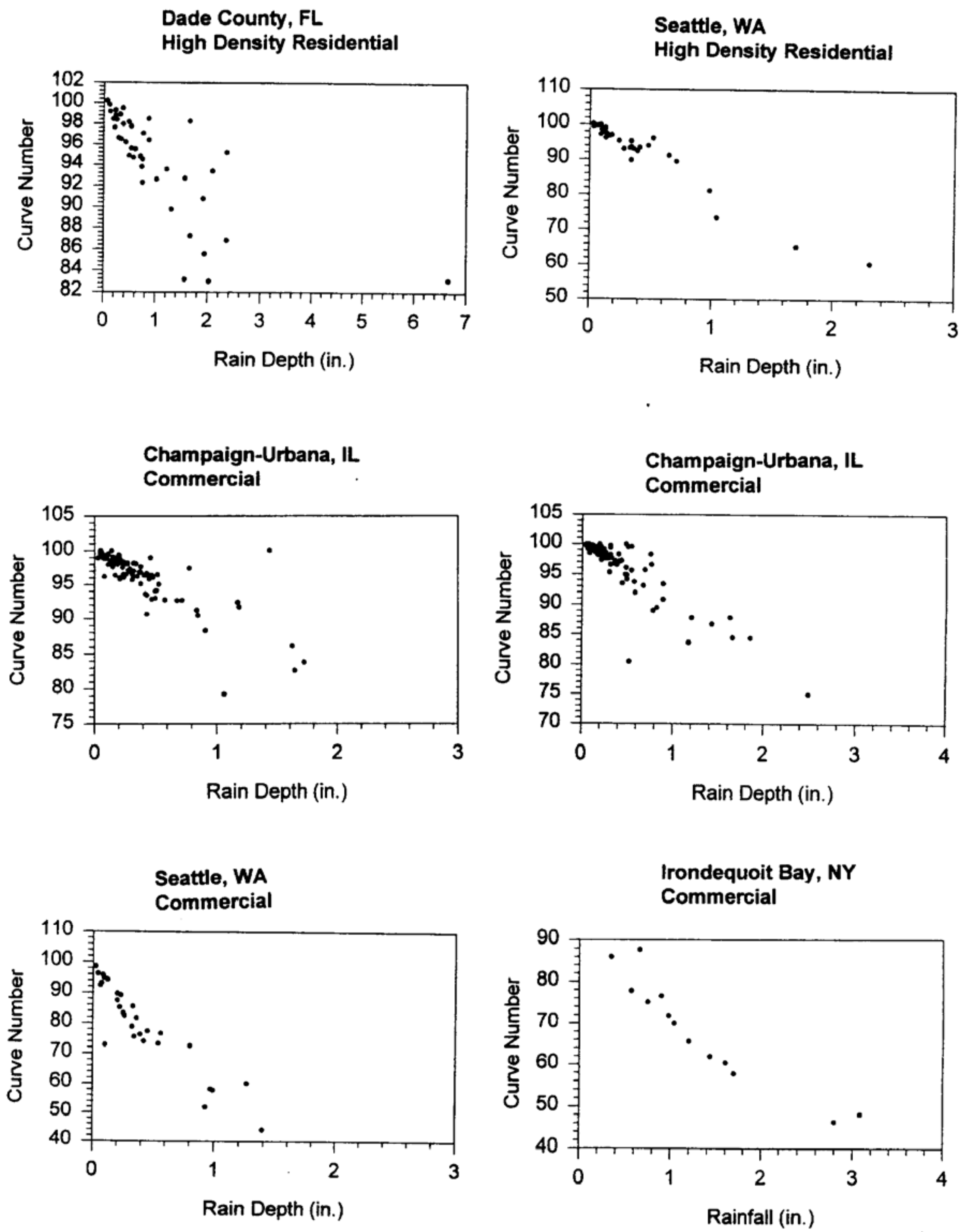


Figure A-25. High density residential and commercial area observed CN vs. rain depth plots.

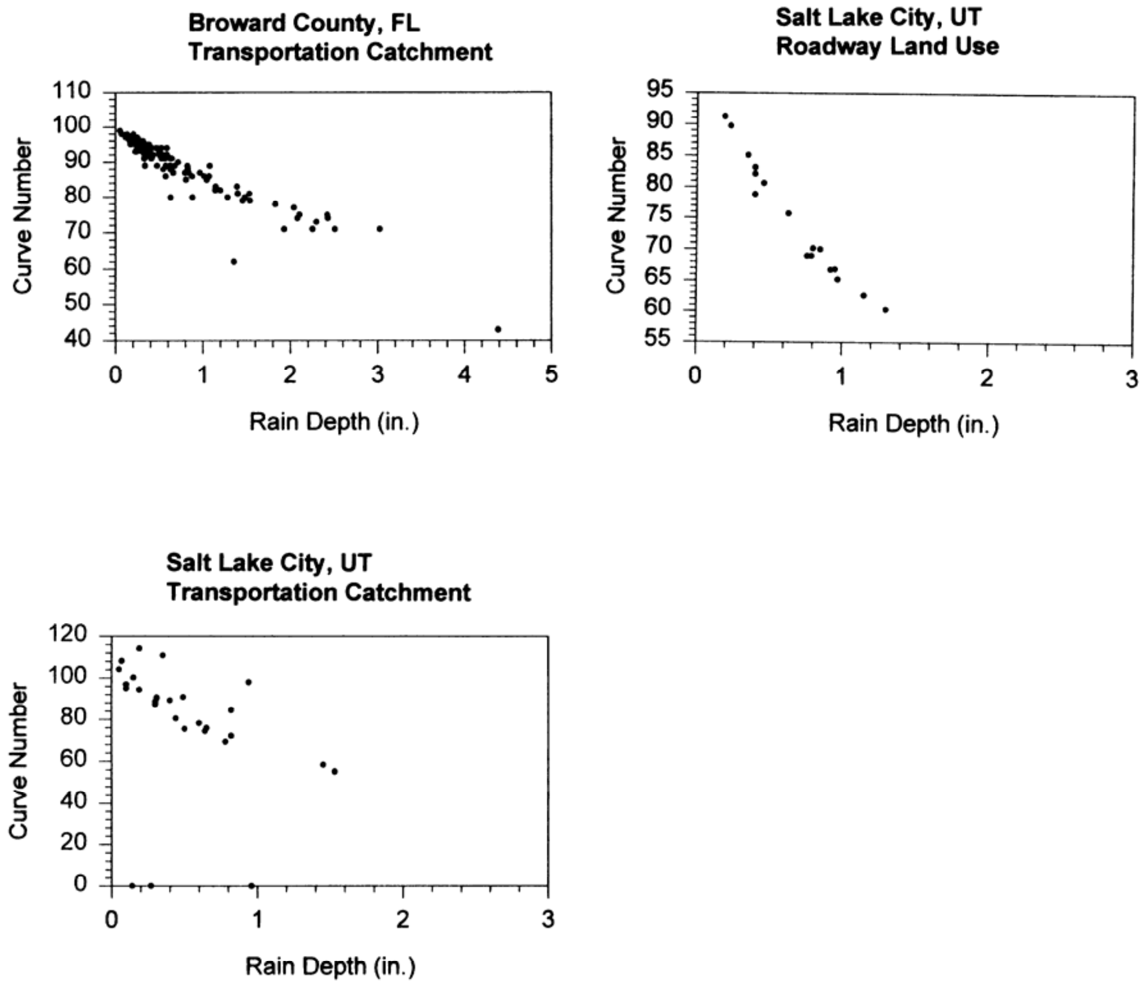


Figure A-26. Transportation land use area observed CN vs. rain depth plots.

Table A-2. Observed Curve Numbers Compared to Typically Used Values

Land Use and Location	Directly connected imperviousness	0.2 in. rain	0.5 in. rain	1 in. rain	3 in. rain	For max. rain observed	Estimated CN from NRCS tables for different soil conditions (if possible, most likely CN highlighted, based on available site description):			
							A (sandy to sandy loam)	B (silt loam or loam)	C (sandy clay loam)	D (silty to clayey)
Low Density/Suburban										
Austin, TX	21%	94	84	72	53	42 (5 in.)	51	68	79	84
Irondequoit Bay, NY	Rv = 0.1	95	88	76	55	52 (4 in.)	46	65	77	82
Irondequoit Bay, NY	Rv = 0.2	94	86	77	57	52 (4 in.)	51	68	79	84
Irondequoit Bay, NY	Rv = 0.2	94	89	84	69	67 (4 in.)	51	68	79	84
Medium Density Residential										
Austin, TX	39%	96	89	82	66	52 (5 in.)	61	75	83	87
Broward County, FL	40% (sandy soils)	96	89	81	65	54 (5 in.)	**61**	75	83	87
Champaign-Urbana, IL	18% (silty, poorly drained soils)	96	94	87	72	71 (4 in.)	51	68	79	**84**
Champaign-Urbana, IL	19 % (silty, poorly drained soils)	98	93	86	74	72 (4 in.)	51	68	79	**84**
Rapid City, SD	mixed	95	92	84	67	63 (4 in.)	?	?	?	?
High Density Residential										
Dade County, FL	“Almost all imperv.” (D soils)	99	97	94	87	82 (7 in.)	77	85	90	**92**
Seattle, WA	?	94	89	80	56 (max.)		77	85	90	92
Commercial										

Champaign-Urbana	40% (silty, poorly drained soils)	97	95	89	81 (max.)		61	75	83	**87**
Champaign-Urbana	55% (silty, poorly drained soils)	99	95	89	74	73 (4 in.)	73	82	88	**91**
Seattle, WA	?	90	76	61	44 (max.)		?	?	?	?
Irondequoit Bay, NY	?	92	82	72	46	46 (4 in.)	?	?	?	?
Transportation										
Broward County, FL	54% (sandy soils)	96	93	86	62	53 (5 in.)	**73**	82	88	91
Salt Lake City, UT	Mostly paved (sandy loam)	91	81	67	na	na	**89**	92	94	95
Salt Lake City, UT	“imperv. roads” (clay loam)	95	84	73	na	na	89	92	94	**95**

Actual Volumetric Runoff Coefficients (Rv) Vary With Storm Size.
Figure A-27 shows how the volumetric runoff coefficients (the ratio of runoff depth to rainfall depth) change with rain depth. After subtracting initial abstractions, continuous losses can be assumed to be mostly infiltration. After a sufficient amount of rain has occurred, all losses have been satisfied. Each unit increase in rain then results in a unit increase in runoff volume.

Small rain depths result in runoff that have small Rv values. As the rain depth increases, the Rv increases. Rv values are only "constant" over a small range in rain depths. During many urban runoff monitoring projects, only small ranges of rains are typically represented. Therefore, "averaged" Rv values are incorrectly used with the understanding that they are useful over a wider range than justified. Appendix B includes rainfall-runoff plots and Rv-rainfall plots for many locations throughout the U.S. Few of these plots are as smooth as indicated for the Milwaukee data. The NURP data was collected in the early 1980s, while the rainfall-runoff-quality data base information was collected much earlier. There was significant variation in the accuracies of monitoring rainfall and runoff for the different locations. This is most evident at test sites having large amounts of directly connected pavement. Many of the measured runoff events had greater runoff volumes than the measured rainfall volumes (Rv values greater than 1.0 and calculated CN values greater than 100). This of course cannot occur in the absence of other flow sources and was likely associated with random measurement errors. The best measurements were probably made with errors approaching 25%, while some test sites used newly available equipment and errors may have been greater. These errors are much more obvious at high density and commercial sites than at the more commonly monitored medium density residential sites.

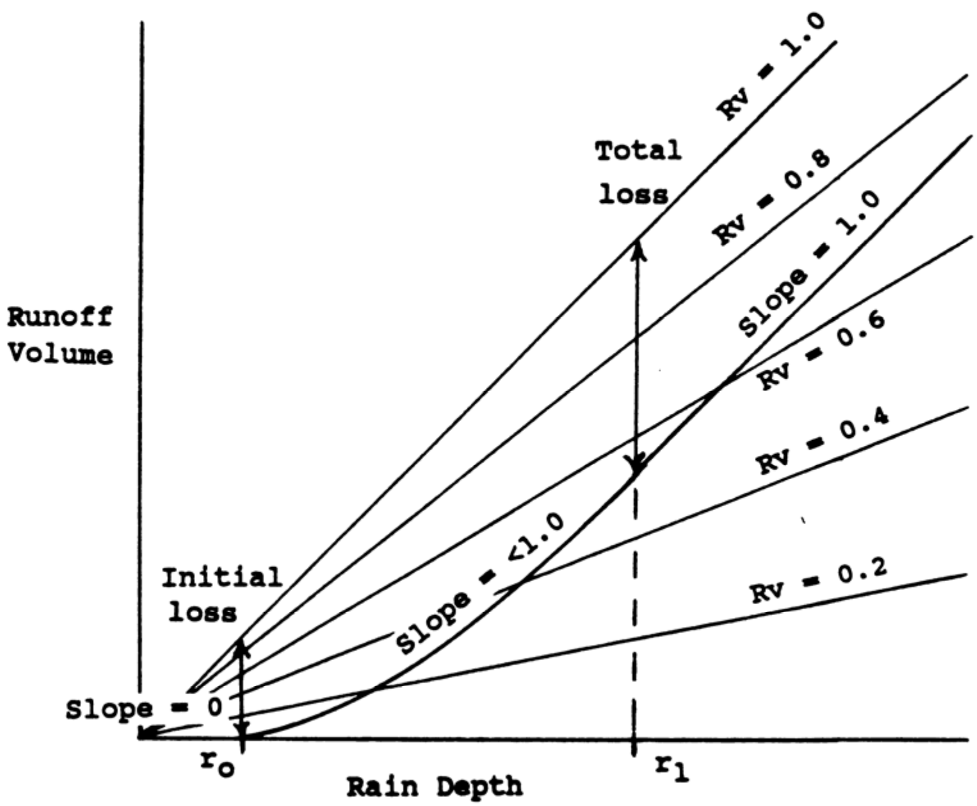


Figure A-27. Rainfall-runoff plot showing losses and Rv values (Pitt 1987).

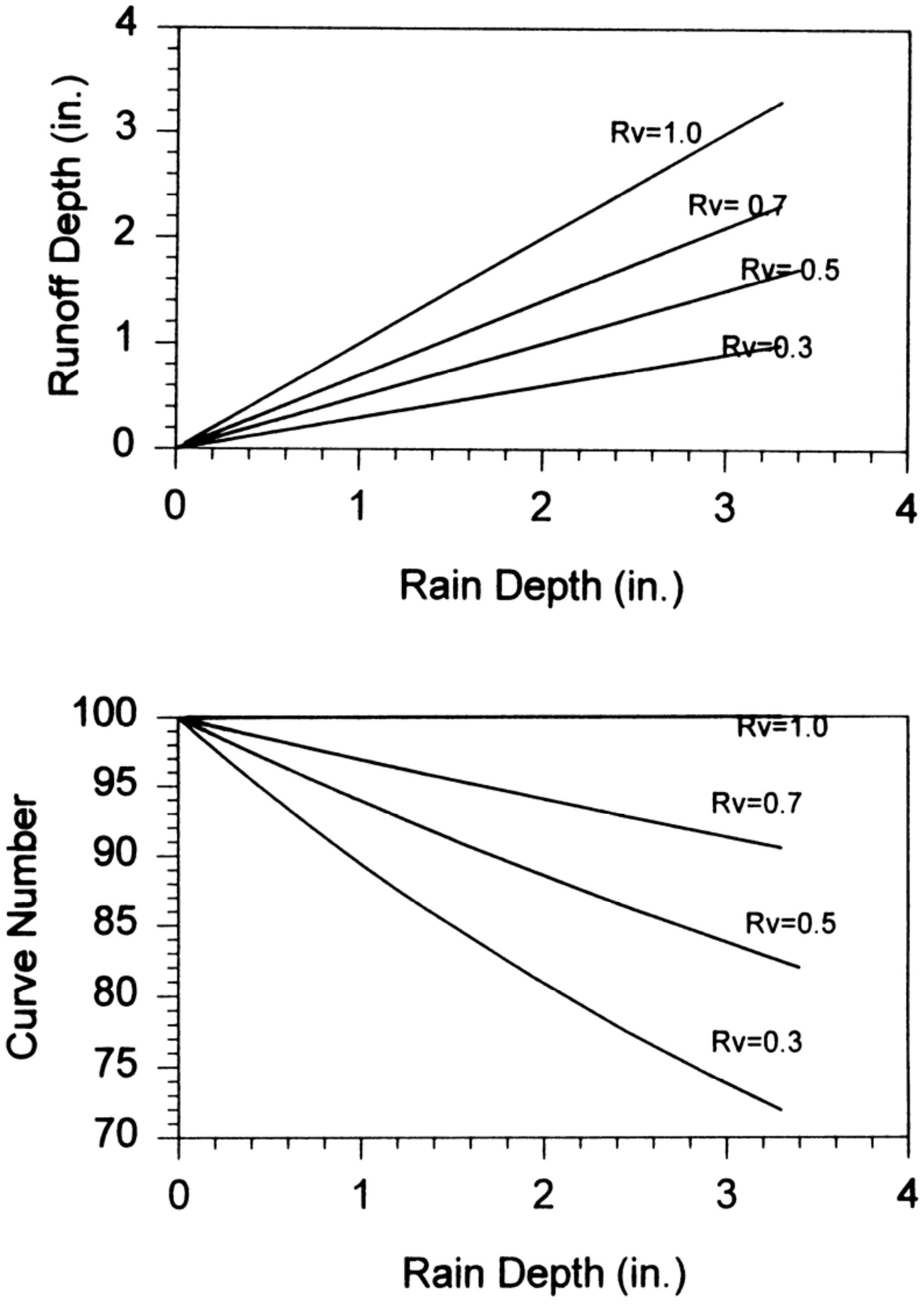


Figure A-28. Idealized plots of Rv and CN values.

Figure A-28 shows a plot of runoff depth versus rain depth and another plot of the NRCS CN versus rain depth for a set of artificial rain and runoff data. These plots were prepared to visually show the relationship between Rv and NRCS CN values. If the data has relatively constant Rv values for all rains, as indicated for most of the sites shown in Appendix B, the CN plots will naturally decrease substantially with increasing rain depth (again, as indicated in almost all of the measured data). It is interesting to note that the calculated NRCS CN is always very close to 100 for very small rain and runoff values, irrespective of the Rv ratio. The Rv values likely increase with increasing rain depth, which is evident if the observations can be obtained with small measurement errors and if the range of rains observed is large. Flow and rainfall measurement errors are much more obvious on the Rv plots, especially for the small rains, than on the CN plots.

Small Storm Hydrology Model

Runoff Process for Paved Surfaces

When rain falls on an impervious surface, much of it will flow off the surface and contribute to the total urban runoff. With the exception of infiltration, these losses are mostly associated with the initial portions of the rain and are termed initial abstractions. Water may also infiltrate through pavement, or through cracks or seams in the pavement. For small rains, a much greater portion of the rain will be lost to these runoff loss processes than for large rains.

Paved surfaces are usually considered impervious, implying no infiltration. However, some researchers have concluded that paved surfaces do indeed experience infiltration losses. Falk and Niemczynowicz (1978) found that smooth paved surfaces had lower infiltration losses, compared to poorly maintained surfaces which had losses of about 7 percent of the total rain. Pratt and Henderson (1981) were asked after their presentation at the *Second International Conference on Urban Storm Drainage* if the variation of the runoff coefficient that they observed for pavement could be due to infiltration through the surface which is commonly considered to be zero. They agreed that this variation was likely due to the difference in the permeability of the “impervious” catchment surfaces. They found that gaps between concrete sections in the curbs and gutters were the principal means of runoff losses. Willeke (1966) found that cracks in gutters could allow significant amounts of water to infiltrate, especially if sandy soils underlaid concrete. Davies and Hollis (1981) found an average runoff loss from a paved road surface to be about 85 percent of the rain depth. This loss was considered about evenly divided between detention storage and infiltration through the pavement, especially through cracks in the gutter. Cedergren (1974) measured infiltration rates through typical “sealed” seams of about 20 mm per hour (with pavement seams located about every 8 meters).

Infiltration of Rain Water Through Pavement Can be a Substantial Portion of the Total Rain for Most Events

Initial abstractions are dependent of pavement texture and slope, while infiltration is dependent on pavement porosity and pavement cracks. Pavement is relatively porous. It is the pavement base course that is much more resistant to percolation. Infiltrated water is therefore forced to flow laterally towards the pavement edges. If the flow path is long, then the resulting infiltration is limited. Figure A-29 is an example from a typical pavement runoff test (Pitt 1987). Initial abstractions may be about 1 mm for pavement, while the total infiltration may be between 5 and 10 mm. The maximum losses may occur after about 20 mm of rain.

Variable Runoff Losses as a Function of Time Indicate Very Different Infiltration Values for Different Rain Intensities

Figure A-30a shows that high infiltration rates are associated with high rainfall intensities (Pitt 1987). The Horton equation predicts a single infiltration relationship as a function of time, irrespective of rain intensity. When variable runoff losses are plotted against total rain depth (Figure A-30b) a single relationship is seen (rain intensity multiplied by time duration gives rain depth). Horton actually recommended infiltration as a function of rain depth, but current practice of using double-ring infiltrometers to calibrate the Horton equation does not allow infiltration measurements to be made as a function of rain depth, only as a function of time for the ponded test conditions.

Infiltration in Disturbed Urban Soils

Disturbed Urban Soils Do Not Behave as Indicated by Typically Used Models

More rain infiltrates through pavement surfaces and less rain infiltrates through soils than typically assumed. Double-ring infiltrometer test results from Oconomowoc, WI, urban soils (Table A-3) indicated highly variable infiltration rates for soils that were generally sandy (NRCS A/B hydrologic group soils). The median initial rate was about 3 in/hr, but ranged from 0 to 25 in/hr. The final rates also had a median value of about 3 in/hr after at least two hours of testing, but ranged from 0 to 15 in/hr. Many infiltration rates actually increased with time during these tests. In about 1/3 of the cases, the observed infiltration rates remained very close to zero, even for these sandy soils. Areas that experienced substantial disturbances or traffic (such as school playing fields) had the lowest infiltration rates, typically even lower than concrete or asphalt! These values indicate the large variability in infiltration rates that may occur in areas having supposedly similar soils. Obviously, these variations can significantly affect site specific runoff predictions. The lowest infiltration rates were observed in areas having heavy foot traffic and in areas obviously impacted by silt, while the highest rates were in relatively undisturbed areas.

Table A-3. Ranked Oconomowoc, WI, Double Ring Infiltration Test Results

	Observed urban soil Infiltration rates (in/hr):	
Initial Rate	**Final Rate (after 2 hours)**	**Total Observed Rate Range**
25	15	11 to 25
22	17	17 to 24
14.7	9.4	9.4 to 17
5.8	9.4	0.2 to 9.4
5.7	9.4	5.1 to 9.6
4.7	3.6	3.1 to 6.3
4.1	6.8	2.9 to 6.8
3.1	3.3	2.4 to 3.8
2.6	2.5	1.6 to 2.6
0.3	0.1	<0.1 to 0.3
0.3	1.7	0.3 to 3.2
0.2	<0.1	<0.1 to 0.2
<0.1	0.6	<0.1 to 0.6
<0.1	<0.1	all <0.1
<0.1	<0.1	all <0.1
<0.1	<0.1	all <0.1

In an attempt to explain much of the variation shown in the above early tests, recent tests of infiltration through disturbed urban soils were conducted in the Birmingham, AL, area by the author and UAB students. Eight categories of soils were tested, with about 15 to 20 individual tests conducted in each of eight categories (comprising a full factorial experiment). Numerous replicates were needed in each category because of the expected high variation in infiltration rates. The eight categories tested were as follows:

Category	Soil Texture	Compaction	Moisture
1	Sand	Compact	Saturated
2	Sand	Compact	Dry
3	Sand	Non-compact	Saturated
4	Sand	Non-compact	Dry
5	Clay	Compact	Saturated
6	Clay	Compact	Dry
7	Clay	Non-compact	Saturated
8	Clay	Non-compact	Dry

Figure A-31 contains plots showing the interactions of moisture and compaction on infiltration for both soil texture conditions. Four general conditions were observed to be statistically unique:

- noncompact sandy soils
- compact sandy soils

- noncompact and dry clayey soils
- all other clayey soils

Compaction has the greatest effect on infiltration rates in sandy soils, with little detrimental effects associated with soil moisture. Clay soils, however, are affected by both compaction and moisture. Compaction is seen to have about the same effect as moisture on these soils, with saturated and compacted clayey soils having very little effective infiltration. In most cases, the mapped soils were similar to what was actually measured in the field. However, significant differences were found at many of the 146 test locations. Table A-4 shows that the 2-hour averaged infiltration rates and their COVs in each of the four major categories were about 0.5 to 2. Although these COV values are generally high, they are much less than if compaction was ignored. These data are being fitted to conventional infiltration models, but the high variations within each of the four main categories makes it difficult to identify legitimate patterns, implying that average infiltration rates within each event may be most suitable for predictive purposes. The remaining uncertainty can be considered using Monte Carlo components in runoff models. More detailed analyses of these data will be presented in the Toronto stormwater modeling conference next year.

Table A-4. Infiltration Rates for Different Soil Texture, Moisture, and Compaction Conditions

	Number of tests	Average infiltration rate (in/hr)	COV
noncompact sandy soils	29	17	0.43
compact sandy soils	39	2.7	1.8
noncompact and dry clayey soils	18	8.8	1.1
all other clayey soils	60	0.69	2.1

Very large errors in soil infiltration rates can easily be made if published soil maps and typical models are used for typically disturbed urban soils. Knowledge of compaction (which can be mapped using a cone pentrometer, or estimated based on expected activity on grassed areas) can be used to much more accurately predict stormwater runoff quantity.

Basic Characteristics of the Small Storm Hydrology Model

Figure A-29 earlier showed the small storm hydrology model which describes the shape of the relationship between rainfall and runoff. Both small-scale and large-scale tests, described by Pitt (1987), obtained data to calibrate and verify this model for homogeneous impervious and pervious areas. The runoff response curve shown on Figure A-29 departs from the x-axis at the rainfall depth when runoff begins (r_0). This depth lag corresponds to initial runoff losses. After some rain depth (r_1), runoff losses become insignificant. For impervious areas, this is when the detention storage volume becomes filled, evaporation becomes insignificant due to pavement cooling, infiltration through the pavement or through cracks slows practically to nothing, and dirt and debris become saturated. Between these two rain depths, infiltration losses occur.

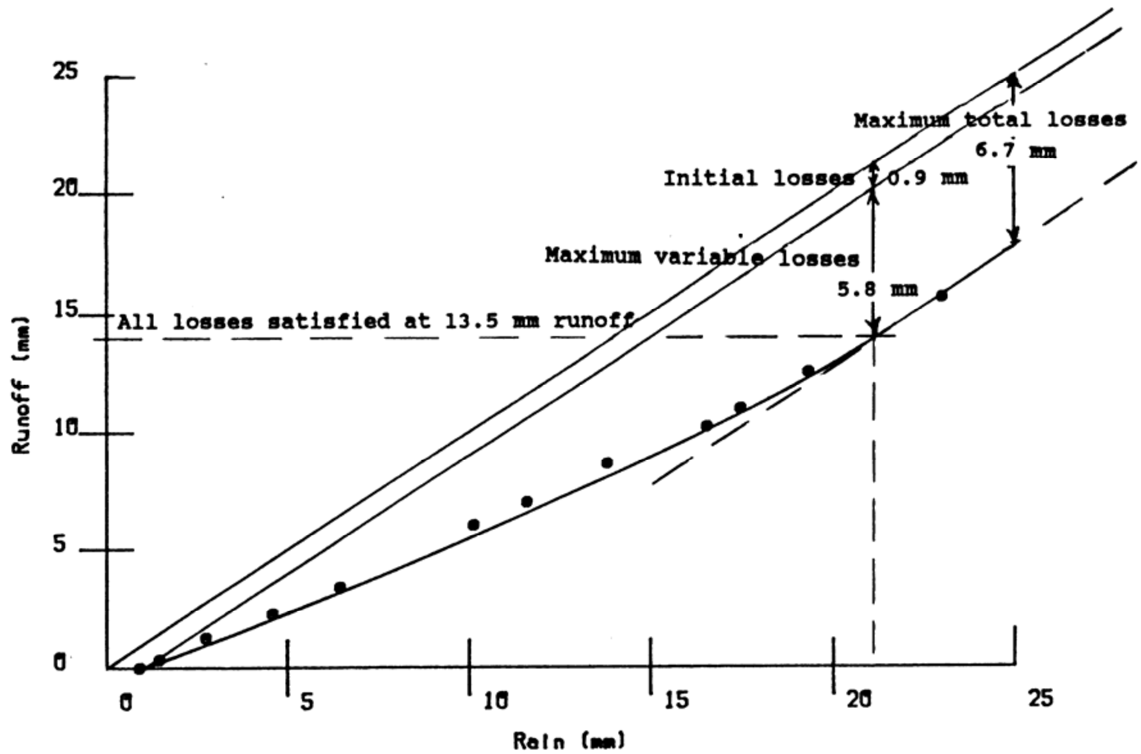


Figure A-29. Example pavement test runoff-rainfall plot for high intensity rains, clean and rough streets (Pitt 1987).

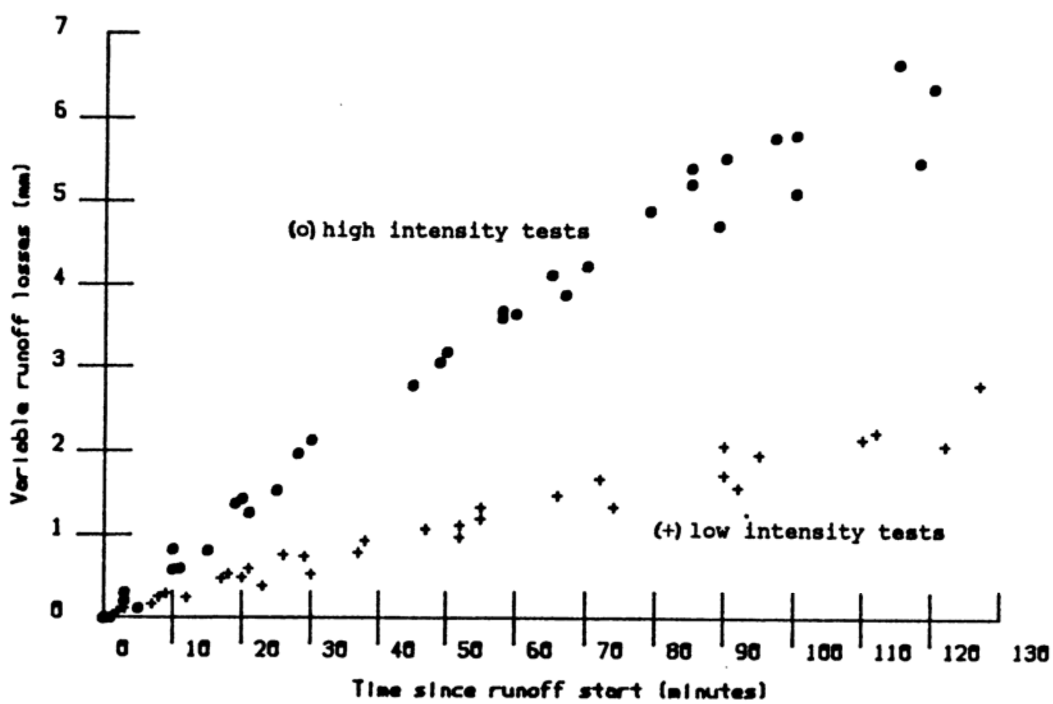


Figure A-30a. Pavement infiltration rates for time since start of rain (Pitt 1987).

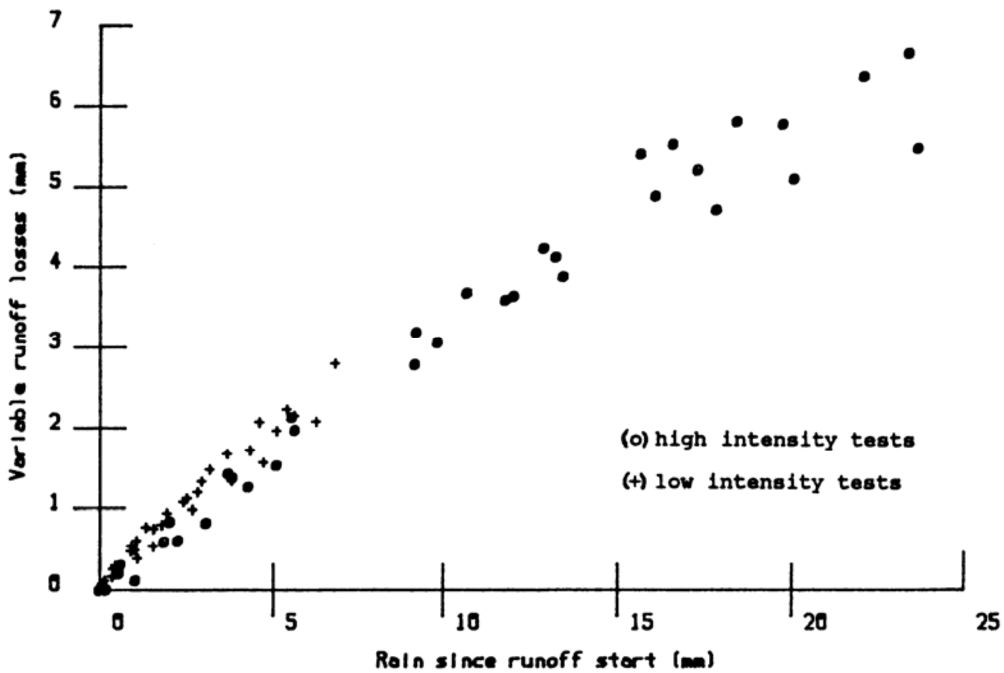


Figure A-30b. Pavement infiltration rates for rain depth since start of rain (Pitt 1987).

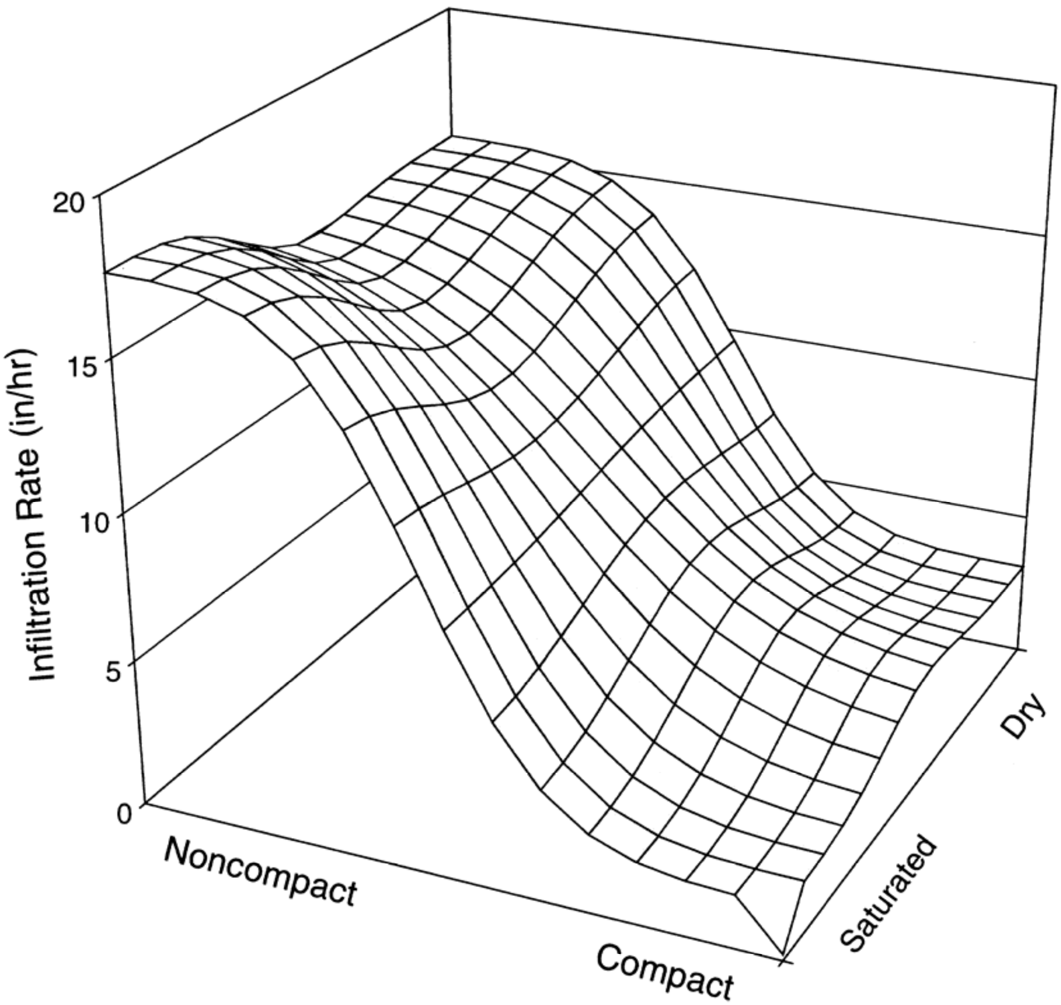


Figure A-31. 3-D plots showing interactions affecting infiltration rates in sandy soils.

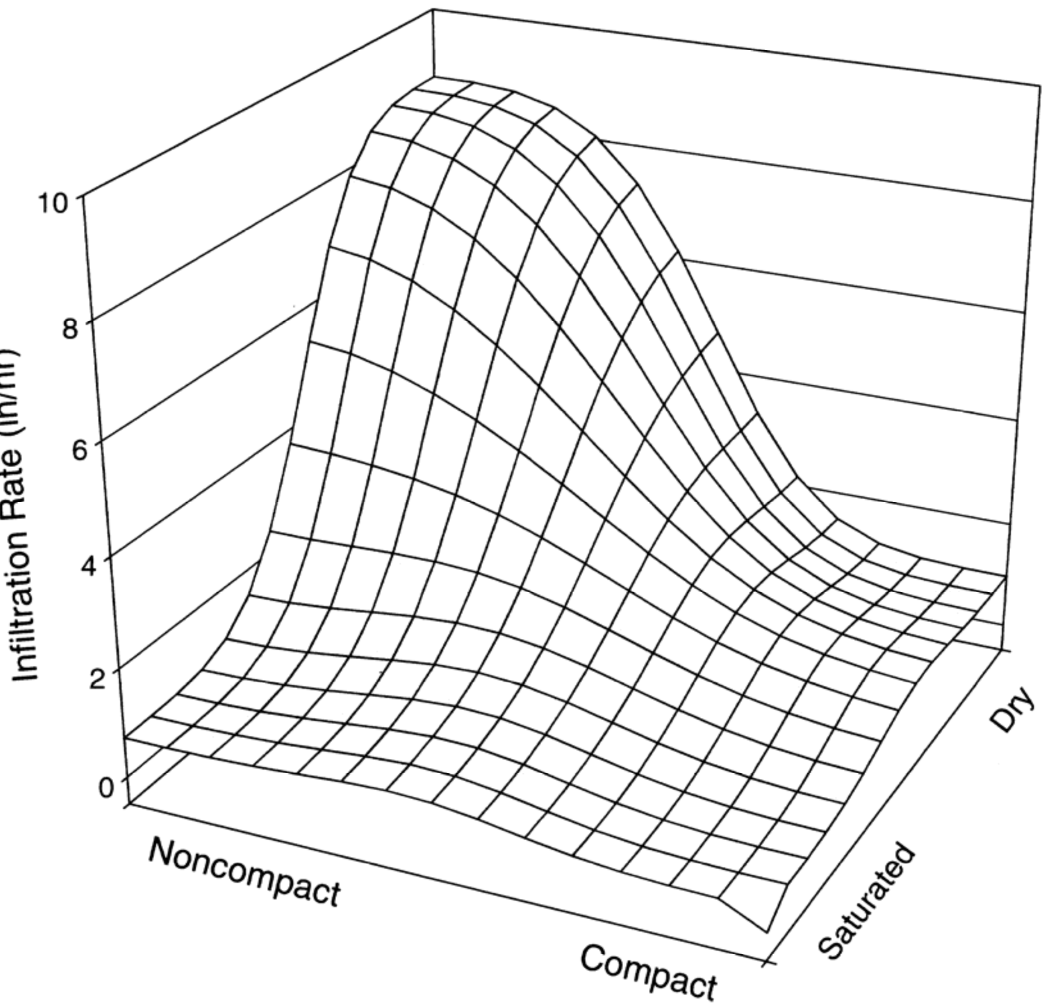


Figure A-32. 3-D plots showing interactions affecting infiltration rates in clayey soils.

Both small-scale and large-scale tests, described by Pitt (1987), obtained data to calibrate and verify a model for homogeneous impervious and pervious areas. The runoff response curve departs from the x-axis at the rainfall depth when runoff begins. This depth lag corresponds to initial runoff losses (detention storage, evaporation losses due to pavement cooling, and dirt and debris absorbing moisture for pavements). After some rain depth, infiltration into the ground (or pavement or through cracks) slows practically to nothing, and each additional increment of rainfall results in a similar increment of runoff. Between these two rain depths, infiltration losses occur. Figure A-33 shows the model describing these infiltration losses. This figure plots cumulative variable runoff losses (F, inches or mm), ignoring the initial losses, versus cumulative rain (P, inches or mm), after runoff begins. The slope of this line is the instantaneous variable runoff loss (infiltration) occurring at a specific rain depth after runoff starts. A simple nonlinear model can be used to describe this relationship which is similar to many other infiltration models. For a constant rain intensity (i), total rain depth since the start of runoff (P), equals intensity times the time since the start of runoff (t). The small storm hydrology nonlinear model for this variable runoff loss (F) is therefore:

$$F = bit + a(1 - e^{-git}) \quad \text{or} \quad F = bP + a(1 - e^{-gP})$$

Three basic model parameters were used to define the model behavior, in addition to initial runoff losses and rain depth: “a”, the intercept of the equilibrium loss line on the cumulative variable loss axis; “b”, the rate of the variable losses after equilibrium; and “g”, an exponential coefficient. If variable losses are zero at equilibrium, then “b” would be zero. Because this plot does not consider initial runoff losses, the variable loss line must pass through the origin. This model reduces to the SCS model when the “b” value is zero and “a” is S’, and when Ia is 0.16 (80% of 0.2) of “a”. This general model also reduces to the Horton equation when cumulative rain depth since the start of the event is used instead of just time since the start of rain.

Observed runoff data from both small- and large-scale tests were fitted to this equation to determine the values for a, b, and g for observed i and t (or P), and F values. In addition, outfall runoff observations from many different heterogeneous land uses were used to verify the calibrated model (Pitt 1987).

Comparison of the Small Storm Hydrology Model with the Horton Infiltration Equation

The Horton equation is used in many urban runoff models to predict infiltration losses (Skaggs, *et al*. 1969). The small storm hydrology model can be directly compared to the Horton infiltration equation. The total storm infiltration rate is:

$$F = \int F(t)dt$$

where F(t) is an instantaneous infiltration rate. The instantaneous infiltration rate is then:

$$F(t) = df/dt.$$

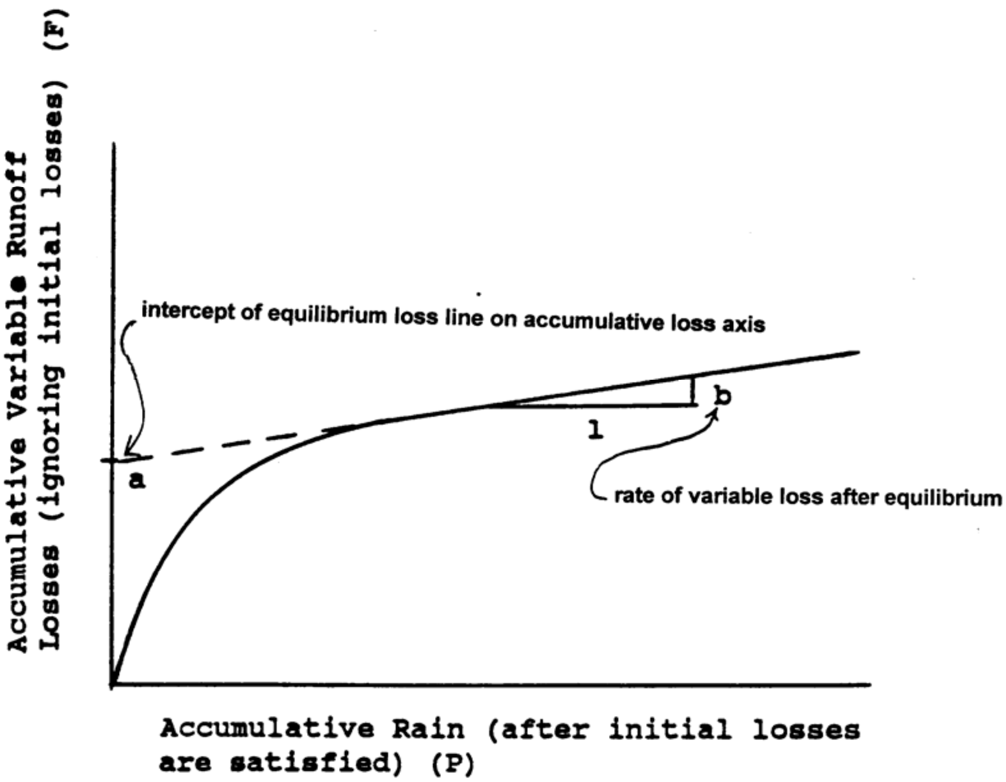
From the small storm hydrology model:

$$F(t) = bi + agi(e^{-git}).$$

Therefore, the Horton infiltration equation is:

$$F(t) = Fc + (Fo - Fc)(e^{-kt}),$$

where Fc is the final equilibrium infiltration rate, Fo is the initial infiltration rate, k is the decay coefficient, and t is the time since the rain began. Therefore the small storm hydrology model and the Horton equation are equivalent if the following relationships are simultaneously true:



$$F = bP + a(1 - e^{-gP})$$

where F = accumulative variable losses

g = exponential coefficient

P = accumulated rainfall

If b = 0, then a = total losses and no steady state losses occur (equivalent to SCS model)

Note: time since runoff started is not a factor (as implied by most users of Horton equation).

Figure A-33. Small storm rainfall-runoff infiltration model (ignoring initial abstractions) (Pitt 1987).

$bi = Fc$, or $b = Fc/i$

$-git = -kt$, or $g = k/i$

$agi = Fo - Fc$, or $a = (Fo - Fc)/gi$, or $a = (Fo - Fc)/k$.

Rearranging gives:

$Fc = ib$ (if Fc is zero, then b is also zero),

$Fo = ib + aig = i(b + ag)$, and

$k = ig$.

Based on these relationships, it is seen that the time since runoff began (t) is not a factor in determining any of the Horton infiltration parameters; but rain intensity (i) is a factor.

During the small-scale pavement runoff tests (Pitt 1987), the measured accumulative infiltration rates for the high rain intensity tests were much greater than for the low rain intensity tests for the same time since the start of the rain. The infiltration rates (depth per time) were therefore much greater for the high intensity tests. In urban hydrology studies, infiltration losses in pervious areas are usually considered to be the most important loss mechanism (Hromadka 1982). The previous discussion shows that infiltration is also an important loss mechanism for pavements. Simple infiltration estimation methods have received much attention in runoff analyses (Singh and Buapeng 1977). Singh and Buapeng found that errors in infiltration estimation may be large and may therefore be responsible for major errors in runoff predictions. One of the possible sources of infiltration estimation errors is the general lack of consideration of the apparent relationship between infiltration rate and rain intensity.

The relationship between rain intensity and infiltration can be related to the concept of variable contributing areas in heterogeneous watersheds. Areas having low infiltration capacities produce runoff during rains having relatively low intensities, while greater intensity rains are required to produce runoff from areas having high infiltration capacities. Therefore, an overall area infiltration rate appears to be variable and dependent on rain intensity. These variations have not been reported in the literature for homogeneous areas (such as large paved areas). However, infiltration in pavement “systems” includes infiltration through the pavement itself, infiltration through pavement cracks and seams, and infiltration through the pavement base. These different processes would have different infiltration rates; infiltration analysis for the whole system would therefore be intensity dependent.

Comparison of the Small Storm Hydrology Model with the NRCS Curve Number Procedure

The Natural Resources Conservation Service curve number procedure (SCS 1986) is commonly used in the design of storm drainage systems. The following paragraphs illustrate how the small storm hydrology model can interface with models using curve numbers. The small storm hydrology model can be used to select curve numbers, allowing the better incorporation of the mutual drainage and flood control benefits of many water quality control measures into the design of storm drainage systems (Pitt 1987).

The NRCS CN procedure can also be compared with the small storm hydrology model and the Horton infiltration equation. The small storm hydrology model can be rewritten, knowing that $P = it$ so that $F = bP + a(1 – e^{-gP})$. However, the NRCS procedure assumes that the final equilibrium infiltration rate is zero ($Fc = 0$), therefore b is also zero, leaving: $F = a(1 - e^{-gP})$. When b is zero, the intercept of the runoff loss line is equal to the maximum runoff losses, ignoring initial runoff abstractions. Therefore, the NRCS S' value (maximum variable loss, without Ia, the initial abstractions) can be substituted for “a” in this equation:

$$F = S'(1 - e^{-gP}).$$

There is a distinct relationship between S and CN [$CN = 1,000/(S + 10)$], and therefore between S' (which is assumed to be equal to 0.8S by the NRCS) and CN in the NRCS procedure. Therefore, each curve number has a unique S' value. Because the NRCS CN procedure assumes zero final infiltration, the small storm hydrology model b value is zero and the "a" value is equal to S', as shown above. The small storm hydrology model g value was determined using a nonlinear computer program (the NONLIN module of SYSTAT - The System for Statistics, Version 3, 1986, from SYSTAT, Inc., Evanston, Ill.) for the specific F verses P relationships unique for each curve number (and S' value). The maximum runoff loss, S', which ignores initial abstractions, occurs after little rain for large curve numbers, but is not reached even after 90 mm of rain for curve numbers less than about 80.

Table A-5 shows the fitted small storm hydrology model equation parameter g values for several curve number values, using SYSTAT's NONLIN module. This table also shows the NRCS S' values and the Horton initial infiltration rate (Fo) and decay coefficients (k) for these curve numbers. According to the small storm hydrology model, the Horton equation parameters are all related to rain intensity for impervious surfaces, and the small storm hydrology model g parameter is directly related to the curve number (Pitt 1987).

Table A-5. Small Storm Hydrology Model and Horton Infiltration Equation Parameters for Different NRCS Curve Number Values (Pitt 1987)

Curve Number	Fitted g from hypothesized model	SCS S' Value (ignores Ia) (mm)[1]	Initial Horton Infiltration Rate (Fo) (mm/hr)[2]	Horton Equation Decay Coefficient (k)[3] (1/hr)
99	0.22	2.03	0.45i	0.22i
95	0.042	10.7	0.45i	0.042i
90	0.022	22.6	0.50i	0.022i
85	0.016	35.8	0.57i	0.016i
80	0.012	50.8	0.61i	0.012i
75	0.010	67.8	0.67i	0.010i
70	0.0081	87.4	0.71i	0.0081i
60	0.0057	136	0.78i	0.0057i
50	0.0041	203	0.83i	0.0041i
40	0.0029	305	0.88i	0.0029i

(1) S' = 0.8S assumed by SCS. S' also equals a.
(2) Fo = S'gi, where i equals rain intensity (mm/hr).

Note: The SCS curve number procedure assumes that the final infil tration rate (Fc) is zero.

(3) K = gi, or Fo/S'

Volumetric Runoff Coefficients can be Calculated for Different Surfaces and Rains using the Small Storm Hydrology Model

Table A-6 is a summary of the volumetric runoff coefficients (Rv, the ratio of runoff to rainfall volume) for different urban surfaces and rain depths from detailed source area runoff tests and through calibrating the small storm hydrology model (Pitt 1987). Flat roofs and unpaved parking areas behave strangely similar because of similar detention storage volumes and no infiltration. Large impervious areas have the largest runoff yields because of very poor pavement under-drainage. The drainage path through the pavement base is relatively thin and very long, making it very difficult for infiltrated water to drain from the base. Street widths are much narrower than the widths of large impervious areas and the base water can drain much more effectively. Pitched roofs have no infiltration rates, but do experience limited initial losses associated with flash evaporation and sorption of moisture in leaves and other roof or gutter debris. After three inches (no longer a "small" rain) the runoff yields from all impervious surfaces are similar (within 10%), but the differences can be very large for the small rains of most concern in water quality evaluations.

Table A-6. Summary of Volumetric Runoff Coefficients for Urban Runoff Flow Calculations (Pitt 1987).

Rain Depth		Runoff Coefficients for Directly Connected Areas:						
mm	inches	Flat roofs* (or large unpaved parking areas)	Pitched roofs*	Large impervious areas*	Small impervious areas and streets	Sandy soils	Typical urban soils	Clayey soils
1	0.04	0.00	0.25	0.93	0.26	0.00	0.00	0.00
3	0.12	0.30	0.75	0.96	0.49	0.00	0.00	0.00
5	0.20	0.54	0.85	0.97	0.55	0.00	0.05	0.10
10	0.39	0.72	0.93	0.97	0.60	0.01	0.08	0.15
15	0.59	0.79	0.95	0.97	0.64	0.02	0.10	0.19
20	0.79	0.83	0.96	0.97	0.67	0.02	0.11	0.20
30	1.2	0.86	0.98	0.98	0.73	0.03	0.13	0.22
50	2.0	0.90	0.99	0.99	0.84	0.07	0.16	0.26
80	3.2	0.94	0.99	0.99	0.90	0.15	0.24	0.33
125	4.9	0.96	0.99	0.99	0.93	0.25	0.35	0.45

*If these "impervious" areas drain for a significant length across sandy soils, the sandy soil runoff coefficients will usually be applied to these areas, however, if these areas drain across typical, or clayey soils, the runoff coefficients will be reduced, depending on the land use and rain depth, according to the following table:

	Reduction factors for different rain depths (mm):									
	1	3	5	10	15	20	30	50	80	125
Strip commercial and shopping centers:	0.00	0.00	0.47	0.90	0.99	0.99	0.99	0.99	0.99	0.99
Other medium to high density land uses, with alleys:	0.00	0.08	0.11	0.16	0.20	0.29	0.46	0.81	0.99	0.99
Other medium to high density land uses, without alleys:	0.00	0.00	0.11	0.16	0.20	0.21	0.22	0.27	0.34	0.46

If low density land uses, use typical or clayey soil runoff coefficients.

The impervious and roof area values are for directly connected surfaces. If runoff is allowed to drain across grass areas, then the runoff yield may significantly decrease. However, sufficient length of drainage across the pervious surface in good condition is needed. For a relatively small paved surface, short pervious drainage paths are all that are needed. If the paved area is large, or if the pervious area has clayey or compacted soils, then much longer drainage paths are needed before significant infiltration occurs.

Table A-6 does not accurately incorporate the effects of disturbed urban soils presented earlier, but the runoff coefficients shown generally bracket the range of likely conditions expected. Some users have had good success using an intermediate soil Rv value, half way between the clayey and sandy soil conditions shown, and only using the extreme values for more unusual cases. The four urban soil categories identified earlier better represent the conditions encountered, and appropriate coefficients are currently being developed.

The runoff coefficients and indirect connection correction values were determined from calibrating the small storm hydrology model for large urban watersheds having variable complexities in Toronto and in Milwaukee (Pitt 1987). The first calibrations were conducted for simple areas. The first area was the large parking area of a commercial shopping area. The runoff coefficients for this area were used to determine the runoff relationships from large flat roofs from another shopping area that was made of mostly paved large parking and roof areas in order to determine runoff characteristics for flat roofs. The next step was to evaluate runoff data for two high density residential areas that had very little pervious areas and had all of the impervious areas directly connected. The street runoff was subtracted from the total area runoff observations to obtain information solely for pitched roofs. Finally, two medium density residential areas were studied in areas that had clayey soils and all of the impervious areas were directly connected. Roof, street and other impervious area runoff information was subtracted to obtain clayey soil runoff coefficients. Similarly, a medium density residential area was studied in an area having sandy soils to obtain sandy soil runoff coefficients. Finally, two medium density residential areas having unconnected impervious areas were studied to obtain correction coefficients.

Excellent Verification of Small Storm Hydrology Model for Many Conditions

The final runoff coefficients were verified using additional runoff data from these same areas (that were not used in the calibration efforts) and from areas located elsewhere. Figures A-34 through A-37 show how well the small storm hydrology model works over a wide range of rain depths and for two very different land uses. The “Post Office” site was a commercial shopping center, the “Burbank” site was a medium density residential area. These sites were monitored as part of the EPA’s NURP project in Milwaukee (Bannerman, *et al.* 1983). Figures A-36 and A-37 are for two residential sites monitored by the WI DNR in Superior, WI, and in Marquette, MI, during 1993 and 1994. These last two sites were compared to the small storm hydrology component of SLAMM with no local calibration, demonstrating the excellent fit of observed and predicted flows.

The model was subsequently calibrated for these two sites to enable better fits for the larger events. It was originally expected that this model would not work very well for very large storms, especially in areas having appreciable pervious areas, where rain intensity was expected to have a more significant effect on infiltration than for small rains. The largest rains observed for the two Milwaukee sites were greater than three inches, a very large rain that would not be expected to commonly occur. Even these rains had runoff quantities that were well predicted by this runoff model.

Example Application using the Small Storm Hydrology Model

The small storm hydrology model can be used to predict runoff volume yields for many different land uses and development conditions. It was specifically developed to determine runoff yields and corresponding water pollutant yields for small storms for stormwater quality investigations. As shown during the verification process, it is also useful for predicting runoff yields for moderate storms that are used for drainage design. If used in conjunction with a model that can account for water losses associated with stormwater controls (such as SLAMM, the Source Loading and Management Model, Pitt 1986 and 1992) it can also be used to show the mutual drainage benefits associated with these controls. As an example, the use of roadside swales, disconnections of impervious areas from the drainage system, or using infiltration devices, can all have dramatic benefits in reducing runoff volumes, even for relatively large rains.

The small storm hydrology model can be used to predict runoff yields associated with different land uses and development practices. It can also be used to predict sources of water within the drainage area. If the variable quality of runoff from each source area is known, then runoff pollutant yield estimates (and reductions) can also be made. SLAMM uses this approach. This information is very important when determining the best management strategy for water volume and runoff pollutant reduction. This example problem shows how the runoff yield predictions and sources of water for a simple area can be predicted for different rain depths. The benefits of source area disconnections are also shown.

Predicting Runoff Yields from Different Source Areas

- Calculate runoff quantity (inches) and distributions (%) by source area for the following conditions:

  - Rain depths: 0.12; 0.79; 3.2 inches
  - Medium density residential area (conventional curb and gutters, all impervious areas are directly connected to the drainage system and clayey soils are common), having the following surface area distribution:

pitched roofs	6%
driveways	5
sidewalks	3
streets	12
front yards	45
back yards	29

- Calculations:

		0.12 inch (3 mm) rain			0.79 inch (20 mm) rain		
area:	%	Rv	weighted Rv	contrib-ution	Rv	weighted Rv	contrib-ution
roofs	6	0.75	0.045	31 %	0.96	0.058	17 %
driveways	5	0.49	0.025	17	0.67	0.034	10
sidewalks	3	0.49	0.015	10	0.67	0.020	6
streets	12	0.49	0.059	41	0.67	0.080	24
frontyards	45	0.00	0.00	0	0.20	0.090	24
backyards	29	0.00	0.00	0	0.20	0.058	17
Total:	100	n/a	0.14	100	n/a	0.34	100

The Rv values are from Table A-6 for the appropriate rain depths and source area. Weighted Rv values are determined by multiplying the Rv values by the percentage of the area represented. The weighted Rv values are summed to obtain a Rv value for the whole land use area. The percentage runoff yields are the ratios of the individual weighted Rv values to the summed whole area Rv.

- runoff for the 0.12 inch rain: (0.14)(0.12in)=0.017 in runoff
- runoff for the 0.79 inch rain: (0.34)(0.79in) = 0.27 in runoff
- similar calculations for the 3.2 inch rain results in a Rv of 0.48, therefore, the runoff for this rain: (0.48)(3.2 in) = 1.6 in runoff.

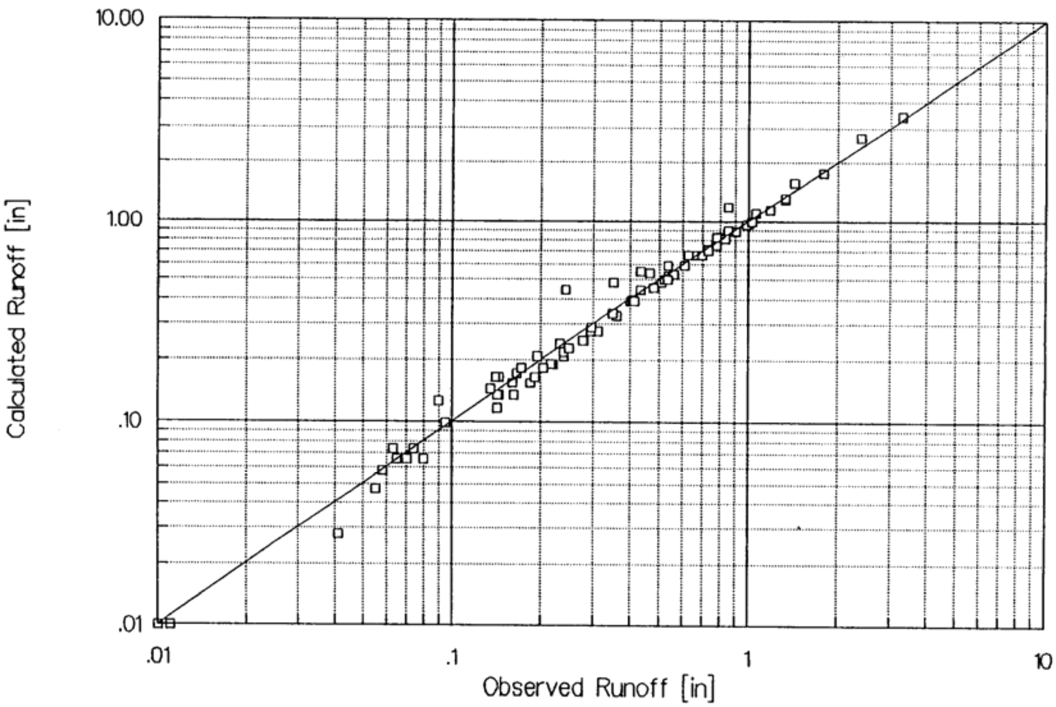


Figure A-34. Verification of SLAMM hydrology component – Post Office commercial site, Milwaukee, WI.

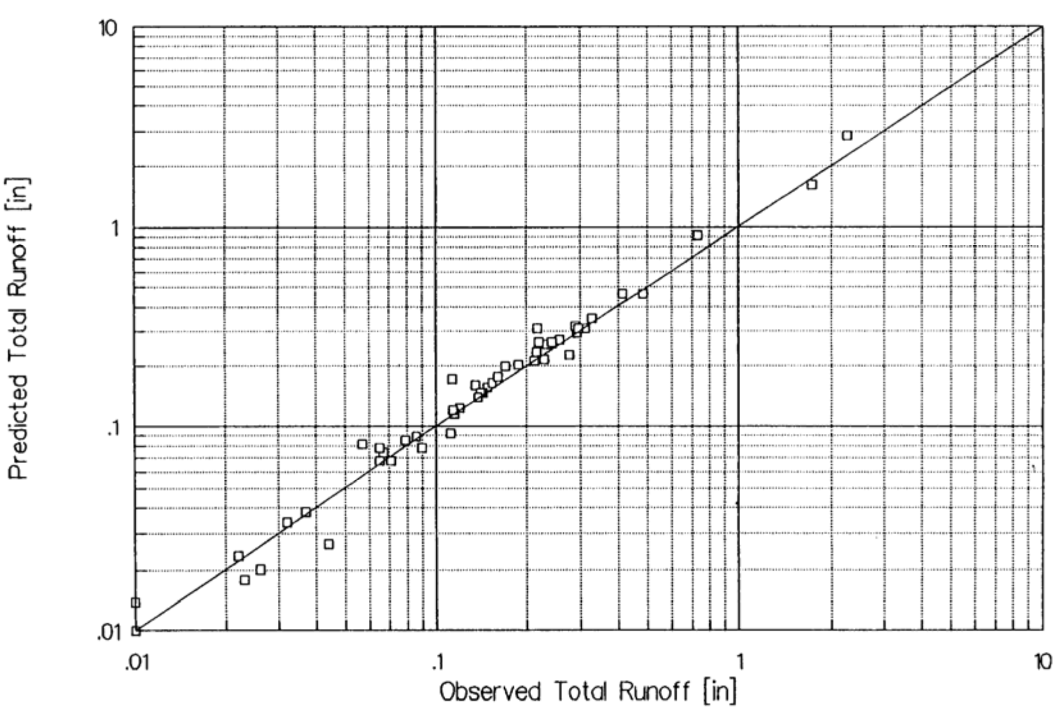


Figure A-35. Verification of SLAMM hydrology component – Burbank residential site, Milwaukee, WI.

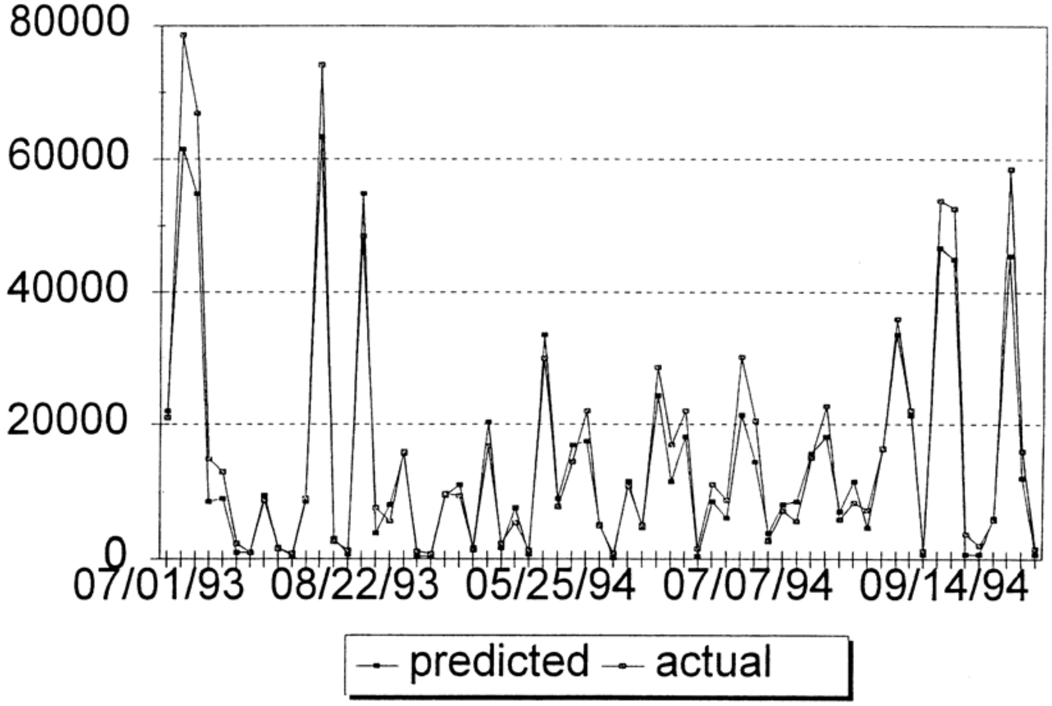


Figure A-36. Verification of SLAMM hydrology component – Superior, WI, test site.

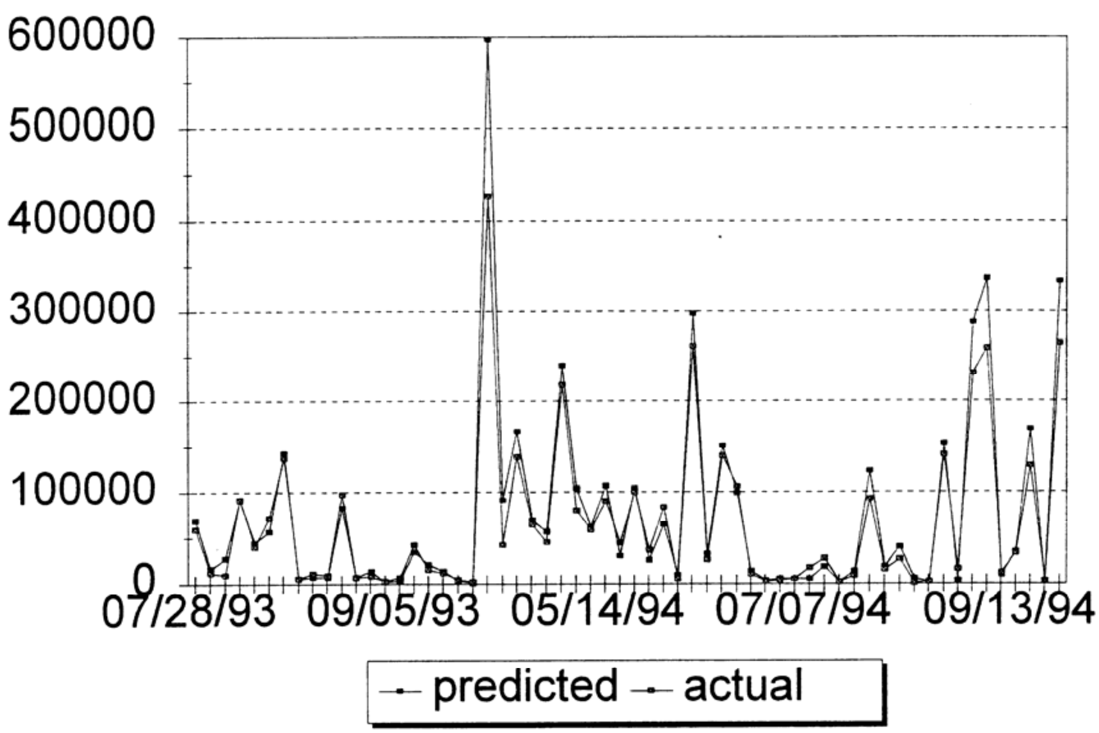


Figure A-37. Verification of SLAMM hydrology component – Marquette, MI, test site.

As the rain depth changes, the percentage contributions from each area also changes. For the smallest rain, all of the runoff is contributed from the directly connected impervious areas. However, pervious areas contribute almost half (44%) of the runoff for the 0.79 inch rain.

Benefits of source area drainage disconnections can also be predicted for this example. The following calculations show the effects of disconnecting all of the roof, driveway and sidewalk areas for this land use:

Original weighted Rv values:

	0.12" rain	0.79" rain	3.2" rain
roofs+ driveways+ walks	0.084	0.11	0.13
streets	0.059	0.08	0.11
yards	0	0.15	0.24
total Rv:	0.14	0.34	0.48
total runoff:	0.017"	0.27"	1.6"

With disconnections:

	0.12" rain	0.79" rain	3.2" rain
roofs+ driveways+ walks	(0)(0.084)= 0	(0.21)(0.11)= 0.023	(0.34)(0.13)= 0.044
streets	0.059	0.08	0.11
yards	0	0.15	0.24
total Rv:	0.06	0.25	0.39
total runoff:	0.01"	0.20"	1.3"
approx. % reduction:	60	25	20

The runoff contributions from the disconnected areas are decreased by the factors shown on Table A-6 for medium density areas (with no alleys) having clayey soils. These disconnections can have significant effects on the runoff quantities generated for small rains. The runoff reductions for the larger rain will also likely be important for drainage design. Similar percentage reductions in peak runoff rates are also expected for these conditions.

Conclusions

Runoff volume is the most important hydraulic parameter needed for most water quality studies, while peak flow rate and time of concentration are the most important parameters for most flooding and drainage studies. Common small rains account for much more of the annual runoff volume than rare flooding events. Pitt (1987) showed that estimates of runoff volume could be made with only rain depth information. Other rain characteristics (including antecedent conditions, durations, intensities, etc.) did not substantially improve runoff volume predictions, but are likely needed for peak flow rate predictions.

The literature indicates that both initial runoff abstractions (mostly detention/storage) and continuous runoff losses (infiltration) are important for impervious surfaces. Recent work with disturbed urban soils has also shown that care must be taken when using soil maps for developed conditions. The small storm hydrology model successfully predicts runoff from several types of paved, roofed, and disturbed soil urban surfaces. This model was shown to accurately predict runoff volumes for a wide range of rain conditions.

This model was used to examine long-term rain conditions at many locations throughout the U.S. to indicate the significance of small and moderate sized rains in stormwater management. These smaller rains, compared to the typical "design storm" rains used for drainage system design, contribute the vast majority of stormwater pollutants. Stormwater control practices must therefore effectively address these smaller storms to provide effective pollutant and flow reduction schemes.

References

Bannerman, R., K. Baun, M. Bohn, P.E. Hughes, and D.A. Graczyk. *Evaluation of Urban Nonpoint Source Pollution Management in Milwaukee County, Wisconsin*, Vol. I. PB 84-114164. US Environmental Protection Agency, Water Planning Division, November 1983.

Cedergren, H.R. *Drainage of Highway and Airfield Pavements*. John-Wiley and Sons, New York, 1974.

Davies, H. and T. Hollis. "Measurements of rainfall-runoff volume relationships and water balance for roofs and roads," *Second International Conference on Urban Storm Drainage*, Urbana, Illinois, June 1981.

EPA (U.S. Environmental Protection Agency). *Final Report for the Nationwide Urban Runoff Program*. Water Planning Division, Washington, D.C., December 1983.

Falk, J. and J. Niemczynowicz. "Characteristics of the above-ground runoff in sewered catchments." in *Urban Storm Drainage*. P.R. Helliwell, ed. John Wiley and Sons, New York, 1978.

Gregory. M. and W. James. "Management of time-series data for long-term, continuous modeling." *Advances in Modeling the Management of Stormwater Impacts*. pp. 115 – 151. Computational Hydraulics International, Guelph, Ontario. 1996.

Heaney, J.P., W.C. Huber, M.A. Medina, Jr, M.P. Murphy, S.J. Nix, and S.M. Hasan. *Nationwide Evaluation of Combined Sewer Overflows and Urban Stormwater Discharges, Volume II: Cost Assessment and Impacts*. EPA-600/2-77-064b. NTIS PB-266005. 363 pgs. U.S. Environmental Protection Agency. Cincinnati, Ohio. March 1977.

Hormadka, T.V. II. *Computer Methods in Urban Hydrology, Rational Methods and Unit Hydrograph Methods*. Lighthouse Publications, Anaheim, California, 1982.

Huber, W.C. *Urban Rainfall-Runoff-Quality Data Base: Addendum I: Statistical Analysis and Additional Data*. EPA-600/2-81-238, U. S. Environmental Protection Agency, Cincinnati, Ohio, 1981

Pitt, R. "The incorporation of urban runoff controls in the Wisconsin Priority Watershed Program." In: *Advanced Topics in Urban Runoff Research*, (Edited by B. Urbonas and L.A. Roesner). Engineering Foundation and ASCE, New York. pp. 290-313. 1986.

Pitt, R. *Small Storm Flow and Particulate Washoff Contributions to Outfall Discharges*. Ph.D. dissertation, Department of Civil and Environmental Engineering, the University of Wisconsin, Madison, 1987.

Pitt, R. and M. Bozeman. *Sources of Urban Runoff Pollution and Its Effects on an Urban Creek*. EPA-600/S2-82-090, U.S. Environmental Protection Agency, Cincinnati, Ohio, December 1982.

Pitt, R. and J. Voorhees. "Source loading and management model (SLAMM)." *Seminar Publication: National Conference on Urban Runoff Management: Enhancing Urban Watershed Management at the Local, County, and State Levels*. March 30 – April 2, 1993. Center for Environmental Research Information, U.S. Environmental Protection Agency. EPA/625/R-95/003. Cincinnati. Ohio. pp. 225-243. April 1995.

Pratt, C.J. and R.J. Henderson. "Overland flow and catchment characteristics," *Second International Conference on Urban Storm Drainage*, Urbana, Illinois, June 1981.

SCS (U.S. Soil Conservation Service). *Urban Hydrology for Small Watersheds*. U.S. Dept. of Agriculture Tech. Release No. 55 (revised), June 1986.

Singh, V.P. and S. Buapeng. "Effect of rainfall-excess determination on runoff computation." *Water Resources Bulletin*, Vol. 13, No. 3, June 1977.

Skaggs, R.W., L.E. Huggins, E.J. Monke and G.R. Foster. "Experimental evaluation of infiltration equations." *Transactions of the American Society of Agricultural Engineers*, pp 822-828. 1969.

Willeke, G.E. “Time in urban hydrology.” *Journal of the Hydraulics Division*, Proceedings of the American Society of Civil Engineers, Vol. 92, No. HY1, January 1966.

Appendix B
U.S. EPA Urban Rainfall-Runoff Quality Data, U.S. EPA/USGS NURP Data, and Ontario's TAWMS Data Plots EPA Urban-Rainfall-Runoff-Quality Data Base Analyses

Urban- Rainfall-Runoff Data Base

The Environmental Protection Agency's Urban Rainfall-Runoff-Quality Data Base contains data for over twenty five years, mostly collected by the USGS. Concerns about stormwater runoff quality and the environmental problems caused by combined sewer overflows prompted development of this database. Data collected through this program is intended to provide information with which to verify and calibrate computer drainage modeling programs.

Analyses Performed

In this appendix, data from representative sites contained in the Urban-Rainfall-Runoff-Quality Data Base have been used to examine some of the essential parameters used in drainage design methods, such as: the runoff coefficient (runoff volume/rain volume), the curve SCS number, and in some cases the relationship between rainfall peak intensity and runoff peak flow.

Rainfall-Runoff Relationship

Runoff depth compared to rainfall depth shows the amount of runoff that can be expected from an area based on the amount of rain it receives. The depth of runoff depends on the amount of impervious area, the soil types and several other parameters. Land use, because of its relationship to these parameters, is often used as an indicator of the amount of runoff produced by an area. Examination of actual rainfall and runoff relationships is an evaluation of the usefulness of this method. If the plotted relationship illustrates a reasonably smooth line, then simple method may be useful for this site. If a lot of data scatter exists, then other parameters (especially rain intensity variations, soil moisture, etc.) may play a significant role in determining runoff from that site. The sites examined represent a variety of land uses and geographical locations.

Rainfall-Runoff Coefficient Relationship

Runoff coefficients are often used to predict the amount of runoff an area will produce based on the rainfall amount. A runoff coefficient is generally selected based on the physical characteristics of the area. This coefficient is then used to predict the amount of runoff produced by the area in simplified prediction equations. Runoff coefficients were calculated using the data provided in the EPA data base. These coefficients were plotted against rain depth to indicate variations in their values. Deviations from the straight horizontal line indicate the magnitude of error when using this simple rainfall-runoff model.

Rainfall-Curve Number Relationship

The SCS (now NRCS) curve number method described in TR-55 has also been commonly used for drainage design. The curve number is similar to the runoff coefficient, in that it is used in a single parameter model to predict runoff from rain depth. The main difference is that the curve number increases with increasing rains. The curve number is generally selected from a table of land use and soil characteristics. The same curve number is used for all rains at that site. It is possible to calculate the actual curve number based on observed runoff depths and rain depths for a site. Curve numbers were calculated for sets of runoff and rain data from the EPA data base for each site, and plotted against rain depth. The deviations from a flat horizontal line indicate the magnitude of error likely when using this prediction method and also indicate the rain ranges having the greatest deviations from the established model.

Rainfall-Peak Flow/Peak Rain Relationship

Some of the sites included peak runoff rate and peak rainfall intensity data. The ratio of these rates were also plotted against rain depth. The ratios should be similar to the Rational Equation's coefficient "C" value, if the durations for these peak rates were at least the time of concentration of the site. The averaging periods for runoff and rainfall were likely at least 5 minutes and possibly as long as one hour, and were therefore likely longer that the expected time of concentrations for each site. The deviations of these plots from horizontal bands may indicate the magnitude of error associated with using the Rational equation.

Broward County, Florida, Residential Land Use

Climate

Broward County is located on the Southeastern coast of Florida. The climate of this area is semi-tropical with a considerable amount of rainfall. The average year round temperature is 77^{o}F with 3,000 hours of sunshine. Winter temperatures average 66^{o}F; summer temperatures average 84^{o}F. January is the coldest month and August is the hottest month of the year. A significant amount of the rainfall in this area occurs as late summer afternoon storms of high intensity and short duration. The heaviest rainfalls occur during August and September. Usually these storms last from 30 to 45 minutes. Tropical influences from the Atlantic Ocean and the Gulf of Mexico also influence the climate of the area. The topography is flat and low, with the area west of the coast containing the Everglades. Soils are sandy and the water table is high.

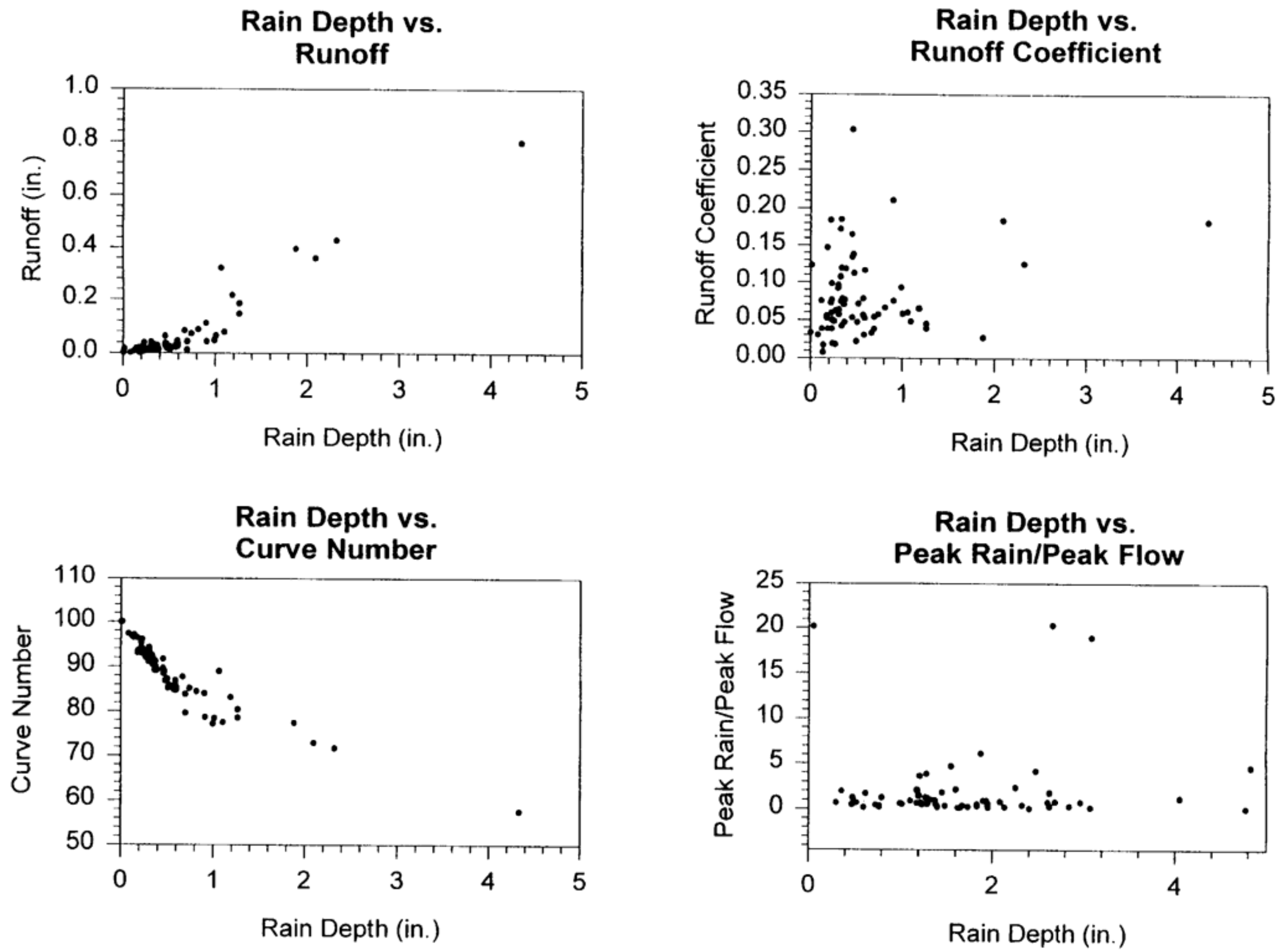
Site Description

The specific study area in this investigation was a 41 acre residential site. 40% of the area was impervious (roofs, driveways, and roads) and 60% was pervious. The pervious area consisted of mostly well maintained lawns. Population of the area was 351, with a total of 151 dwellings.

Data Collection Methodology

To collect rainfall data, three tipping bucket rain gauges having 0.01 inch per tip were used. USGS continuous flow automatic samplers monitored the flow at the outlet of the catchment. A total of seventy four storms were recorded over a seventeen month period. Water quality parameters were also monitored for these storm events. There was no information provided, however, as to the specific soil types, slopes, or channel sizes in the sampling area.

Broward County, Florida
Residential Land Use



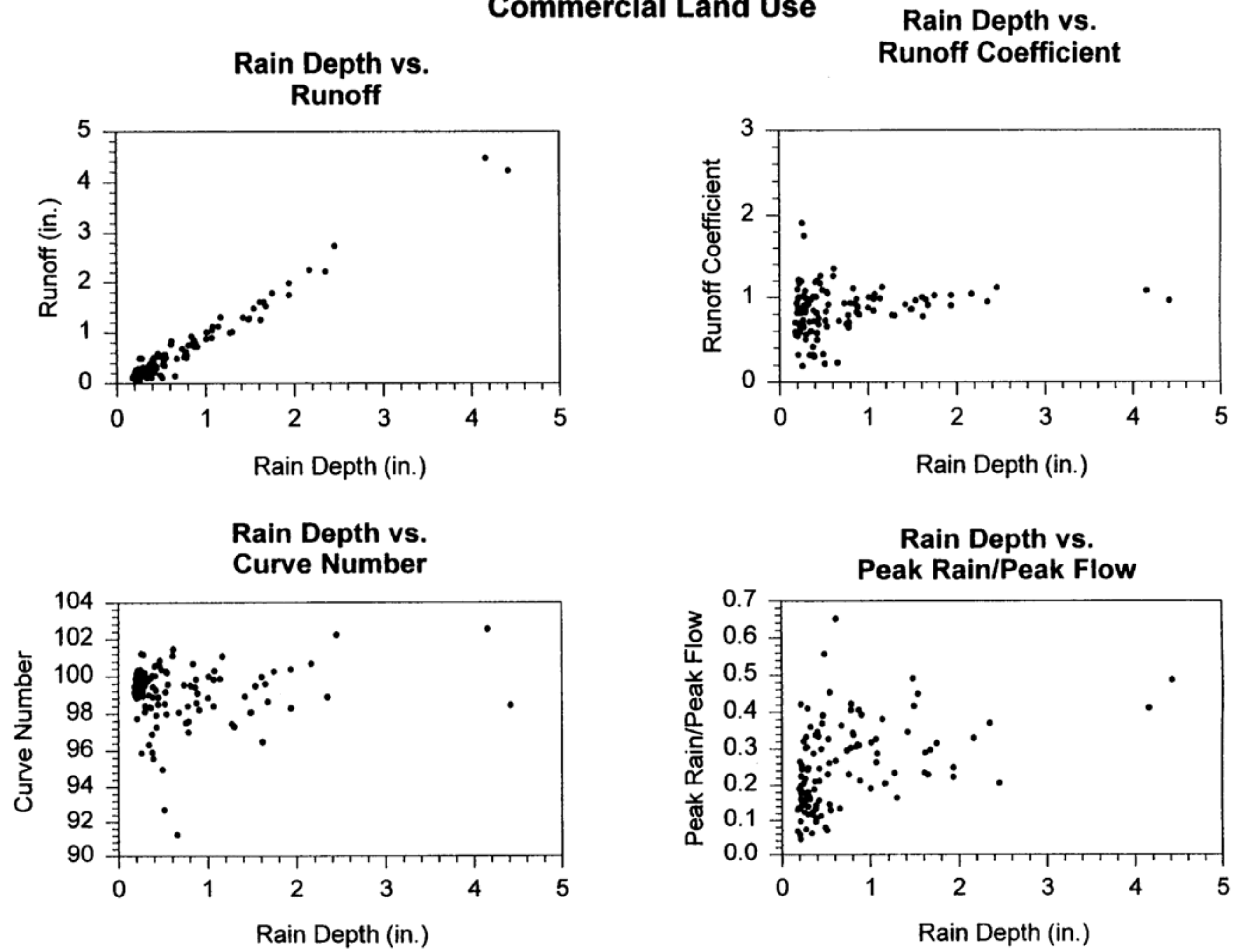
Broward County, Florida, Commercial Land Use

Climate
This rainfall-runoff study site was also located in Broward County, Florida. The climate and precipitation characteristics are described in the previous Broward County study report for the residential area.

Site Description
A commercial site, the Coral Ridge Shopping Plaza near NE 35th Street and US1, in northeast Broward County was monitored. The 28.4 acre area is 98.6% impervious (pavement and rooftops). The other 0.4 acres are covered with vegetation.

Data Collection Methodology
One tipping bucket rain gauge was used to measure rainfall in the area. The Weather Measure model P-501 gauge had a resolution of 0.01 inches per tip. Flow measurements were taken using a fiberglass U-shaped constriction mounted in 36 inch pipes that was calibrated in the laboratory. A nitrogen gas bubbler tube was used to measure the stage. 113 events were monitored during the seven month period of the study.

Broward County, Florida
Commercial Land Use



Broward County, Florida, Transportation Catchment

Climate

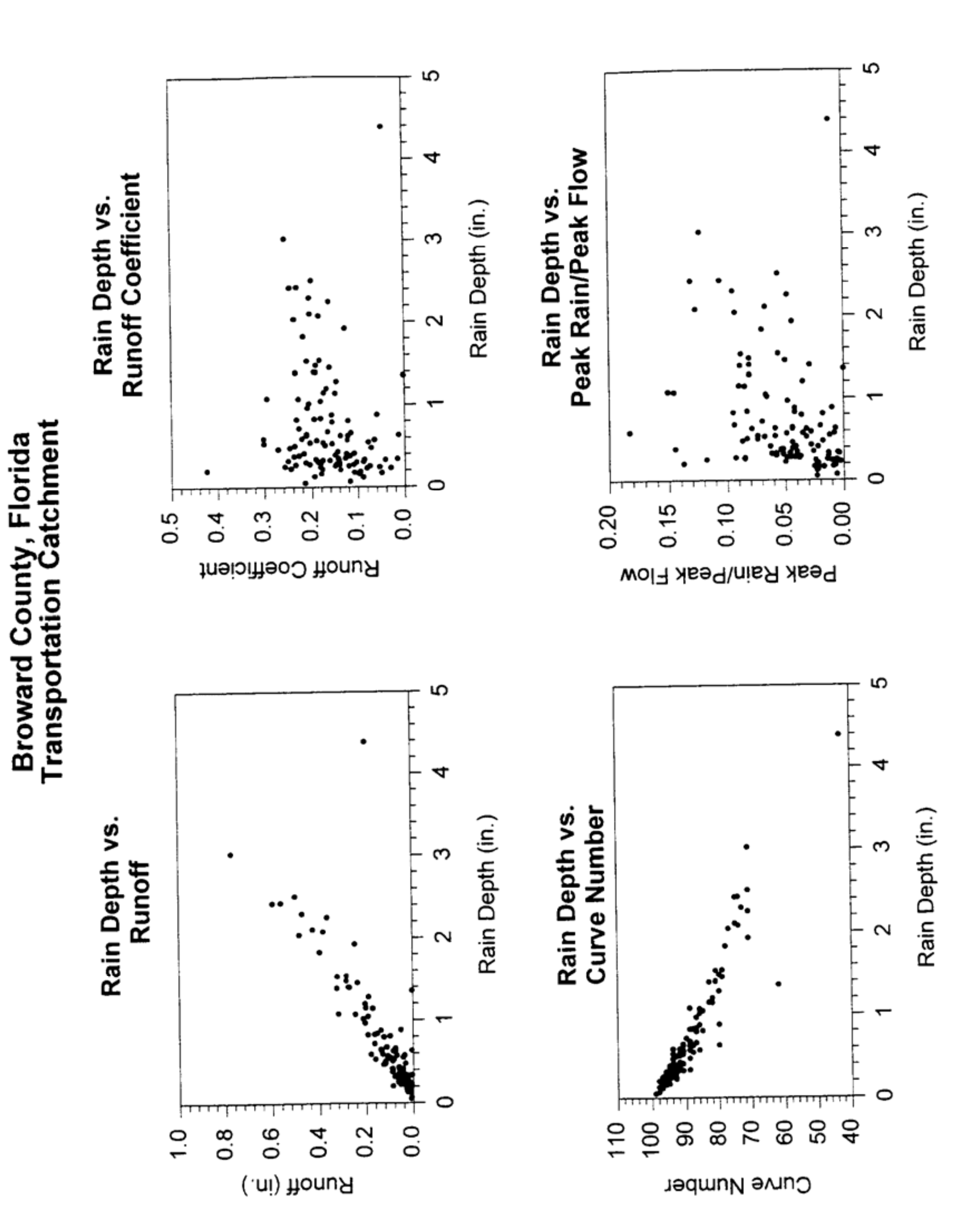
The climatic, topographic, and precipitation characteristics of this Broward County site are the same as previously described for the other Broward County sites.

Site Description

This site was a transportation catchment of 58.3 acres. The catchment surrounds Sample Road which is located between I95 and the Old Federal Highway. The basin in composed of 13.7 acres of roadways and parking lots, 24.3 acres of permeable lawns, and an acre of rooftop. Impervious area made up 21.1 acres while the hydraulically effective impervious area was 10.5 acres, these combine for a total impervious area of 54%.

Data Collection Methodology

Data was collected by the Water Resources Division of the Miami Office of the U.S. Geological Survey.


Broward County, Florida
Transportation Catchment
Rain Depth vs.
Runoff
Runoff (in.)
Rain Depth (in.)
Rain Depth vs.
Runoff Coefficient
Runoff Coefficient
Rain Depth (in.)
Rain Depth vs.
Curve Number
Curve Number
Rain Depth (in.)
Rain Depth vs.
Peak Rain/Peak Flow
Peak Rain/Peak Flow
Rain Depth (in.)

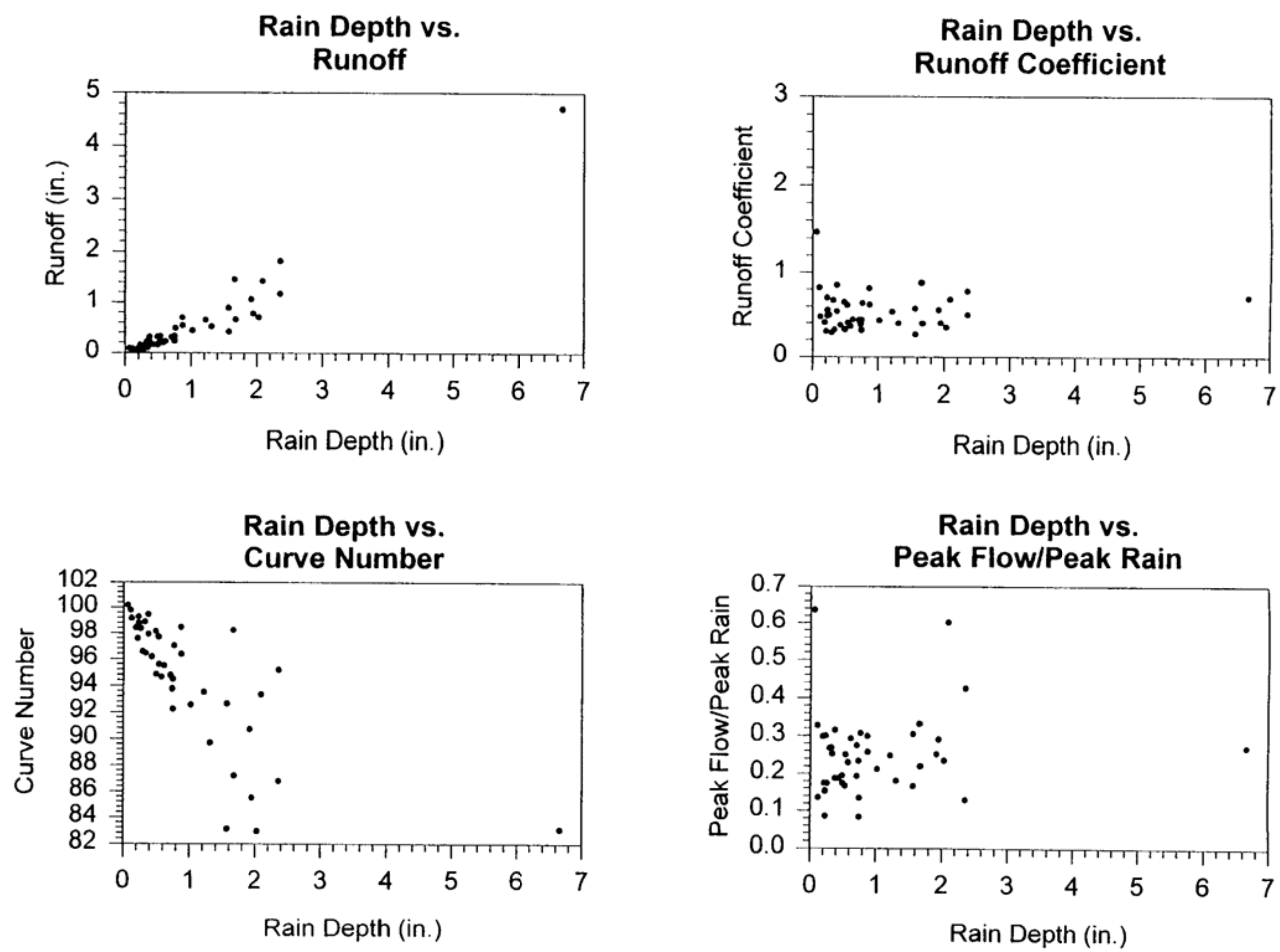
Dade County, Florida, High Density Residential Land Use

Climate
Dade County is located in South Florida near Miami. The climate of this area is semi-tropical with very warm summers and mild winters. Temperatures average in the 80s^{o}F in the summer and the 60s^{o}F in the winter. In the summers, precipitation is in the form of short intense storms and in the winter, storms are longer and less intense. The area is also occasionally affected by tropical weather events such as hurricanes. The land is flat with low elevations and sandy soils.

Site Description
The area of specific study for this project is Kings Creek Apartments located near the intersection of SW 77th Avenue and Camino Real in a densely urbanized area. The site consists of 14.7 acres of high density apartments. Impervious areas of pavement and rooftops make up the majority of the site. The pervious portions are covered with grass. Soils are hydraulic group D, with underlying limestone. The slopes of the area are nearly flat.

Data Collection Methodology
Rainfall measurements were taken with Weather Measure Model P-501 tipping gauge buckets with 0.01 inch resolution per tip. Two gauges collected the data for this area. A fiberglass U-shaped venturi-type constriction was mounted in 48 inch pipes. Stage measurements were made with a nitrogen gas bubbler tube. A total of 43 storms were monitored in the 13 month study period.

Dade County, Florida
High Density Residential Land Use



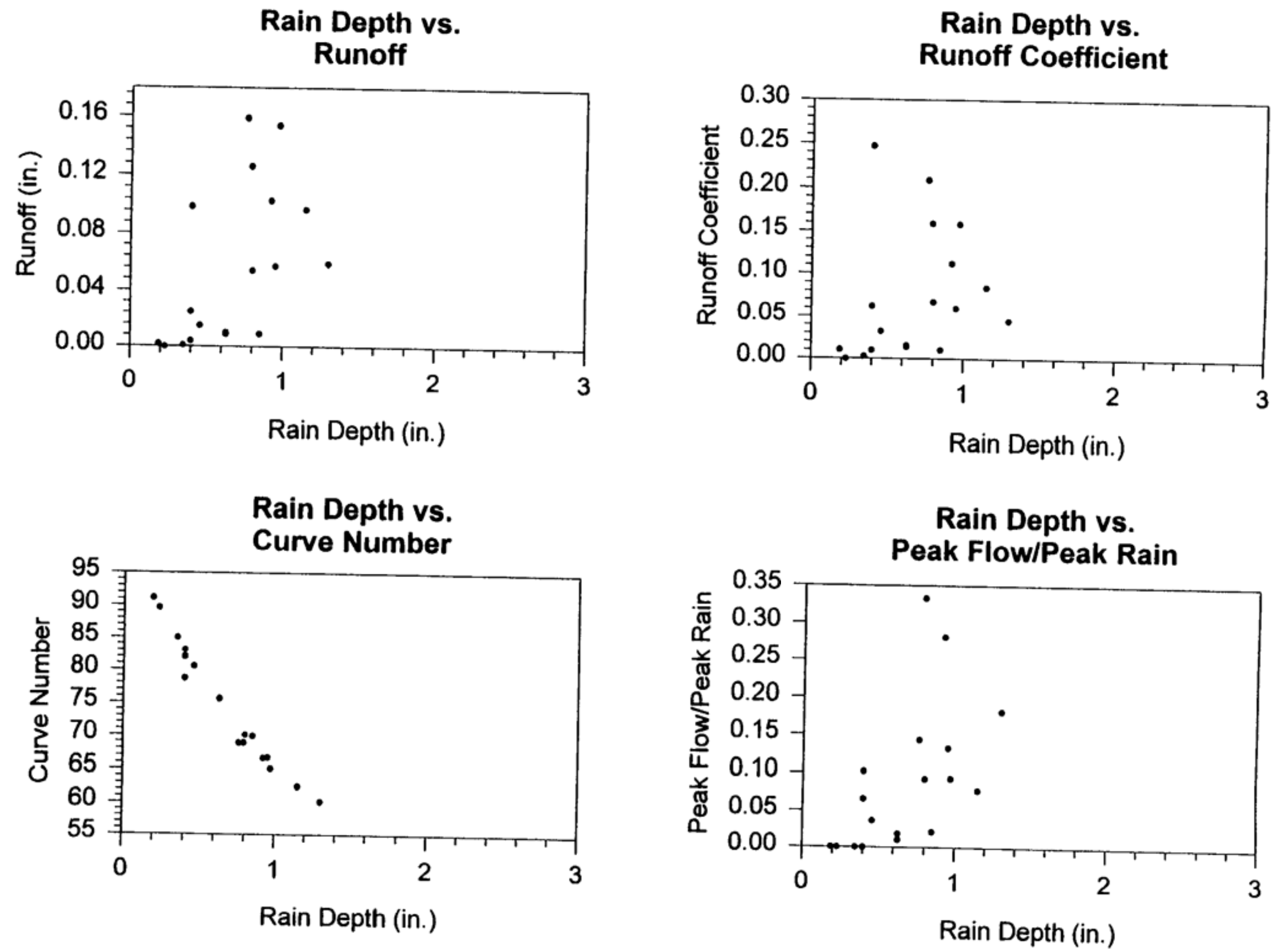
Salt Lake City, Utah, Roadway Catchment

Climate
This study site was located in Salt Lake City, Utah. Located in the northwestern United States, this area has cold winters and mild summers. It is bordered by the Rocky Mountains and is therefore influenced by weather patterns indicative of mountainous regions. Temperatures during the study period ranged from 74 to 28^{o} F.

Site Description
The Layton site is a 1.35 acre roadway catchment. The roadway is impervious and the sideslopes are either paved or grassed. Soil types in the area are well aggregated clay loams. A separate storm sewer serves the area.

Data Collection Methodology
Flow measurements at this site were taken continuously with a 90 degree bobbed tailed cutthroat flume calibrated in the laboratory. A Belfort 5-FW- I level recorder was used to take stage readings. Rainfall measurements were taken with a Belfort 5-780 dual traverse weighing recording gage. 23 storms were monitored during the period from September 1972 to November 1973.

Salt Lake City, Utah
Roadway Land Uses



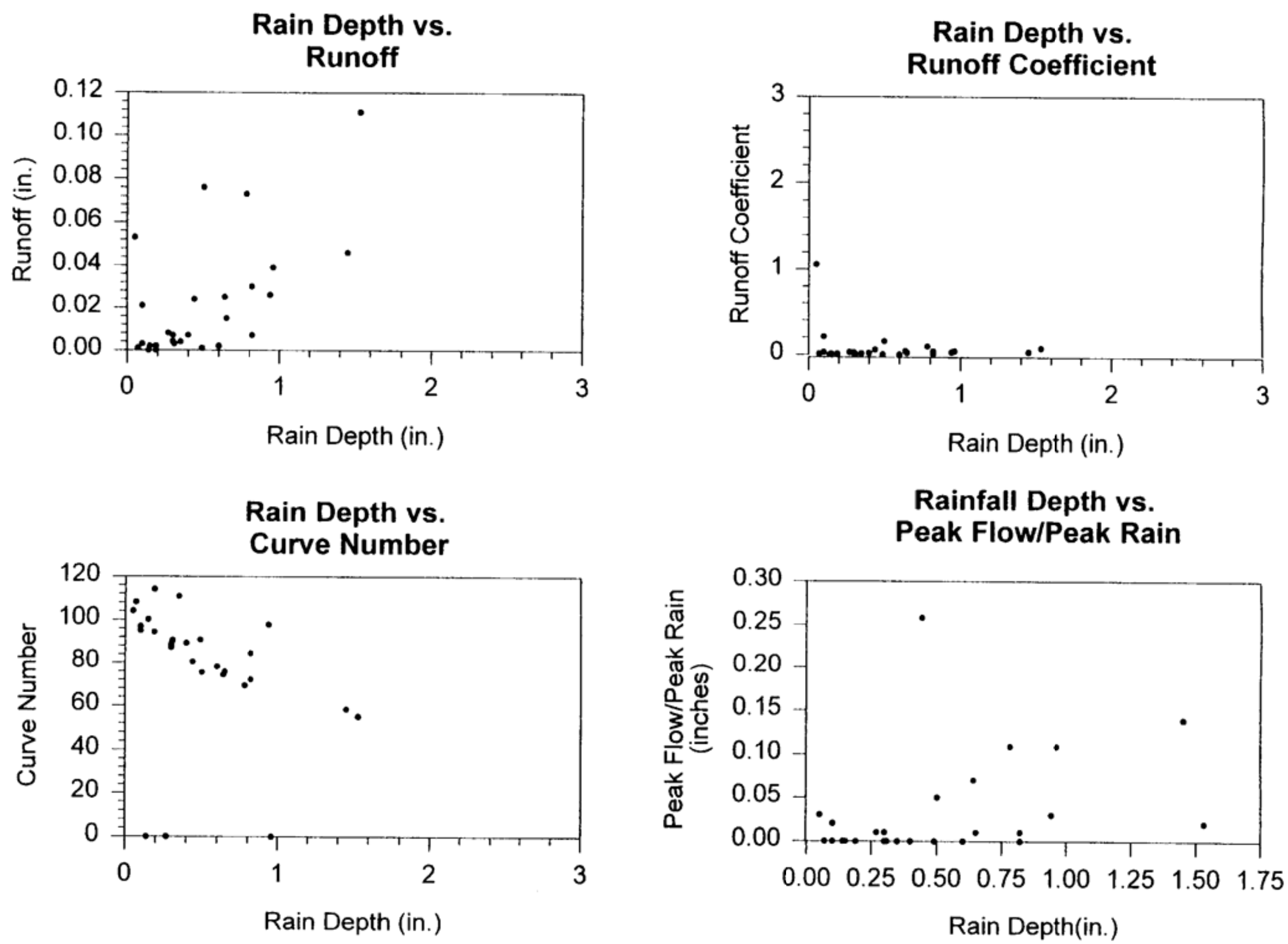
Salt Lake City, Utah, Transportation Catchment

Climate
The climate of Salt Lake City, Utah is described in the previous section.

Site Description
The Parley's Canyon monitoring site was located on 33rd South Street and I215 and comprised 0.54 acres (0.22 ha). The drainage is from a side slope into a gutter. The soil consist of sandy loam with silty clay lenses of very loose, poorly aggregated structure. The sewer is open channel and can be considered a road side drainage ditch**.**

Data Collection Methodology
Data was gathered during the rainfall seasons for 1972 and 1973. Additional measurements including temperatures and wind speeds, along with soil moisture, were measured for this catchment. The flow for the Parley's Canyon catchment was monitored with a 90 bobbed tailed cutthroat flume that was calibrated in the laboratory. The stages were measured using a Belfort 5-fw-1 level recorder. There were 4 gages in the catchment itself and 9 gages near the catchment. Belfort 5-780 dual transverse, 6inches per transverse, were used for monitoring. The rainfall was continuously monitored and data was recorded in 2 minute increments between 8/72 and 10/73 for a total of 27 rain events.

Salt Lake City, Utah
Transportation Catchment



Seattle, Washington, Industrial Land Use

Climate

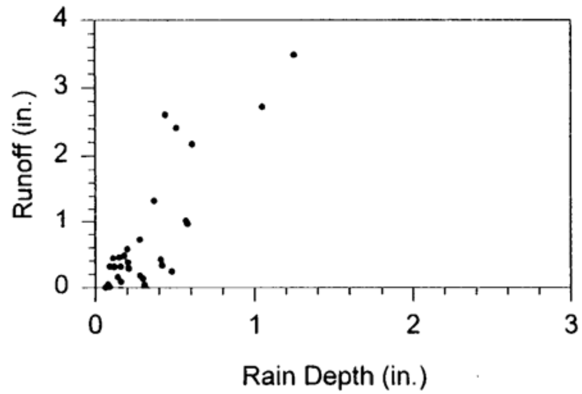
Seattle is located in west central Washington between Puget Sound and Lake Washington. The topography of the area is hilly and the area contains three lakes within the city limits. It is bordered on the west by the mountains of Olympic Park and on the east by the Cascade Mountains. The climate is cold with an annual average temperature of 53^{o}F. January is the coldest month, with an average temperature of 40^{o}F and July is the warmest, with average temperatures of 66^{o}F. The area receives on the average 36 inches of precipitation yearly and is considered an SCS Type IA rain distribution.

Site Description/Data Collection Methodology

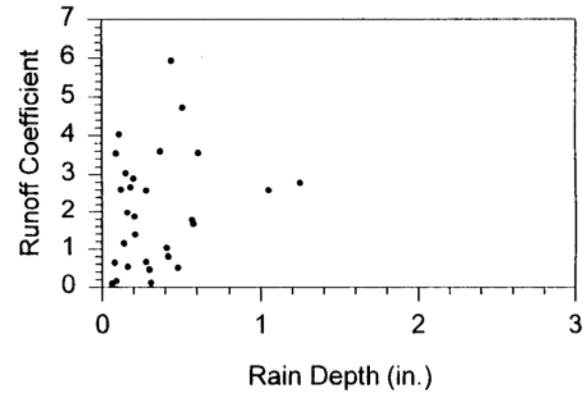
The industrial site monitored for this study was 27.5 square miles. Flow measurements within the area were taken with automatic recorders at manholes. Although there were no rain gauges in the study area, there were two gauges located nearby that were used for measurement. These rain gauges were Steven's tipping bucket rain gauges, used in conjunction with event recorders. For this study, 5 storms were monitored between March and September of 1973, and 26 storms were monitored between October and December of 1975.

Seattle, Washington Industrial Land Uses

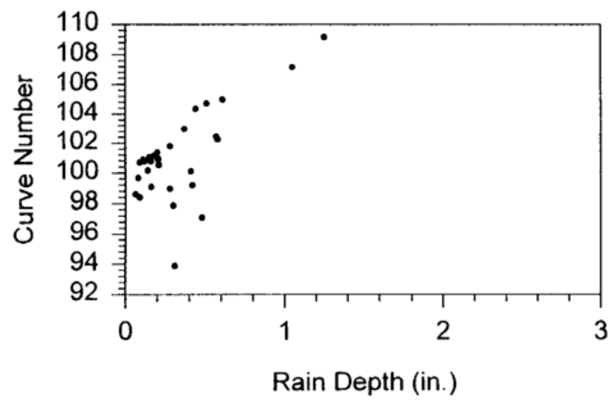
Rain Depth vs. Runoff



Rain Depth vs. Runoff Coefficient



Rain Depth vs. Curve Number

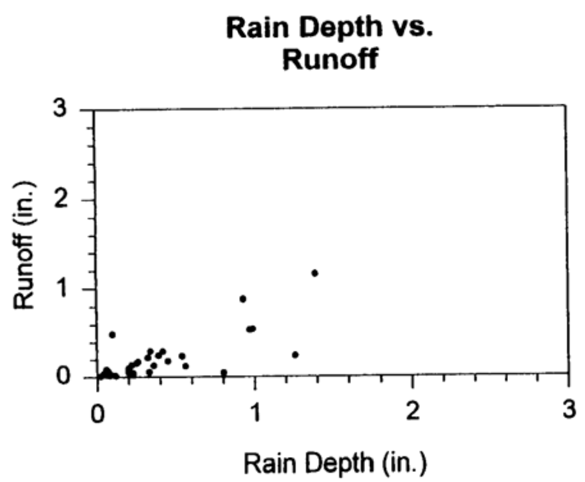


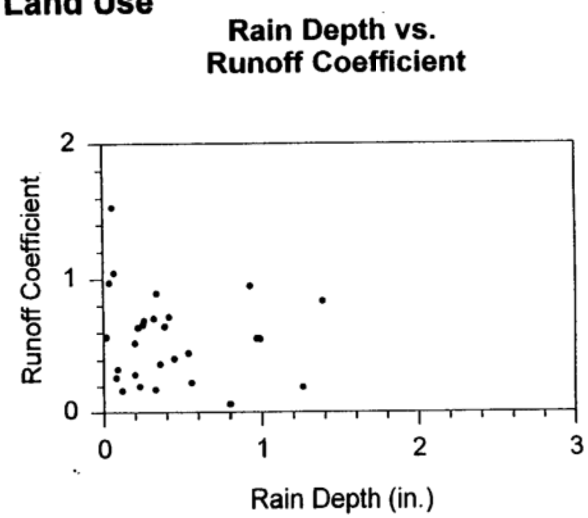
Seattle, Washington
Commercial Land Use

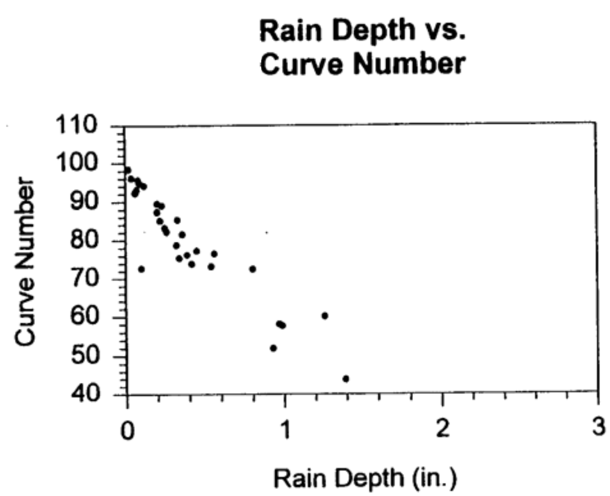
Climate
The geographic and climatic characteristics for Seattle were described previously.

Site Description/Data Collection Methodology
A 24 acre commercial catchment, known as Southcenter, was monitored in this study. Flow measurements were taken with an automatic recorder at a hole in the conduit every 5 to 15 minutes. Stevens tipping bucket rain gauges were used to record the rainfall for the events. Six storms were recorded between February and September 1973. An additional 25 storms were monitored between October 1974 and December 1975.

Seattle, Washington
Commercial Land Use







Seattle, Washington, High Density Residential Land Uses

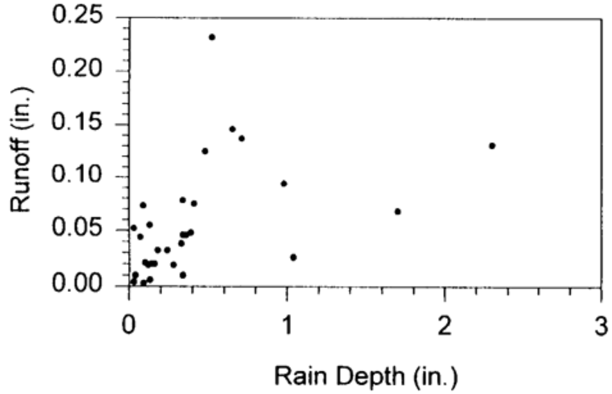
Climate
The geographic and climatic characteristics for Seattle were described previously.

Site Description
A high density residential area, known as View Ridge, was monitored in this portion of the Seattle study. This catchment has an area of 630 acres. Older single family homes cover about 50% of the area, multiple family residences cover about 40% of the area, and the remaining area is covered by commercial and institutional land uses.

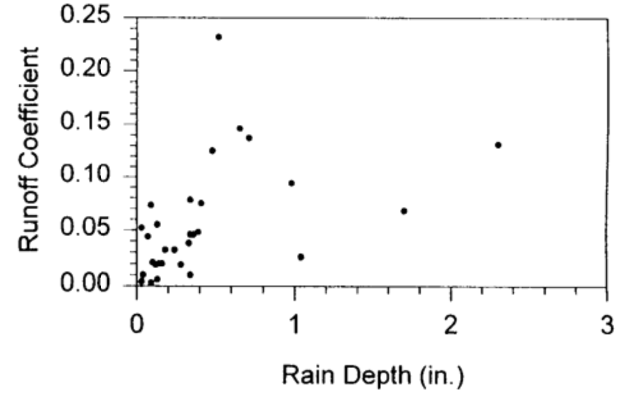
Data Collection Methodology
Water quantity and quality measurements were monitored for this study. All flows were computed from a stage-discharge curve developed through use of Manning's equation. Stage measurements were taken using a Arkon Model 63 Nitrogen Gas Bubbler Tube. Rain data was collected using three Stevens tipping bucket rain gauges. 5 storms were recorded between February and September 1973, and 25 storms were recorded between October 1974 and December 1975. Water quality parameters were also tested for each of the samples collected.

Seattle, Washington
High Density Residential Land Uses

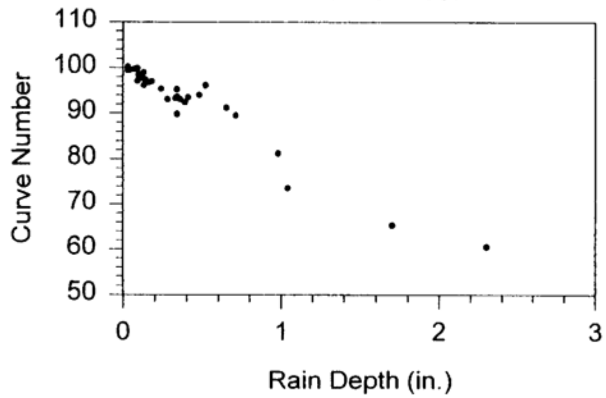
Rain Depth vs. Runoff



Rain Depth vs. Runoff Coefficient



Rain Depth vs. Curve Number



EPA Nationwide Urban Runoff Program (NURP) Data Analyses

Introduction

Throughout the history of stormwater drainage design, the focus has been on quickly moving runoff flows to receiving waters in order to prevent local flooding and other drainage problems. However, after 1960, noticeable adverse environmental effects in receiving waters were beginning to be attributed to stormwater flows. These conditions prompted concerns related to stormwater quality. Although basic ideas on the constituents of stormwater were common, little nationwide information existed. It was felt that little improvement could be accomplished until more specific information was gathered. Data was needed to accurately describe the characteristics of runoff, with respect to its constituents, flow parameters, and volumes.

Objectives

The EPA conducted the Nationwide Urban Runoff Program (NURP) to understand the variability of the characteristics associated with stormwater, and to examine some typical practices used to reduce stormwater-related problems. NURP was designed to accomplish several objectives, the first was to develop a stormwater database containing information as to runoff quality and quantity. In addition, some NURP studies were also conducted to examine stormwater effects on receiving waters. In addition, most NURP studies also examined the effectiveness of a variety of control measures. The control practices tested included structural controls (wet detention ponds, dry detention ponds, grass swales, infiltration systems, etc.), non-structural controls (street cleaning and catchbasin cleaning), and public education programs.

Data Collection

A massive amount of data was required to achieve the program objectives over the complete nation. Monitoring sites were set up in 28 cities, having from two to eight full-scale monitoring stations in each city. These locations were chosen based on their physical characteristics and the information they could provide. For example, Winston-Salem, North Carolina, was chosen because its growth characteristics represented the rapid urbanization being experienced in many areas. Other areas were chosen for their ability to fulfill the program objectives; the existence of control practices of interest, or representative receiving water bodies, for example.

A data collection protocol was established that was used for all sites. Sites collected rainfall and runoff data using automatic samplers, rain gauges, flow recorders, etc. Collected water samples were analyzed for a variety of common and trace pollutants. In addition, some sites investigated stormwater control practices, some examined receiving water effects while others monitored effects on aquatic organisms and habitats. Compilation of all of these data enabled conclusions to be drawn regarding stormwater characteristics (variability and normal concentrations and loads), widespread receiving water effects and control practice effectiveness.

NURP Conclusions

NURP identified three separate criteria to be used to determine if a water quality problem exists; an impairment or restriction of the water's beneficial uses, water quality criteria violations, or local public perception of a problem. In a very general sense, the NURP program confirmed the idea that stormwater pollution is a widespread "problem."

Urban Runoff Characteristics

Several goals were met in terms of characterizing pollutant loads. The variability of the data was concisely summarized into a useable form, comparisons between different sites and events were made, and conclusions were drawn as to the frequency of occurrence of different levels of stormwater contamination. In terms of specific pollutants, heavy metals were found to be the most prevalent priority pollutant, with all 13 metals on the priority pollutant list being found in almost all samples of urban runoff. Fecal coliform bacteria counts were also determined to be significant in stormwater. In addition, high nutrient loads, large discharges of oxygen demanding substances and suspended solids were also documented.

Receiving Water Effects

Receiving water effects were variable based on site characteristics. Factors effecting the magnitude of the effects were the type and size of the water body, along with other hydrologic characteristics.

Rivers. Water quality standards were exceeded for heavy metals from stormwater and that the levels of some of these metals posed a threat to aquatic species. Metals of most concern included copper, zinc and lead. Frequent occurrence of slight violations did not appear to have a significant effect, unusually high concentrations however did. Habitat destruction was another area in which stormwater was detrimental to aquatic life, where sedimentation, erosion, or scour destroyed habitats necessary to support aquatic life. Organic priority pollutants did not pose an obvious threat to aquatic life forms, although their presence was thought to be important.

Lakes. Although the problems found in lakes were different from those experienced by rivers, they also experienced adverse effects due to stormwater pollution. Eutrophication caused by excess nutrient loads was a frequent problem caused in part by stormwater runoff. Degrees of eutrophication and levels of damage to the water body varied greatly from one area to another. Fecal coliform bacteria counts associated with stormwater discharges were noted to have a significant negative impact on recreational uses of lakes as well.

Control Effectiveness
Several stormwater control practices were tested as part of the NURP objectives. These were met with varying degrees of success. Wet detention ponds were determined to be effective in reducing pollutant loads of many stormwater pollutants. However, some ponds worked better than others depending on their design and their physical characteristics (mostly related to pond size in relationship to watershed area). Recharge devices also had reasonable success, however street cleaning did not. Street cleaning was found in all cases to be ineffective in making significant pollutant reductions in stormwater. Grass swales and wetlands were also investigated. Grass swales provided moderate improvements in stormwater quality as did wetlands. More information was needed to in terms of wetland design and performance characteristics before this measure could be promoted for widespread application.

Data Analyses
Data from eight of the 28 NURP projects were collected and plotted for this appendix. For the purpose of this project, the NURP data were used in a manner similar to that previously described for the EPA Urban-Rainfall-Runoff-Data Base. In addition to the rainfall-runoff plots previously described, additional plots were also made to examine patterns of stormwater pollutants. A list of the plots made is as follows, however, not all sites included enough information to complete each graph:

Plots Constructed
Rain & Runoff Probability Distributions
Pollutant Probability Distributions
Rainfall vs. Runoff
Rainfall vs. Runoff Coefficient
Rainfall vs. Curve Number
Rainfall vs. Peak/Average Runoff
Rainfall vs. Total Suspended Concentrations
Rainfall vs. COD Concentrations
Rainfall vs. Phosphorous Concentrations
Rainfall vs. Lead Concentrations
Rainfall vs. Peak Flow/Peak Rain
Peak Rain vs. Peak Flow

NURP - Irondequoit Bay, New York

Introduction

The purposes of this NURP project were threefold. First to determine the impact of stormwater on receiving waters particularly, Irondequoit Bay in New York. The cost effectiveness of control measures were also examined in this study. In addition, the study provided data for use in the nationwide study to examine stormwater pollutant characteristics.

Irondequoit Bay is located on the southern shore of Lake Ontario north of Rochester New York. It is a small, shallow water body with a length of about 6.7 km and a width of 1 km. The climate of the area consists of cold dry winters and hot humid summers. Average annual rainfall is about 80 cm and average annual snowfall is about 216 cm. The bay serves as a drainage basin for an area of about 395 km2 having varying land uses.
This area was chosen for study due to receiving water problems caused by eutrophication. Algae growth, sediment and turbidity all effect the lake's condition. It was believed that the problems occurring in the lake are caused by the addition of excess phosphorous through stormwater flows.

To collect data, the basin areas were divided into five monitoring areas having uniform land uses. Rainfall data was collected at the five NURP monitoring stations, plus at thirteen others in the adjoining areas. Flow measurements were determined by converting stage of depth of flow measurements into discharge values using a stage/discharge relationship.

Sampling Sites

A portion of the study area was divided into five small watersheds to monitor runoff from specific land uses. Two of the watersheds were large areas while the other three are small and very use specific. The Thornell Road watershed is rural and agricultural with the lowest population density. It has a low runoff coefficient (only 0.10). Thomas Creek, the second large watershed, is mainly rural with some suburban areas. These suburban areas account for the increase in the runoff coefficient to 0.20. The three remaining watersheds are significantly smaller with more dense residential areas and also some commercial areas. Specific characteristics are shown in the following table:

Table B-1. NURP Land Uses Monitoring Sites for Irondequoit Bay, New York.

Monitoring Location	Watercourse to which Basin is Tributary	Drainage Area (km^2)	Land Use
Thornell Road	Irondequoit Creek	115	Rural/Agricult
Thomas Creek	Thomas Creek	73.8	Mixed
Cranston Road	Barge Canal	0.67	Middle Density Residential
Southgate Road	White Brook (tributary of Thomas Creek)	0.73	Commercial
East Rochester	(Storm sewer discharging to Irondequoit Creek)	1.55	High density residential/commercial

Data Collection Methodology

Rainfall data was collected at the five sites mentioned above in five minute intervals using automatic rain gauges. Data was also gathered daily at thirteen supplemental sites. For the two larger sites, rainfall was estimated using composite data from numerous gauges, while at the smaller sites, data from one gauge was determined to be adequate. Automatic runoff samplers were also located at the five sites. The apparatus collected one liter samples either at specified intervals or flow rates. During dry periods, samples were collected to determine background flows and pollutant loadings. Once samples were collected they were shipped to the appropriate laboratories for analyses.

Runoff loadings were calculated for the different land uses. Phosphorous was the only pollutant for which detailed loading analyses were conducted due to the concentration of the study on bay eutrophication. However, the USGS in a cooperative study also conducted analyses for seven other constituents: suspended solids, total Kjeldahl nitrogen, chemical oxygen demand, chloride, lead, zinc, and cadmium. These analyses, however, only were conducted for 13 storms that had high rainfall amounts and high runoff volumes.

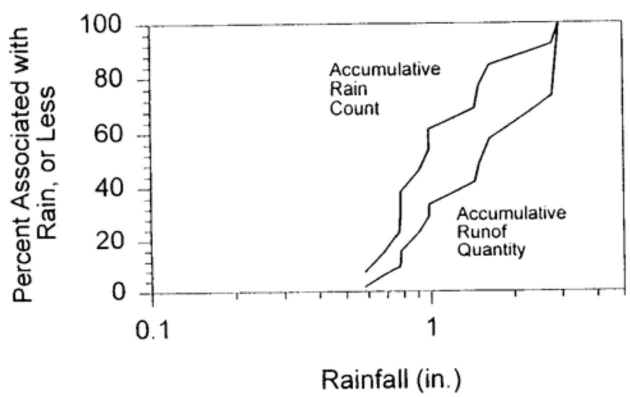
Wetlands treatment, erosion and sediment control and stormwater infiltration were examined considering performance, cost, feasibility, and public acceptance.

Simulation
Two types of models were utilized in this project, one to simulate phosphorous loadings and the other to simulate phosphorous concentrations in the bay water column. The runoff model EPAMAC was used for estimating pollutant loadings to Irondequoit Bay from stormwater. The model utilized runoff coefficients and event mean concentrations with rainfall amounts to generate phosphorous loads. Given the general nature of the model, it is better used to predict annual loadings than individual storm events. Another model was also used to examine the response of the Irondequoit Bay as a receiving water.

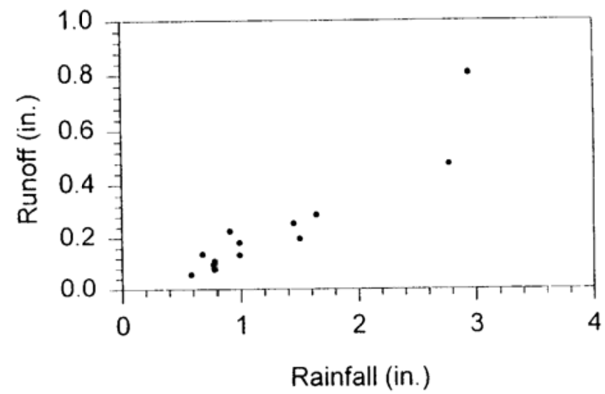
Conclusions
Conclusions from this project focus on the sources and loadings of phosphorous in the Irondequoit Bay area. Information pertaining to runoff volumes, coefficients and other parameters can be extrapolated from the rainfall/ runoff data collected.

Irondequoit Bay, New York
Cranston Site
Surburban Land Use

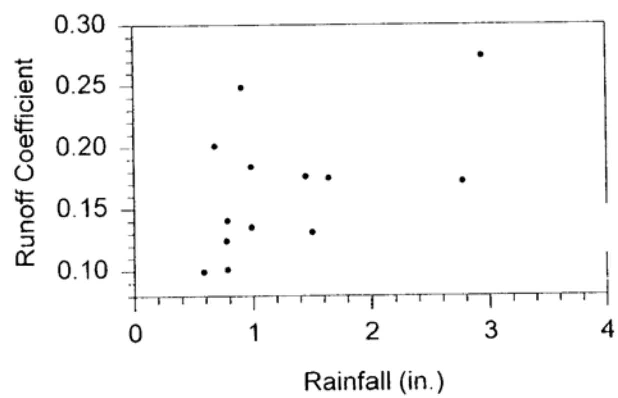
Rainfall & Runoff Distribution



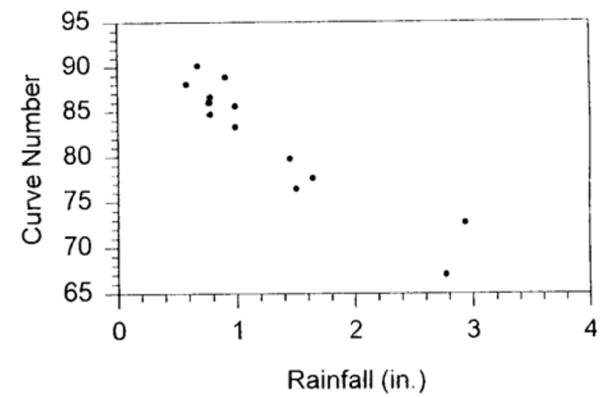
Rainfall vs. Runoff



Rainfall vs. Runoff Coefficient

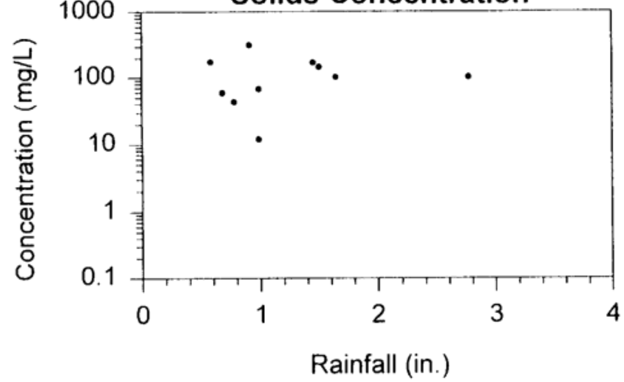


Rainfall vs. Curve Number

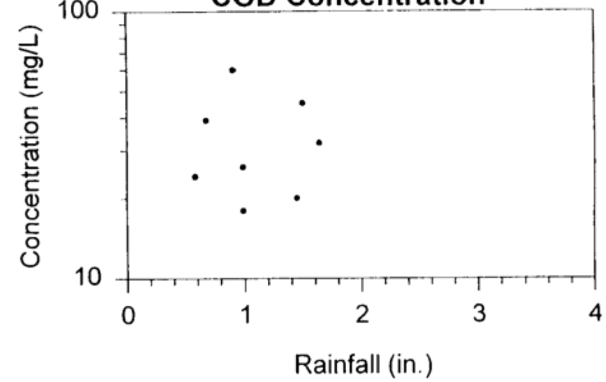


Irondequoit Bay, New York
Cranston Site
Surburban Land Use

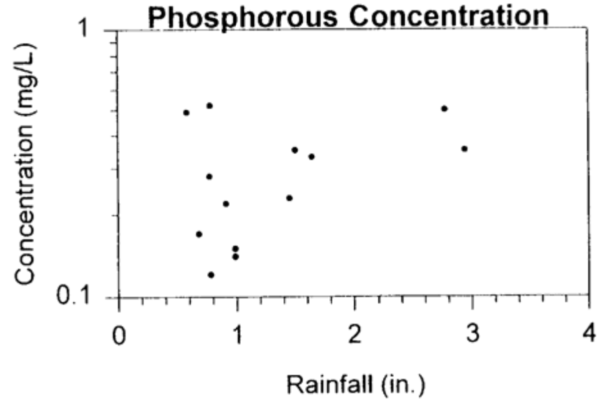
Rainfall Depth vs. Total Suspended Solids Concentration



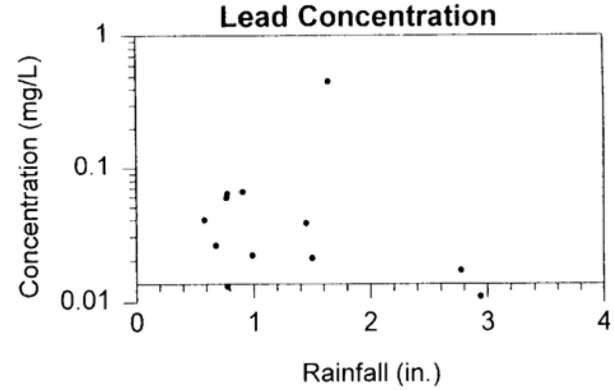
Rainfall Depth vs. COD Concentration



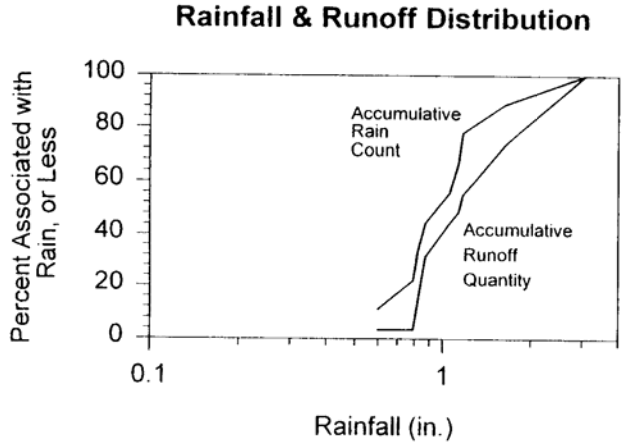
Rainfall Depth vs. Phosphorous Concentration

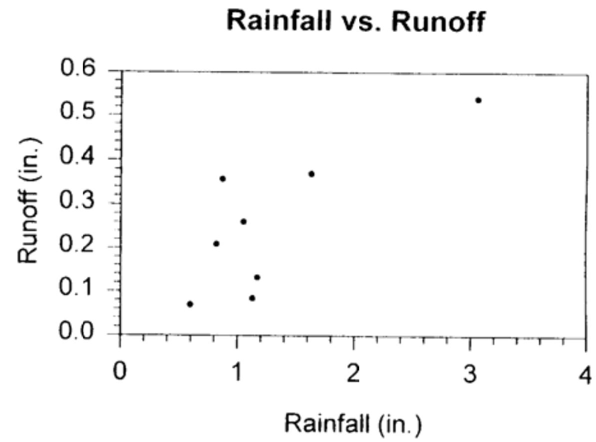


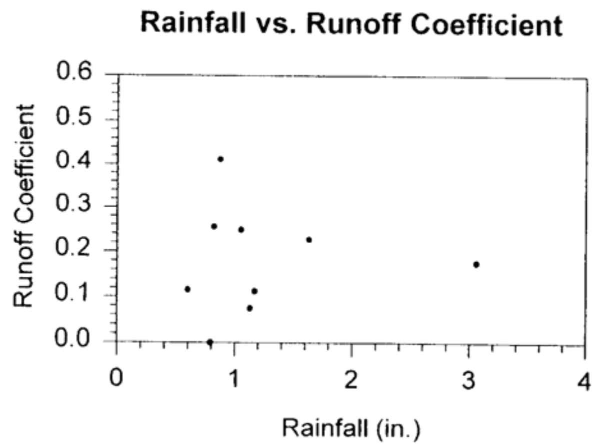
Rainfall Depth vs. Lead Concentration

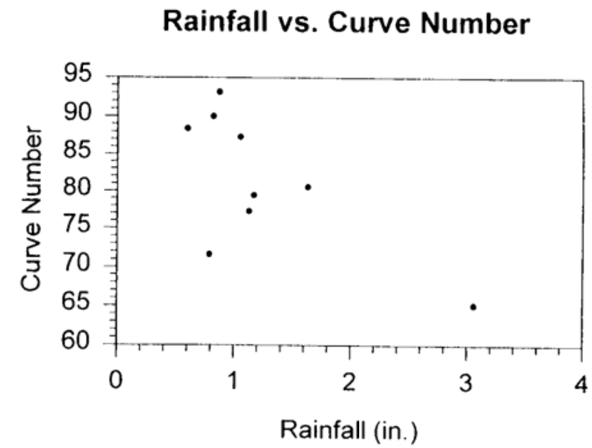


Irondequoit Bay, New York
East Rochester Site
Urban Land Use

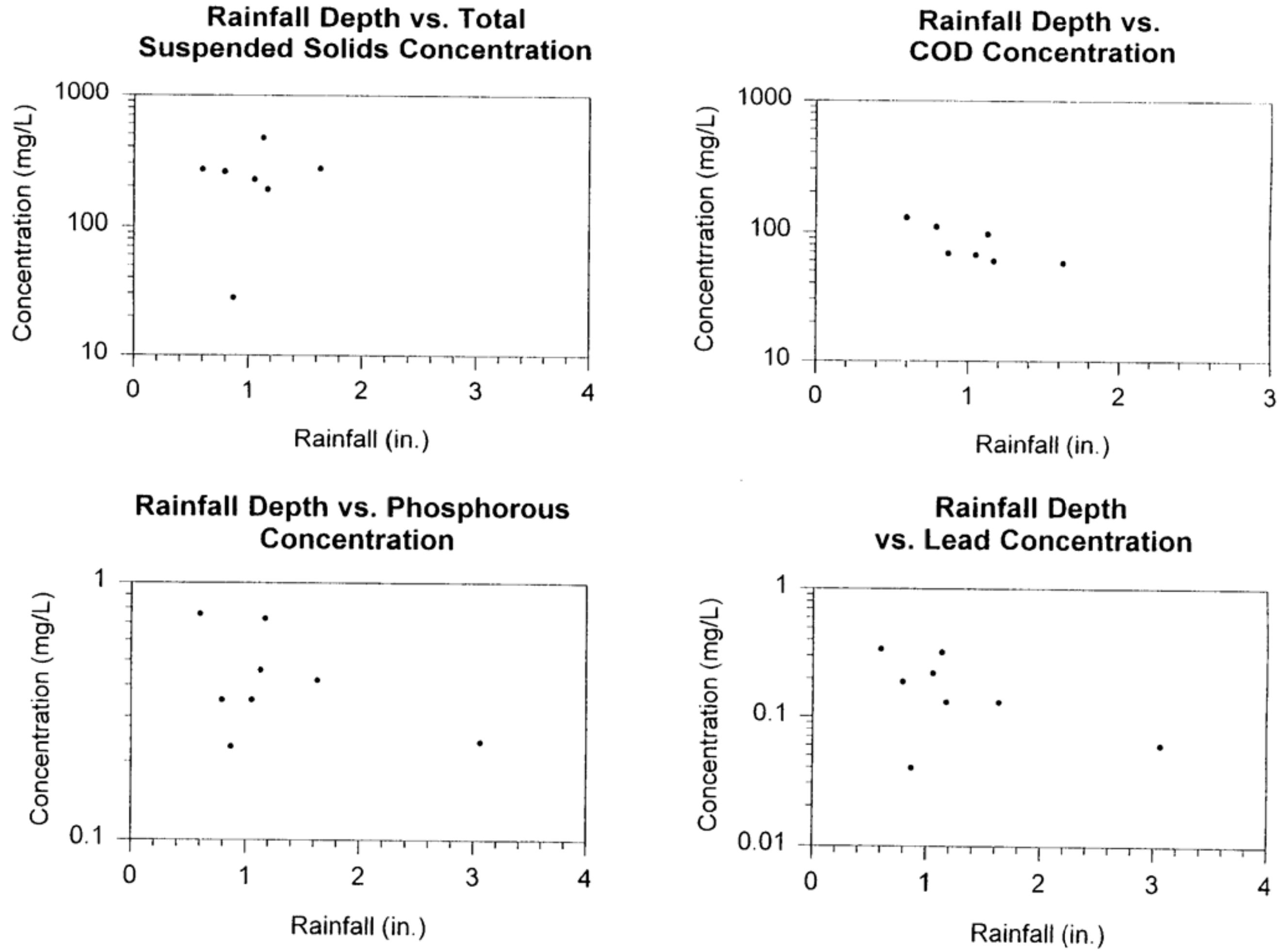




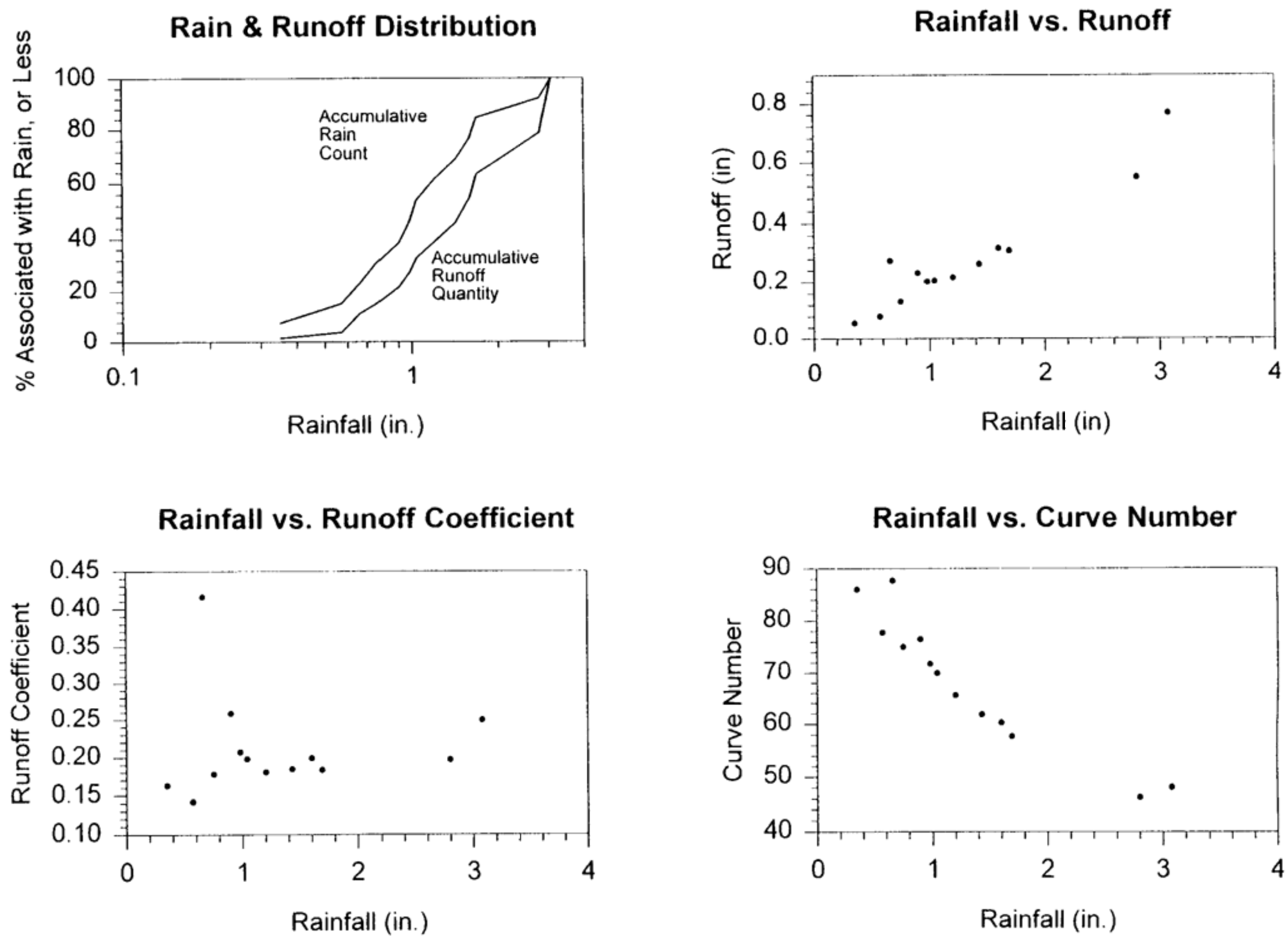


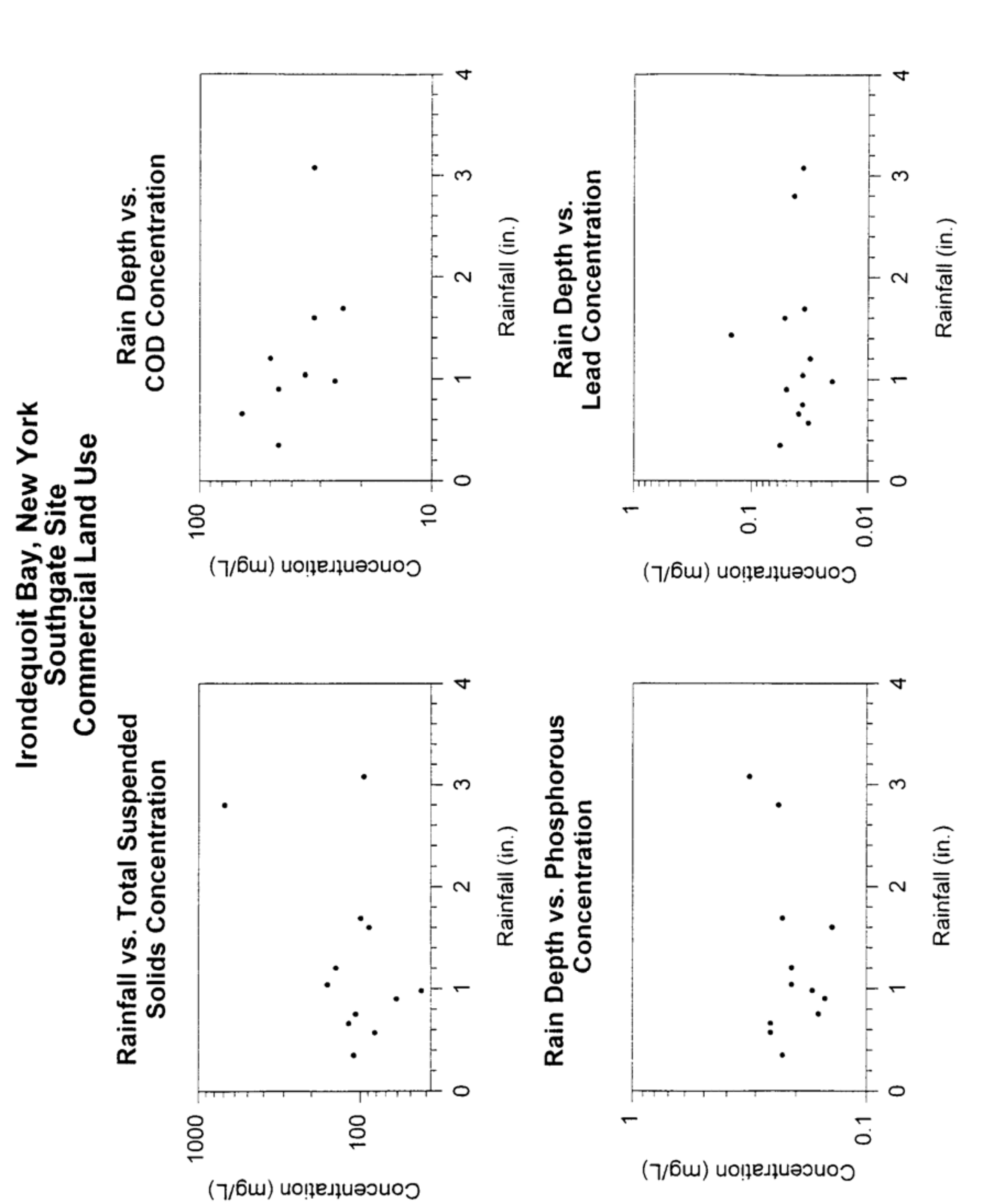


Irondequoit Bay, New York
East Rochester Site
Urban Land Use

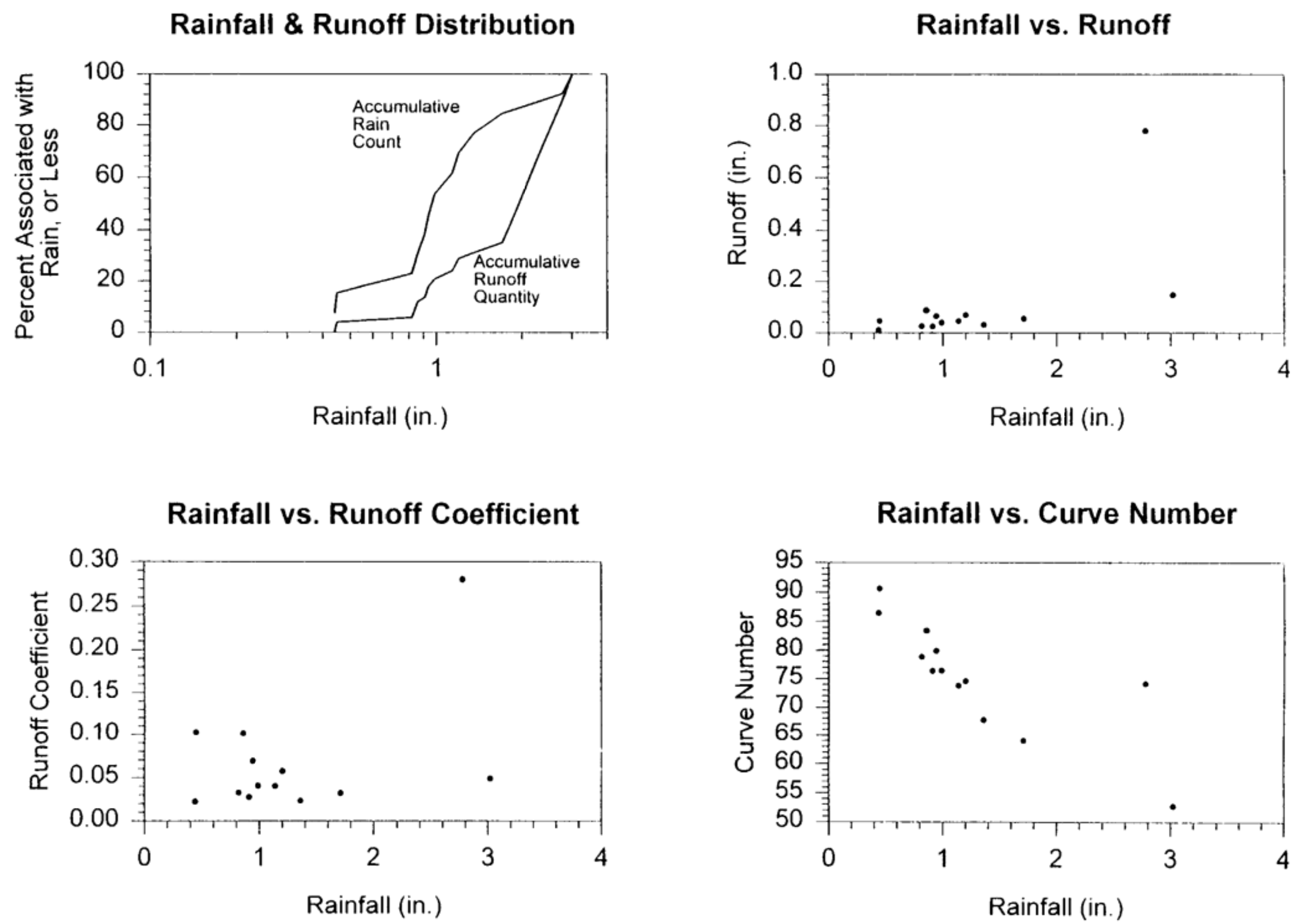


Irondequoit Bay, New York
Southgate Site
Commercial Land Use

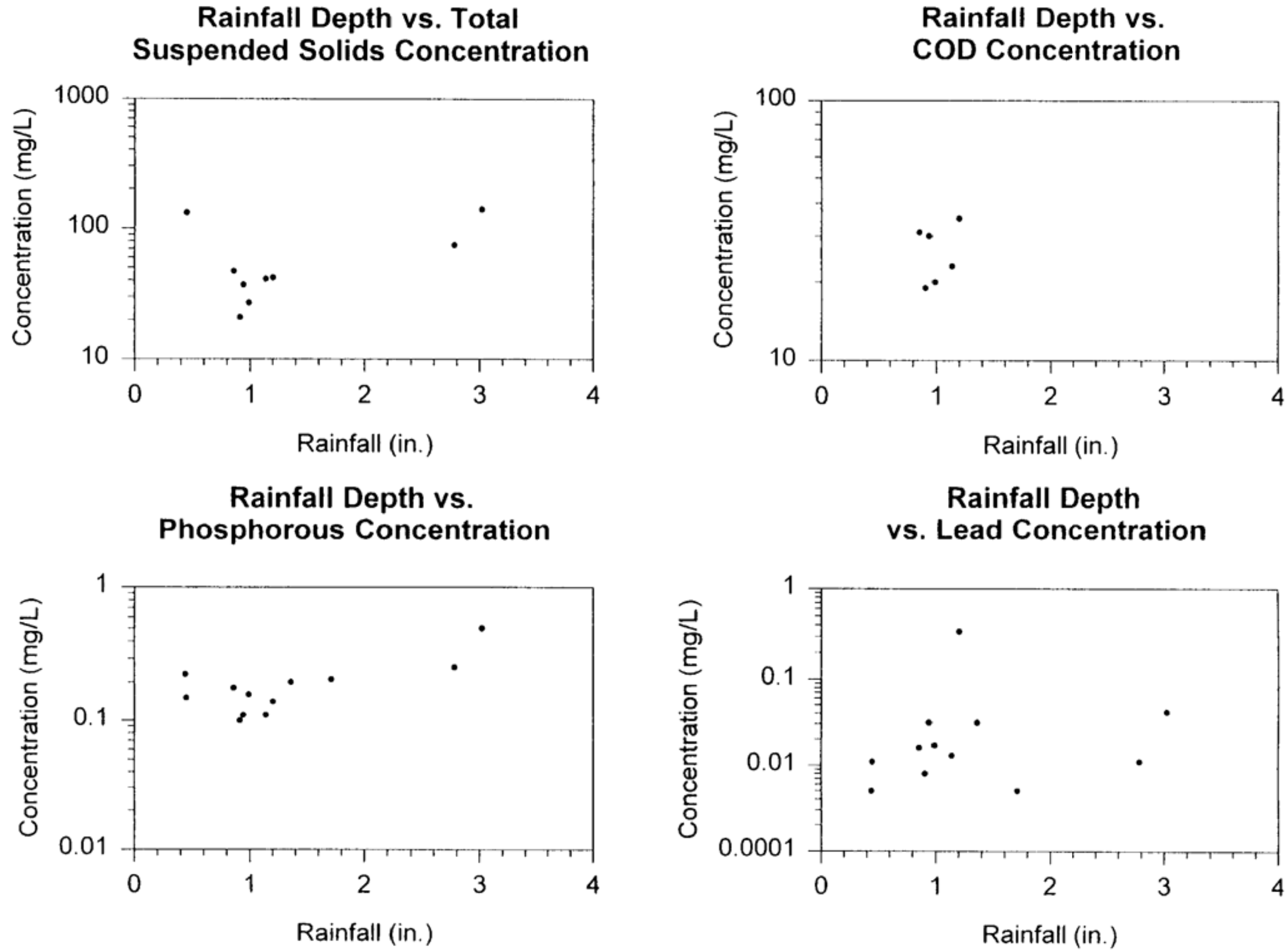



Irondequoit Bay, New York
Southgate Site
Commercial Land Use
Rainfall vs. Total Suspended Solids Concentration
Rain Depth vs. COD Concentration
Rain Depth vs. Phosphorous Concentration
Rain Depth vs. Lead Concentration
Concentration (mg/L)
Rainfall (in.)
1000
100
10
1
0.1
0.01
0
1
2
3
4

Irondequoit Bay, New York
Thomas Creek Site
Rural Land Use

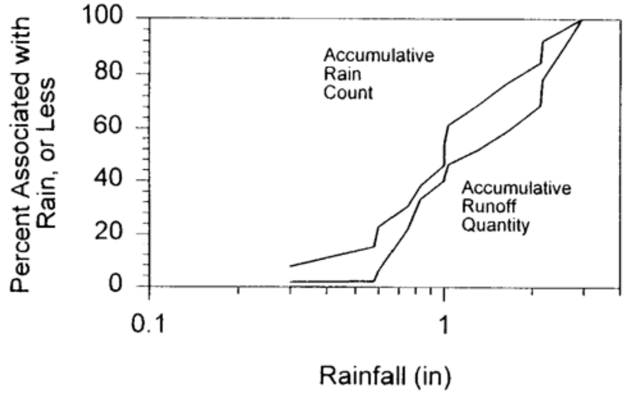


Irondequoit Bay, New York
Thomas Creek Site
Rural Land Use

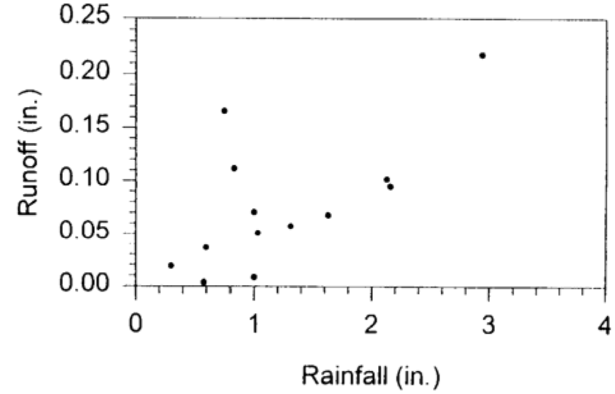


Irondequoit Bay, New York
Thornell Site
Rural Land Use

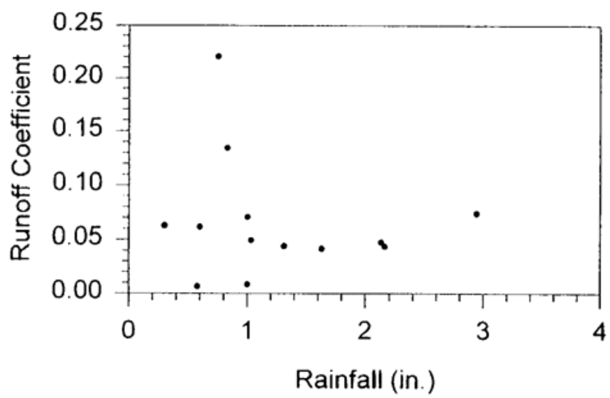
Rainfall & Runoff Distribution



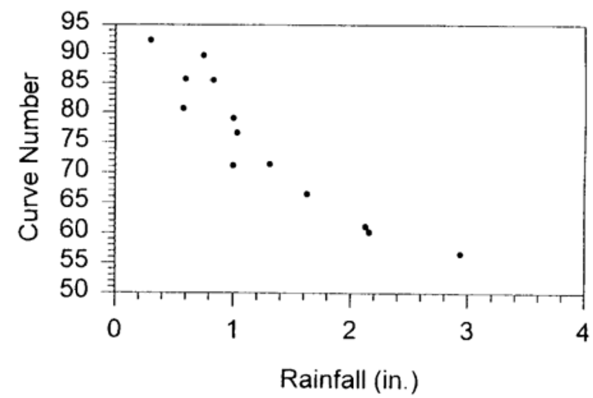
Rainfall vs. Runoff



Rainfall vs. Runoff Coefficient

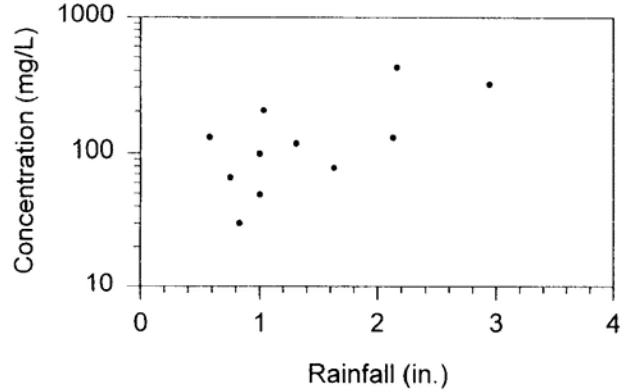


Rainfall vs. Curve Number

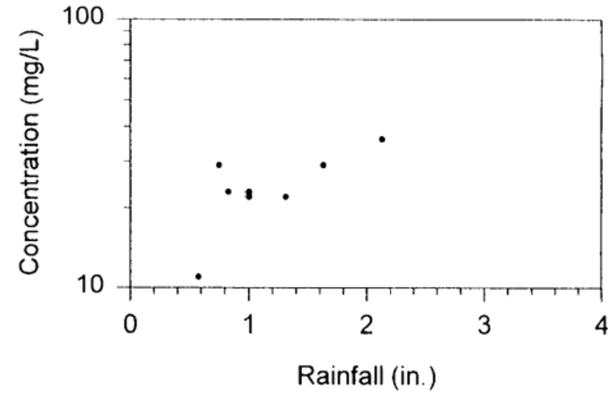


Irondequoit Bay, New York
Thornell Site
Rural Land Use

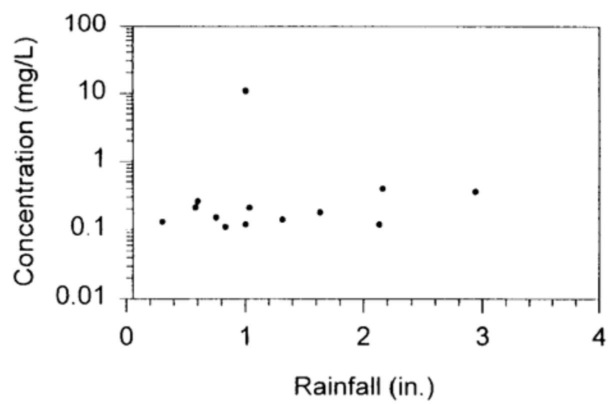
Rainfall Depth vs. Total Suspended Solids Concentration



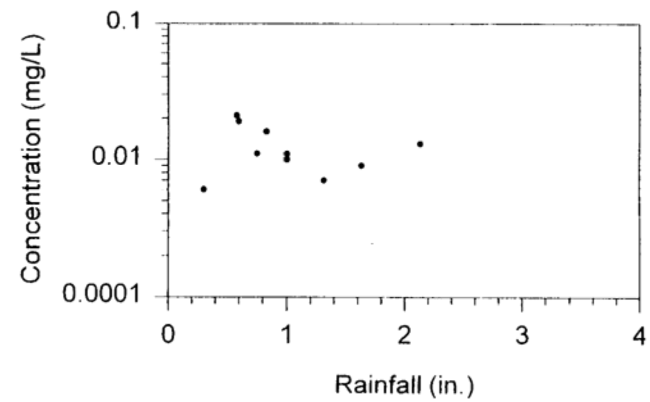
Rainfall Depth vs. COD Concentration



Rainfall Depth vs. Phosphorous Concentration



Rainfall Depth vs. Lead Concentration



NURP - Austin, Texas

Introduction

The purpose of this NURP project was to examine stormwater impacts on water quality in the Austin Texas area. The effects of stormwater on receiving waters with respect to water quality and aquatic ecology were examined. In addition, the characteristic loads from varying land uses were compared in terms of degrees of urbanization. A public opinion study was conducted in the area to determine perceptions of stormwater issues by the public and the scope of controls and the costs associated with them that were deemed acceptable.

The area examined in this study is located in the Highland Lakes area of Austin. This area is hilly with slopes ranging from two to fifteen percent. Three reservoirs along the Colorado River were chosen for study, Lake Austin, Town Lake, and Lake Travis. Lake Travis is located at the top of the lake chain in a relatively undeveloped area. Development increases through Lake Austin and into Town Lake. Depending on the season, water quality conditions in the two lower lakes are either a function of the Lake Travis quality or lake detention time.

Sampling Sites

Three watersheds; Northwest Austin, Rollingwood, and Turkey Creek, were chosen to measure stormwater characteristics and Town Lake and Lake Austin were chosen to monitor receiving water effects. The Northwest Austin watershed has an area of approximately 377 acres and represents residential land use areas. The housing density is about one house per quarter or third acre and there is a large amount of impervious cover. Rollingwood is also a residential land use watershed, but has a lower amount of impervious area than the Northwest site. The housing density is about one house per three-quarter to one acre. Finally, the Turkey Creek watershed was selected to represent an undeveloped watershed as a control measure. The following table illustrates the varying watershed characteristics:

Table B-2. Characteristics of Selected Storm Water Study Sites for Austin NURP Sites

	Northwest Austin (Medium Density Residential)	Rollingwood (Low Density Residential)	Turkey Creek (Undeveloped)
Area of Housetops and Driveways (acres)	101.86	6.31	na
Paved Roads (acres)	46.33	6.57	na
Total Watershed Area (acres)	377.71	60.21	1,297
Weighted Runoff Curve Number	79	78	75
Total Impervious Cover (percent)	39.23	21.39	1
Slope of Watershed Channel (percent)	2.6	6.9	1.9
Overland Flow Slope (percent)	4.6	5.9	7.5
Street Surface Gutter Slope (percent)	3.5	2.5	na
Estimated Time of Concentration (hours)	0.53	0.23	1.92

Data Collection Methodology

Continuous discharge and daily rainfall measurements, in addition to water quality, were monitored. A total of 38 events were monitored using a combination of NURP operated and USGS rain gauges during the program. The average rainfall for each study area was then determined using composite data from all gauges in the area.

At the four sites monitoring stormwater runoff, a water level meter recorded discharge and indicated sampling times to the samplers. Modifications were periodically made to the monitoring and sampling equipment to improve performance. Samples were tested in labs to identify pollutant characteristics:

Table B-3. Analyses

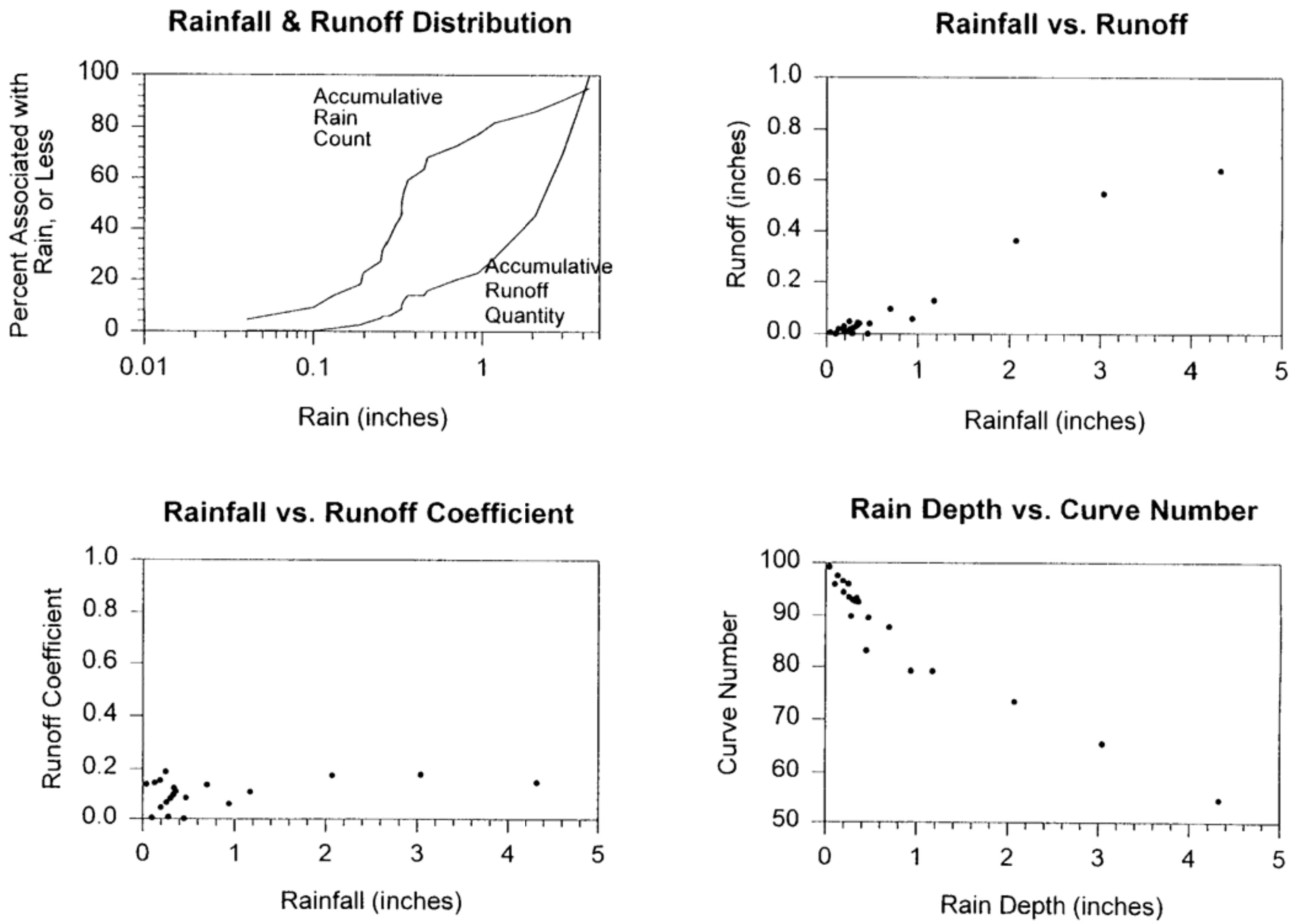
Acidity as $CaCO_3$

Alkalinity as $CaCO_3$
Ammonia
COD
Hardness as $CaCO_3$
Nitrate-N
Total Kjeldahl Nitrogen
Total Phosphorous
Total Suspended Solids
Total Dissolved Solids
TOC
Fecal Coliform

Conclusions

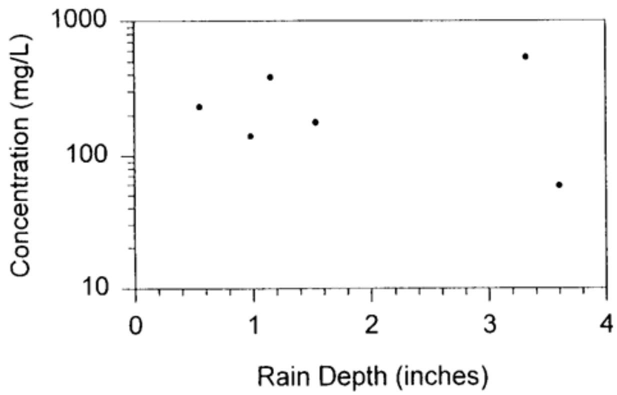
Several significant conclusions can be made from the information collected in this study. It was shown that the percent impervious area increase between the Northwest Austin and Rollingwood sites significantly degraded the quantity of stormwater runoff. Data from Turkey Creek demonstrated that developed area pollutant loads in stormwater runoff increase with increased development. No significant levels of toxic pollutants were detected in the residential watersheds and only trace levels were detected in other samples.

Austin, Texas
Northwest Austin Site
Medium Density Residential

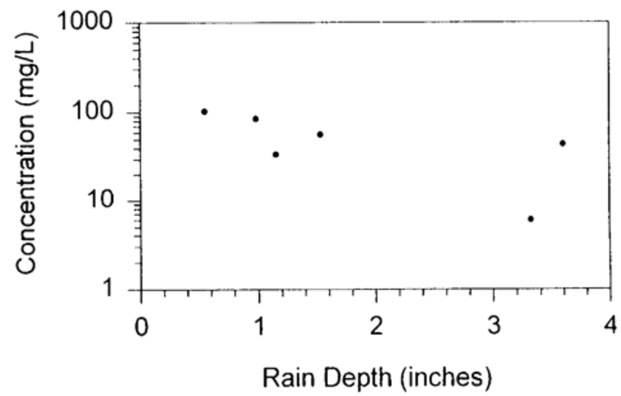


Austin, Texas
Northwest Austin Site
Medium Density Residential

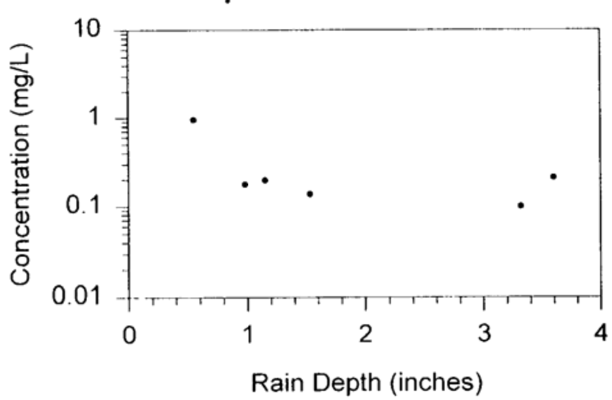
Rain Depth vs.Total Suspended Solids Concentration



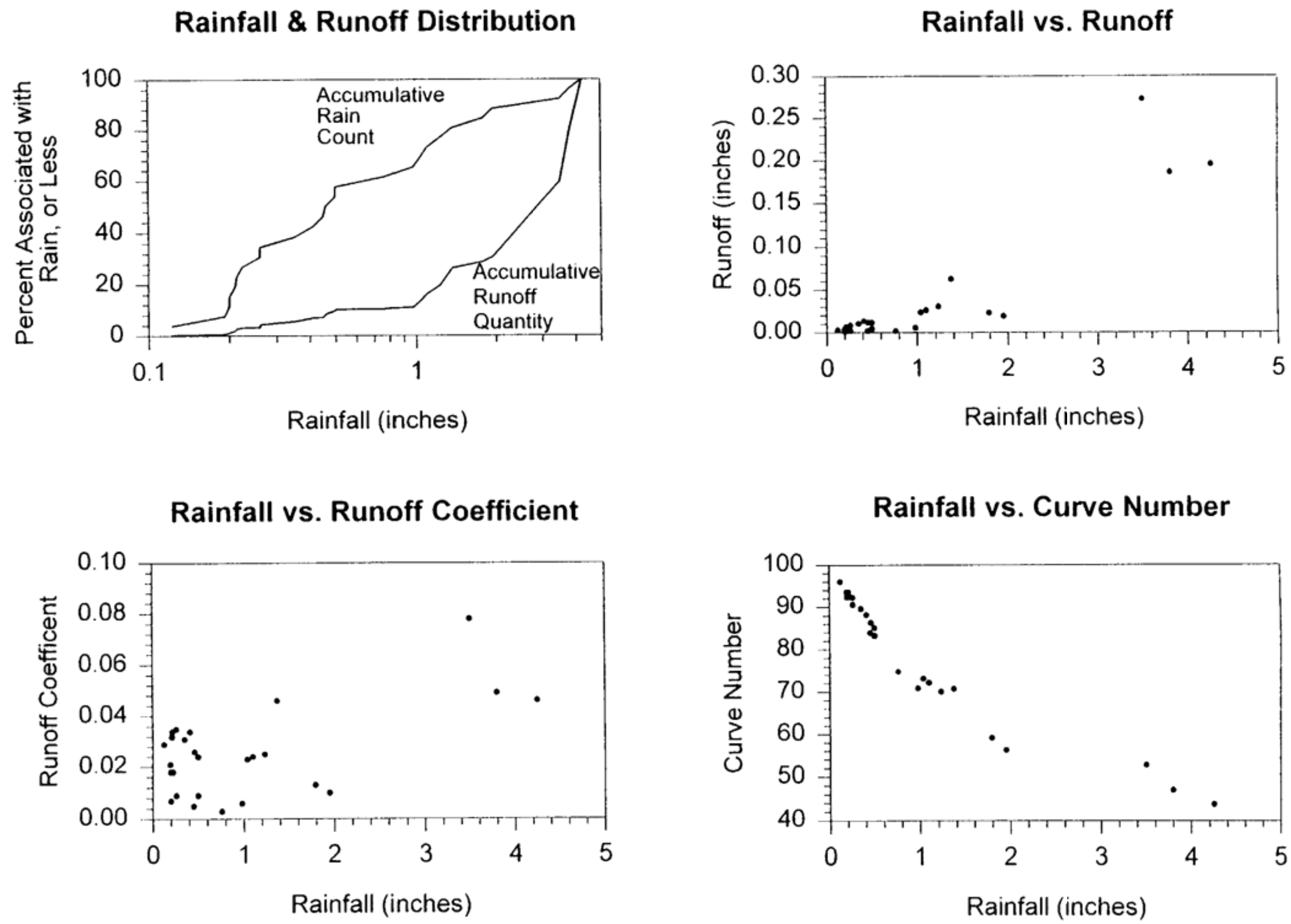
Rain Depth vs. COD Concentration

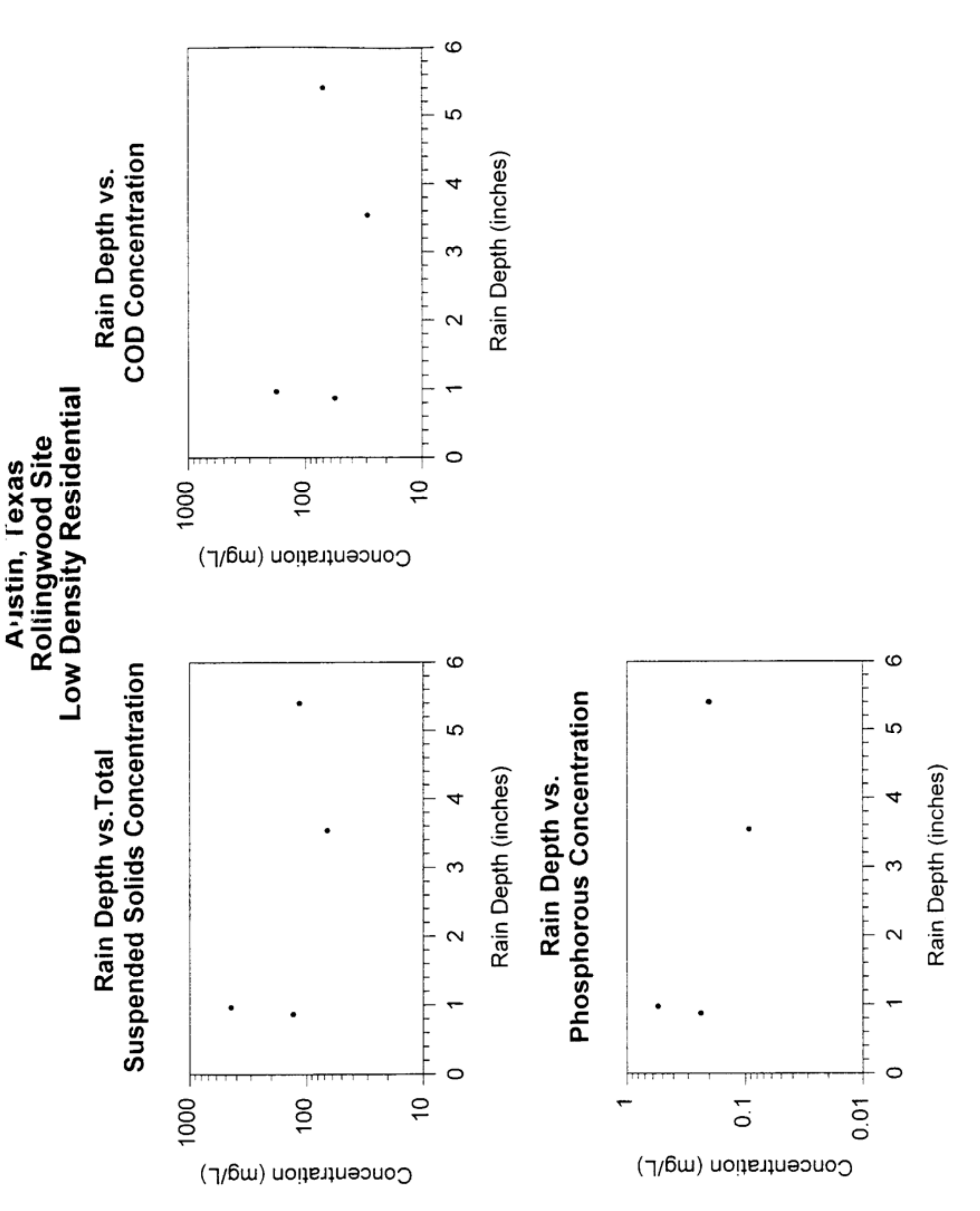


Rain Depth vs. Phosphorous Concentration



Austin, Texas
Rollingwood Site
Low Density Residential





Austin, Texas
Rollingwood Site
Low Density Residential
Rain Depth vs.Total
Suspended Solids Concentration
Rain Depth vs.
COD Concentration
Rain Depth vs.
Phosphorous Concentration
Concentration (mg/L)
Rain Depth (inches)
1000
100
10
1
0.1
0.01
0
1
2
3
4
5
6

NURP - Tampa, Florida

Introduction

The purposes of this NURP project were: to determine stormwater contributions to pollutant loadings, to characterize rainfall and runoff characteristics in the area, to evaluate several control devices as to their effectiveness in removing pollutants, and to develop a stormwater management plan for the city of Tampa. This study was divided into three phases, Phase I outlined the first objective in demonstrating stormwater concerns. Phase II of the project dealt with the collection of rainfall and runoff quality and quantity data for use in runoff characterization. A receiving water quality study, concentrating on the Hillsborough River, was also conducted in this phase of the project. The final phase of the project, Phase III, developed the stormwater plan for the city.

The Tampa study area is in a semi-tropical region in Central Florida. The annual rainfall is about fifty inches, with much of this rain occurring in summer months in the form of short, but intense, storms. The climate is warm with hot summers, high temperatures in the nineties, and mild winters, high temperatures generally in the seventies. The land in the study area is flat with only slight slopes. The Tampa area includes a variety of land uses including residential, institutional, commercial, and industrial.

Five basins were chosen for study in order to collect rainfall and runoff data for characteristic land use categories. Runoff was monitored with respect to quantity and quality within each of these five basins. To obtain rainfall quantity data, four rain gauges, located near the test basins, were installed for the project.

Sampling Sites

Basins were chosen based on two main criteria; they must possess uniform land uses within their boundaries, and these land uses must be indicative of land uses in the Tampa area. Once the basins were selected, sampling sites were located. The first basin was located in an apartment community in north Tampa (J.L. Young Apartments). This area drains about 9 acres of mostly impervious area. The second basin, Wilder Ditch, drains about 195 acres of residential land with a small amount of commercial and institutional use mixed in. The North Jesuit High School Basin drains about 30 acres of land with land uses again being residential, commercial and institutional. The third basin drains about 42 acres of residential land uses (Charter & Harding Streets Basin). The Norma Park basin contain about 46 acres of commercial and highway area. The following table summarizes the basin characteristics:

Basin		**J.L. Young Apartments**	**Wilder Ditch**	**North Jesuit High School**	**Charter & Harding St.**	**Norma Park**
Area (acres)		8.8	193.9	29.5	42.2	46.6
Max Length (ft.)		460	5300	1800	1720	2200
Max Width (ft.)		830	1120	1570	1480	1530
Length/Width Ratio		0.6	4.7	1.2	1.2	1.5
Min Elev. (ft., MSL)		21	29.3	28.7	15	15
Max Elev. (ft.,MSL)		36	46.3	35	22.6	16.5
Normal Elev. Range (ft., MSL)		27-30	35-42	30-32	18-21	15-16
Predominant Ground Slope Direction		South	West	West	South	South
Representative Slope (ft/ft)		0.023	0.0029	0.0027	0.003	0.001
Land Use						
Low Density	acres	0	105.7	14.1	37.6	0
Residential	(% of basin)	0	54.5	47.8	89.1	0
Med. Density	acres	0	0	0	0	4.3
Residential	(% of basin)	0	0	0	0	9.3

High Density	acres	8.8	0	0	0	0
Residential	(% of basin)	100	0	0	0	0
Commercial	acres	0	48.1	0	0	42.3
	(% of basin)	0	24.8	0	0	90.7
Institutional	acres	0	14.4	15.4	0	0
	(% of basin)	0	7.4	52.2	0	0
Open	acres	0	25.8	0	4.6	0
	(% of basin)	0	13.3	0	10.9	0
Total	acres	8.8	193.9	29.5	42.2	46.6
	(% of basin)	100	100	100	100	100

Data Collection Methodology

Nine rain gauges were used for the collection of rainfall data. Five of these gauges were in use prior to the NURP study and the other four were installed for the specific purposes of this study. Belfort automatic rain gauges were located in or adjacent to the five study basins. These gauges were operated continuously for nine months from May 1982 to February 1983. Parameters measured by these gauges included rainfall intensities, and depths and durations of storms. Much of this information was summarized by IDF curves, mean values and average monthly values.

Runoff monitoring and sampling were accomplished using Sigmamotor Flow Measurement and Automatic Samplers housed in instrument shelters. Each site has between twelve and fifteen composite events sampled. Discrete samples were collected for 111 events at all of the stations. Each site had between twenty and twenty-five events analyzed using discrete samples.

A list of the analyses conducted on the composite data is as follows:

Table B-4. Analyses

BOD_5
COD
TSS
Total-P
Nitrate
Nitrite
Ammonia
Organic-N
Total-N

Upon completion of the sample collection and analyses, the data was organized into detailed event summaries, precipitation event analysis, and discharge hydrographs for the sampled period.

Simulation

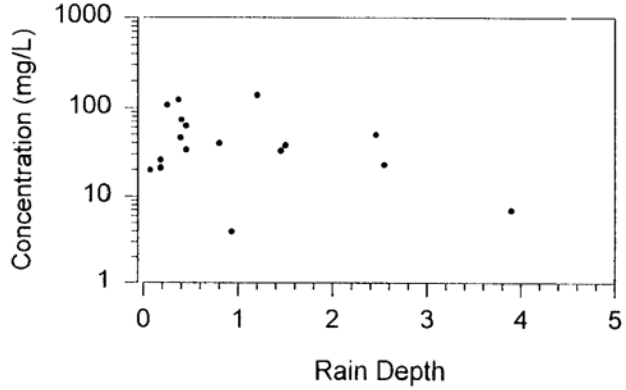
SWMM was utilized to simulate stormwater conditions for the entire Tampa area using the specific data collected from the above mentioned sites. To utilize SWMM, the basins in the study area were divided into sub-catchments as dictated by their drainage characteristics. SWMM was then calibrated using available data. After model verification, SWMM was applied to simulate runoff conditions and estimate pollutant loads and concentrations. Conclusions were then drawn as to the quality of storm runoff in the Tampa area based the model outputs.

Conclusions

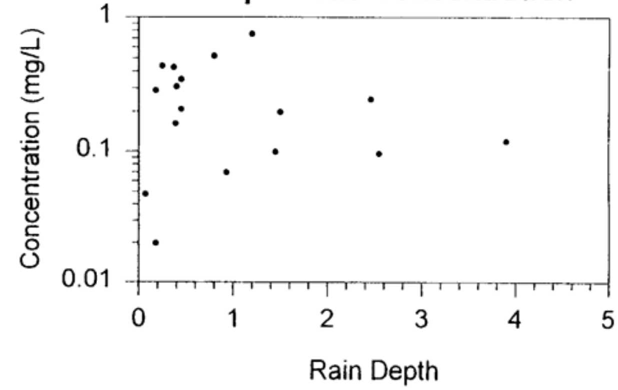
It was concluded that the quality of stormwater in Tampa was better than that found in other locations in the NURP program. Conclusions were also drawn as to receiving water quality in the Hillsborough River.

Tampa, Florida
J.L. Young Basin
High Density Residential

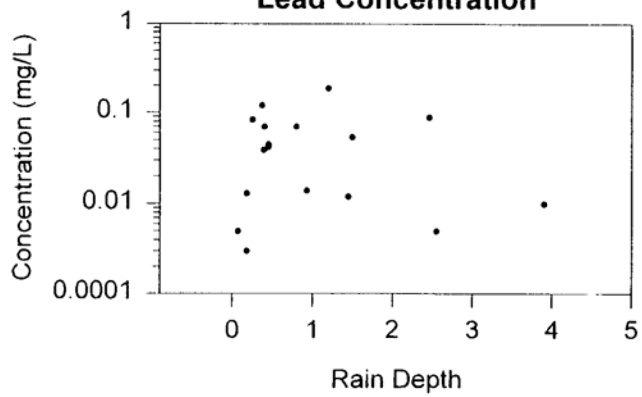
Rain Depth vs.
COD Concentration



Rain Depth vs.
Phosphorous Concentration

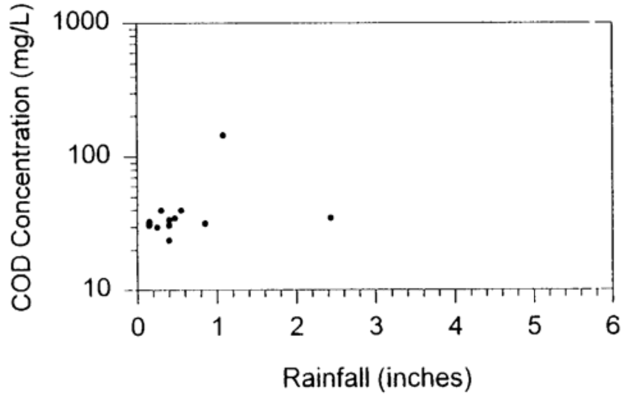


Rain Depth vs.
Lead Concentration

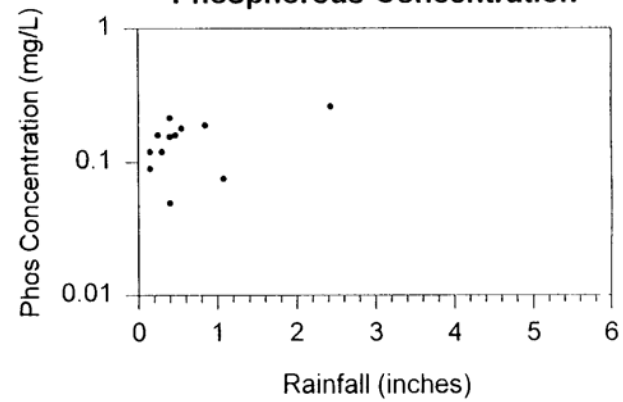


Tampa, Florida
Basin 10
Residential/ Instuitutional Land Use

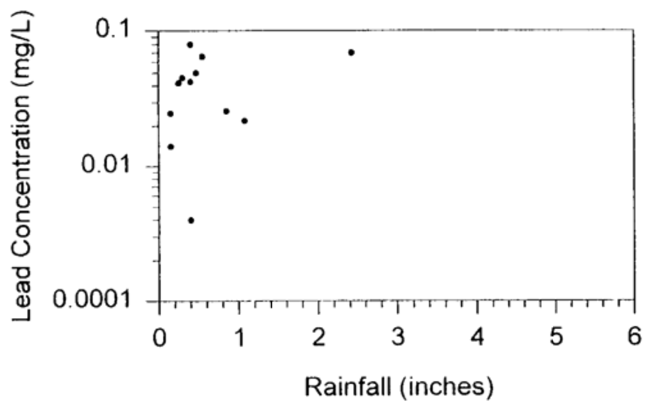
Rain Depth vs.
COD Concentration



Rain Depth vs.
Phosphorous Concentration

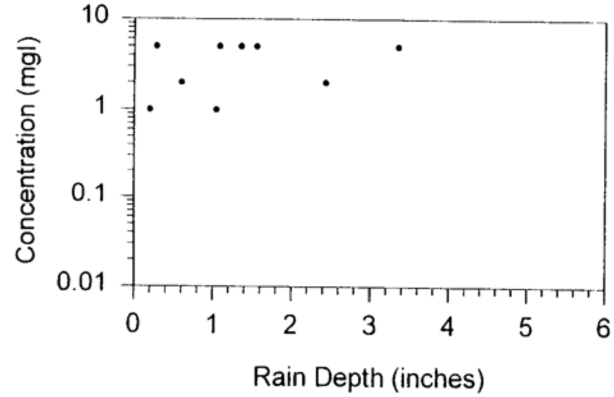


Rain Depth vs.
Lead Concentration

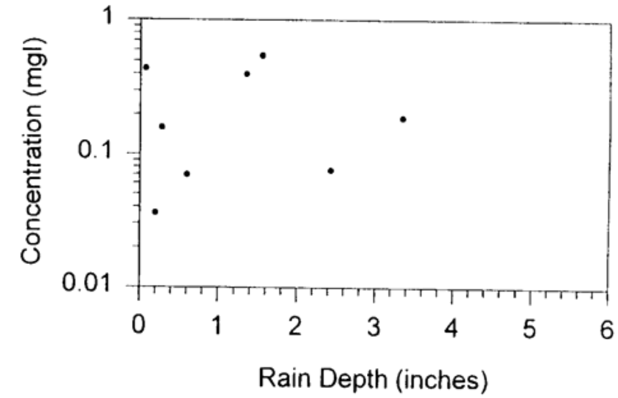


Tampa, Florida
Basin 11
Residential/Institutional Land Uses

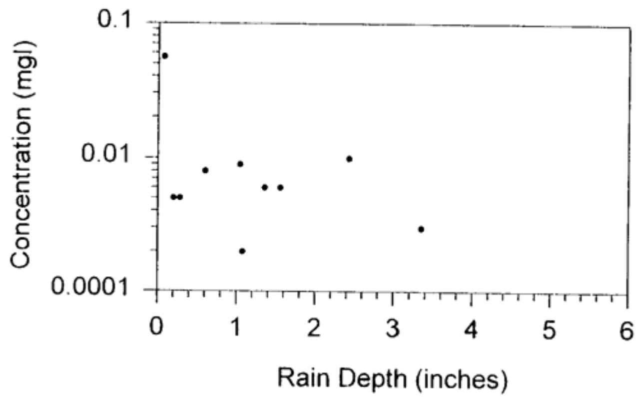
Rain Depth vs. COD Concentration



Rain Depth vs. Phosphorous Concentration

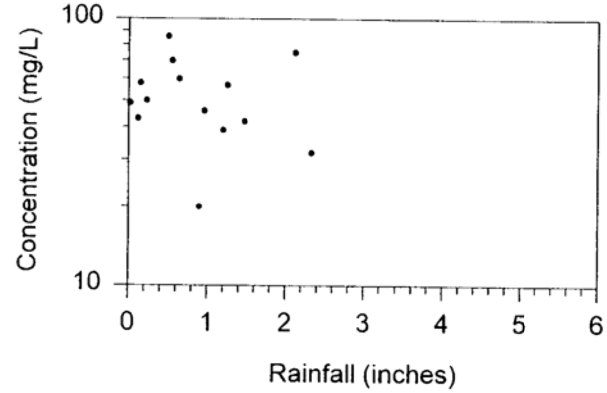


Rain Depth vs. Lead Concentration

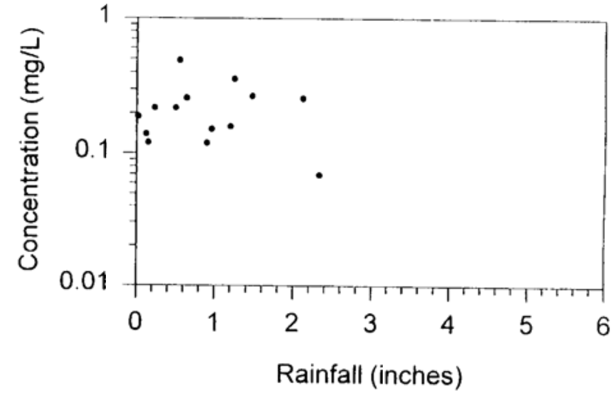


Tampa, Florida
Basin 3
Mixed Land Uses

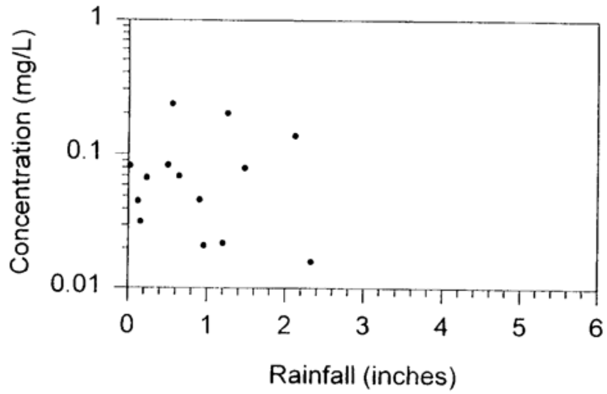
**Rain Depth vs.
COD Concentration**



**Rain Depth vs.
Phosphrous Concentration**

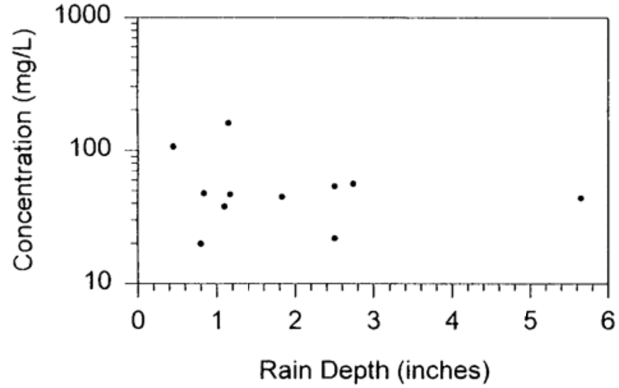


**Rain Depth vs.
Lead Concentration**

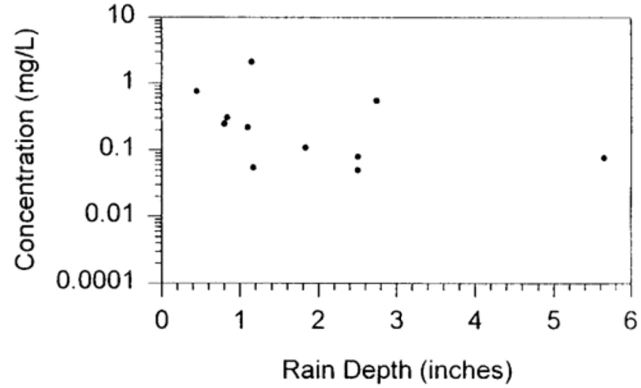


Tampa, Florida
Basin 8
Commercial Land Use

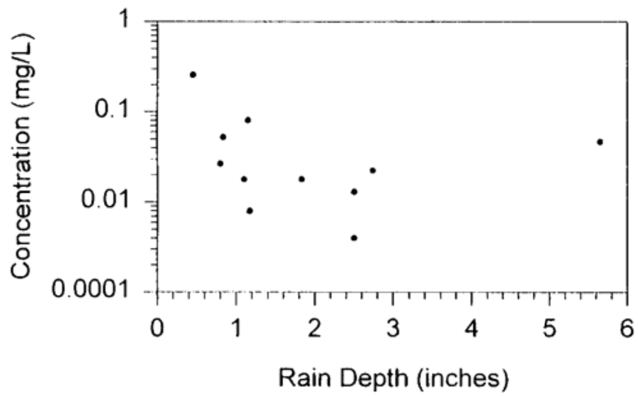
Rain Depth vs. COD Concentration



Rain Depth vs. Phosphorous Concentration



Rain Depth vs. Lead Concentration



NURP - Champaign, Illinois

Introduction

The purpose of this project was to determine the effectiveness of municipal street cleaning to control urban storm runoff pollution discharges. This project also devoted attention to data collection and interpretation. The project had six specific goals to accomplish: 1) To relate the accumulation of street dirt to land use, traffic count, time, and type and conditions of street surface; 2) To define the washoff of street dirt in terms of rainfall rate, flow rate, available material, particle size, slope and surface roughness; 3) To determine what fraction of pollutants occurring in stormwater runoff may be attributed to atmospheric fallout; 4) To modify the ILLUDAS model to permit water quality simulation as a function of surface sediment removal; 5) To calibrate the modified model uses the monitored data; 6)To develop accurate production functions and corresponding cost functions for various levels of municipal street cleaning. A three year study of the area's urban storm runoff was conducted in order to accomplish these goals.

The Champaign-Urbana area consists of relatively flat terrain located in east central Illinois. The characteristics of the area make it ideal for study: a variety of land uses are represented; separate sanitary and storm sewers serve the entire area. The annual rainfall is about 36.5 inches per year and the soil in the area consists mainly of silty, poorly drained soils that are barely sloping.

Five sites in the study area were chosen representing different land uses. Continuous measurement and water quality analysis of rainfall and runoff were conducted at the sites along with chemical analysis of dry atmospheric fallout; determination of loads, rates of deposition, and rates of accumulation of street dirt; and particle size distribution and chemical analysis of street dirt.

Sampling Sites

The sites selected for study were made up of two pairs of similar basins to monitor mixed and residential land uses and a micro basin to measure data from a completely paved area. The first pair of basins consisted of uniform single-family land use areas of similar size. The second pair also were of similar size but consisted of mainly commercial area with heavily traveled streets. Table B-5 summarizes the basin characteristics. Directly impervious area represents the area which travels directly to the drainage system without encountering any pervious area. Supplemental impervious areas direct runoff towards pervious areas before the runoff reaches the drainage system. The roadway areas in all cases comprise much of the directly connected impervious areas. Basin slope values are based on the longest primary flow path in each basin. The slope value is calculated from the fall and length of the same path between points 15 percent and 85 percent of the total length upstream from the outlet.

Table B-5. Comparison of Physical Basin Parameters

Parameters	Mattis North	Mattis South	John North	John South	Micro Basin
Total Area (acres)	16.7	27.6	54.5	39.1	0.76
Directly Connected Imperv. Area (% of total)	58.0	40.0	18.5	17.5	18.0
Roadway (% of total)	26	21	14	13.4	15
Lane Miles	2.70	3.21	4.79	3.36	0.07
Curb Miles (% of total)	1.15	1.33	4.79	3.36	0.07
Supplemental Imperv. Area (% of total)	3	11	14.5	14.7	18
Grassed Area (% of total)	39	49	67	67.8	64
Basin Slope (% of total)	.54	1.2	.67	1.31	1.75
Fall (ft)	17.5	29.8	21.9	33.3	6.1
Length (ft)	3225	2480	3260	2535	350

Slope 15-85 (% of total)	.51	1.27	.69	1.52
Fall (ft)	11.6	22	15.9	26.9
Length (ft)	2280	1735	2285	1775

Data Collection Methodology

A telemetry network consisting of a central station and four remote stations collected data for this study. The telemetry system included the samplers, raingages and depth sensors. It indicated rainfall, flow and the status of the samplers. The equipment was installed at secure sites either under manhole covers or in protective shelters. The automatic data collection system was run nearly constantly with the exceptions being on dry days for short periods of time. The system provided a continuous record of precipitation at three raingages and depths of flow at five sampling points. Rainfall data was reported to the nearest 0.01 of an inch; depth of flow data in units of 0.01 foot for seven locations, sites 4 and 5 each had two monitors. This data was measured at one minute intervals. Two additional raingages, one an ISWS gage and the other a U.S. Weather Bureau gage, produced the rainfall data for two of the test sites, both of these gages were read to the nearest 0.01 of an inch as well. Data storage, equipment monitoring and the samplers were controlled by the computer program RUNOFF.

During a storm event, RUNOFF would issue instructions to the samplers which would, after purging the intake line, pump a sample. These samples would then be picked up by field personnel and taken to Illinois State Water Survey (ISWS) offices. Appropriate tests were then performed at the lab. The project called for discrete as well as composite sampling through both were not performed throughout the entire study period. Discrete sampling was conducted early in the project, through 1980, then replaced with composite sampling. For almost all events in 1981, flow weighted composite sampling was conducted in the following manner: RUNOFF calculated the incremental runoff volumes and updated them every minute, at specific flow volumes instructions were issued to collect a sample, these samples were combined and analyzed for the applicable constituents.

Three categories of pollutant constituents were examined during this study: total suspended solids and total dissolved solids; total metals; and total nutrients. The total solids group relates to basin loads and accumulations of solids in dry and washoff periods. Metals tested in this study included lead, copper, iron, chromium, cadmium and zinc. These metals were chosen because of their association with street dirt and urban runoff problems. Included in the nutrients analyzed were organic carbon, chemical oxygen demand, ammonia, nitrate-nitrate, Kjeldahl nitrogen, and phosphorous. These were chosen for their expected contributions to quality problems in urban runoff in residential areas. Other tests were occasionally tested but not regularly. Table B-6 is a complete list of all tests performed.

Table B-6. Maximum Constituent List for Stormwater and Street Dirt Samples

Total Suspended Solids	
Particle Size Determination	
Total Dissolved Solids	
pH	
Specific Conductance	
Nitrate plus Nitrate (as N)	Dissolved, Total
Ammonia Nitrogen (as N)	Dissolved, Total
Kjeldahl Nitrogen (as N)	Dissolved, Total
Phosphorous (as P)	Dissolved, Total
Lead	Total
Copper	Total
Iron	Total
Chromium	Total
Cadmium	Total
Zinc	Total
Mercury	Total
Organic Carbon (as C)	Dissolved, Total
Chemical Oxygen Demand	
Biochemical Oxygen Demand	5- Day, Ultimate (20-50 Day)
Fecal Coliform Bacteria	
Fecal Streptococcal Bacteria	
Temperature	
Dissolved Oxygen	
Color	

Turbidity
Hardness
Other special constituents: PCBs, Pesticides, Oil and Grease

As this project focused on the evaluation of street cleaning as a stormwater control measure, data was also collected on street dirt loads, their contribution to runoff, and the effects of cleaning on these loads. Methods were developed to periodically collect dirt from the area that would be representative of the street loads in each area. These samples were then analyzed to determine their constituents. A street sweeping pattern was also developed using the basin pairs as control and experimental components for specified time periods allowing comparisons to be made. The once or twice a week frequencies were used to simulate reasonable sweeping practices if the program is implemented upon the conclusion of testing.

Correlating the runoff and street dirt analyses with the street cleaning schedule provides a means to judge the effectiveness of street sweeping in controlling stormwater pollutants. Initially, data was collected during a control period in which no street cleaning was done, this data was used to set standards for street dirt loads and corresponding runoff quality for each basin. Then the basins were cleaned as follows; starting in late July one residential basin and one commercial basin were swept twice a week and the other two were left unswept. This pattern continued until mid-November. During April and May of 1981 the same two basins were swept once per week and then from June to August they were left unswept. In this last three month period the second basins in each pair were swept once per week. For all sweeping events the city provided gross weights and samples of the material removed by sweeping.

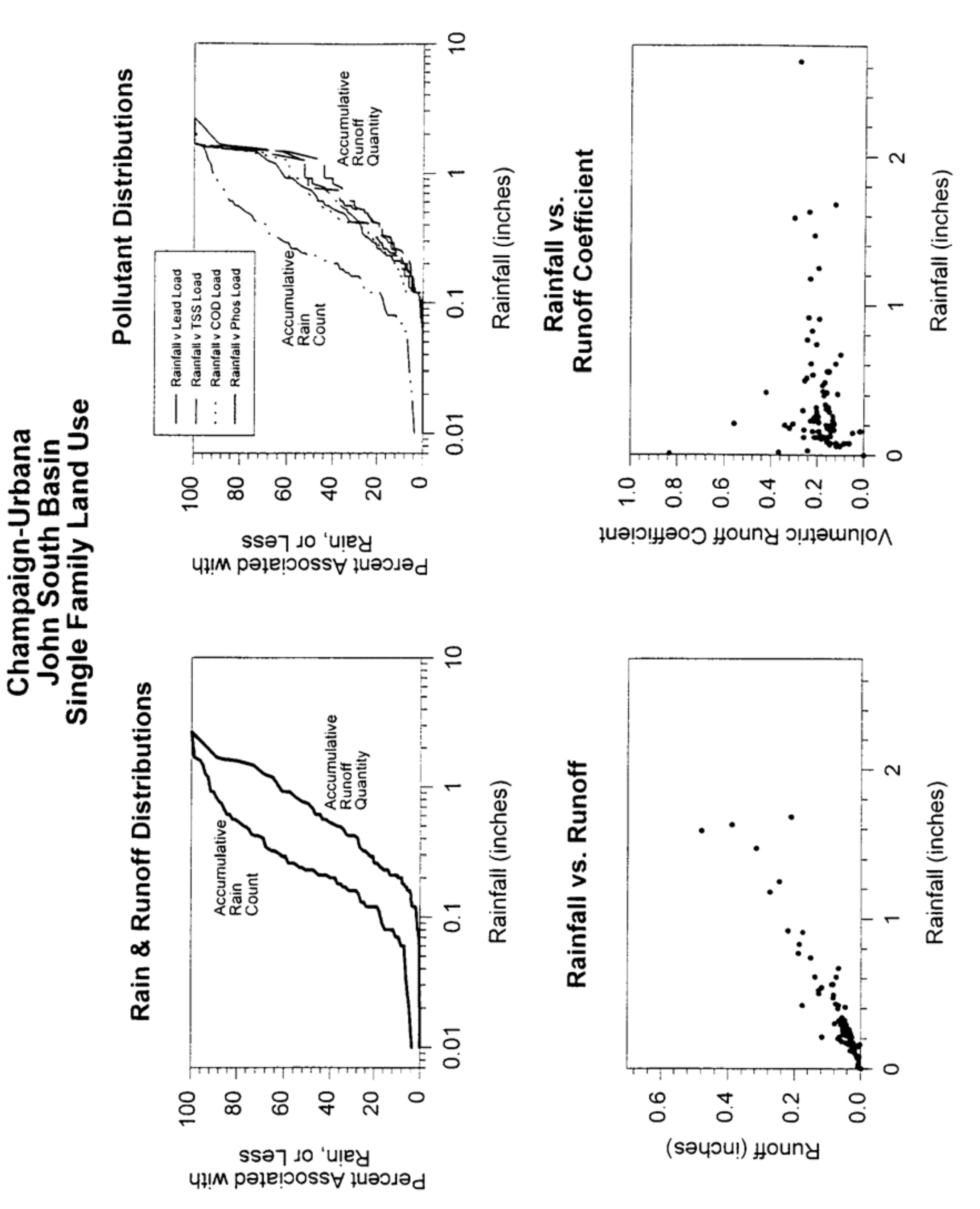
Simulation

The results of the data collection were used to modify the computer program ILLUDAS designed to simulate urban storm runoff. The new program Q-ILLUDAS is a " quasi- continuous urban runoff quantity- quality model". The model accounts continuously for rainfall and soil moisture, and as precipitation occurs pipe and stream flow are simulated. The model accounts for directly connected impervious area, contributing grassed areas and areas that are a combination of grassed and impervious areas. Particulate washoff in the basins are used to predict urban runoff water quality. A set of work equations dependent on rainfall and basin characteristics are utilized to determine particulate amounts that settle or runoff into the basins. Concentrations of constituents can be determined as well.

Model verification was done by comparing actual data and simulated data for several parameters including total event rainfall, event five-minute maximum rainfall, observed peak, and runoff coefficient. Data pertaining to runoff water quality was also compared to simulation data to verify the models accuracy. In verifying water quality simulation, events compared demonstrated similarities in hydrograph peaks, volumes, runoff coefficients and overall shapes. In terms of hydrologic modeling, the model is classified as very good, and in the area of water quality it is in the fairly good range.

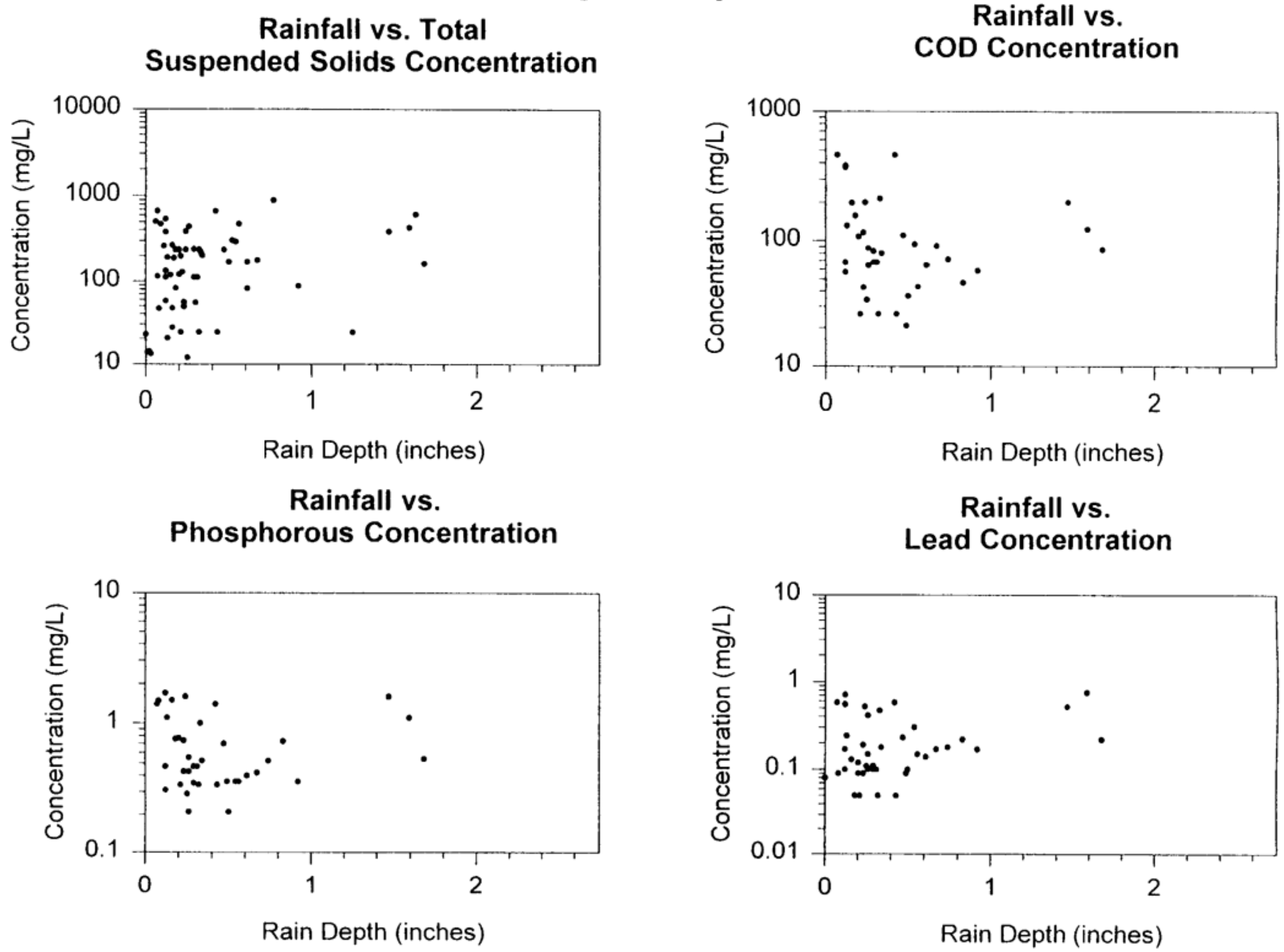
Conclusions

Detailed analyses of the relationships between runoff pollutants, street dirt composition and street cleaning were performed on the collected data. Two types of comparisons were made; parallel and series. In the parallel comparison, like basins were compared for the same rainfall events when one basin was cleaned and the other was not. In the series comparisons, the basins were considered individually for different runoff events based on whether it was swept or not. Regardless of the type of comparison made, it was concluded that street cleaning does not significantly improve stormwater quality.

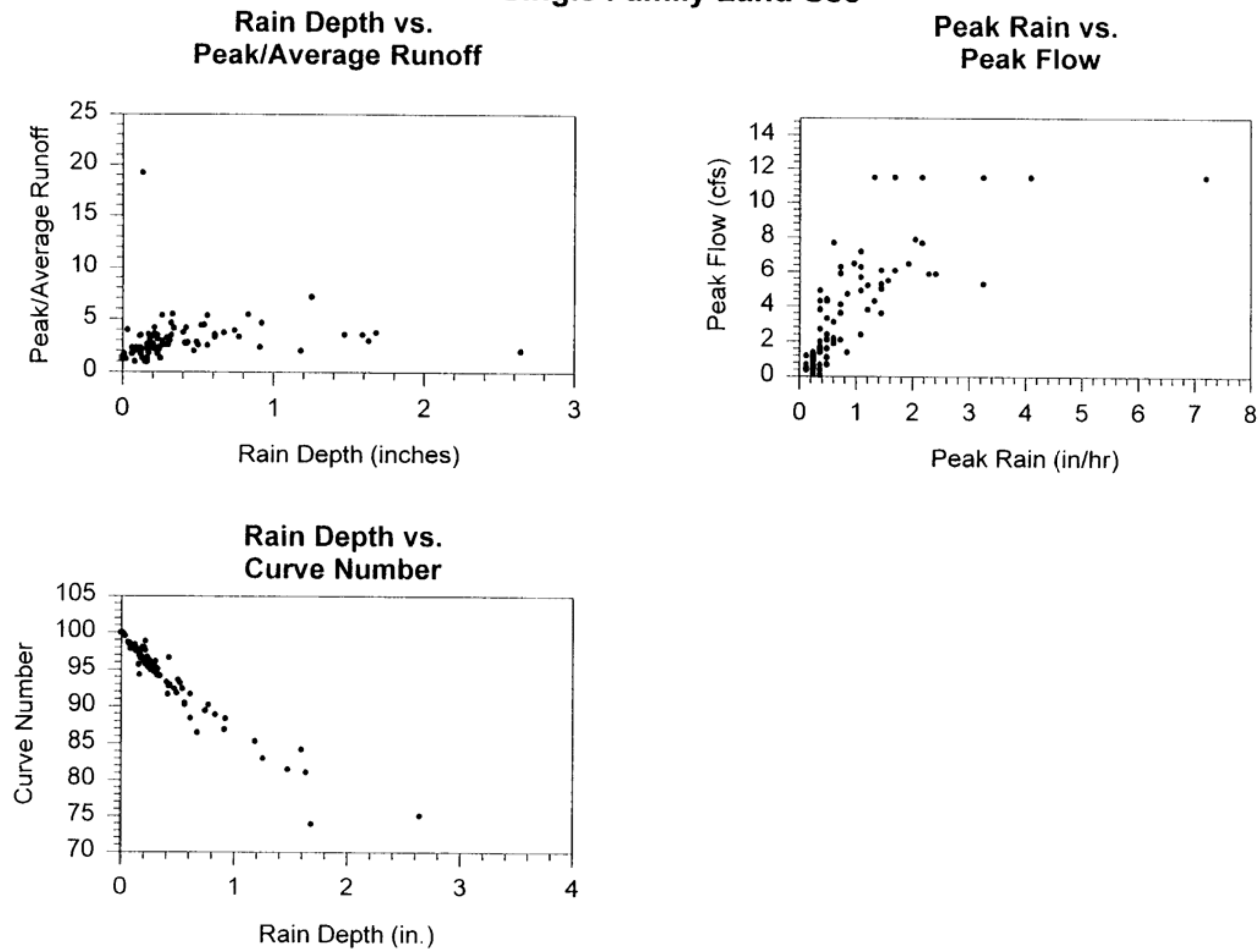


Champaign-Urbana
John South Basin
Single Family Land Use
Rain & Runoff Distributions
Percent Associated with Rain, or Less
Accumulative Rain Count
Accumulative Runoff Quantity
Rainfall (inches)
0.01
0.1
1
10
100
80
60
40
20
0
Pollutant Distributions
Rainfall v Lead Load
Rainfall v TSS Load
Rainfall v COD Load
Rainfall v Phos Load
Rainfall vs. Runoff
Runoff (inches)
0.6
0.4
0.2
0.0
0
1
2
Rainfall vs. Runoff Coefficient
Volumetric Runoff Coefficient
1.0
0.8
0.6
0.4
0.2
0.0

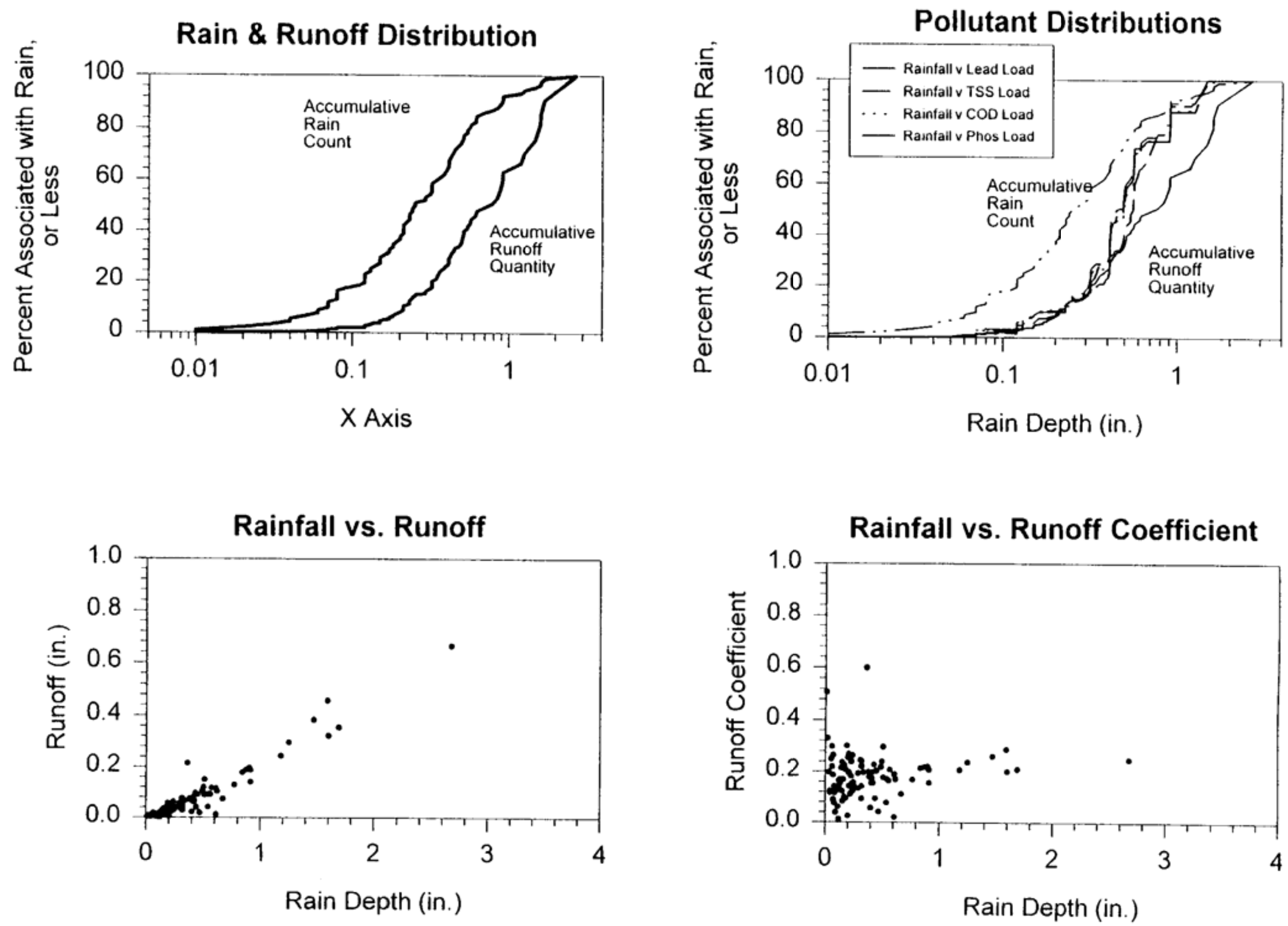
Champaign-Urbana
John South Basin
Single Family Land Use



Champaign-Urbana
John South Basin
Single Family Land Use

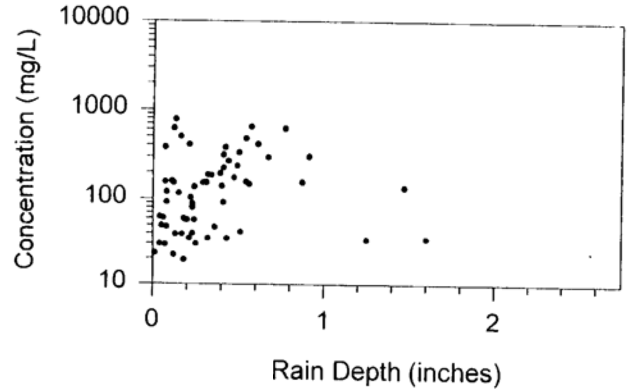


Champaign-Urbana
John North Basin
Single Family Land Use

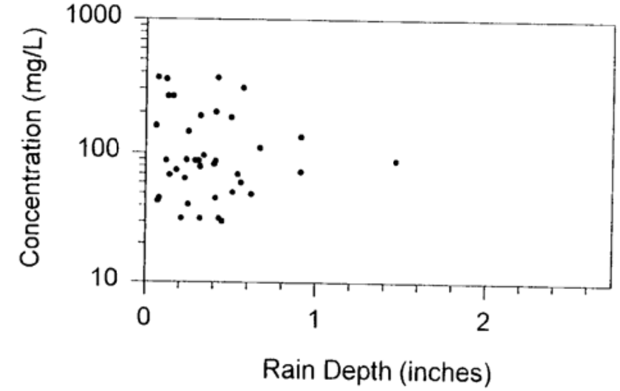


Champaign-Urbana John North Basin Single Family Land Use

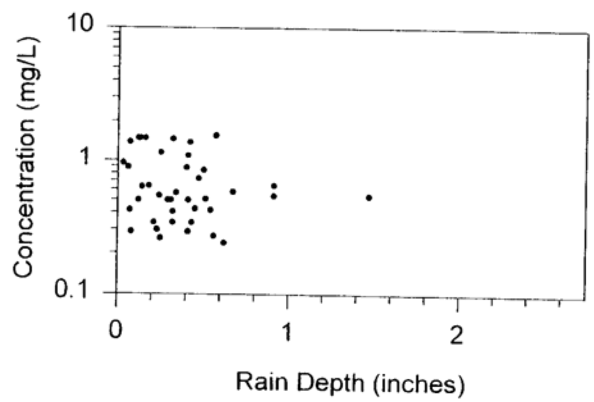
Rainfall vs. Total Suspended Solids Concentration



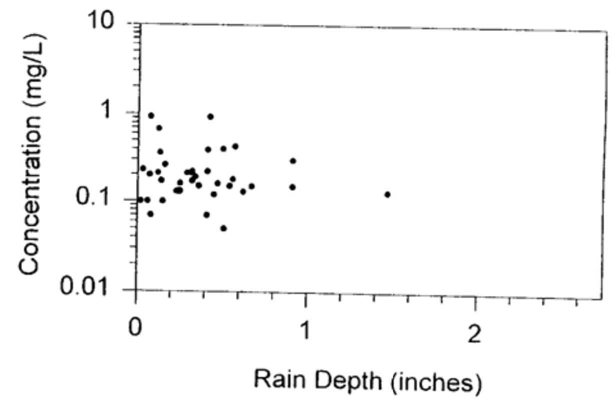
Rainfall vs. COD Concentration



Rainfall vs. Phosphorous Concentration

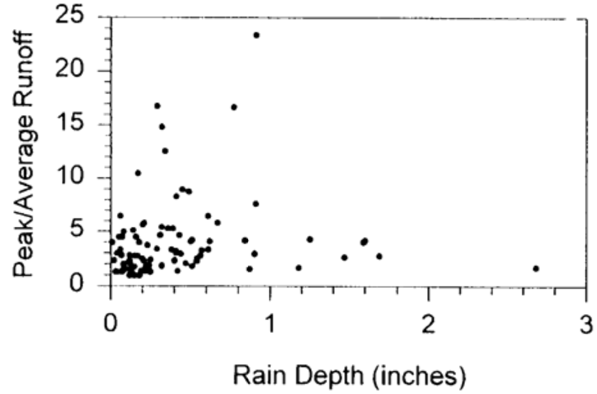


Rainfall vs. Lead Concentration

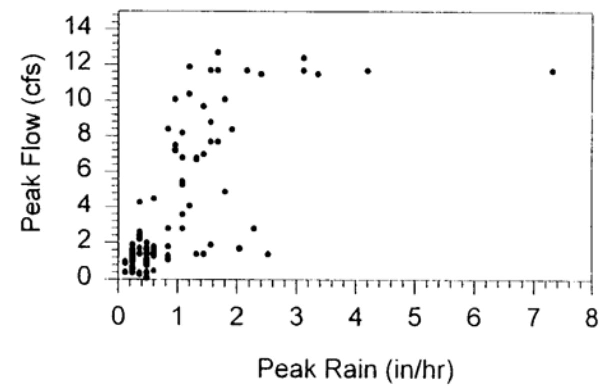


Champaign-Urbana
John North Basin
Single Family Land Use

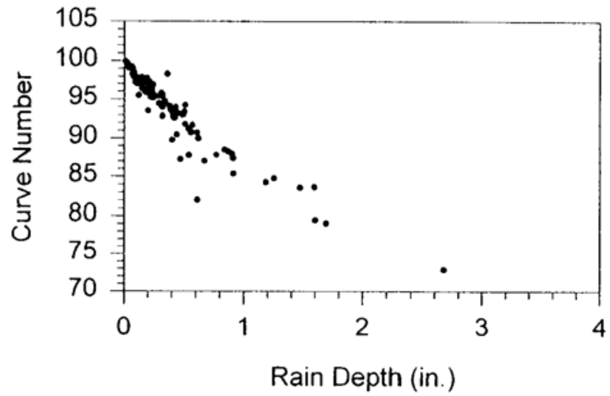
**Rain Depth vs.
Peak/Average Runoff**



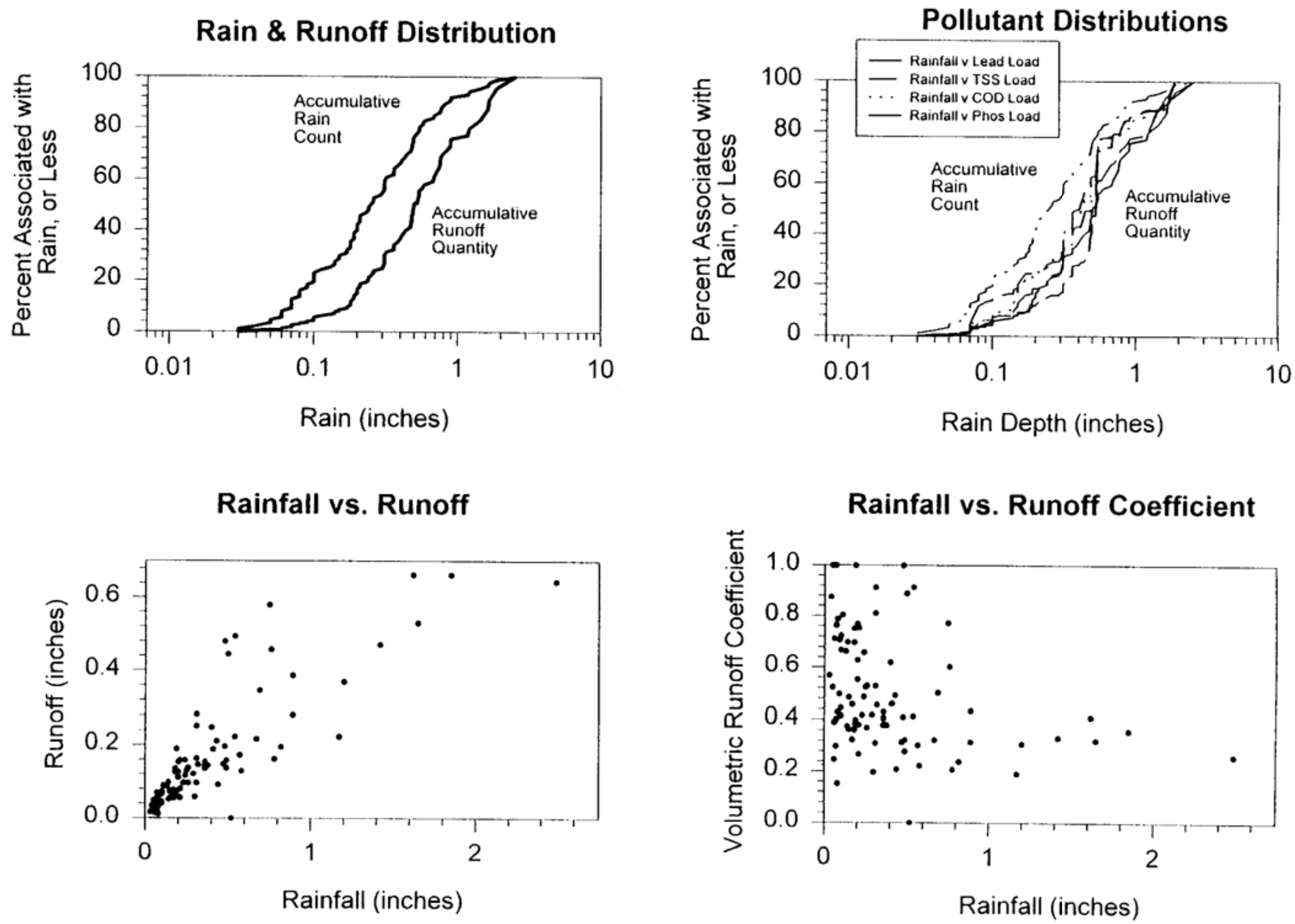
**Peak Rain vs.
Peak Flow**



**Rain Depth vs.
Curve Number**

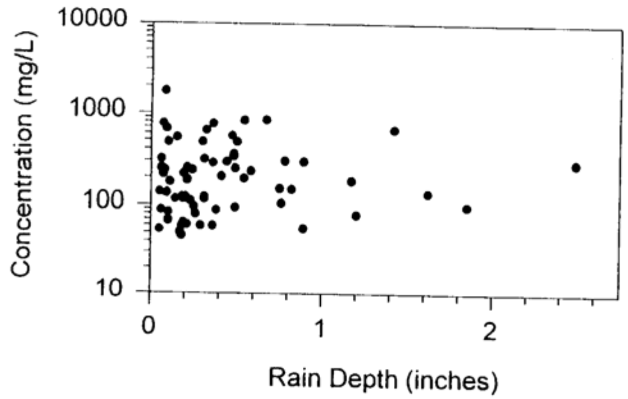


Champaign-Urbana
Mattis North Basin
Commercial Land Use

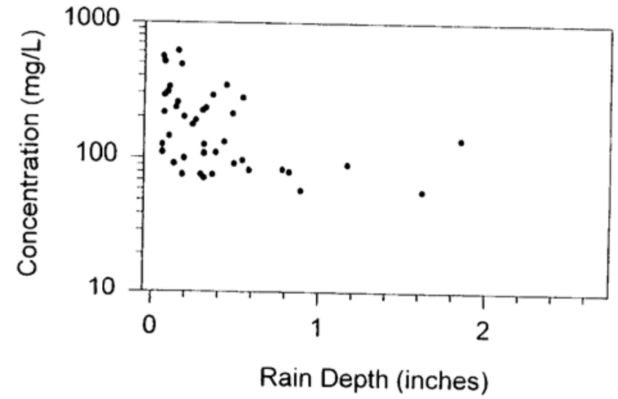


Champaign-Urbana
Mattis North Basin
Commercial Land Use

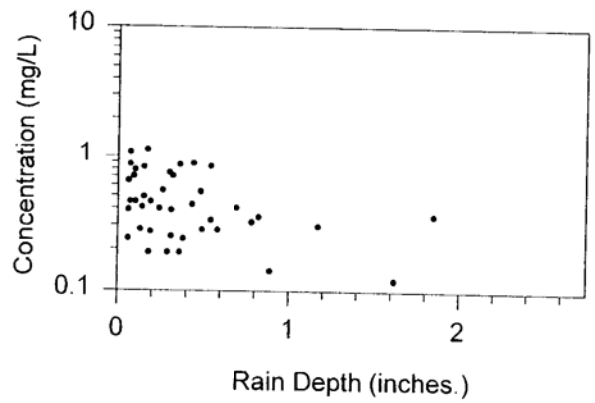
Rainfall vs. Total Suspended Solids Concentraion



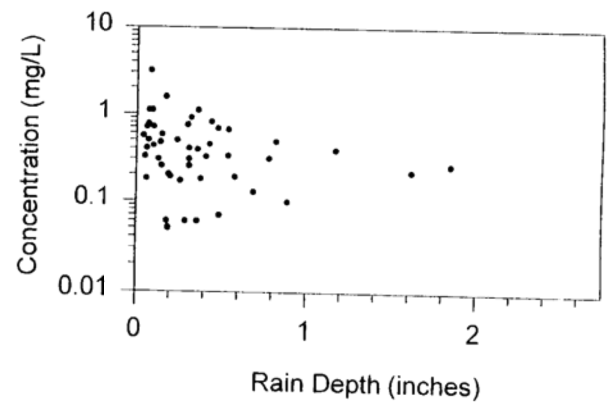
Rainfall vs. COD Concentration



Rainfall vs. Phosphorous Concentration

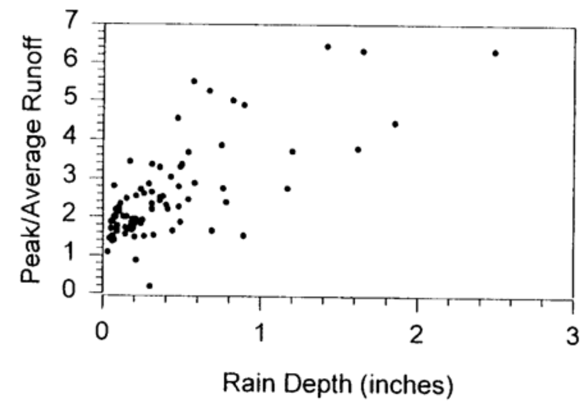


Rainfall vs. Lead Concentration

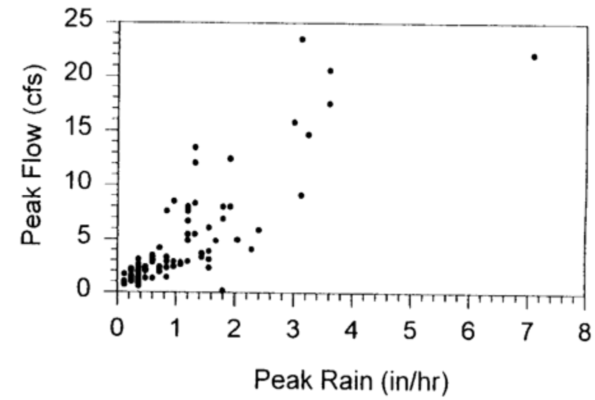


Champaign-Urbana
Mattis North Basin
Commercial Land Use

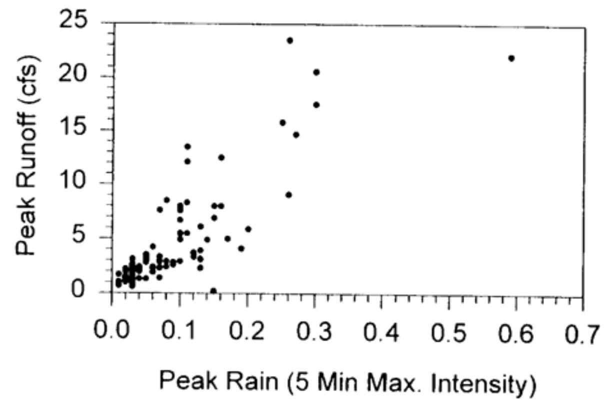
**Rain Depth vs.
Peak/Average Runoff**



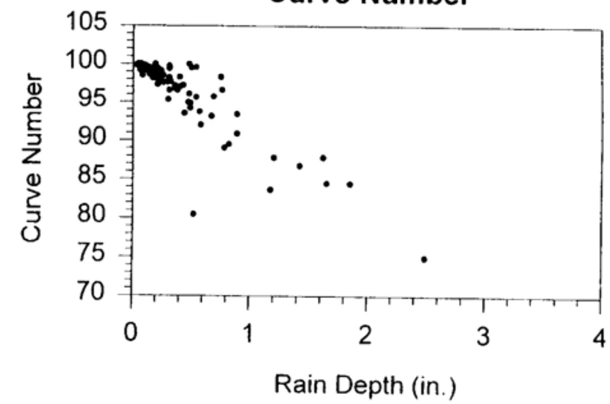
**Peak Rain vs.
Peak Flow**



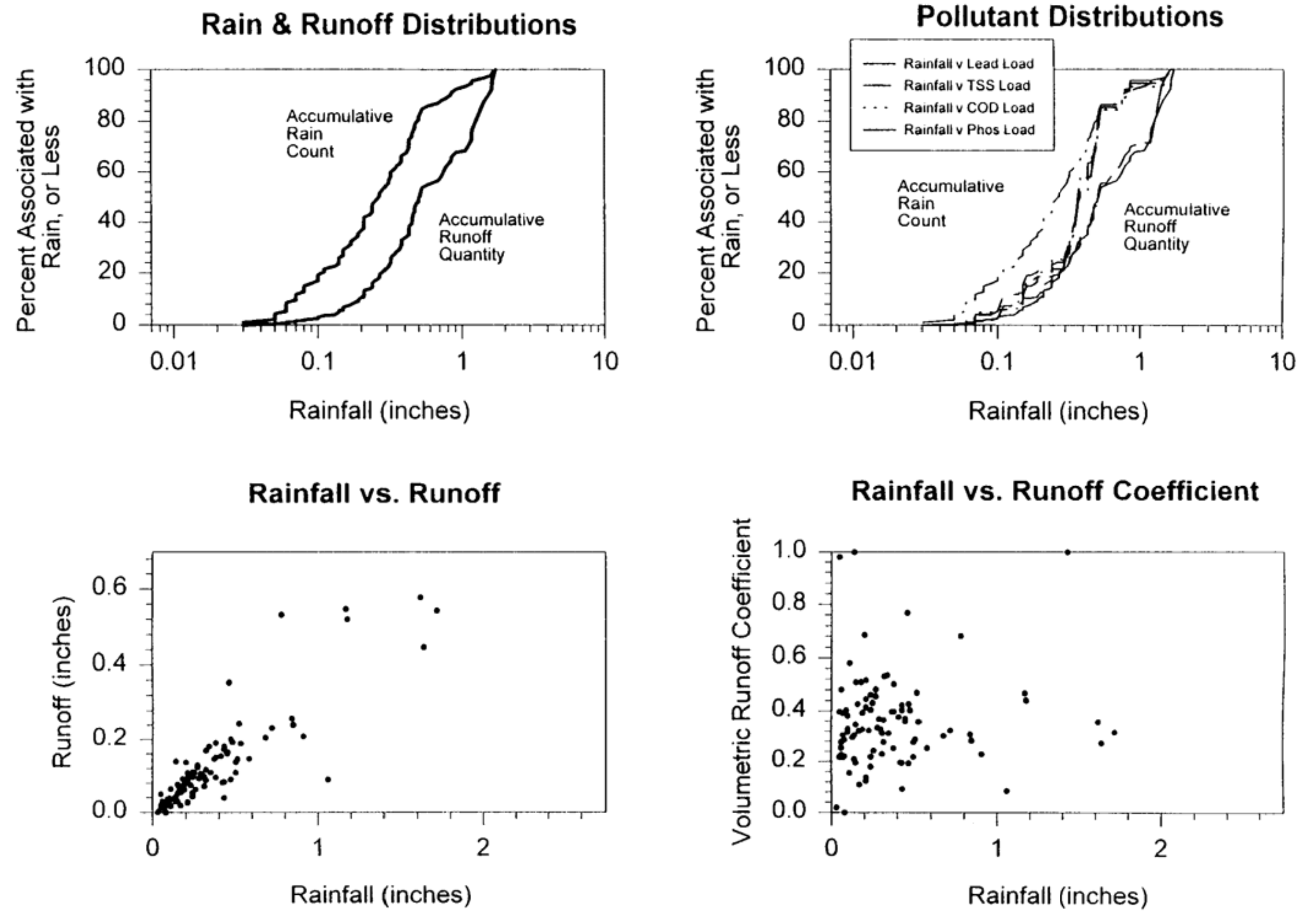
**Peak Rain vs.
Peak Runoff**



**Rain Depth vs.
Curve Number**

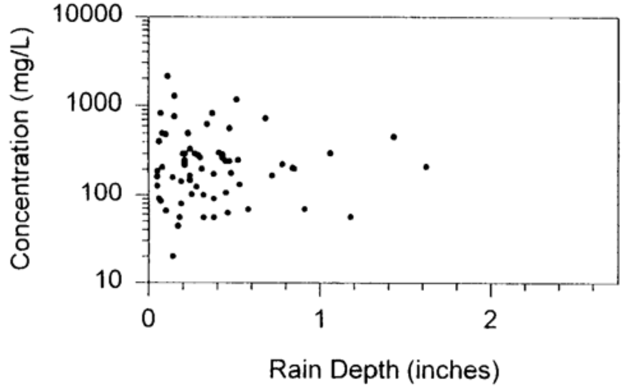


Champaign-Urbana
Mattis South Basin
Commercial Land Use

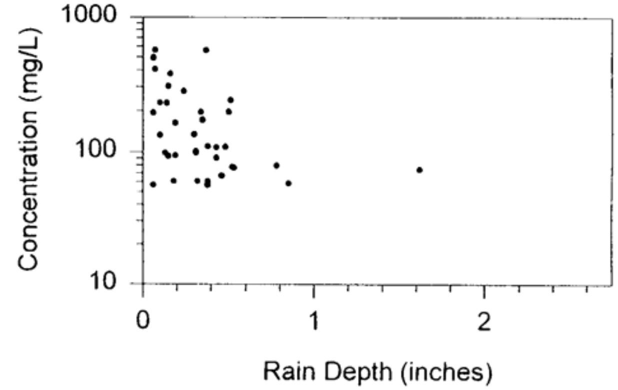


Champaign-Urbana
Mattis South Basin
Commercial Land Use

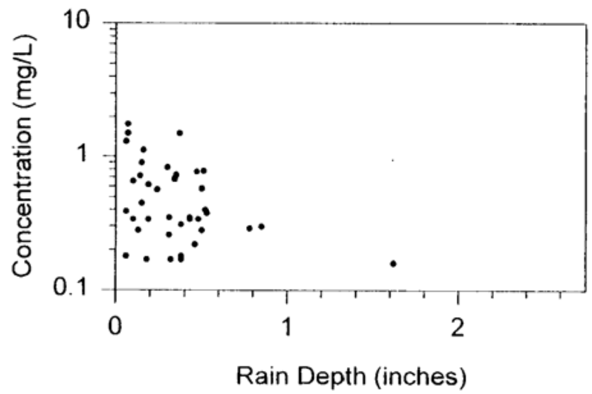
Rainfall vs. Total Suspended Solids Concentration



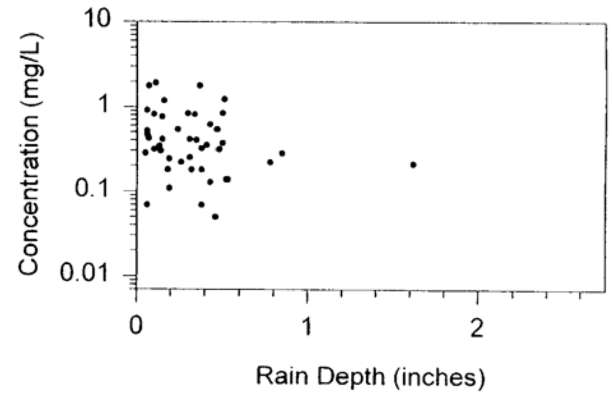
Rainfall vs. COD Concentration



Rainfall vs. Phosphorous Concentration

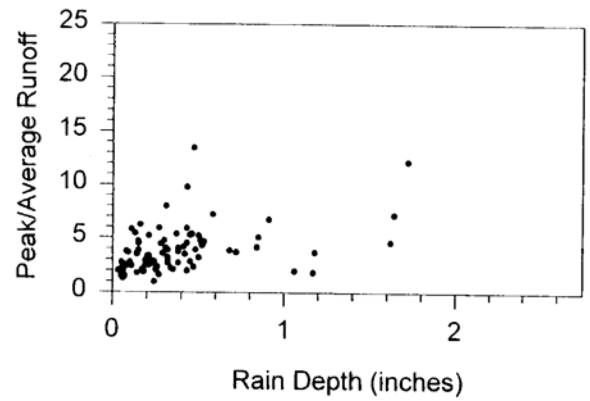


Rainfall vs. Lead Concentration

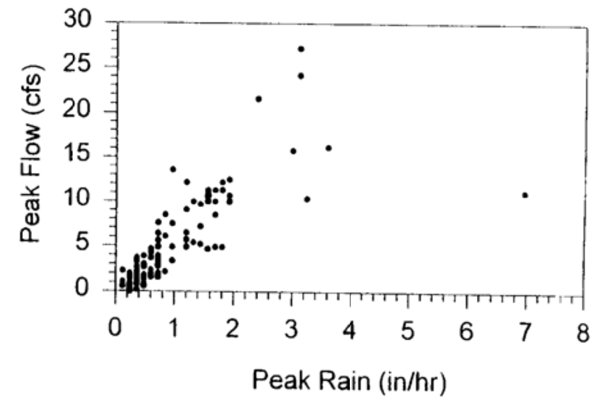


Champaign-Urbana
Mattis South Basin
Commercial Land Use

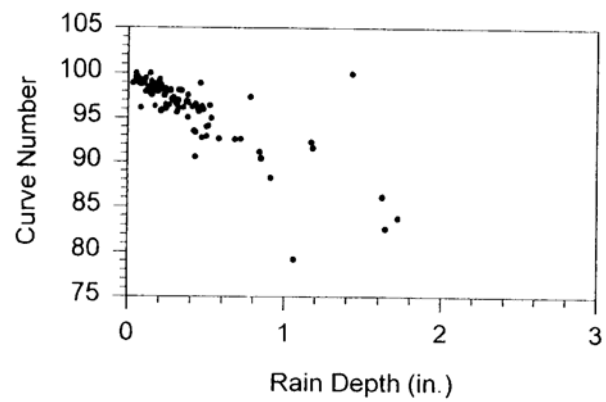
Rain Depth vs. Peak/Average Runoff



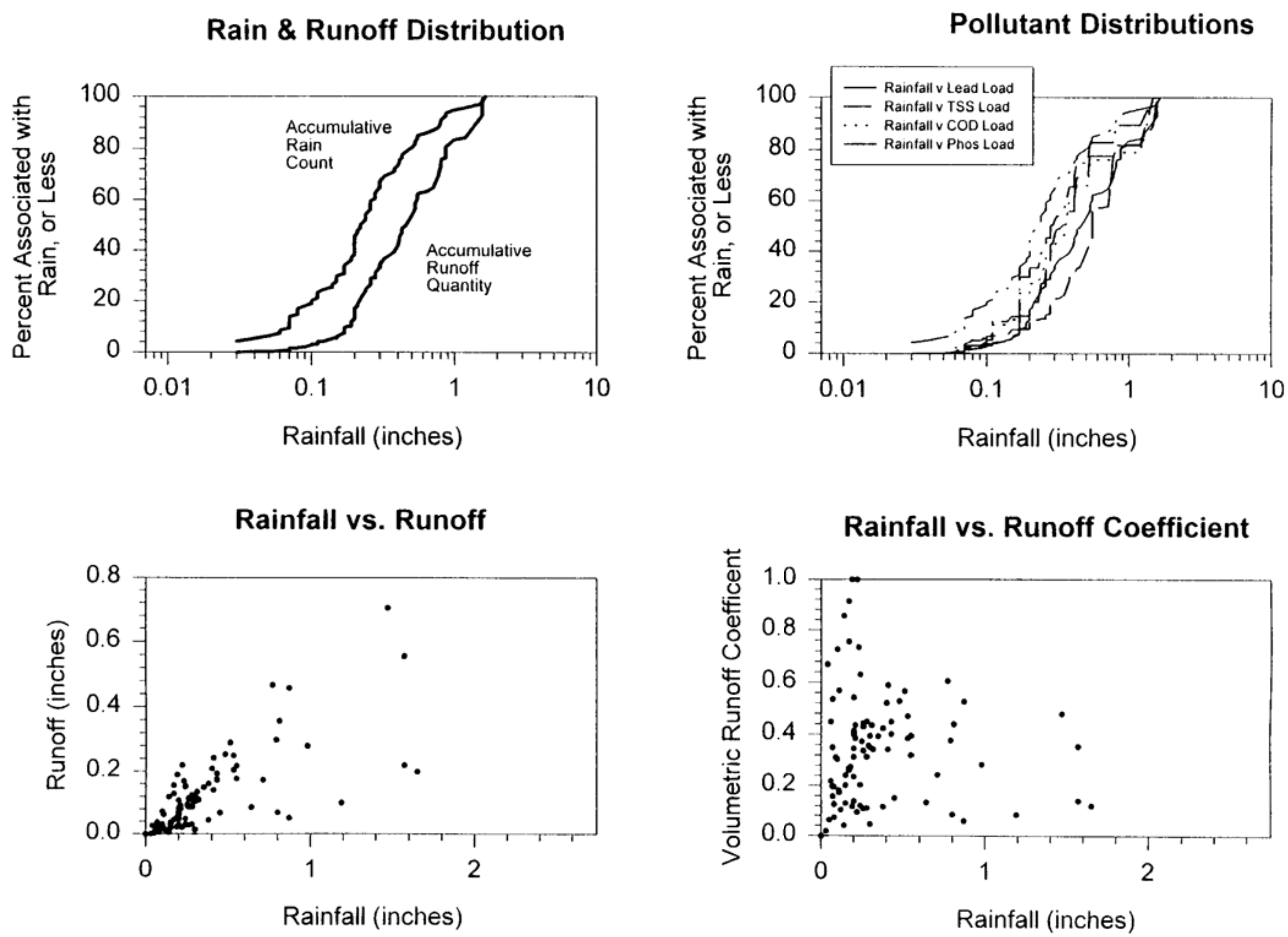
Peak Rain vs. Peak Flow



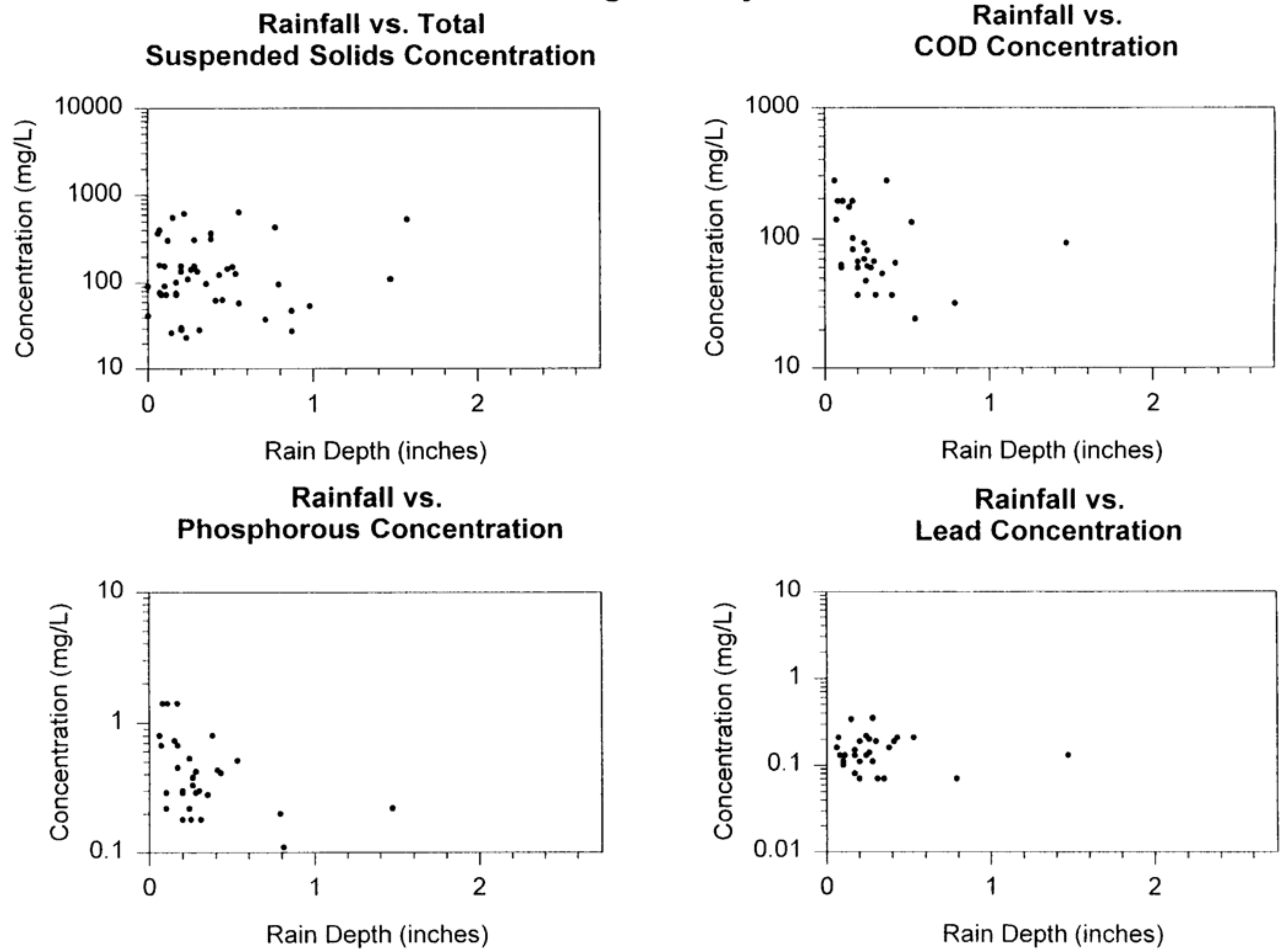
Rain Depth vs. Curve Number



Champaign-Urbana
Micro Basin
Single Family Land Use

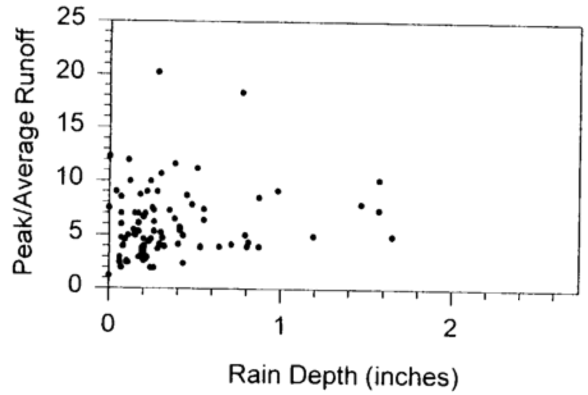


Champaign-Urbana
Micro Basin
Single Family Land Use

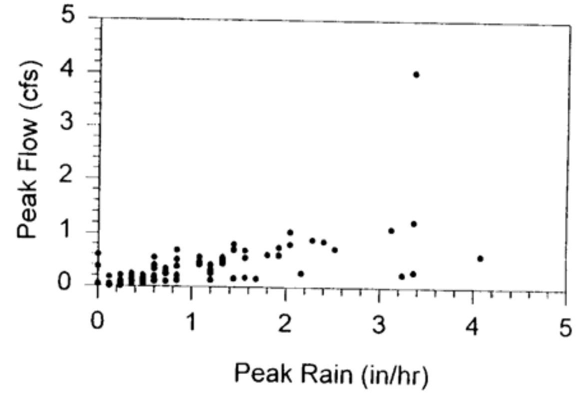


Champaign-Urbana
Micro Basin
Single Family Land Use

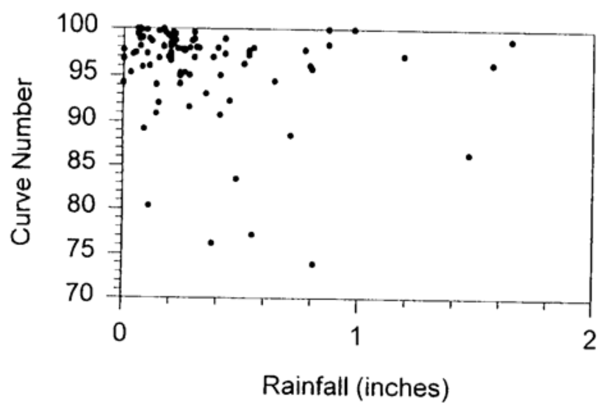
**Rain Depth vs.
Peak/Average Runoff**



**Peak Rain vs.
Peak Flow**



**Rainfall vs.
Curve Number**



NURP - Rapid City, South Dakota

Introduction

The purpose of this NURP project were to characterize impacts of runoff from both rainfall and snow melt, determine the effects of runoff discharge on fish habitat, review in-stream water quality standards during storm events, and to determine the effects of runoff on beneficial stream uses.

The study area for this project is located in Rapid City, in the western part of South Dakota. Geographically, it is positioned in the foothills of the Black Hills. The climate is semi-arid with widespread variation in temperatures. Average yearly rainfall is 18 inches. The area contains a variety of land uses divided into five categories, urban and rural residential, commercial and industrial, institutional, non-urban and other. Included in the other category are parks, quarries and undeveloped areas.

The study area was divided into six watersheds in order to collect data. Five of these stations were in-stream stations measuring the quality of the water in Rapid Creek. While the sixth measured the flow from a drainage channel. 33 runoff events were sampled during a three year period. Tests were conducted on the collected water to determine pollutant loads delivered to the creek. Three snowmelt events were also tested.

Sampling Sites

Five of the sampling sites were located in Rapid Creek. The locations for these sites were chosen in order to give a measure of increased loadings with increased runoff. The first sampling station was located to provide au upstream control. The water collected from this site represents baseline conditions before the introduction of urban runoff. Station two was positioned further down stream and was influenced by some urban runoff. Station three samples were influenced by discharges draining all of western Rapid City, a cement plant and quarries. The fourth station samples the stream with the addition of runoff from North Rapid City and the downtown area. Station five was located in the creek below town in an effort to give an indication of the total loads contributed by Rapid City. The final station was located at the outfall of a drainage channel. This channel drains a large portion of the community and therefore can give a good indication of the pollutants contained in the urban runoff. The following chart shows the areas and % of land uses contributing to each sampling station. Non -urban land use includes forestland, grassland, agricultural land and water. Urban residential signifies city communities with respect to housing and streets. Rural residential consists of larger lots and more unpaved areas. Commercial and industrial are areas with stores, offices, plants etc. Institutional areas consist of schools, hospitals, and retirement homes. Parks, undeveloped areas and quarries are included in the other category.

Table B-7. Station Characteristics

	Non-Urban Area	%	Residential Urban Area	%	Rural Area	%	Commercial & Industrial Area	%	Institutional Area	%	Other Area	%	Total Area
Station 1	32,350	95.9		0	1,350	4	25	0.1	5	0	0	0	33,730
Station 2	16,349	77.8	1,581	7.6	1,866	8.9	92	0.4	410	1.9	692	3.3	20,990
Station 3	2,288	59.1	85	2.2	15	0.4	699	18	62	1.6	723	18.6	3,872
Station 4	1,171	32.1	1,137	31.2	160	4.4	498	13.6	159	4.4	525	14.4	3,650
Station 5	303	18.8	303	18.8	23	1.4	415	25.8	162	10.1	404	25.1	1,610
Station 6	696	34.3	944	46.5	14	0.7	131	6.4	103	5.1	142	7	2,030

Data Collection Methodology

Several different sampling methods were utilized in this study, including both manual and automatic water sampling. During the 1980 rain season, all rain samples were collected manually by wading in the stream and collecting 10 to 15 depth integrated samples. The samples were collected in new gallon milk jugs and cooled to 40 degrees C. During the 1981 season, runoff was collected using automatic samplers at sites 1, 3, 5, and 6. For the 1982 season, the station 1 sampler was moved to station 4 because it was not possible to collect significant station 1 data due to the low flow.

Data was collected at pre-determined time intervals with respect to time, date, stage and rainfall. These intervals ranged from 30 seconds to 1 hour giving nearly continuous data. In the event of a rapid rise in stream stage, the timing device was overridden to collect additional samples. Again, samples were collected in plastic gallon jugs, cooled and transported to a lab for testing. Flow weighted composite samples were used for testing of the water characteristics:

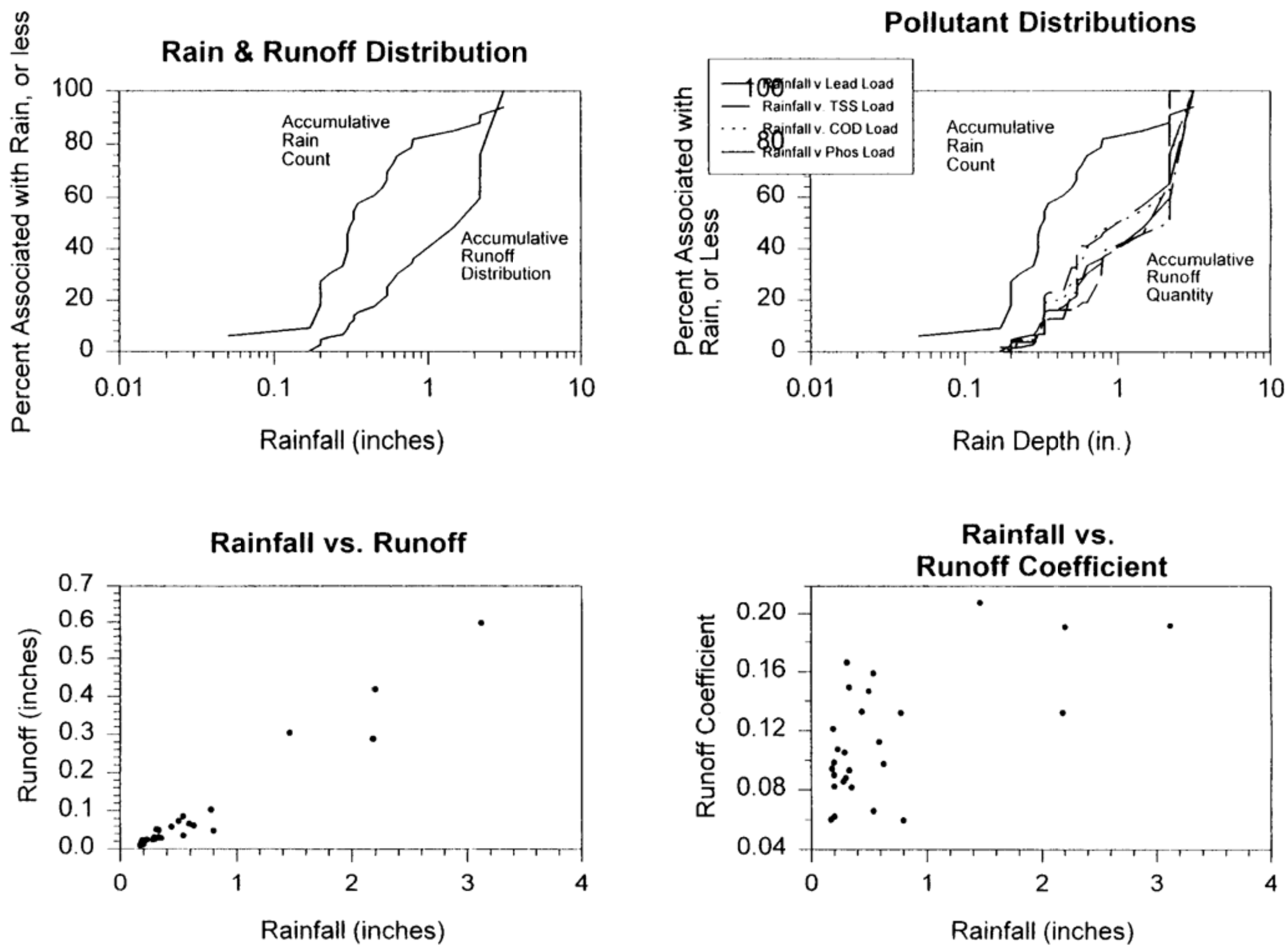
Table B-8. Analyses

Alkalinity		
BOD		5day, Ultimate
Calcium		
COD		
Chloride		
Ammonia nitrogen	Dissolved	
Kjeldahl nitrogen	Dissolved, Total	
Nitrate-nitrite nitrogen	Dissolved	
Phosphorous	Dissolved, Total	
Fecal Coliform		
Lead		
Magnesium		
Oil & Grease		
pH		
Potassium		
Sodium		
Specific conductance		
Sulfate		
Suspended solids		
Total residue		
Turbidity		
Volatile Suspended Solids		

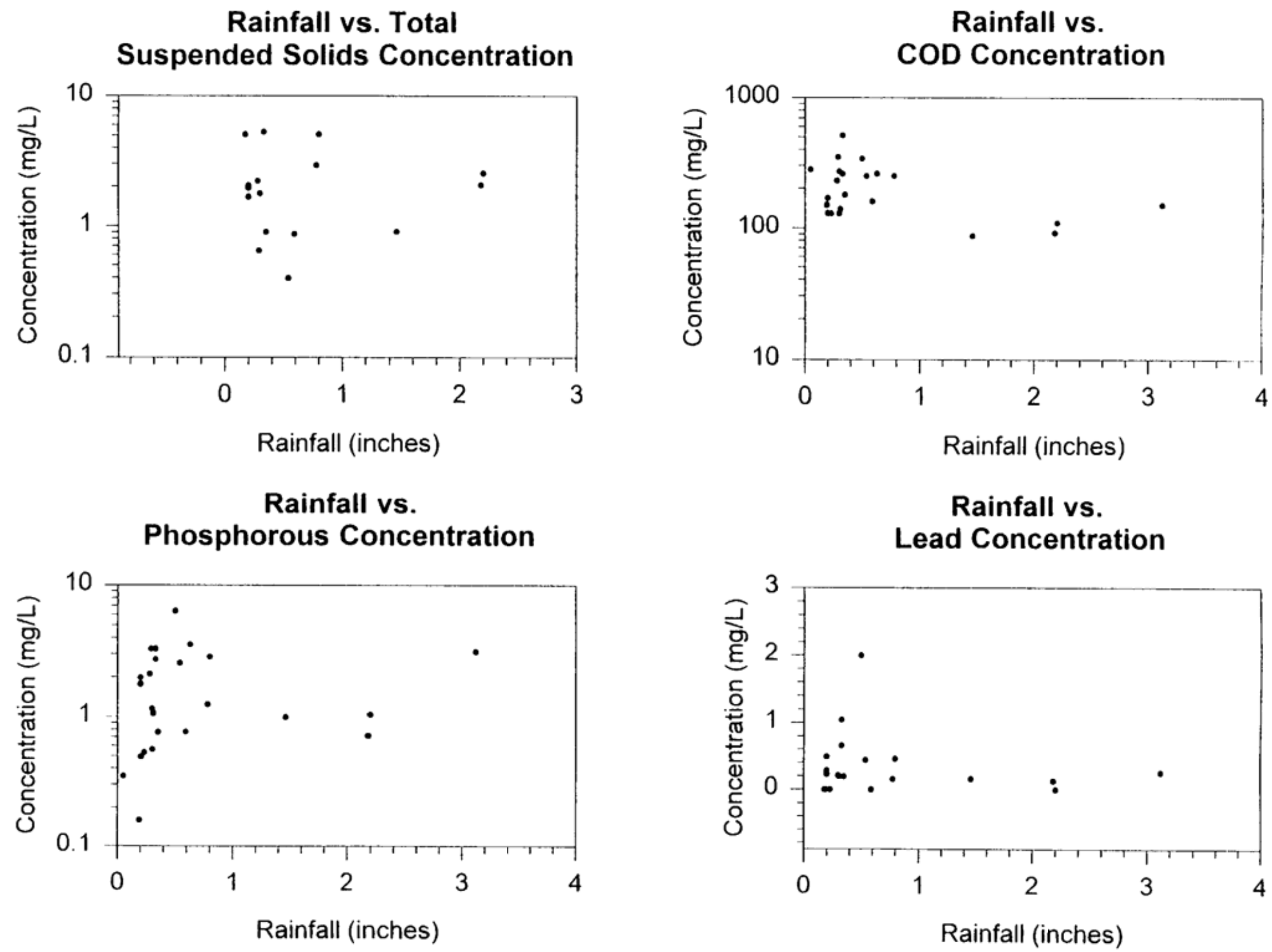
Conclusions

The data collected in this study showed that runoff discharges adversely effect the quality of water in Rapid Creek. As one moves down the stream, the number of runoff discharges increases. The concentrations of pollutants steadily increases in response to these additional flows. This condition seriously effects the water quality of Rapid Creek during rainfall events. In-stream water quality standards are not met during precipitation events, toxicants have also been reported in the creek at these times. Most pollutant problems seem to be associated with sediment and those pollutants that attach to sediment. Lead was the only priority pollutant to be found in significant amounts. It was concluded that snowmelt can also contribute significant loads to the stream and measures should be taken to reduce these discharges.

Rapid City, South Dakota
Mixed Land Uses

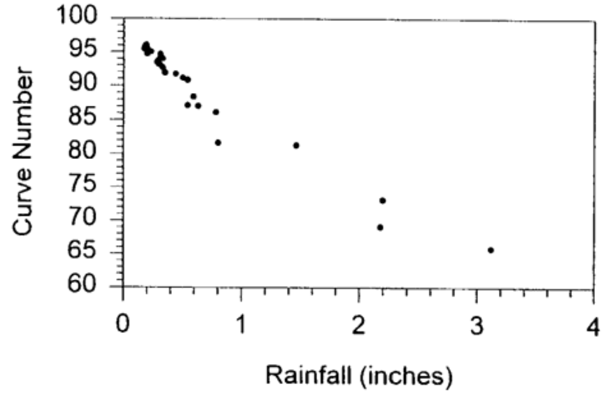


Rapid City, South Dakota
Mixed Land Uses

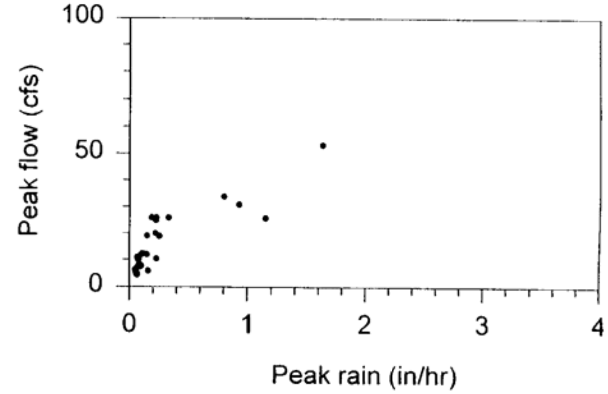


Rapid City, South Dakota
Mixed Land Uses

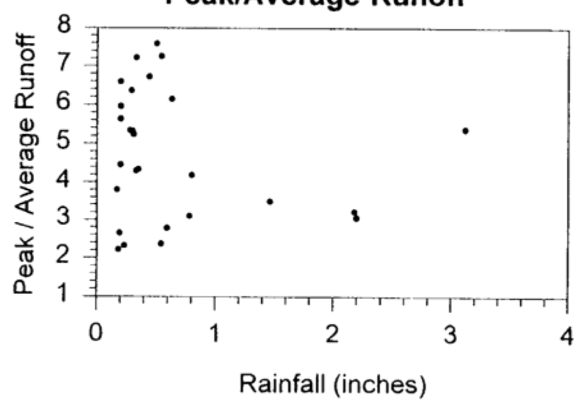
**Rainfall vs.
Curve Number**



**Peak Rain vs.
Peak Flow**



**Rainfall vs.
Peak/Average Runoff**



NURP - Winston Salem, North Carolina

Introduction

The purposes of this NURP study were to provide information for the urban stormwater database and to examine street cleaning as a stormwater control measure. Specifically, the study quantified pollutant loads generated by urban runoff in different types of watersheds. Data collection and analysis were concentrated in two drainage areas typical of the area. One of the basins was residential while the other was commercial. Both drainage areas were located in the same watershed to better correlate data specifically to land uses.

The specific study area for this project was the Winston-Salem area of North Carolina. This city and its surrounding communities are located in what is known as the Piedmont region of the state. This region is the most highly urbanized in the state having a wide range of industrial and manufacturing activities. Industry is mainly in the form of small plants located in smaller towns or rural areas. The manufacturing sector is dominated by the textile, furniture and tobacco manufacturers. Accompanying this, the Piedmont is the most populated region of the state, with 54 percent of this population located in urban areas.

The climate of the Winston-Salem study area is typical of the southeastern United States, in the summer rains are mostly short with high intensity and in the winter long rains with a lower intensity predominate. However, rainfall depths are reasonably consistent, with little seasonal variation. The average rain depth was 0.5 inches, with a 30 percent probability of exceeding the mean depth. Runoff from the area is contained mostly in Dan-Roanoke River Basin, although a significant portion is conveyed to the Yadkin River. The test basin studied in this area consisted of 43 percent residential, 9 percent commercial, and 5 percent other urban lands.

Sampling Sites

Two drainage areas were chosen for study in this NURP project. A commercial drainage basin and a residential drainage were monitored with respect to their rainfall and runoff quantities. The runoff was also collected and analyzed as to its quality.

The commercial drainage area is designated as Central Business District (CBD) and consists of 22.7 acres of commercial land with high traffic volumes. There are 0.78 curb miles within the basin and all roads are curbed and guttered. 93% of the roads are considered in fair condition with the rest being classified as poor. Soil type is mostly Pacolet-urban and covers 31% of the basin. However, two-thirds of the pervious areas are unpaved gravel parking lots, reducing the expected permeability associated with pervious areas. The area is served entirely by separate sewers. There were two atmospheric deposition and meteorological sites and one water quality site.

The residential study area is a medium density middle income housing subdivision of about 324 acres. The watershed is served by separate sewers with about 98% of the area having a stormwater collection system. The 6.5 curb miles are 98% curbed and guttered with most of the roads being considered in fair condition. Soils in the area consist of loams, sandy loams and Pacolet-urban soils in slopes of 6 to 45%. 28% of the watershed is impervious. Land uses are divided between, parkland, light industrial, strip commercial, and differing concentrations of residential. The majority of the watershed is residential, with the remaining portion divided as follows:

> 39.5 acres urban parkland (12%)
> 6.30 acres light industrial (2%)
> 6.31 strip commercial (2%)
> 1.52 acres residential with 78 dwelling units per acre
> 269.9 acres residential with 2.5 to 8 dwelling units per acre

In the residential monitoring basin, there was one water quality monitoring site and one atmospheric deposition meteorological monitoring site.

Data Collection Methodology

Wetfall and dryfall sampling were utilized in assessing the stormwater runoff quantity and quality in this study. Samples of rainfall were collected using automatic samplers for each rain event during the monitoring period. An "event" was considered to be an occurrence of rain sufficient to create runoff from the streets and each event was separated by at least six dry hours. The rainfall samples collected were analyzed for pH, conductivity, nutrient and metal analyses. Dryfall samples were also collected automatically at all three locations. These samples were taken discretely and analyzed with respect to nutrients and metals.

Water quality sampling measures were taken at the three testing locations as well. Liquid level and rainfall were recorded at five minute intervals. The liquid level data was then transformed into flow values using a stage discharge rating curve. Runoff water quality samples were taken using automatic samplers programmed to sample at specified values. The sampler in the commercial watershed was programmed according to the volume of water that passing the sampling point, once a particular volume had passed, a pulse was sent to the sampler to begin sampling. The residential watershed sampler was programmed a little differently. For this sampler, the stage monitor would send a pulse to begin sampling. Subsequently, each time the stage changed a designated amount (about 0.25 feet) another pulse was sent. For either sampler, the number of pulses could be adjusted to collect the desired data. It should be noted that all samples collected were discrete samples.

These samples were tested for nutrients, metals, and solids. Chemical analyses were conducted at the DEM laboratory according to Standard Methods.

The actual measured concentration values were linearly interpolated and a change in concentration per five minute interval was computed. These five minute increments were then assigned a concentration value using a specified formula. Once the concentration values were assigned, unit load values were calculated by multiplying the flow unit values by the concentrations and conversion factors. The data collected (stage, rainfall and pollutant information) were reduced to yield storm volumes, intensities, loads and mean concentrations.

The investigation of street cleaning was carried out by randomly selecting 25 curb feet for sweeping and testing. A 12 foot zone with homogeneous loading was selected within these sites. These zones were then used as the study site for the remainder of the project.

Accumulation rates were studied as well as differences in accumulation between adjacent sites. When cleaning was taking place, samples of street dirt were taken before and after sampling to estimate the dirt removal efficiency. In the particular watershed, sampling sites were set up to measure runoff characteristics before and after areas of street cleaning.

The wetfall and dryfall samples were tested for the following parameters:

- Nitrogen compounds
- Phosphorous
- Metals including copper, zinc, lead and mercury
- Total particulate solids
- Total suspended solids
- pH

Conclusions

The conclusions made in this study pertained to characterizing rainfall and runoff in the Winston-Salem area of North Carolina. The report also drew conclusions as to the effectiveness of street cleaning as a stormwater control measure.

It was determined that nutrient associated pollutants were most often found in wetfall samples, while metal pollutants were most often found in dryfall samples. All nutrients tested were detected in the two years of study. Only four of the metals analyzed were ever present in amounts over the minimum detection limit (mdl).

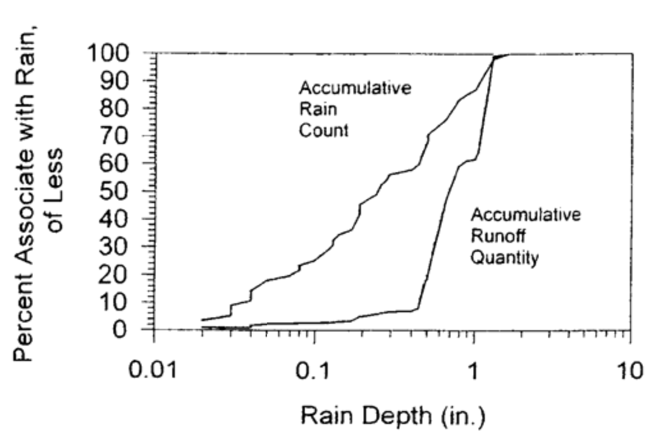
Ammonia was found at all sites. There was however a noticeable increase in ammonia in the wetfall samples when compared to the dryfall samples. Most nitrogen compounds were found in similar concentrations at all sites. There was an increase in nitrate/nitrite in the commercial watershed, attributed to the additional traffic in this watershed. Also present in all samples was phosphorous, but with no significant difference found between the two sites.

No relation was found between land use or season with respect to copper. Zinc appeared more often in the commercial watershed than the residential. Concentrations also increased in dryfall as opposed to wetfall samples. Similarly, lead was more often found in dryfall than wetfall samples, and also more often in the commercial district when compared to the residential.

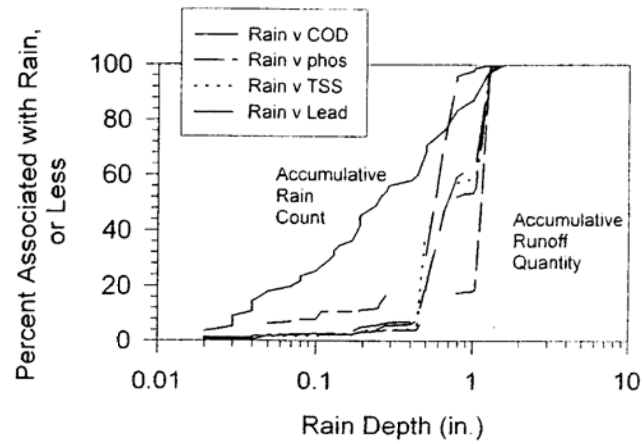
It was determined that street cleaning is not an effective stormwater control measure. Pollutants loads present in runoff were not significantly decreased by street cleaning.

Winston-Salem
Commercial Land Uses

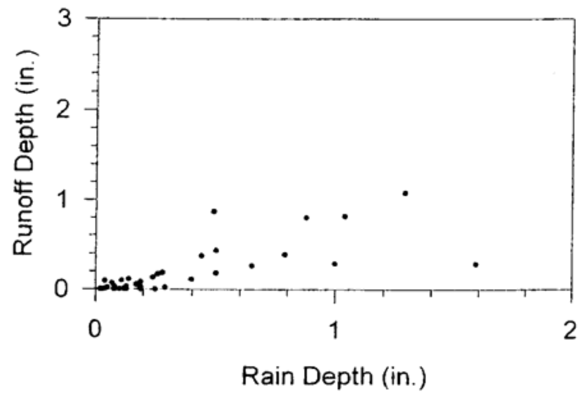
Rain & Runoff Distribution



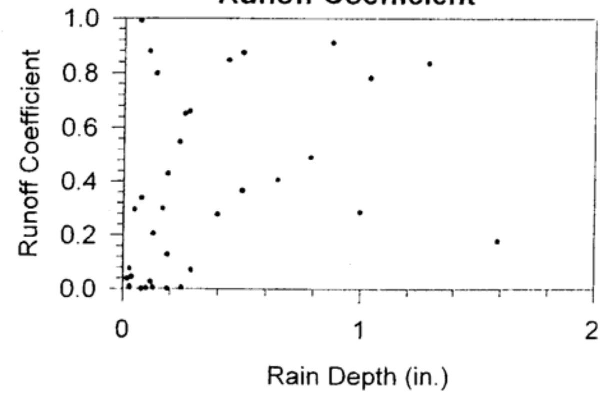
Pollutant Distributions



Rain Depth vs. Runoff Depth

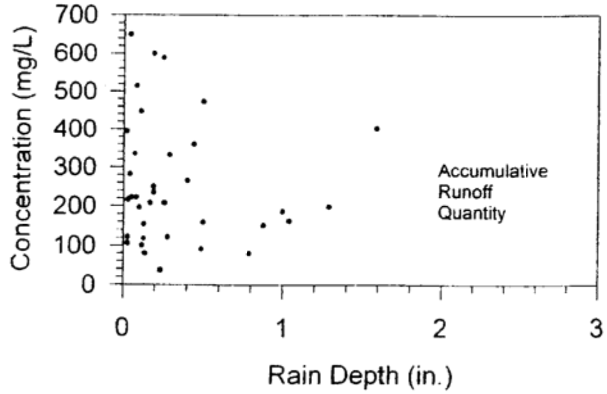


Rain Depth vs. Runoff Coefficient

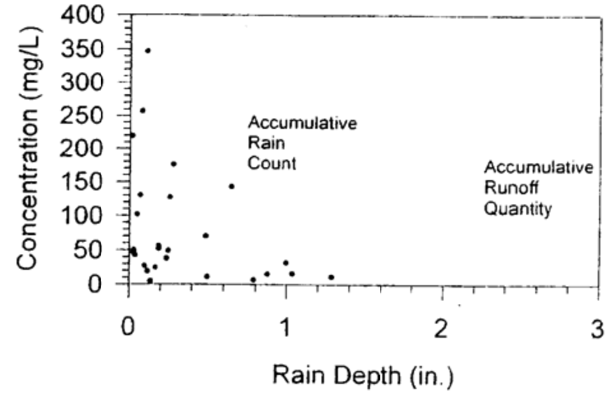


Winston-Salem
Commercial Land Uses

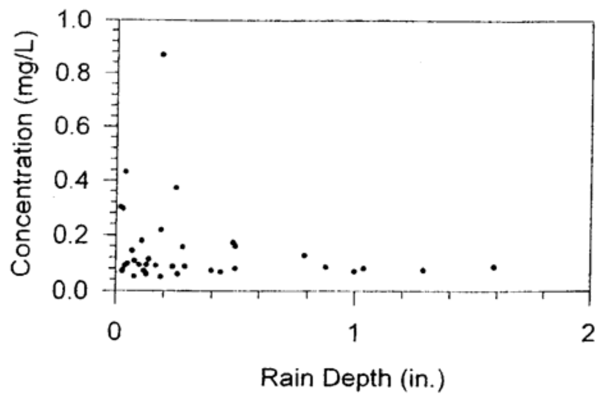
Rain Depth vs.Total Suspended Solids Concentration



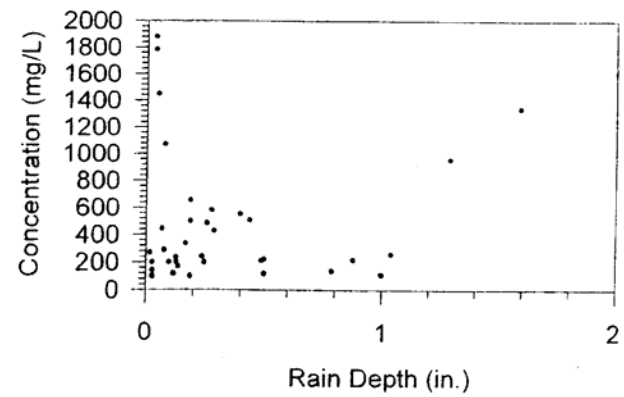
Rain Depth vs. COD Concentration



Rain Depth vs. Phosphorous Concentration

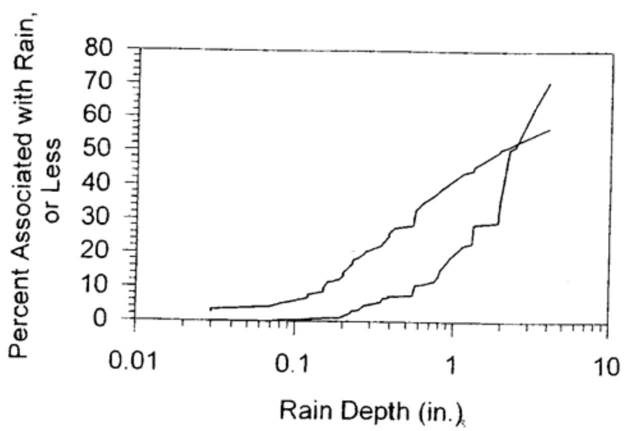


Rain Depth vs. Lead Concentration

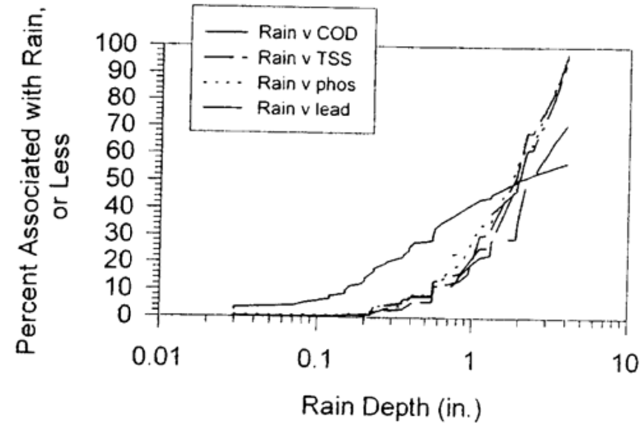


Winston-Salem
Residential Land Uses

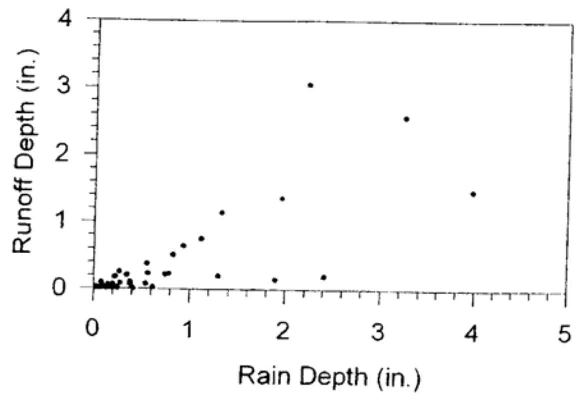
Rain & Runoff Distribution



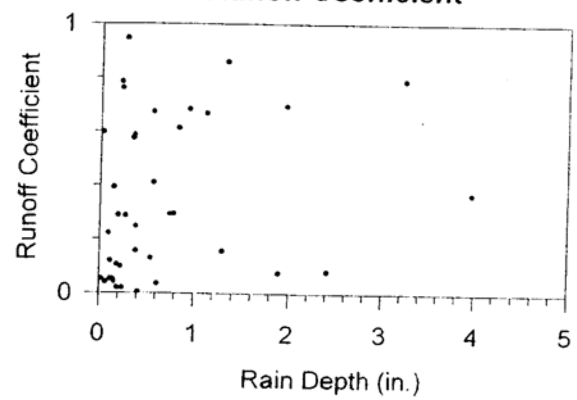
Pollutant Distributions



Rain Depth vs. Runoff Depth

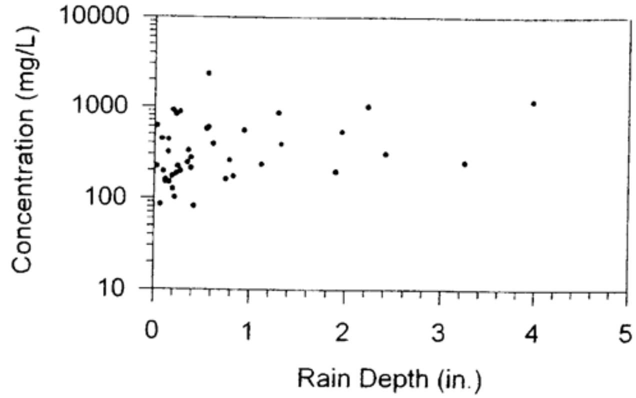


Rain Depth vs. Runoff Coefficient

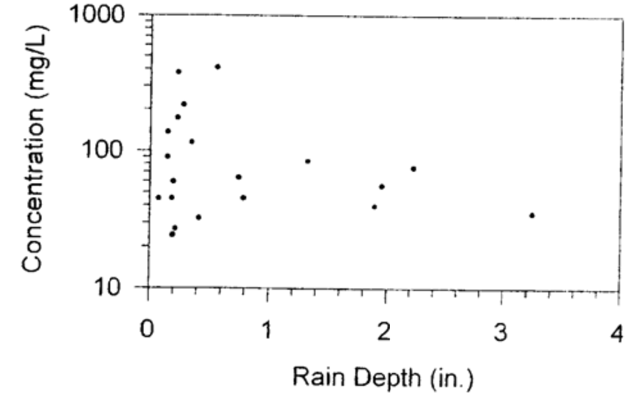


Winston-Salem
Residential Land Uses

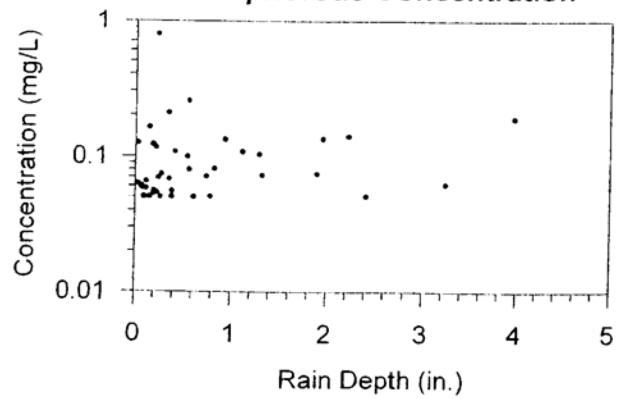
Rain Depth vs. Total Suspended Solids Concentration



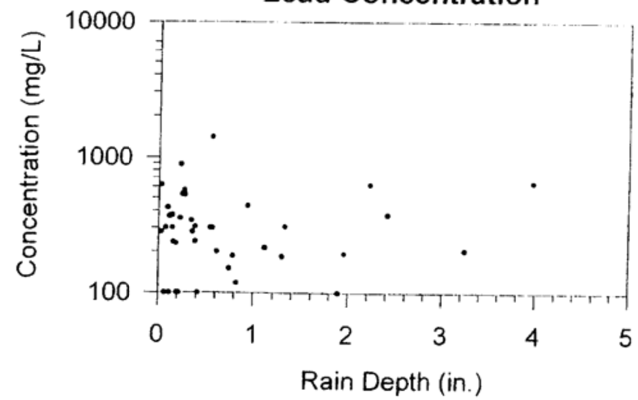
Rain Depth vs. COD Concentration



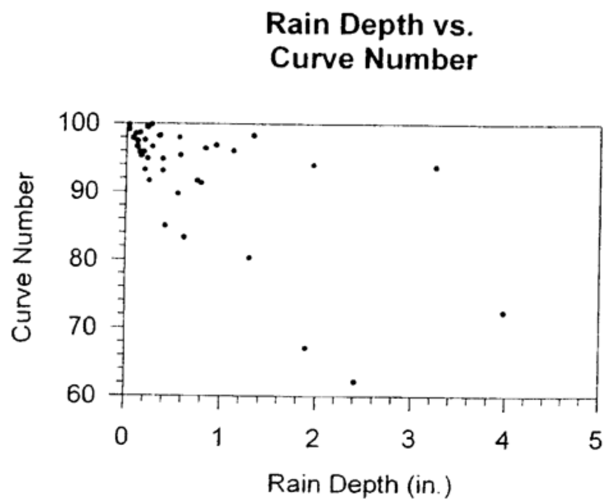
Rain Depth vs. Phosphorous Concentration



Rain Depth vs. Lead Concentration



Winston-Salem
Residential Land Uses



NURP - Bellevue, Washington

Introduction
This program collected characterization data and examined the effectiveness of street cleaning and a small dry detention pond as stormwater control measures. The study area was located in the city of Bellevue, Washington. Situated in the Puget Sound lowlands, the area is about 4 miles east of Seattle. The city is an urbanized area with a variety of land uses. The population at the time of the study was approximately 74,000. Annual precipitation is around 35 inches. Annual precipitation is about 35 inches, mostly associated with frontal storms originating over the Pacific Ocean.

Sampling Sites
Three catchments were chosen for study in the project. Two of the catchments contained mostly single family residential land uses, while the third was a commercial site. Rainfall was measured and runoff was collected at each location.

The Surrey Downs area (a residential neighborhood), was first developed in the late 1950s, making the age of development at the time of the study approximately 20 years. Land uses in the area were mostly single family residential with a few apartments and duplexes. The area also contained Bellevue Senior High School. The design of the streets and the general layout of the area reduces through traffic. The total area of the catchment was 95 acres, with moderate to steep slopes. Nearly all streets had curb and gutter systems, and the collection system was in good condition overall.

The Lake Hills catchment was also a single family residential area developed in the late 1950s. This area, in addition to the residential land uses, contained a church and school. Two through streets carried a moderate amount of traffic, more than a typical residential street. The area of the catchment was about 102 acres, with moderate slopes. Streets all had curbs to aid in drainage, although none have guttters. The flow was discharged to a open channel that conveyed the flow from the area.

The 148th Avenue catchment consisted of commercial land uses; the area contained a portion of a four-lane arterial street, sidewalks, apartments, parking lots, office buildings and a variety of other uses. The area was about 24 acres, with minimal slopes. The effects of a small dry detention pond were studied in a small subarea, about 37.5 acres of Robinswood Park. The area was served by the trunk line of the storm sewer system; laterals connected catch basins to the line. The storm system in this area had weirs and valves at five points that allowed the flow to be restricted from the trunk line and retained in grassy dry detention ponds.

Data Collection Methodology
Within each catchment, an instrument shelter housed a data recording and a sample control-collection system. Runoff data was collected at 5-min intervals when flows exceeded a predetermined threshold level, or whenever there was measurable precipitation. Each catchment also contained two or three tipping bucket rain gauges. Stage discharge relationships were used to determine discharges from the catchments. The stage was measured to the nearest 0.01 foot behind V-notched weirs.

Rainfall data were recorded at 5-min intervals with tipping bucket rain gauges. The Surrey Downs catchment had three gauges, and Lake Hills and the 148th Avenue catchments both had two gauges. Stormwater quality data were also collected in the study. Discrete runoff samples were gathered at the outfall of each catchment. These samples were then analyzed for a variety of pollutant constituents, as shown in Table B-9.

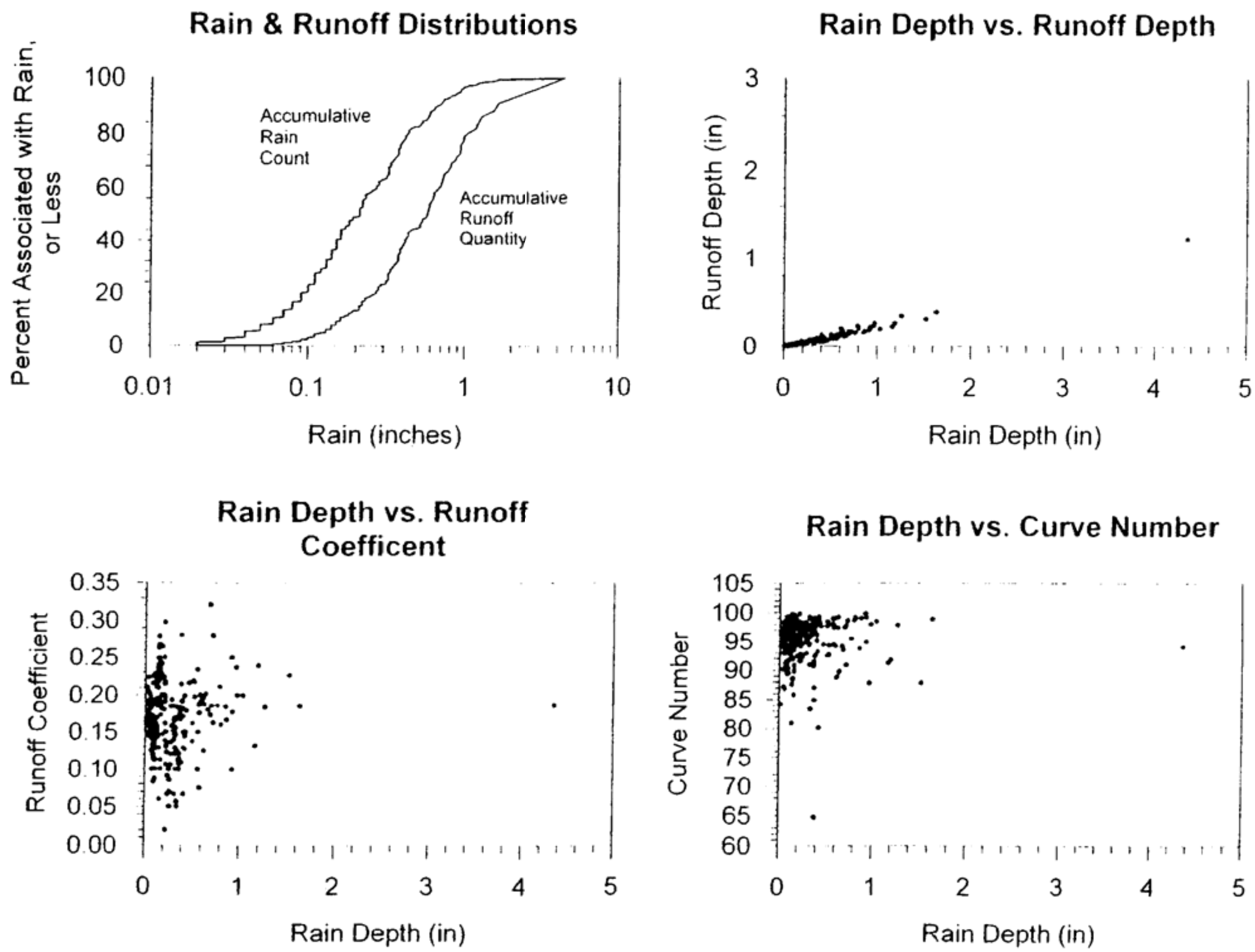
Conclusions
Data collected from this study were compiled to establish a database of information reflecting stormwater quantity and quality. This information can be utilized to predict runoff characteristics from similar watersheds. Drainage designs can then be developed based on these predictions. From the information gathered, it was determined that street cleaning, using available equipment, was not a cost effective stormwater control practice for the Pacific Northwest. A special street cleaner was also tested that had enhanced abilities to remove fine material and resulted in less fugitive dust emissions. This modified street cleaner resulted in significantly reduced street loadings

compared to the conventional street cleaner, but with insignificant effects on runoff quality. Similar disappointing results were also found for the small dry detention ponds.

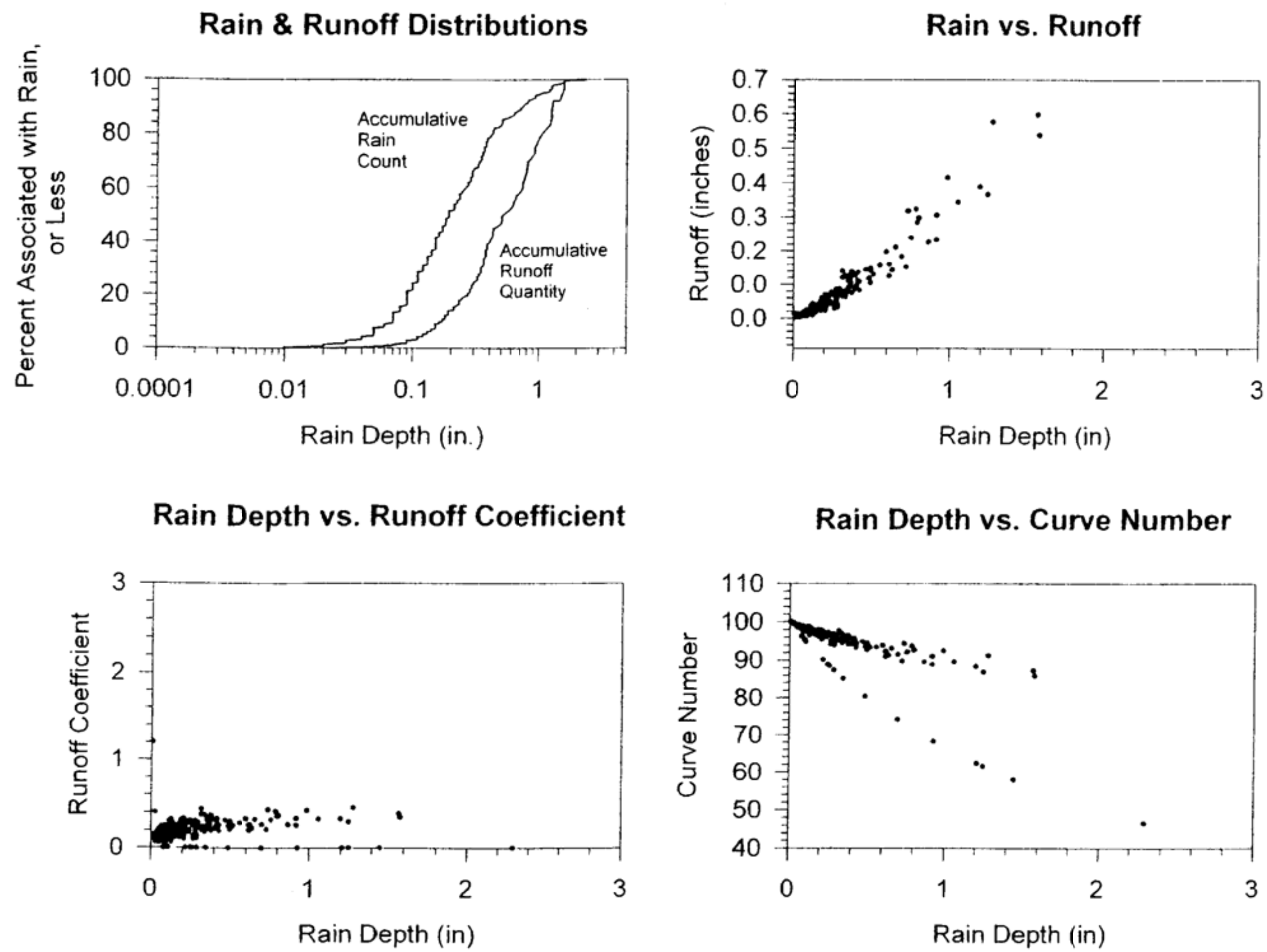
Table B-9. Constituents Analyzed in Bellevue

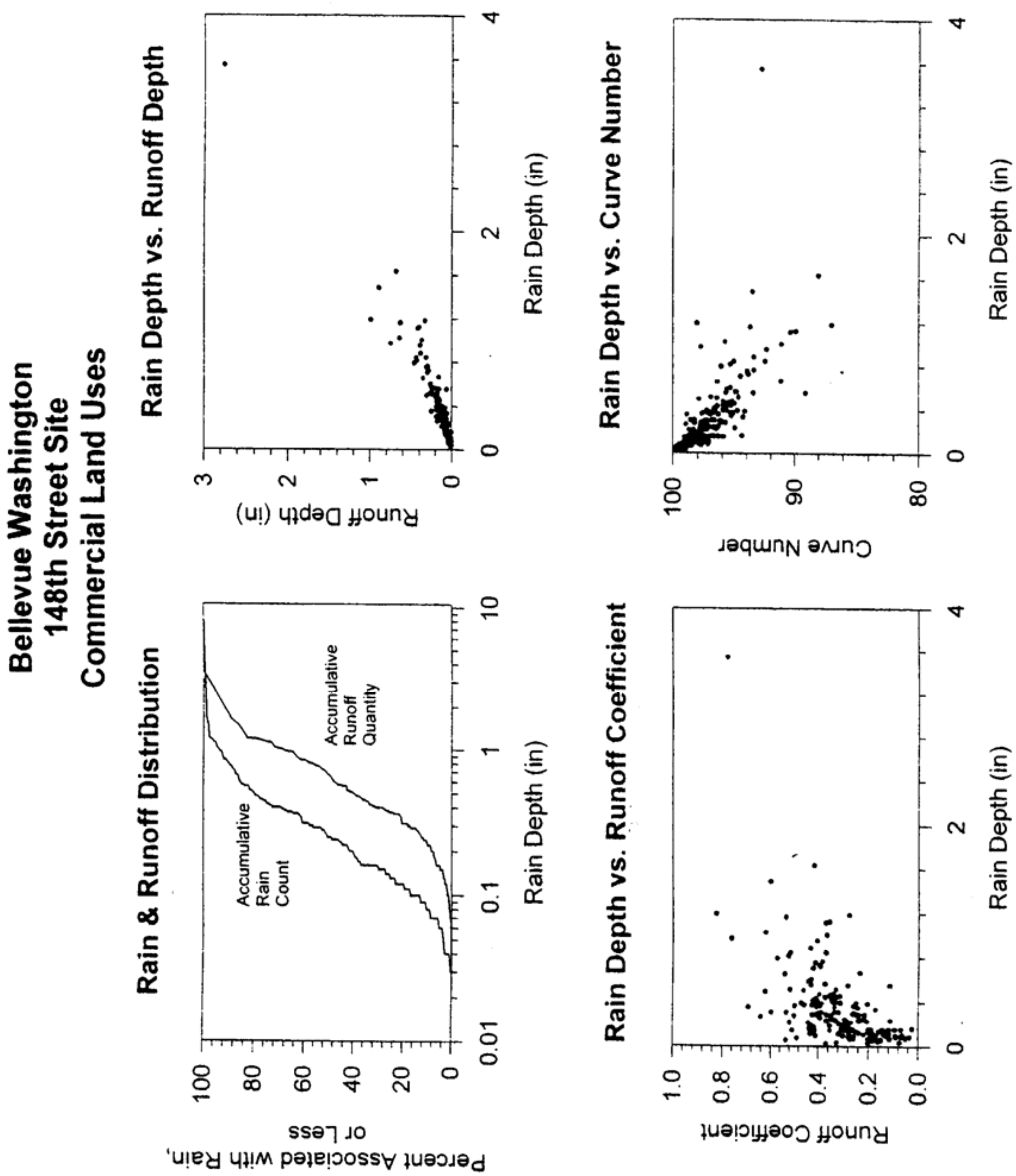
Field measurements:	
	Specific conductance
	pH
Major nutrients:	Dissolved nitrite-plus-nitrate (as N)
	Dissolved ammonia (as N)
	Total ammonia plus organic nitrogen (as N)
	Dissolved ammonia plus organic nitrogen (as N)
	Total phosphorus (as P)
	Dissolved phosphorous (as P)
Trace elements:	Total recoverable lead, copper, and zinc
Organic and biological constituents:	
	Chemical oxygen demand
	Carbonaceous biochemical oxygen demand,
	5-day Dissolved organic carbon
	Suspended organic carbon
	Fecal coliform bacteria
Other constituents:	
	Suspended solids
	Dissolved solids

Bellevue, Washington
Surrey Downs Site
Single Family Residential Land Uses



Bellevue, Washington
Lake Hills Site
Single Family Residential Land Uses




Bellevue Washington
148th Street Site
Commercial Land Uses
Rain & Runoff Distribution
Percent Associated with Rain, or Less
Accumulative Rain Count
Accumulative Runoff Quantity
Rain Depth (in)
Rain Depth vs. Runoff Depth
Runoff Depth (in)
Rain Depth (in)
Rain Depth vs. Runoff Coefficient
Runoff Coefficient
Rain Depth (in)
Rain Depth vs. Curve Number
Curve Number
Rain Depth (in)

NURP - Milwaukee, Wisconsin

Introduction
Data was collected in Milwaukee delineating runoff amounts and pollutant concentrations for various land uses. This project also developed a model to extrapolate flow and pollutant information to other areas of interest. In addition, information was also collected and analyzed addressing the effectiveness of street cleaning as a control measure in reducing stormwater pollution.

Data Collection Methodology
Eight watersheds within Milwaukee County were monitored for a period of two and a half years during this project. Two monitoring sites were chosen in each land use category: one to represent conditions without the application of any control measure and the other with the use of street cleaning as a control measure. Other than the application of street cleaning, the two sites at each basin were as similar as possible.

Rainfall and runoff amounts were monitored using automatic samplers, rain gages, and flow instruments. The collected runoff was analyzed for pollutant concentrations.

Sampling Sites
The eight sites chosen contained the following land uses; medium density residential, commercial business, and commercial parking lots. The watershed characteristics are as follows:

The Hastings and Burbank sites were both medium density residential areas. Both sites had predominately silt loam soils, but the Burbank location also contained clayey soils. Slopes in the Burbank area were somewhat steeper, at about 6%. The Hastings watershed drained about 32.8 acres and had an imperviousness of 52%. Burbank drained an area of 65.6 acres and had an imperviousness of 51%.

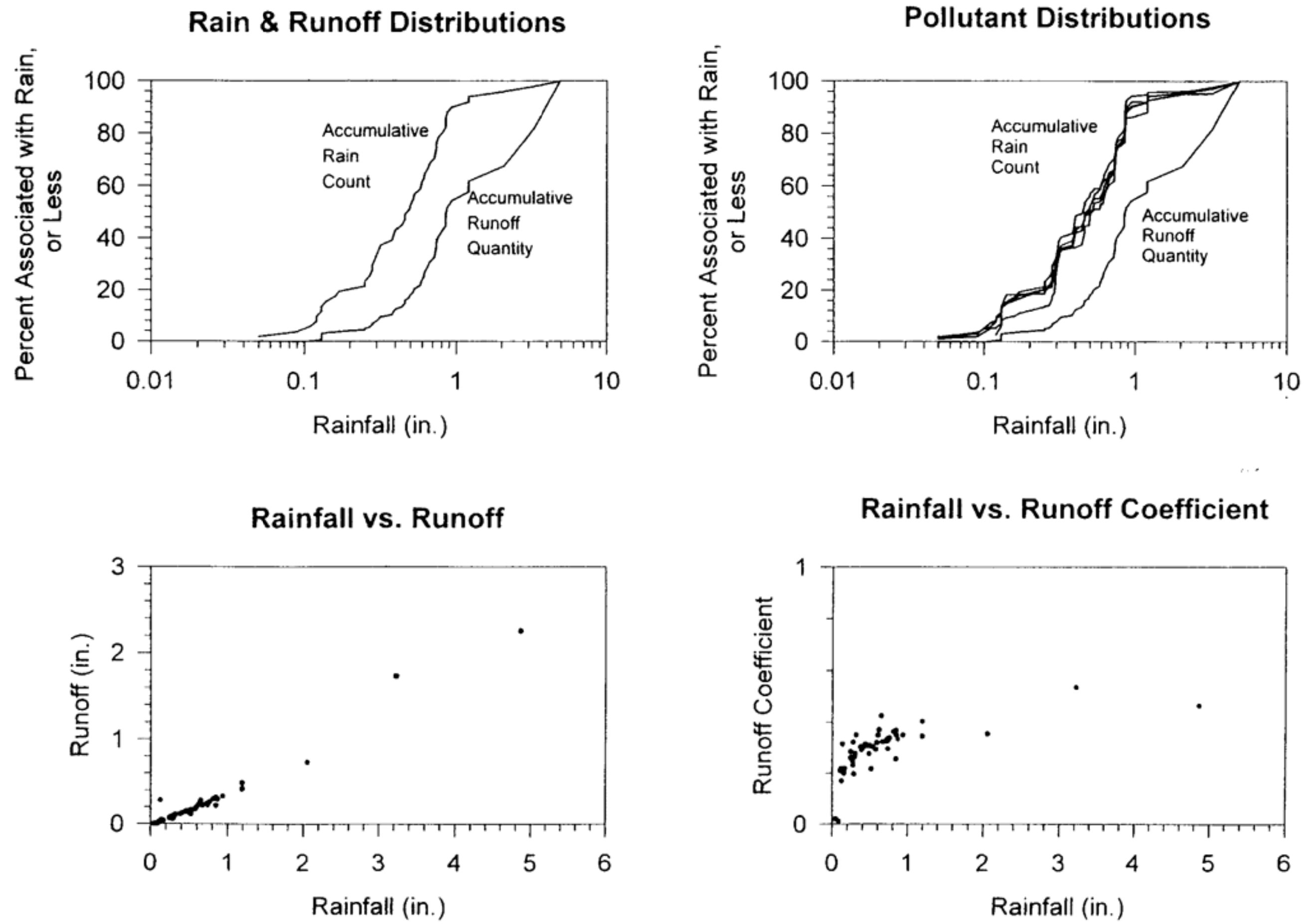
The other residential study areas were the Lincoln and Congress basins. Soils in these basins were both 20% clay and 55% silt, with very flat slopes (about 1%). The Lincoln basin drained 36.1 acres and had an imperviousness of 57%. Congress had a drainage area of 33 acres and had an imperviousness of 50%.

Commercial, residential and other land uses made up the State Fair and Wood Center sites. In the State Fair site, 29 acres were drained with the area being divided between commercial (18.2 acres) and residential (10.8 acres). The Wood Center site drained commercial (23.3 acres), residential (15.5 acres) and industrial (6.1 acres) lands. The percent imperviousness differed significantly within the areas. For the State Fair watershed, the commercial area was 95% impervious and the residential area was 47% impervious. In Wood Center, the commercial area was 98% impervious, the residential area was 55 % impervious, and the industrial area was 82% impervious. Soils in both locations were 20% clay and 55% silt, and the areas had slopes of about 1%.

The final two sites, Rustler and Post Office, were both commercial areas. The Rustler site consisted of both smooth and rough pavement parking areas and was comprised of about 42% flat roofs, 48% paved parking, and 10% streets. The parking pavement at the Post Office site was all smooth, and the monitored site was 86% parking lot, and 11% streets. Soil information is not important, as both areas were completely paved.

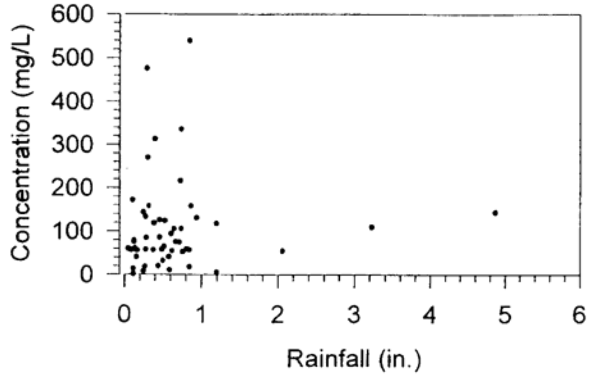
Conclusions
As in the previous studies that examined street cleaning, this control practice produced insignificant changes in stormwater runoff quality. This project did result in much data at the paired locations and produced important characterization information. As an example, two extreme rainfall events occurred during the monitoring period producing some of the largest stormwater flows ever monitored for quality.

Milwaukee County, Michigan
Burbank Site
Residential Land Uses

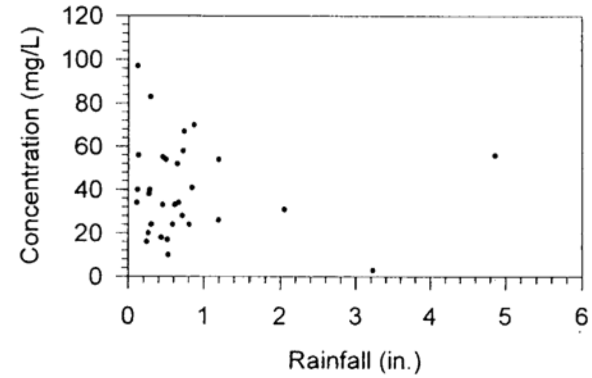


Milwaukee County, Michigan
Burbank Site
Residential Land Uses

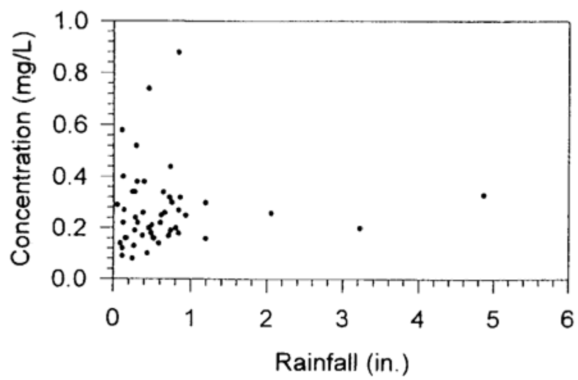
Rainfall vs. Total Suspended Solids Concentration



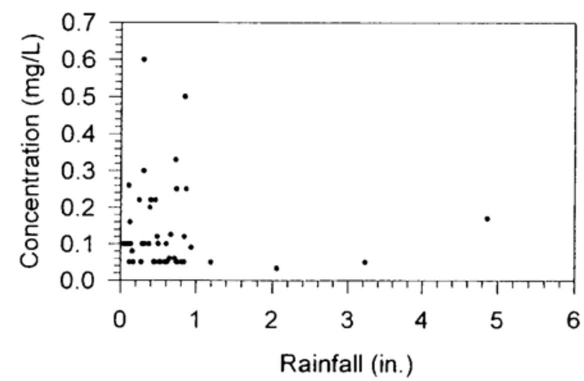
Rainfall vs. COD Concentration



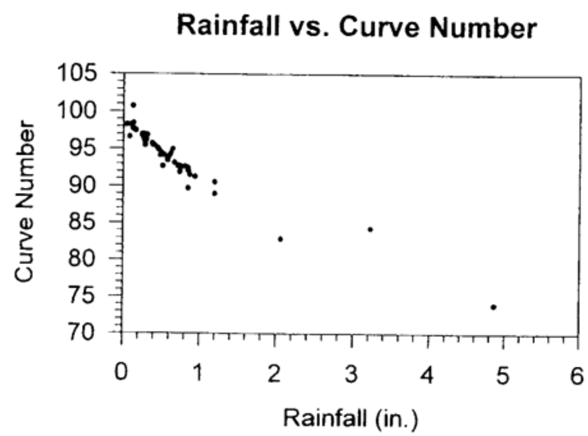
Rainfall vs. Phosphorous Concentration



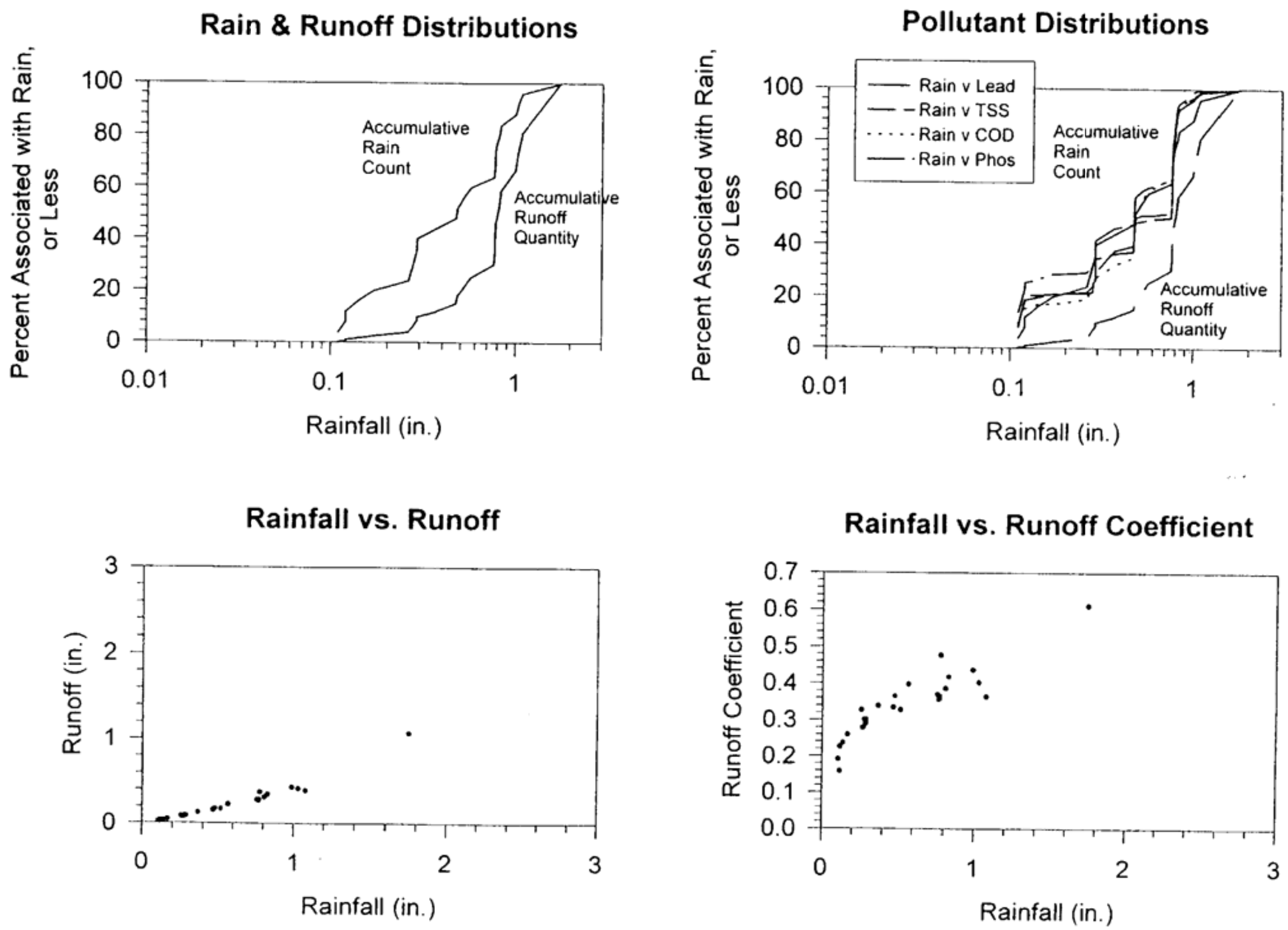
Rainfall vs. Lead Concentration



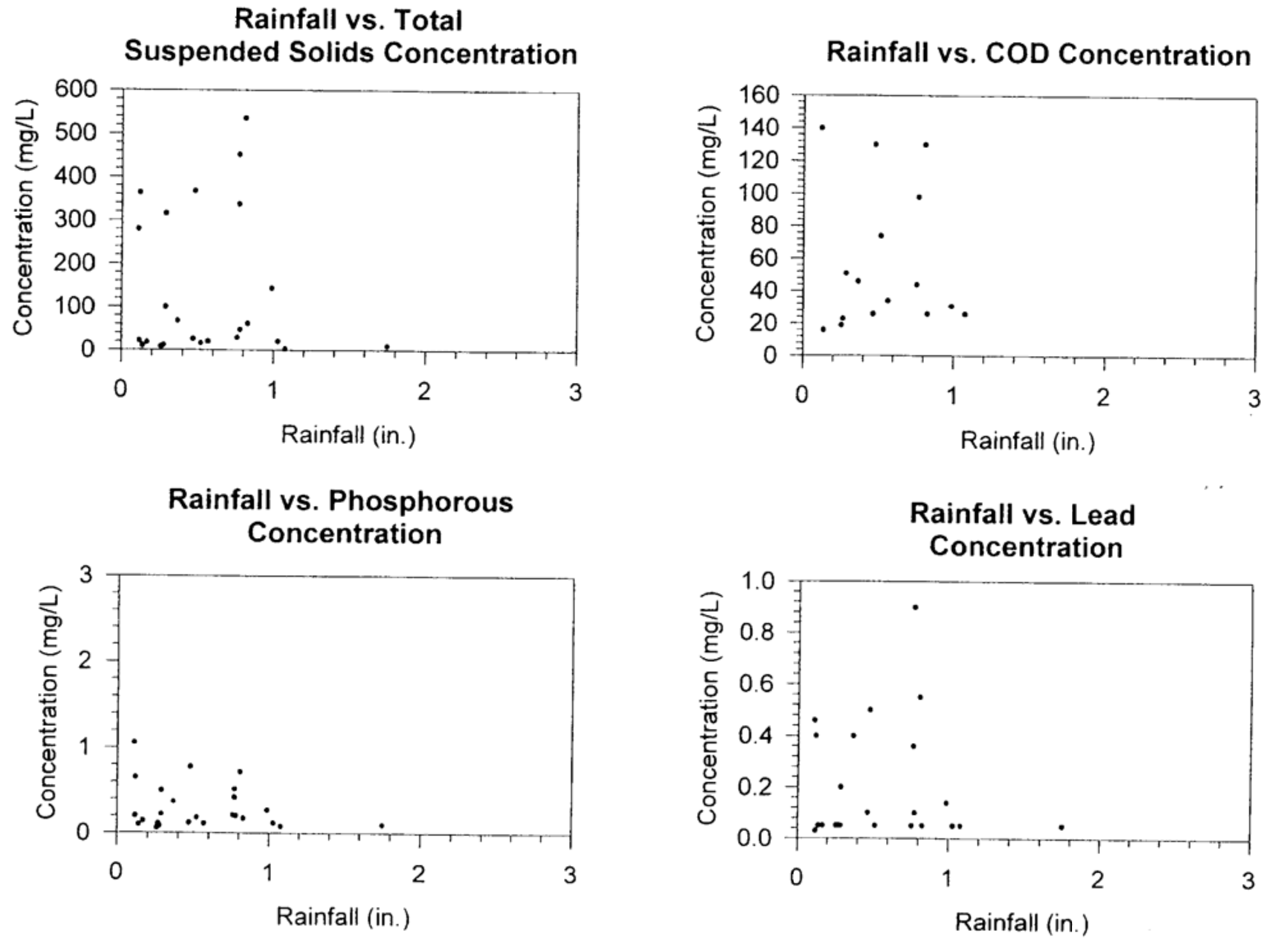
Milwaukee County, Michigan
Burbank Site
Residential Land Uses



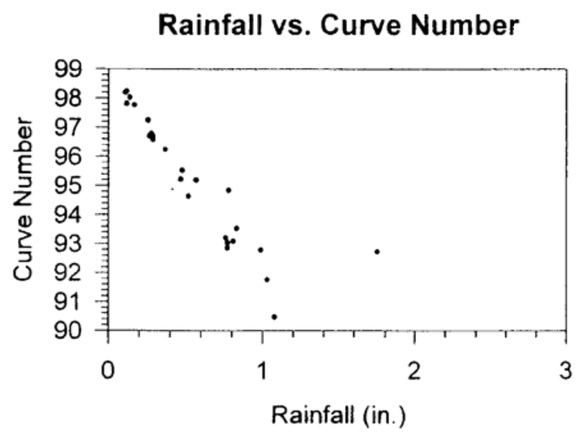
Milwaukee, Wisconsin
Congress Site
Medium Density Residential Land Uses



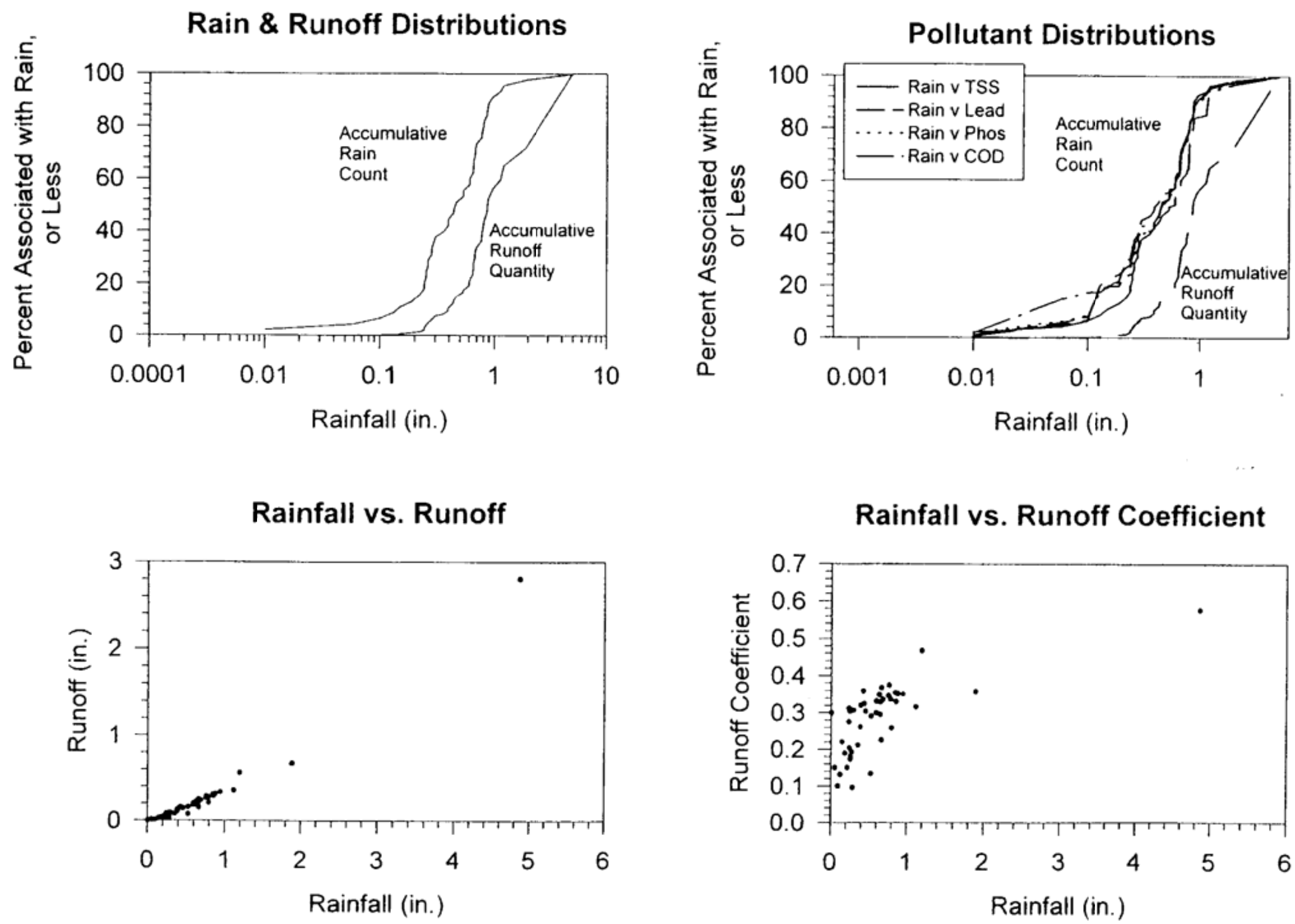
Milwaukee, Wisconsin
Congress Site
Medium Density Residential Land Uses



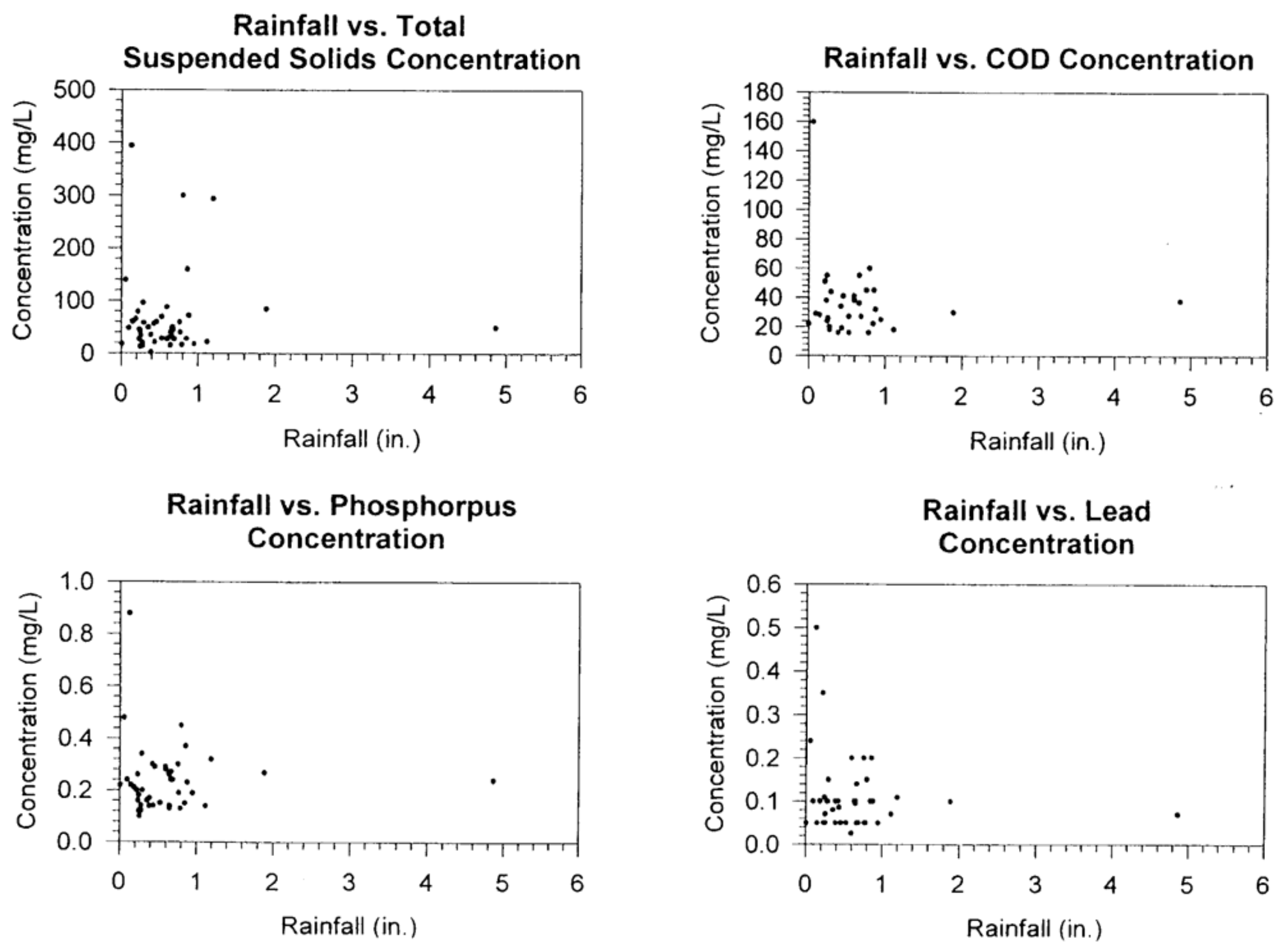
Milwaukee, Wisconsin
Congress Site
Medium Density Residential Land Uses



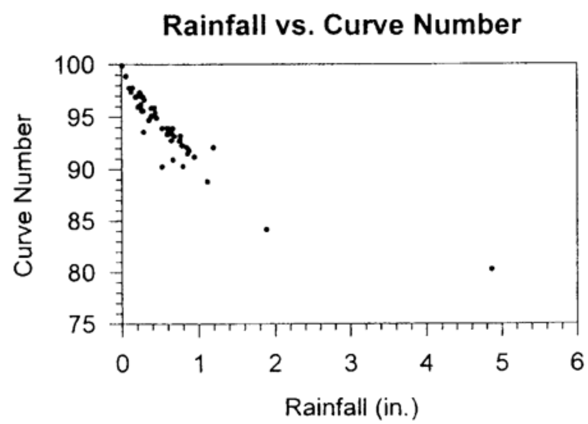
Milwaukee, Wisconscin
Hastings Site
Medium Density Residential Land Uses



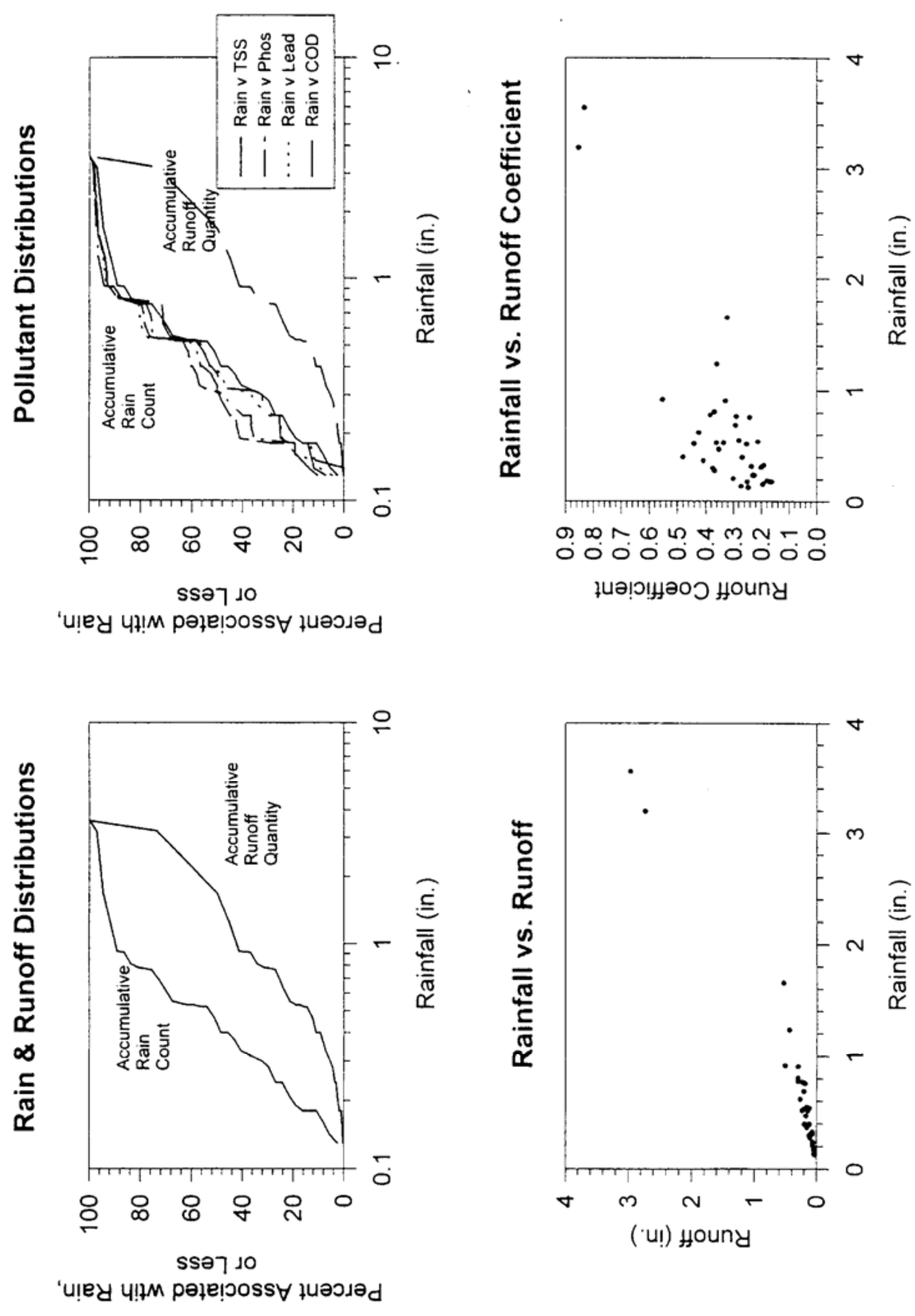
Milwaukee, Wisconscin
Hastings Site
Medium Density Residential Land Uses



Milwaukee, Wisconscin
Hastings Site
Medium Density Residential Land Uses

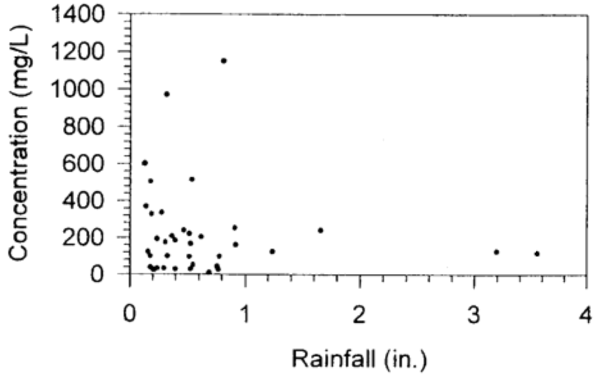


Milwaukee, Wisconscin
Lincoln Site
Medium Density Residential Land Uses

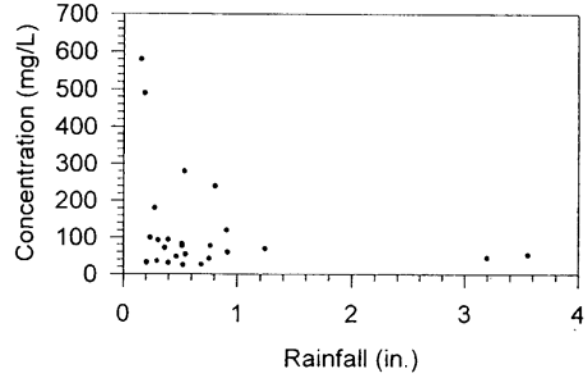


Milwaukee, Wisconscin
Lincoln Site
Medium Density Residential Land Uses

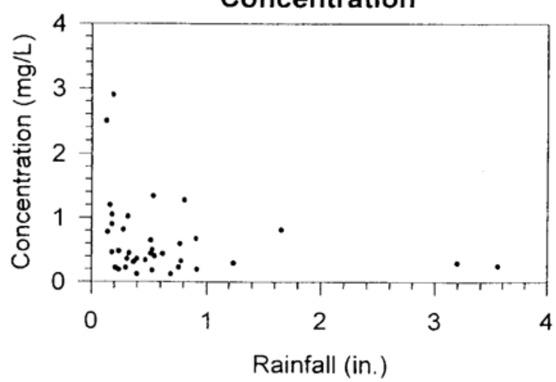
Rainfall vs. Total Suspended Solids



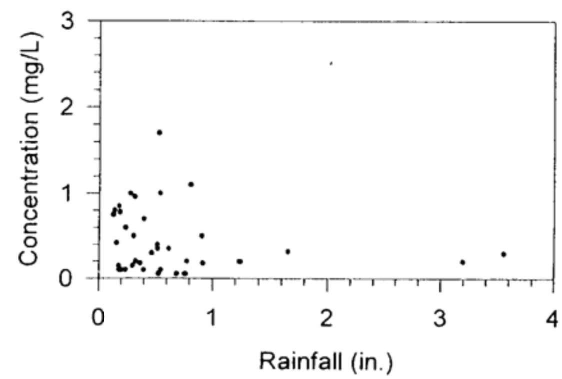
Rainfall vs. COD Concentration



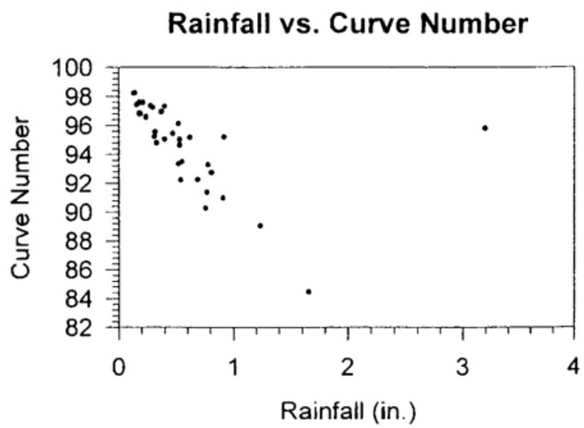
Rainfall vs. Phosphorous Concentration



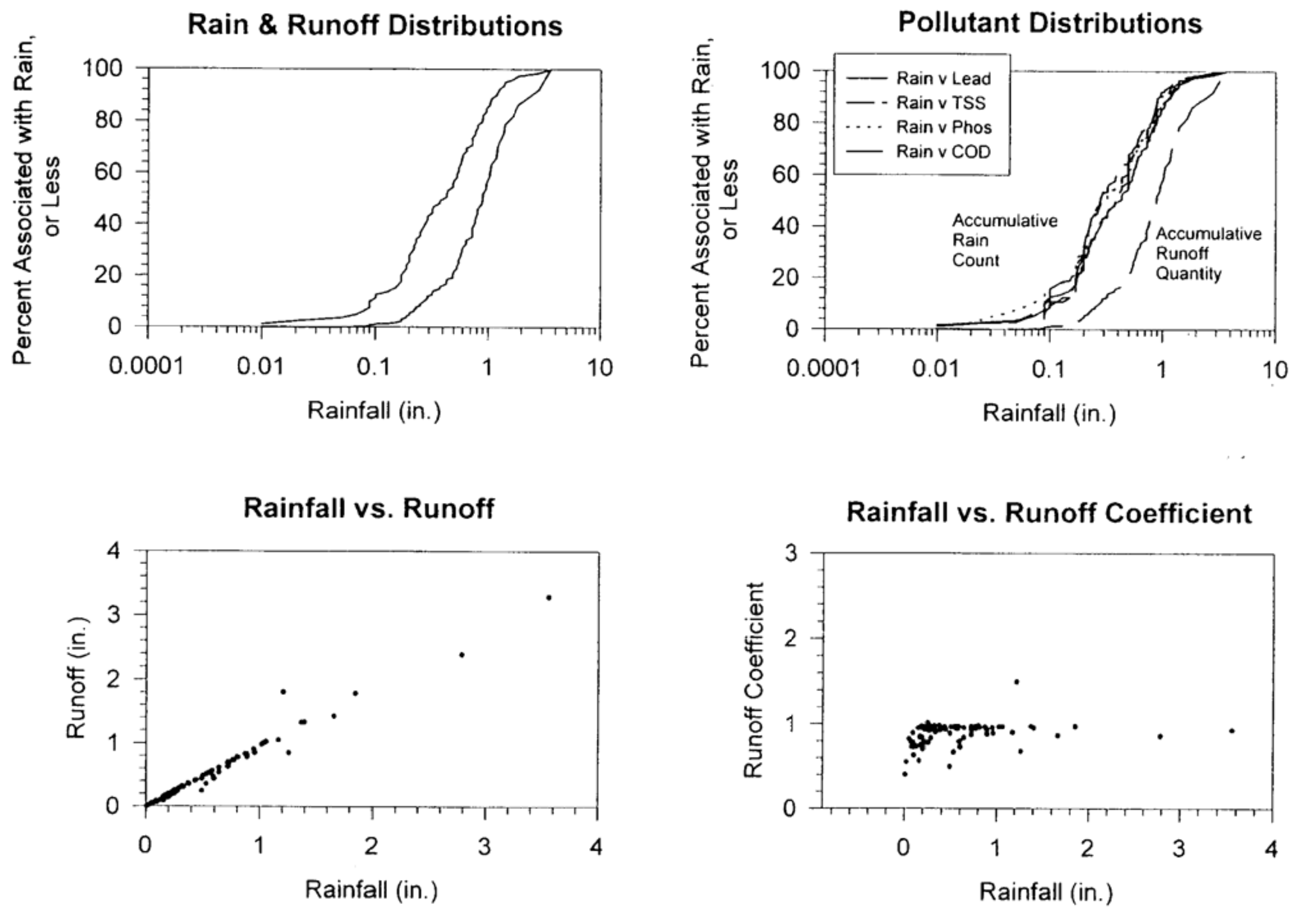
Rainfall vs. Lead Concentration



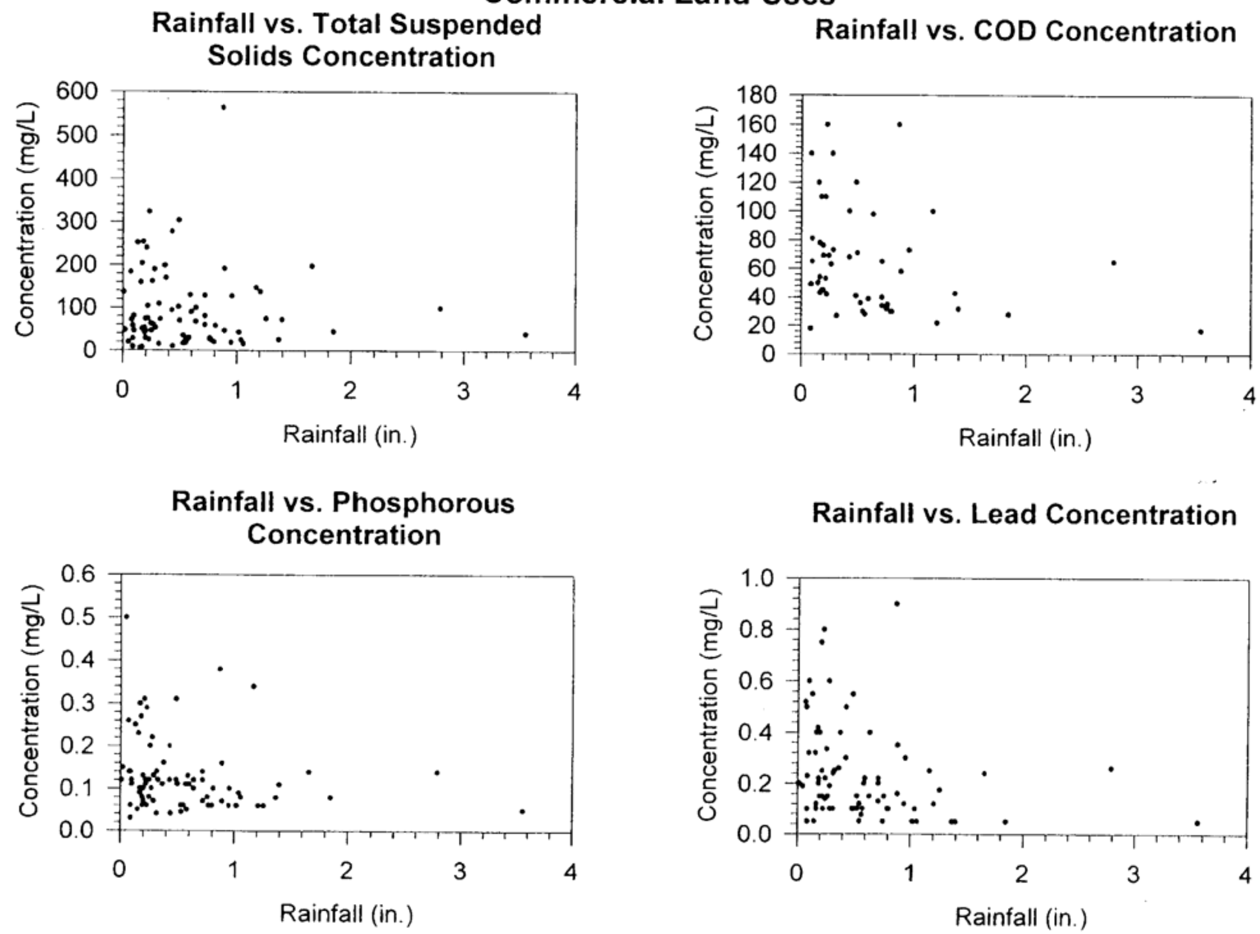
Milwaukee, Wisconscin
Lincoln Site
Medium Density Residential Land Uses



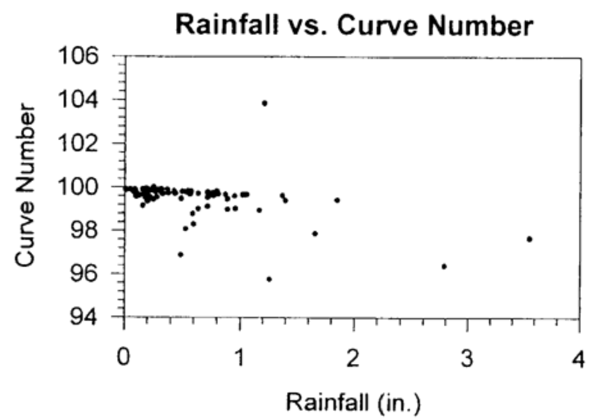
Milwaukee, Wisconscin
Post Office Site
Commercial Land Uses



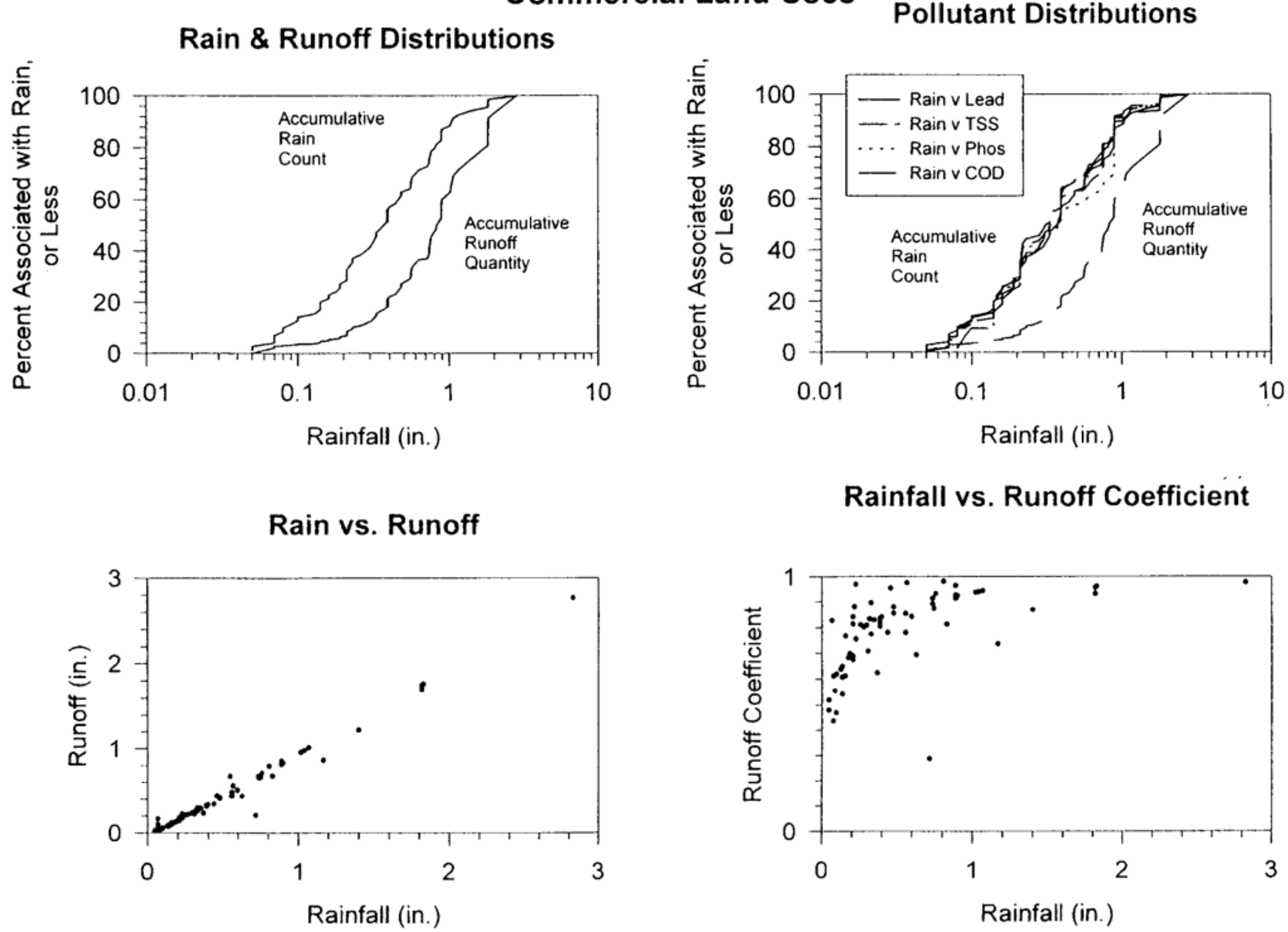
Milwaukee, Wisconscin
Post Office Site
Commercial Land Uses



Milwaukee, Wisconscin
Post Office Site
Commercial Land Uses

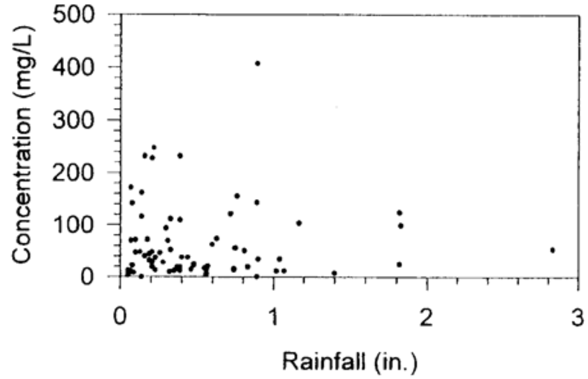


Milwaukee, Wisconscin
Rustler Site
Commercial Land Uses

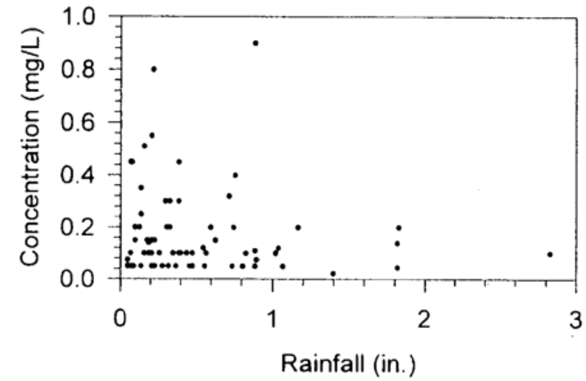


Milwaukee, Wisconscin
Rustler Site
Commercial Land Uses

Rainfall vs. Total Suspended Solids Concentration

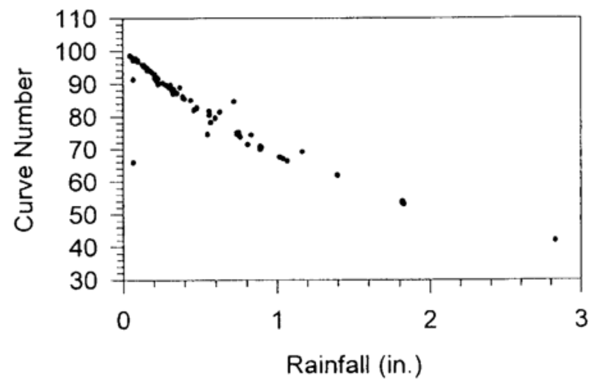


Rainfall vs. COD Concentration

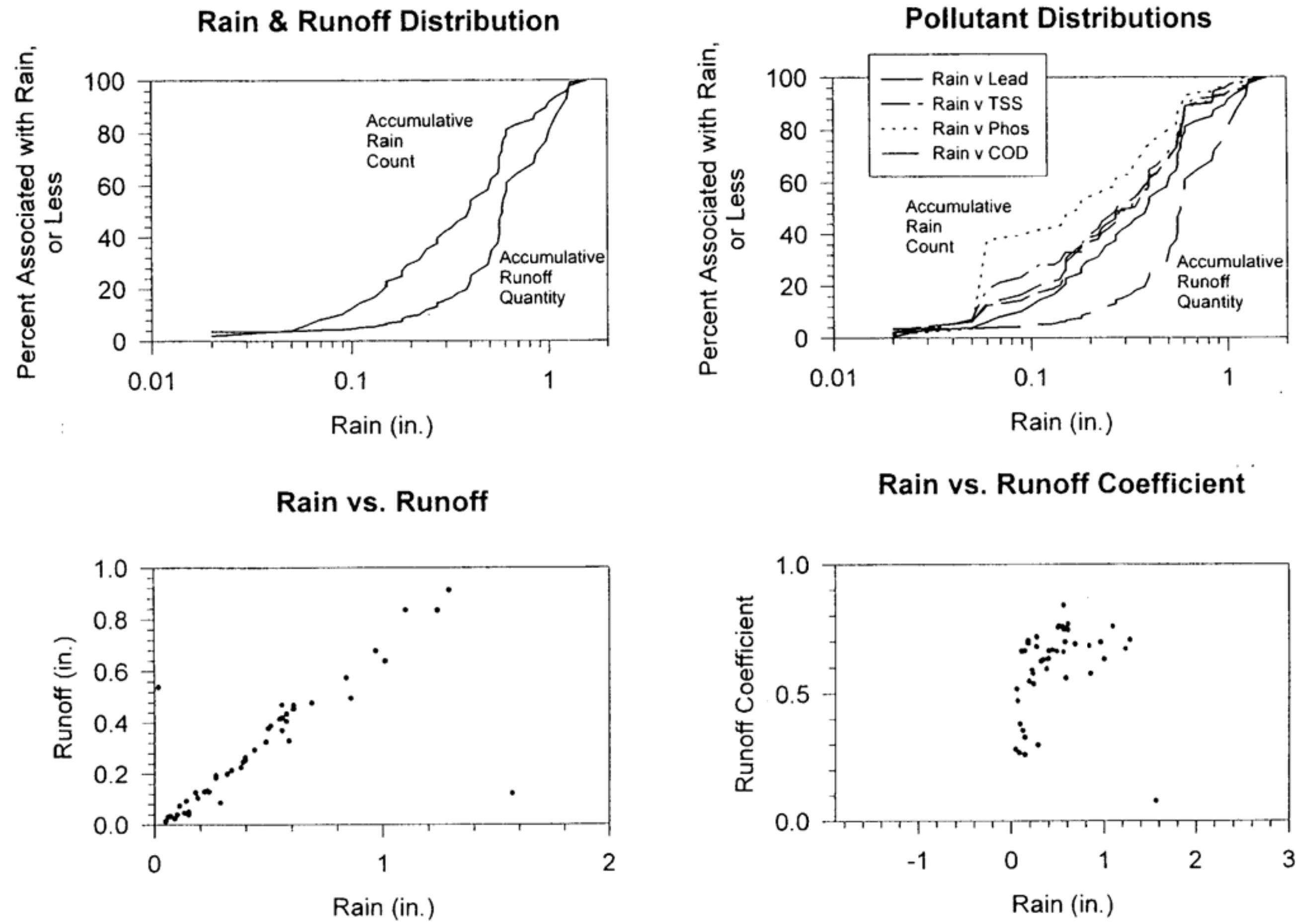


Milwaukee, Wisconscin
Rustler Site
Commercial Land Uses

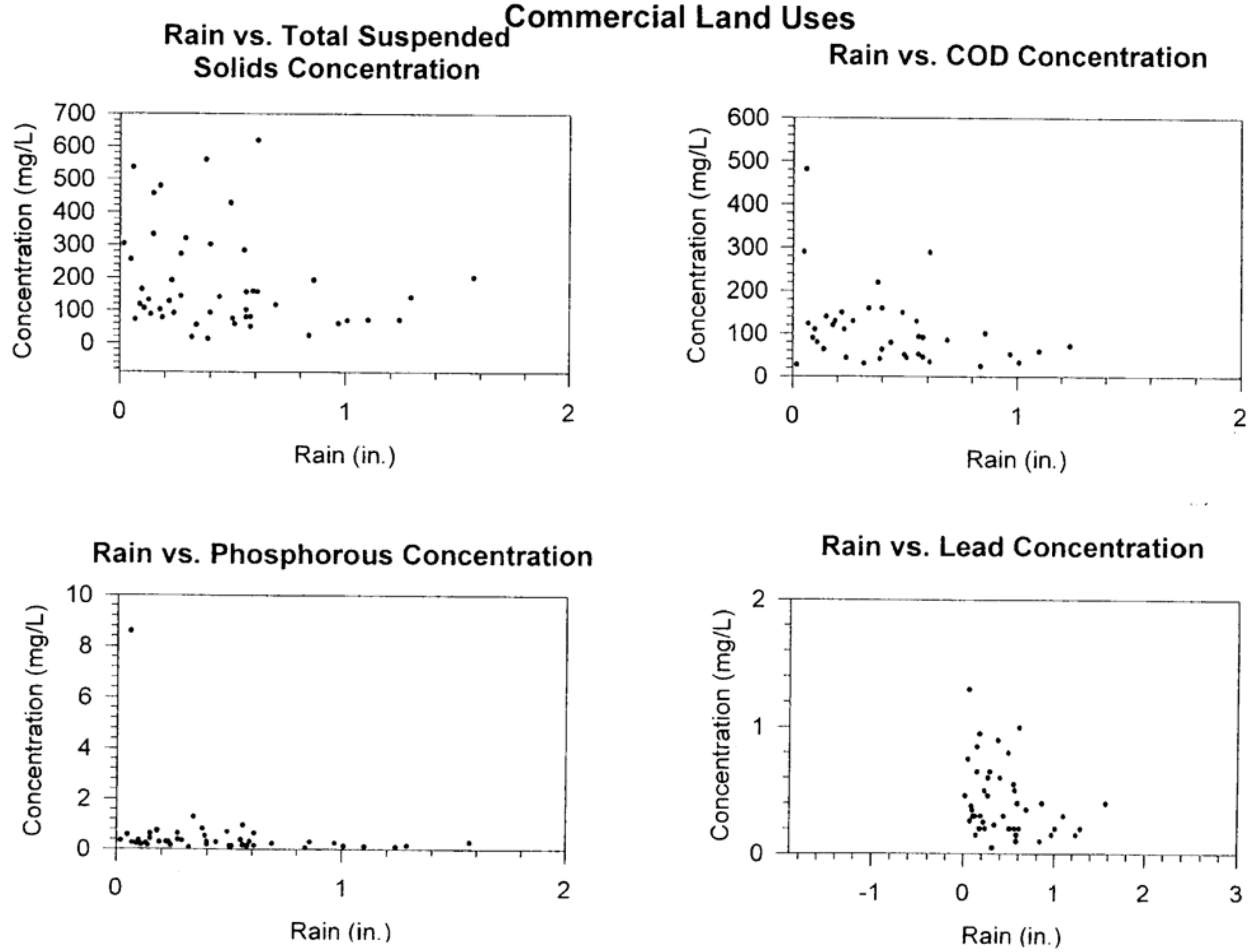
Rainfall vs. Curve Number



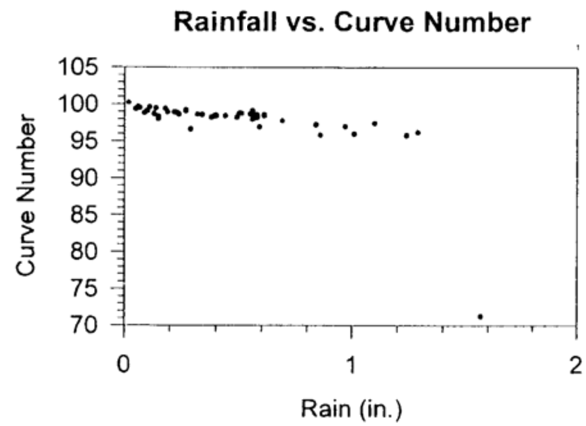
Milwaukee, Wisconscin
State Fair Site
Commercial Land Uses



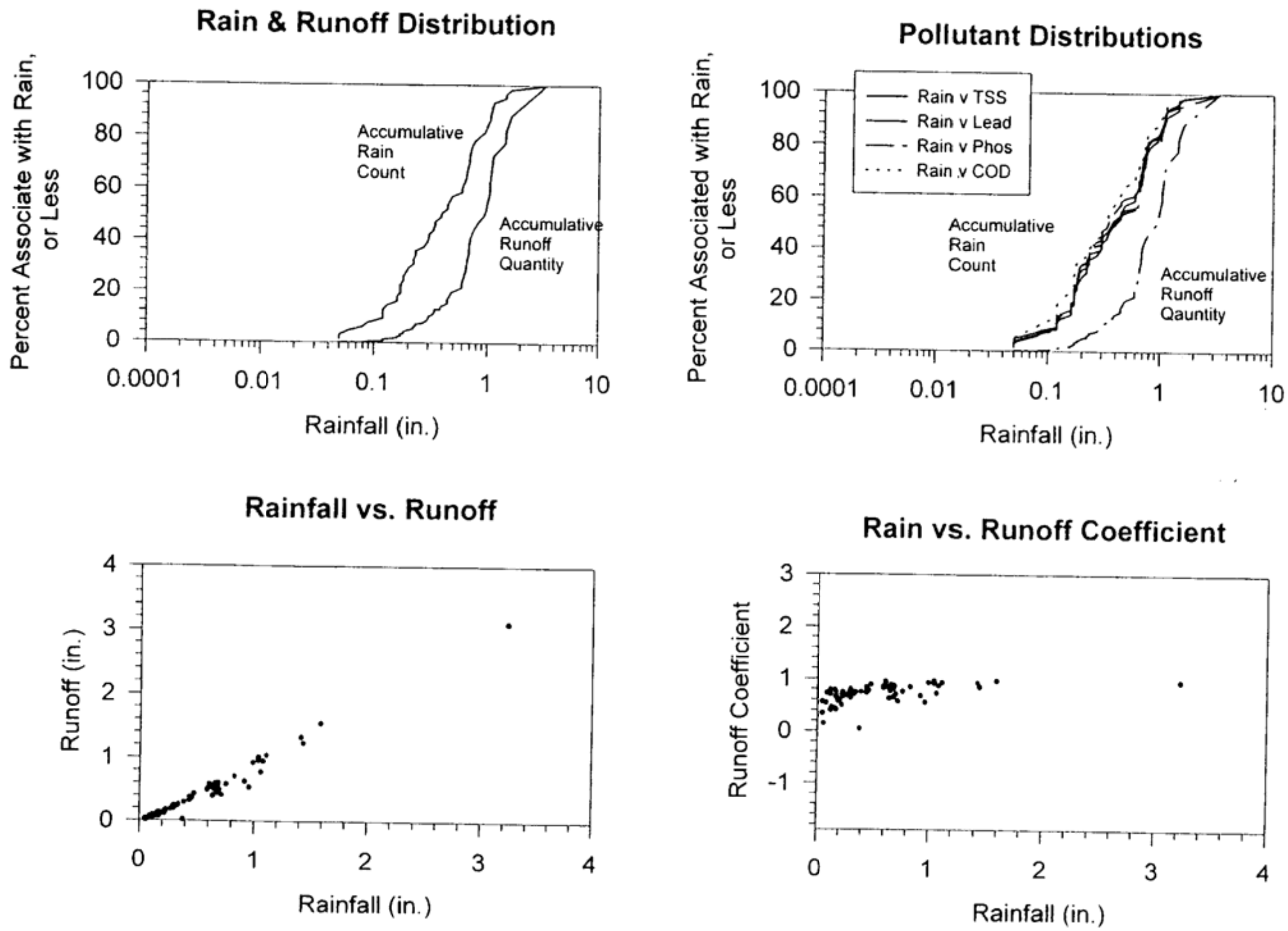
Milwaukee, Wisconscin
State Fair Site
Commercial Land Uses



Milwaukee, Wisconscin
State Fair Site
Commercial Land Uses

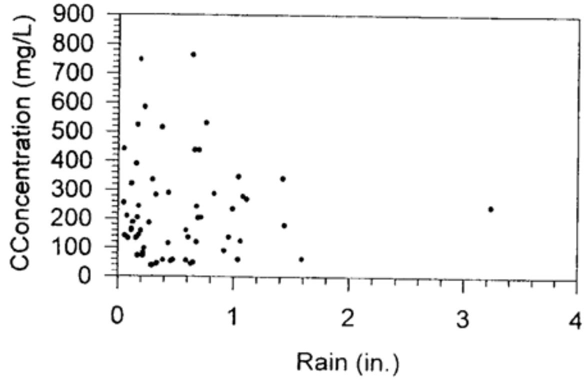


Milwaukee, Wisconscin
Wood Center Site
Commercial Land Uses

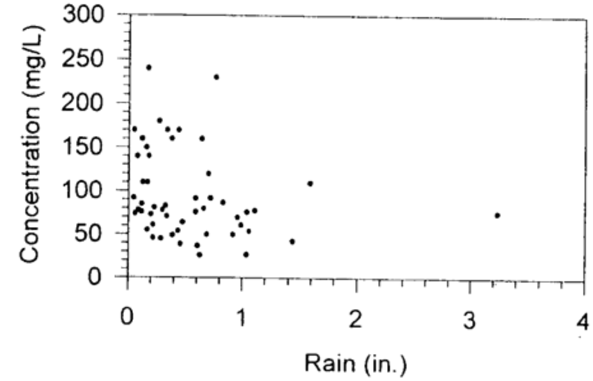


Milwaukee, Wisconscin
Wood Center Site
Commercial Land Uses

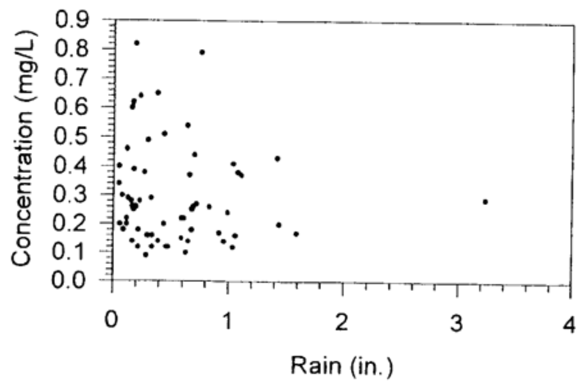
Rain vs. Total Suspended Solids Concentration



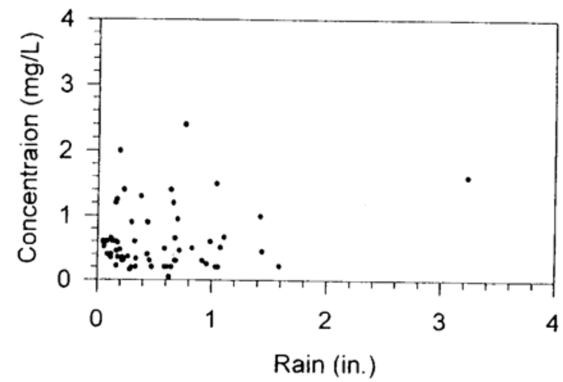
Rain vs. COD Concentration



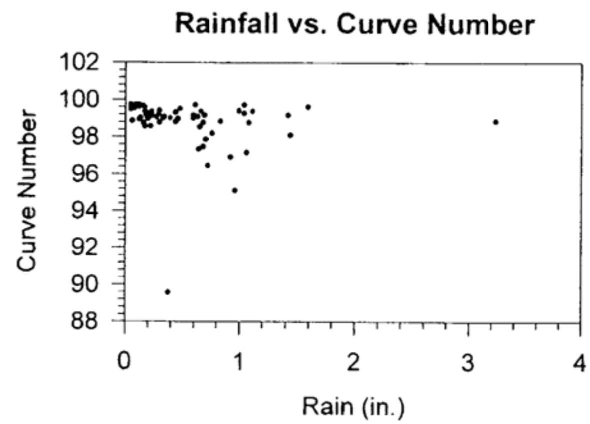
Rain vs. Phosphorous Concentration



Rain vs. Lead Concentration



Milwaukee, Wisconscin
Wood Center Site
Commercial Land Uses



Toronto Area Watershed Management Strategy Study (TAWMS)

TAWMS - Toronto, Ontario, Canada

Introduction

Data collected for Toronto, Ontario, was done through the Humber River Pilot Watershed Study of the Toronto Area Watershed Management Strategy Study (TAWMS). This study was conducted to measure street dirt accumulations, to conduct artificial precipitation washoff experiments, to collect sheet flow samples during runoff and snowmelt events, to collect source area particle samples, to monitor outfall water quality and flow rates during baseflow, runoff and snowmelt conditions and finally to collect precipitation data. This information was collected to establish a basis for developing watershed management options, especially by developing a better understanding about the sources of stormwater contaminants.

Data Collection Methodology

Collection of runoff data was accomplished through monitoring of two outfalls conveying storm water to the receiving stream. Both of these outfall locations were served by separate storm and sewer systems. The two outfalls chosen were the Emery and the Thistledowns outfalls. A tipping bucket rain gauge was located on the top of a five-meter tower at the Emery Site. To supplement this on-site data, the extensive rain gauge network located in the Toronto area was utilized.

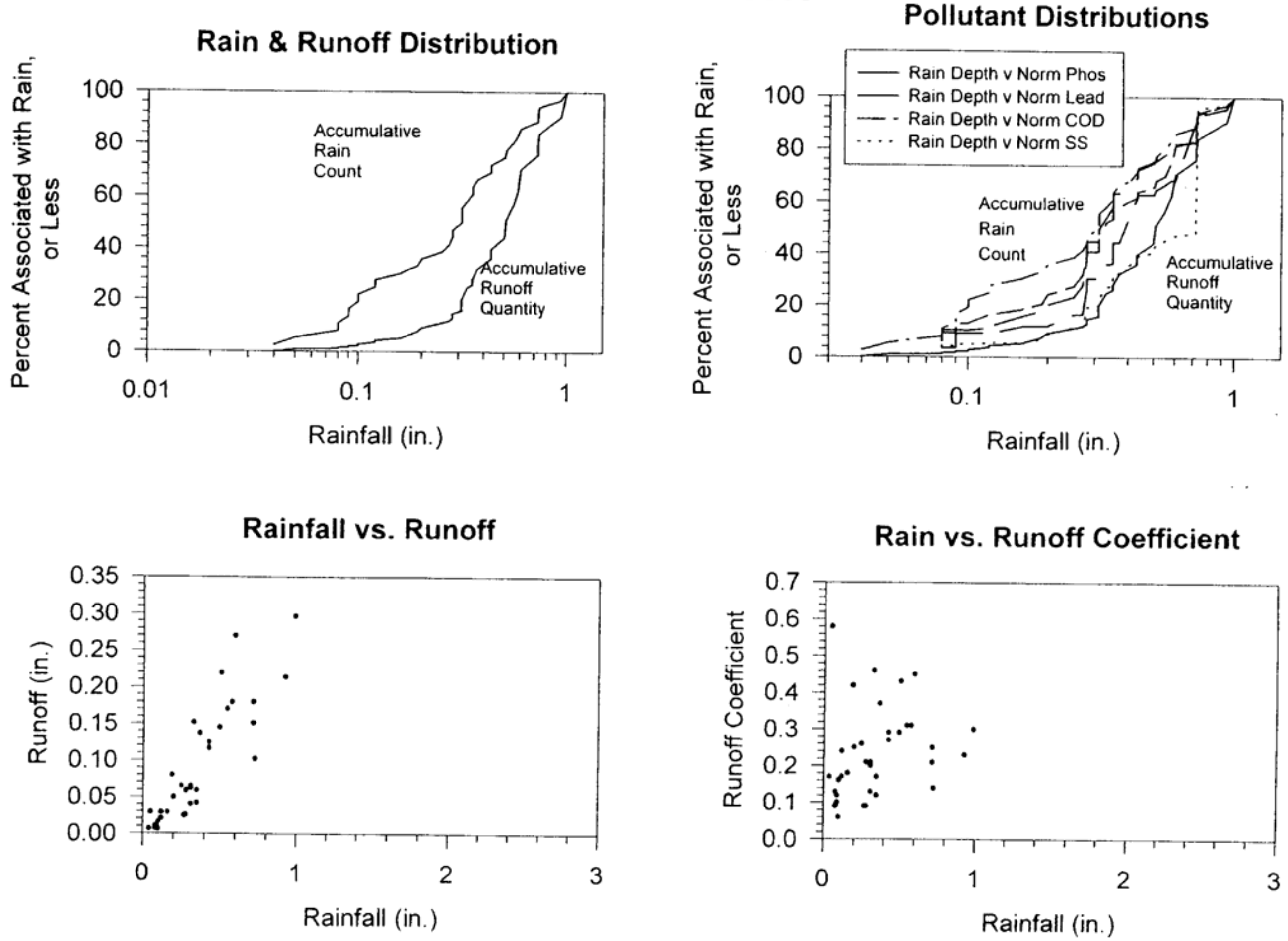
The Emery outfall consisted of a 2m-diameter corrugated steel pipe draining an industrial catchment. This pipe discharges into a stream that feeds Emery Creek and eventually drains into the Humber River. The sampling station located at the outfall consisted of flow recorders and water samplers. An ISCO water level monitor was used to continuously monitor the discharge from the outfall. Water samples were collected by an ISCO automatic sampler, which was prompted by pulses from the rain gauges to collect samples. This sampler was run in two different modes: flow-weighted composite samples were taken during runoff events, and time-weighted samples were collected during dry weather flows. This monitoring site operated from May 1983 to March 1984.

The other outfall monitored was located at the Thistledowns site. This site consisted of a 1.2-m diameter concrete pipe draining a residential area. This pipe discharged directly into the Humber River. At this location, runoff flow was measured using an ISCO water level monitor and samples were obtained using an ISCO automatic water sampler. At the Thistledowns site, the baseflow was about 30 mm in depth and the sampler was therefore programmed to collect samples above this depth during runoff events. During dry weather, time-composite samples were also collected. This sampler operated from July 1983 until March 1984.

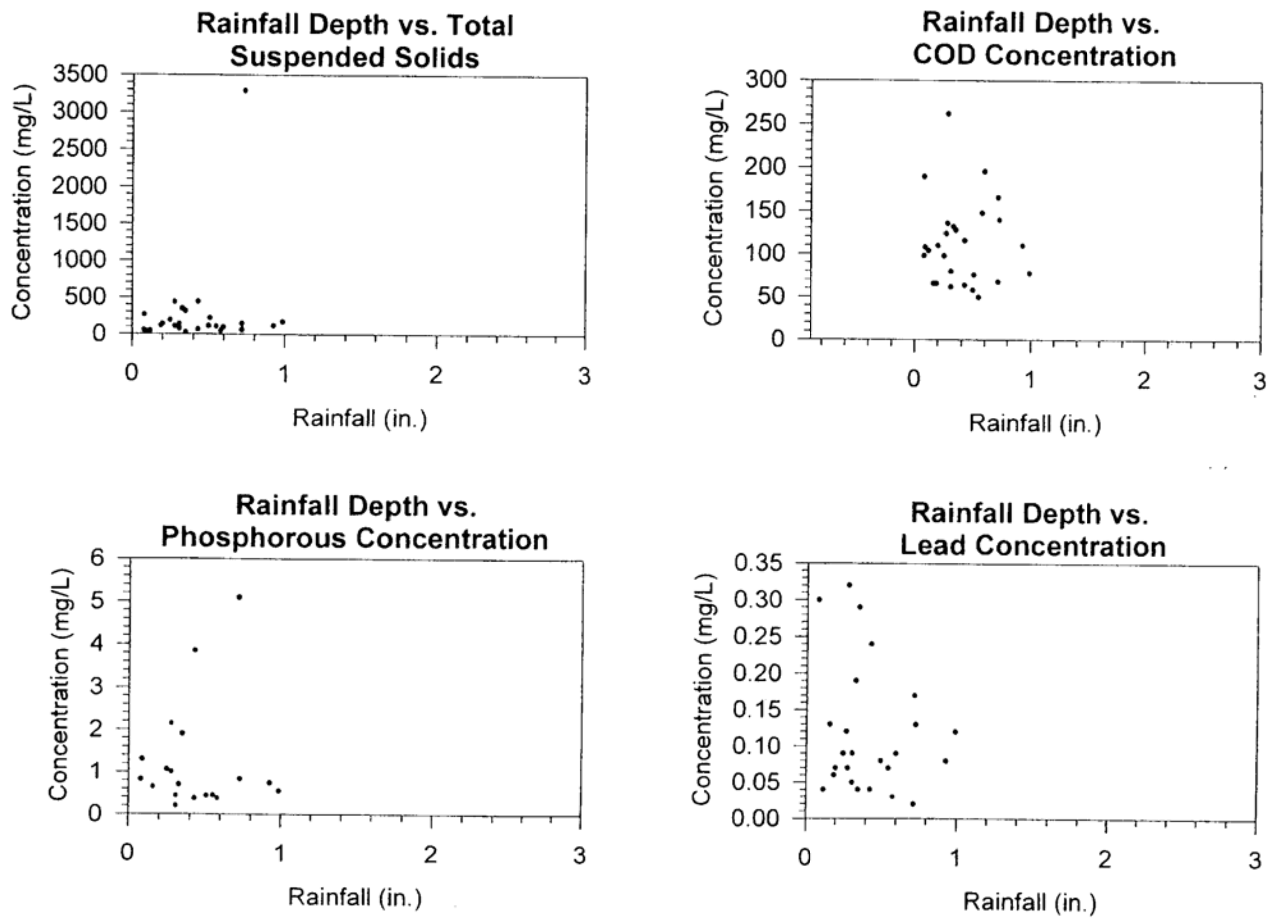
Conclusions

This monitoring activity included the first large-scale effort to characterize industrial runoff, snowmelt, and source flows during rains and snowmelt events. Snowmelt was determined to be a significant portion of the annual urban runoff pollutant discharges. In addition, many other source areas, in addition to streets, were found to be significant sources of stormwater pollutant discharges.

Toronto, Canada
Emery Site
Industrial Land Uses

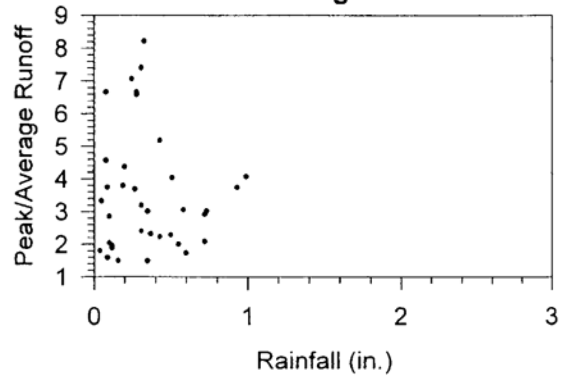


Toronto, Canada
Emery Site
Industrial Land Uses

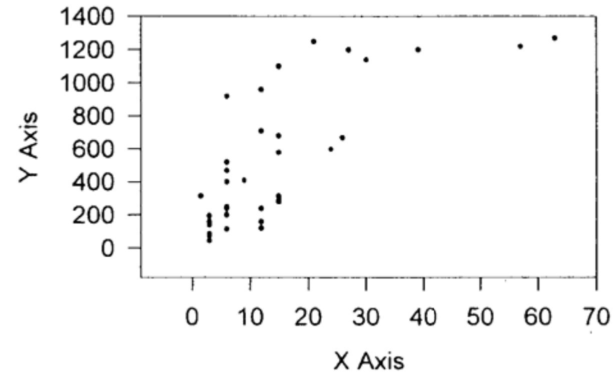


Toronto, Canada
Emery Site
Industrial Land Uses

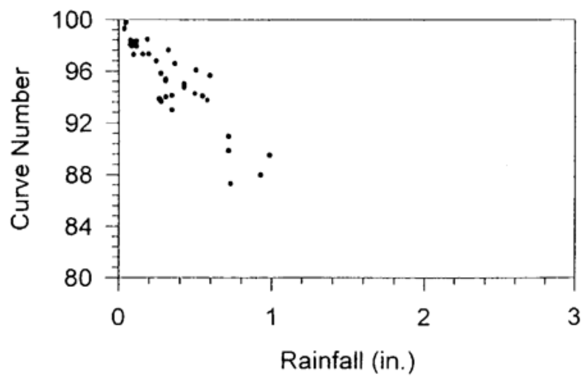
Rain Depth vs. Peak/Average Runoff

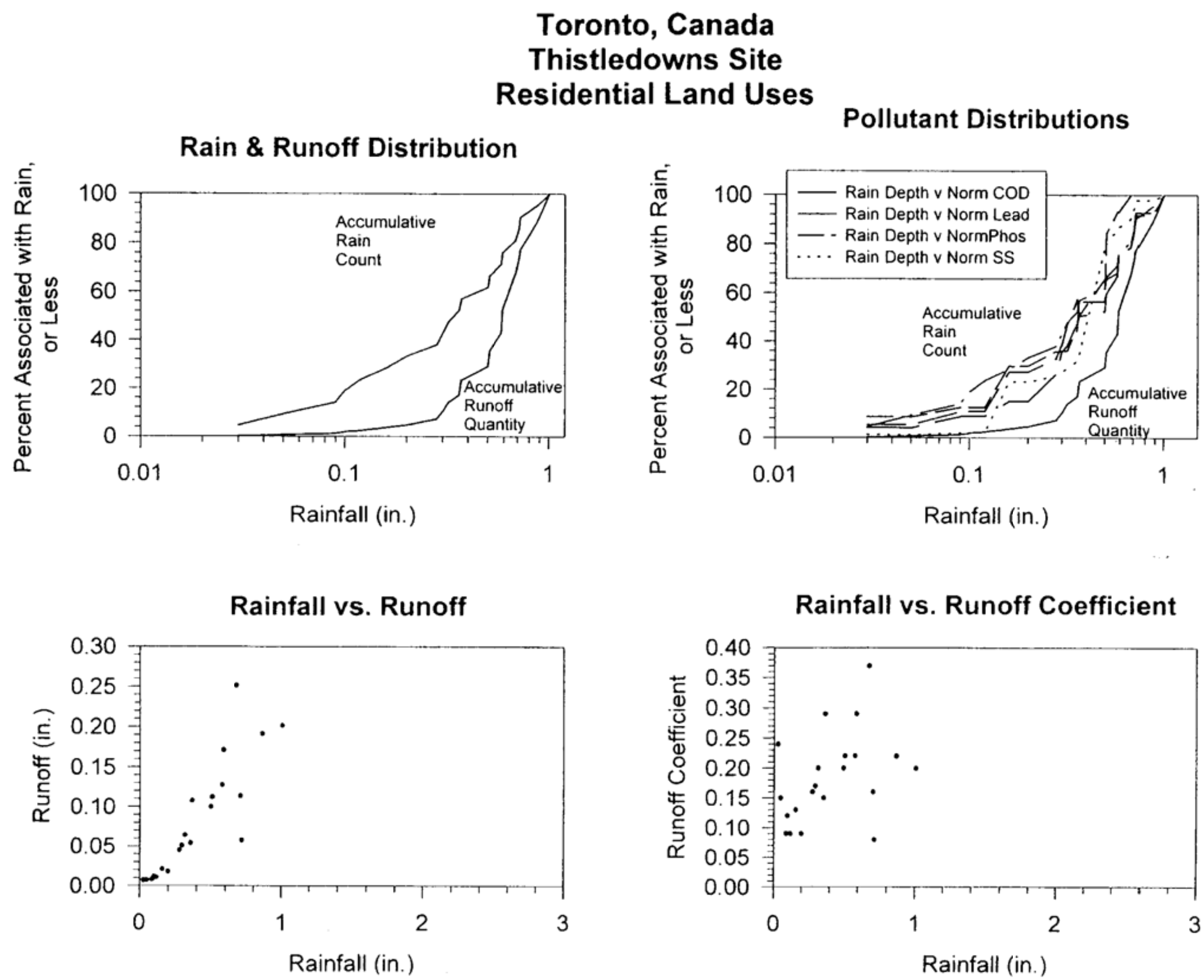


Peak Rain vs. Peak Flow



Rainfall vs. Curve Number

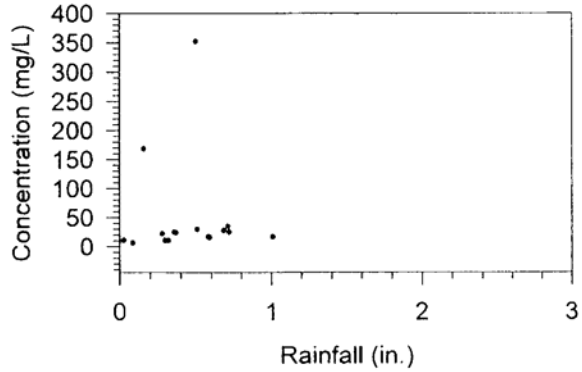




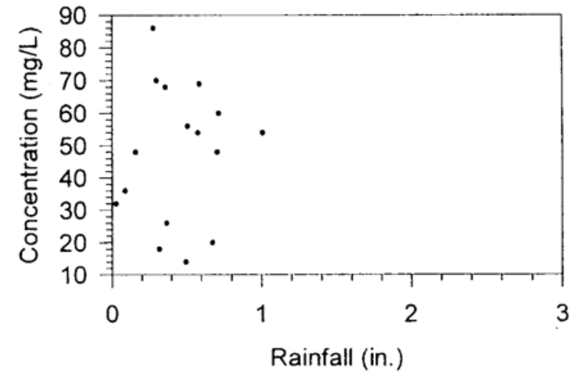
Toronto, Canada
Thistledowns Site
Residential Land Uses
Rain & Runoff Distribution
Percent Associated with Rain, or Less
Accumulative Rain Count
Accumulative Runoff Quantity
Rainfall (in.)
Pollutant Distributions
Rain Depth v Norm COD
Rain Depth v Norm Lead
Rain Depth v NormPhos
Rain Depth v Norm SS
Accumulative Rain Count
Accumulative Runoff Quantity
Rainfall (in.)
Rainfall vs. Runoff
Runoff (in.)
Rainfall (in.)
Rainfall vs. Runoff Coefficient
Runoff Coefficient
Rainfall (in.)

Toronto, Canada
Thistledowns Site
Residential Land Uses

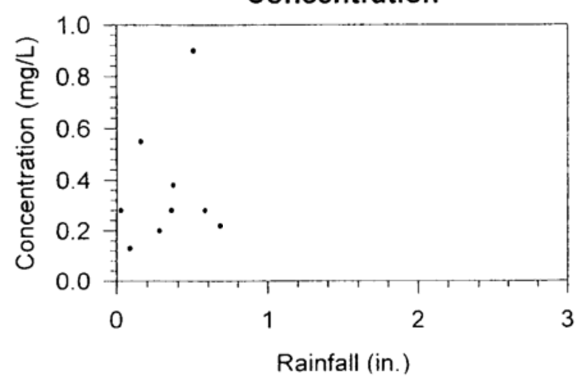
Rainfall vs. Suspended Solids Concentration



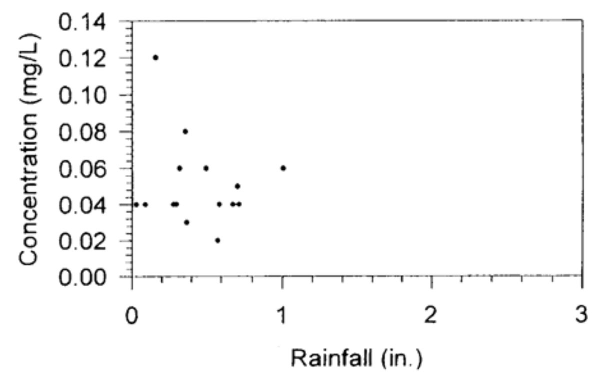
Rainfall vs. COD Concentration



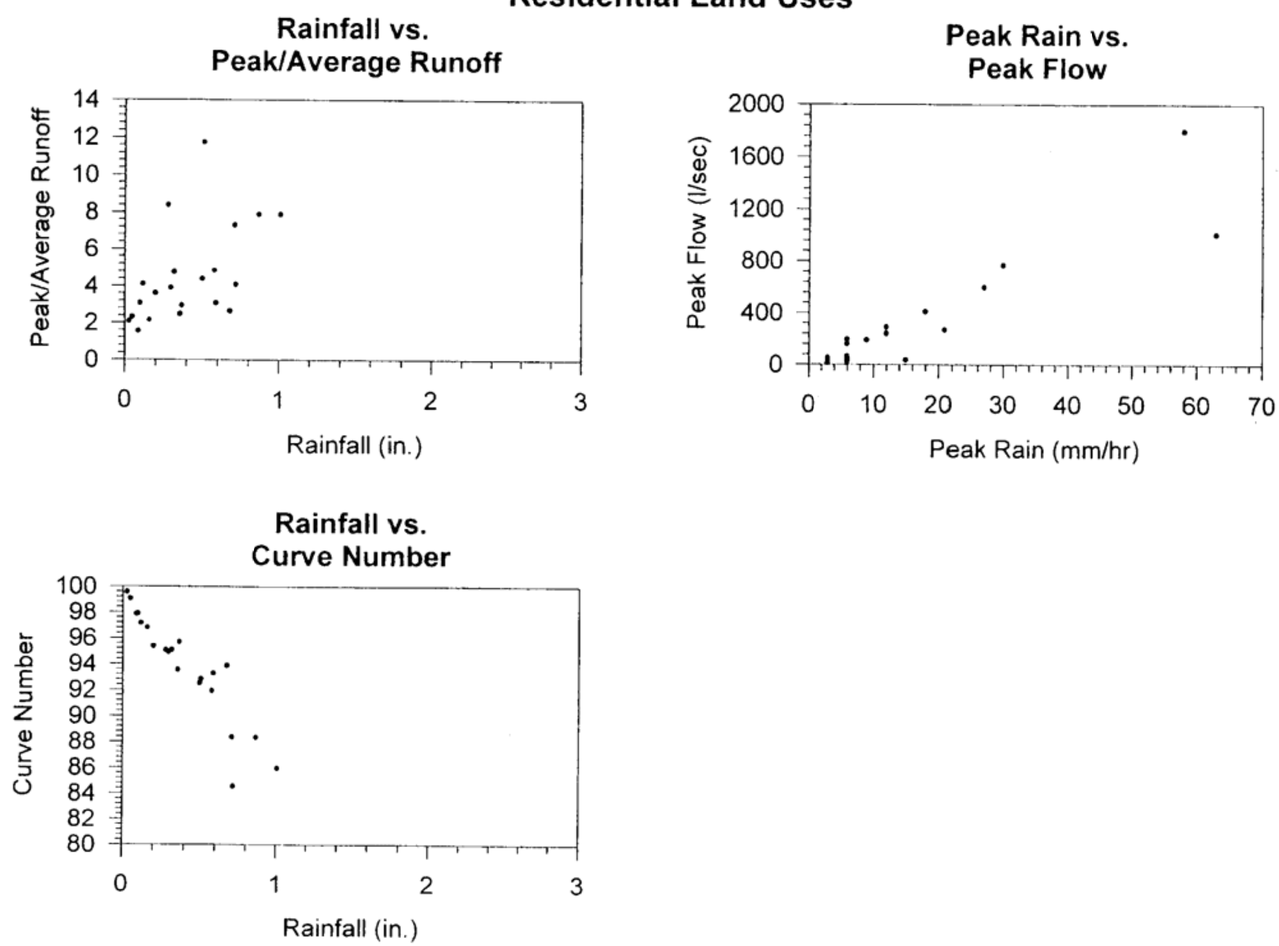
Rainfall vs. Phosphorous Concentration



Rainfall vs. Lead Concentration



Toronto, Canada
Thistledowns Site
Residential Land Uses



Appendix C
Using SLAMM

Introduction

This appendix is a detailed discussion of the calculation procedures developed for the original DOS based version of SLAMM and now found in the Windows version, WinSLAMM. Over the past few years, the program was completely re-written in Visual Basic, version 5, to be completely Windows-based. The current version is numbered 8. Version 6 added Monte Carlo components to the model, developed with funding from Region 5 of EPA. Version 7 was a hybrid version, using many of the older DOS calculation modules, but with the initial windows user interface modules. It also included numerous additional changes. This version 8 is the first complete Windows-based version (including the basic data input, calculation, and output modules found in the DOS version) and closely resembles version 7 in content and capabilities, with a few additional changes. We are planning a new version 9 soon to incorporate many new features from our recent stormwater research conducted over the past several years. The main changes made to the program since the original user guide and algorithm documentation was prepared include the following:

- Practically all of the variable names given in this section and the use of goto statements have been changed to reflect current programming practice. The HELP files in the model provide accurate guidance for the model in its present form. The current calculation source code is included in Appendix E. The "parameter" file maintenance programs are still DOS-based, but have been modified. The rain module, however, cannot review or edit the large rain files that can be produced from CD-ROM data sources. SLAMM can now easily evaluate large rain files - examples containing more than 4 decades of data and many thousands of individual rain events have been successfully run.

- Monte Carlo stochastic components have been added to the pollutant calculations to provide better representations of the random nature of stormwater pollutants.

- The batch processor program, originally developed for the DOS program, was modified for use with the Windows-based program. It now works with users interfacing WinSLAMM with GIS programs.

- Selected processes have been corrected or changed to reflect bug fixes or process modifications. These changes include adding additional controls and flexibility for the analyses of detention ponds, more accurate descriptions of catchbasins in an area, and modifying the pollutant listing.

- An interface program for the use of WinSLAMM as a replacement for the RUNOFF block in SWMM was developed as the main activity of the EPA-sponsored activity reported in this report. This interface program is described in Section 5.

WinSLAMM (the **Win**dows version of the **S**ource **L**oading **A**nd **M**anagement **M**odel) is an urban rainfall runoff water quality model. It calculates runoff volumes and urban pollutant loadings from individual rain events. It also allows the user to reduce pollutant loadings from a source area such as a roof or street area by using control measures such as detention ponds or infiltration devices.

The model is in many ways a very large pollutant mass and flow accounting program. Runoff volumes are calculated by multiplying the rain depth by varying runoff coefficients. The resulting source area runoff volumes are then multiplied by particulate residue concentrations to get particulate residue loadings for each source area for the rain. The runoff coefficient is a function of rain depth, land use (*eg*, a residential land use), and source area. The particulate residue concentrations are a function of runoff depth, land use and source area. Other particulate pollutants are then related to the particulate residue values, while filterable pollutants are related to the runoff volumes.

Much of the program is devoted to identifying the appropriate runoff and particulate residue concentration values for a given rain depth, land use, and source area. The process is complicated by the large number of source areas within each land use and by the large number of variable combinations needed for a specific source area.

Hardware Requirements and Recommendations

WinSLAMM runs on personal computers under Windows 95, Windows 98, or Windows NT. The following computer features are required:

• Memory Requirements:
The model uses many dynamic, or variable-size, arrays. If a computer runs out of memory, either reduce the number of WinSLAMM source areas and rainfall events, or close other programs that are running on your computer. A typical Pentium computer can analyze a typical situation in a few seconds to a few minutes, even for a complete set of many rain years. The addition of detention ponds or a long list of pollutants in an analysis will significantly increase the computer computational time.

• Disk Storage:
The model creates and erases many temporary files while running. It requires only a few mb of storage on the hard drive, depending on the size of the rain files, etc.

• Printer:
The output may be sent to a printer or saved as a file. However, output can be many columns wide, and so users may need a printer operating in landscaped mode with a small sized font to print the output. The output can also be quite extensive, so we recommend that all output be saved to a file where it can be formatted as needed.

Description of the Files Associated WinSLAMM

WinSLAMM.EXE

This Windows version SLAMM combines the DOS Input, Calculation, and Output modules of the DOS version of SLAMM. The program generates a site description file needed to run WinSLAMM, which has the extension .DAT (referred to as data.DAT). Besides the basic site development data requested, alternative runoff controls are also described using this program. The program must be installed using the appropriated installation files. Place the first disk in the installation drive (or the CD if you have the CD version of the installation program) and run setup from the run command or use the “install new software” option in the control panel, then follow the on-screen directions.

The files needed to run SLAMM include:

• A mandatory rain.RAN file to describe the rain series.

• A mandatory runoff.RSV file containing the runoff coefficients for each surface type to generate surface runoff volume quantities.

• A mandatory particulate.PSC file describing the particulate residue (suspended solids) concentrations for each source area (except for roads) and land use, for several rain categories.

• A mandatory delivery.PRR file to account for deposition of particulate pollutants in the storm drainage system, before the outfall, or before outfall controls. The DELIVERY.PRR file is calibrated for swales, curb and gutters, undeveloped roadsides, or combinations of drainage conditions.

• An optional pollutant.PPD file to describe the particulate pollutant strengths related to particulate residue and to describe the filterable pollutant concentrations for each source area for each land use. This file is not needed if only runoff volume and particulate residue calculations are desired. This file also contains the coefficient of variation (COV) values for each pollutant for Monte Carlo simulation in WinSLAMM.

• An optional size.CPZ files for wet detention pond analyses to describe the runoff particulate size distributions. If no wet detention ponds are included in a WinSLAMM model, these files are not needed.

MPARAXX.EXE
MPARAXX is the utility program that produces, edits, and displays the above files needed by WinSLAMM. This is a DOS-based program and can be executed from the DOS prompt in the DOS shell within Windows. The example parameter files included on the disk can be printed to a file using MPARAXX.EXE and then read using any ASCII text editor.

MSCALCXX.EXE
MSCALCXX was the prior DOS version of the main SLAMM calculation program. It may be executed from the DOS prompt in the DOS shell within Windows. This program only asks for the data.DAT file name, previously prepared using SINPXX.EXE. It automatically links with the output program. SLAMM directs all of its output to a disk file. This file can be viewed and printed using most text editors or word processors. The output format generally requires a printer in landscape mode using a small font. The Windows version executes the calculation module by using the drop-down "Run" menu.

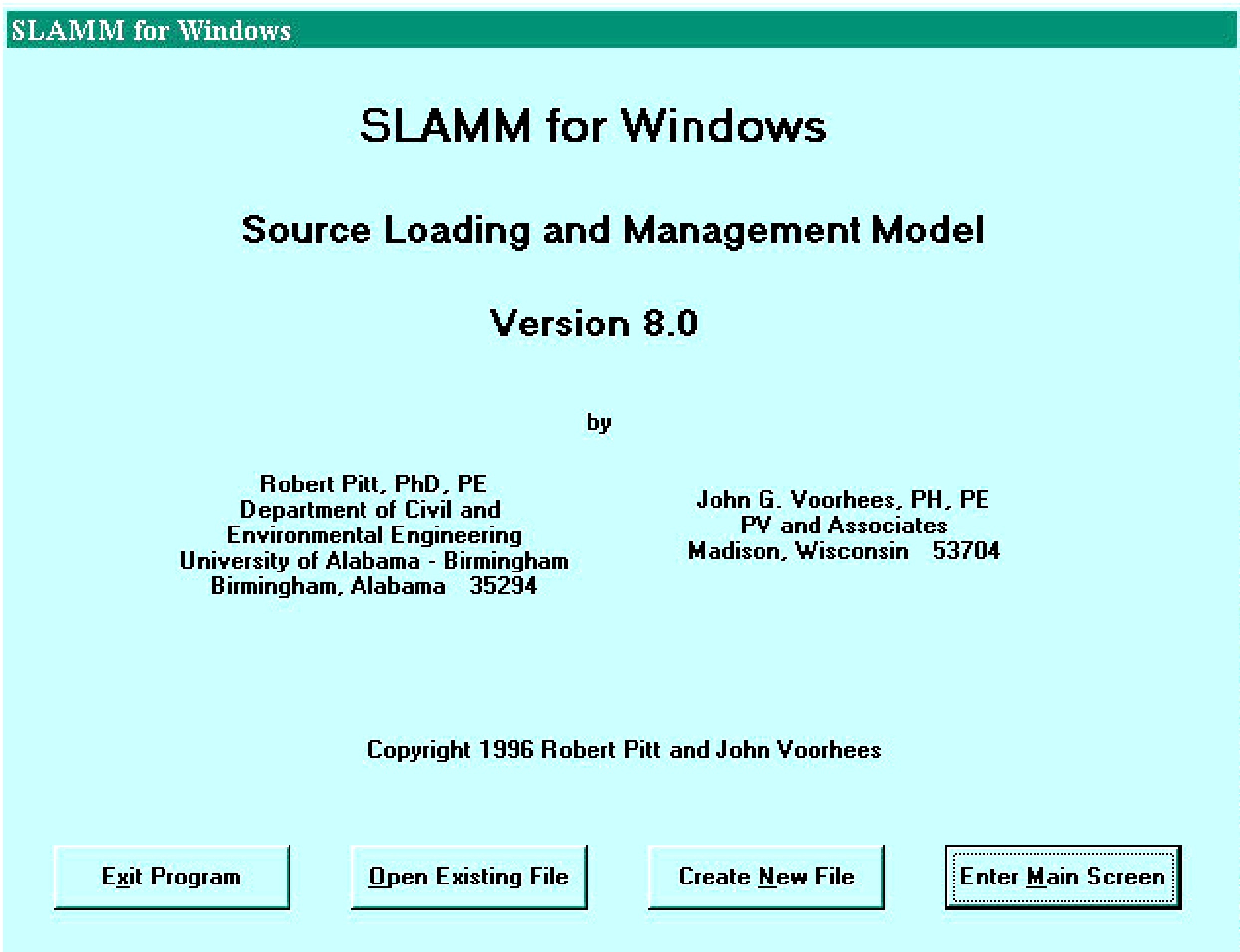
Creating or Editing a SLAMM Data File
Introduction
The information necessary to perform a WinSLAMM model run is stored in a WinSLAMM data file and its associated parameter files. This information includes a description of land uses and source areas, the time period and corresponding rainfall events, the pollutant control devices applied to the site, and the pollutants to be analyzed. This section discusses how to create or edit a WinSLAMM data file that stores this information. The HELP files with version 8 of WinSLAMM offer additional direction for the current version of WinSLAMM.

Table C-1, lists the series of steps necessary to create a SLAMM data file.

Table C-1. Steps For Creating A New SLAMM Data File

1. Start the Program
2. Enter Site, Drainage, and File Information
3. Enter Data
    A. Land use area and source controls information
    B. Catchbasin and drainage control information
    C. Outfall control information
4. Enter Pollutant Analysis Selection Information
5. Save the Data File

Starting the Program
To run the program, double-click the WinSLAMM program icon or double-click WinSLAMM.EXE in Win95/98/NT Explorer. Select "Open Existing File" to open a file that has previously been created, select "Create New File" to create a new .DAT file using the new file data entry sequence editor, or select "Enter Main Screen" to enter the data editor. Press "Exit" to exit the program. The opening screen for WinSLAMM is shown below.

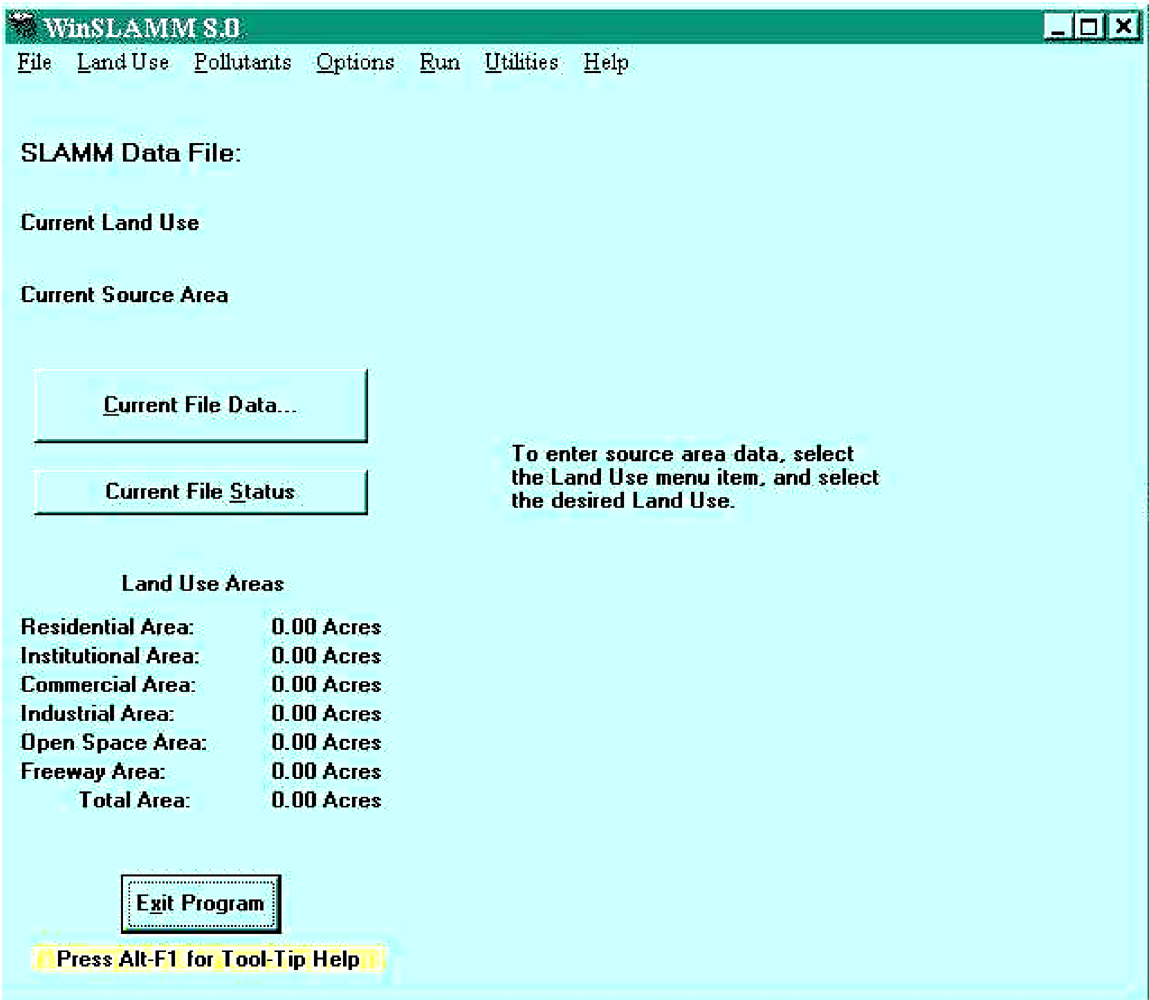


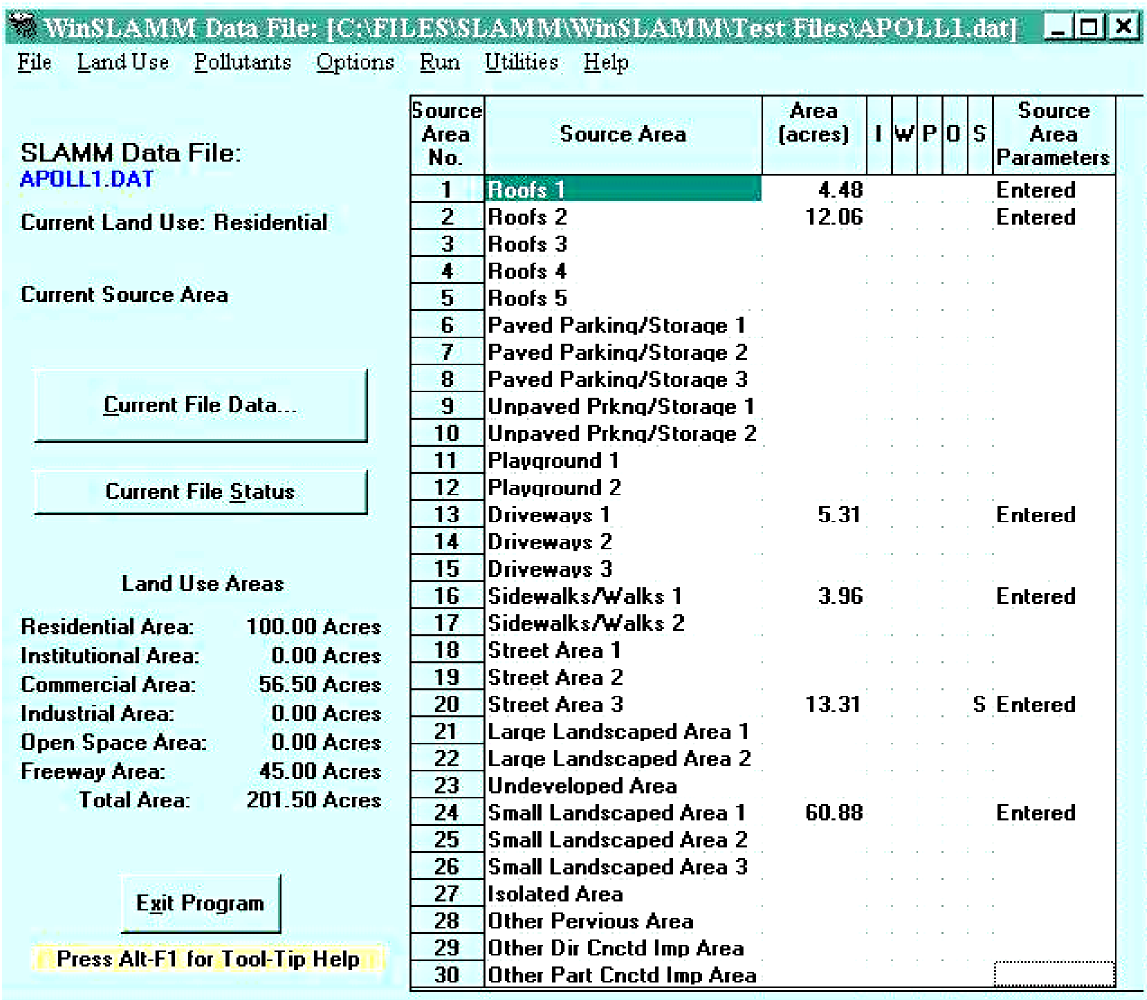
Main Data Entry Form

The main data entry form, which is illustrated below, allows you to enter the data needed to create a SLAMM data file. The main data entry form includes the following items:

- Menu items on the Main Menu bar
- A series of labels that identify the data file name, the current land use and source area, and the areas that have been entered for each land use
- A Current File Data button, described in more detail below
- A Current File Status button that determines if the minimum data needs of a WinSLAMM model run are met
- An Exit Program button
- A grid that lists the source areas for each land use and indicates whether source area parameters and control devices have been entered for each source area. Selecting a land use from the Land Use menu item accesses the grid for that land use.

The main menu is shown below, including a view of the land use screen:


WinSLAMM 8.0
File
Land Use
Pollutants
Options
Run
Utilities
Help
SLAMM Data File:
Current Land Use
Current Source Area
Current File Data...
Current File Status
To enter source area data, select the Land Use menu item, and select the desired Land Use.
Land Use Areas
Residential Area: 0.00 Acres
Institutional Area: 0.00 Acres
Commercial Area: 0.00 Acres
Industrial Area: 0.00 Acres
Open Space Area: 0.00 Acres
Freeway Area: 0.00 Acres
Total Area: 0.00 Acres
Exit Program
Press Alt-F1 for Tool-Tip Help



Current File Data Button

The Current File Data button allows the user to enter data critical to the operation of the model. This includes parameter file names and locations, Monte Carlo seed information, model run start and finish dates, and drainage information. A list of the items in the form is described below, followed by an illustration of the form.

1. SLAMM Data File Name. File names should subscribe to all the Windows file naming conventions. Do not use any extensions; the program will add them.
2. Site description for the file. The description may be up to 230 characters long.
3. Starting date of the study period. This date must be after 1952 and should correspond to the dates of the rain events in the rain file used in this SLAMM file. The format of the dates must be “MM/DD/YY” or “MM.DD.YY.”
4. Ending date of the study period. This date must be after the starting date, and have the same format as the starting date.
5. Seed. The seed is used for Monte Carlo simulations of pollutant strength. The seed must be an integer greater than zero. Enter zero (0) for a randomly generated seed based upon the clock time a model run begins. A negative seed value will force the model to use zeros for any COV values in the pollutant probability distribution file. This has the effect of turning off the Monte Carlo pollutant loading simulation, so the model instead calculates pollutant loadings based upon the average pollutant value.
6. Rain file name. Enter the name of the rain file used in the model run. Do not include the extension.

7. Pollutant probability distribution file name. Enter the name of the pollutant probability distribution file you want to use for the model run. Do not include the extension.
8. Runoff coefficient file name. Enter the name of the runoff coefficient file used in the model run. Do not include the extension.
9. Particulate solids concentration file name. Enter the name of the particulate solids concentration file used in the model run. Do not include the extension.
10. Particulate residue delivery file name. Enter the name of the particulate residue delivery file used in the model run. Do not include the extension.
11. Drainage system data. Enter the fraction of the total area controlled by each drainage system type. The sum of the fractions of each of the drainage types must equal 1. The five drainage types are listed below:

    1. Grass Swales. Enter additional information to characterize grass swales after entering the drainage type area fractions. This information is described in the outfall control section.
    2. Undeveloped roadside. This category is used to represent haphazard drainage along a road.
    3. Curb and Gutters, “valleys,” or sealed swales in poor condition (or very flat). This category may also be used if runoff is channeled along the edge of streets without curb and gutter.
    4. Curb and Gutters, “valleys,” or sealed swales in fair condition.
    5. Curb and Gutters, `“valleys,” or sealed swales in good condition (or very steep).

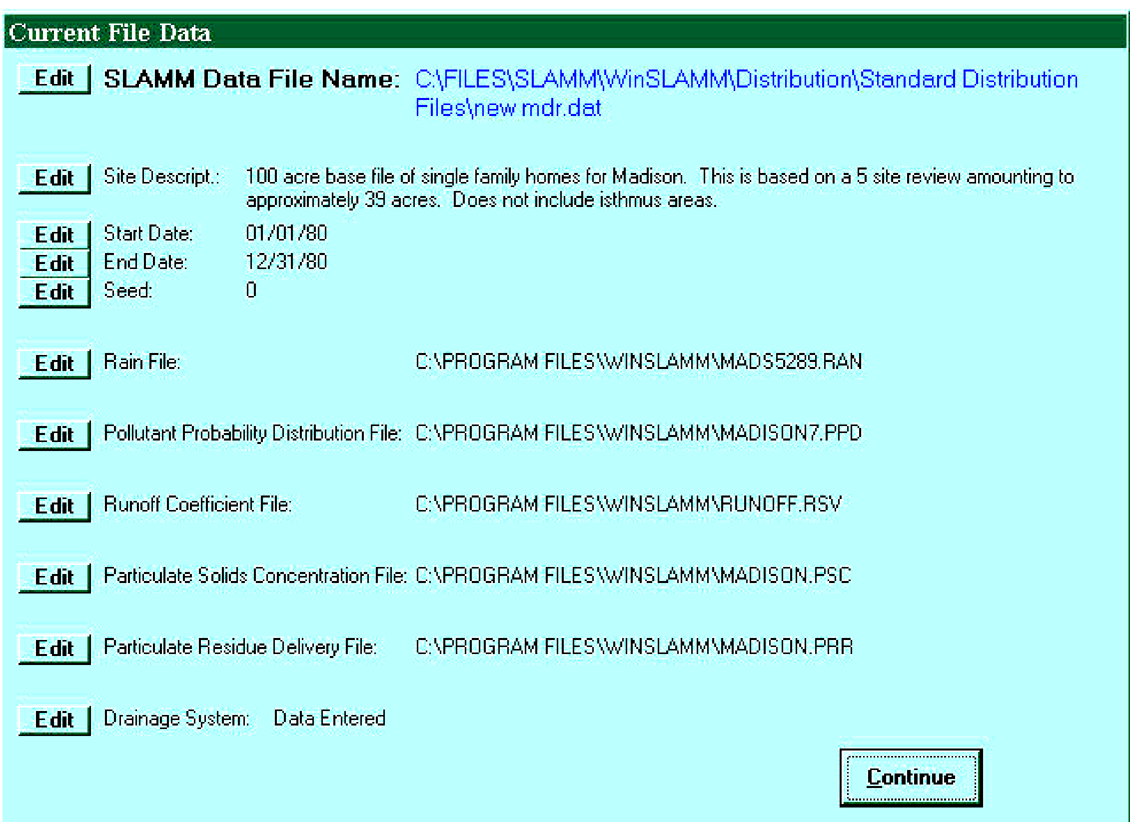


Table C-4. Printing Options

1. Print source areas by land use & outfall for each rain - complete printout.

2. Print source area totals and outfall summaries.
3. Print outfall data only for each rain.
4. Default option - Print outfall summaries only.

Data Entry
This section reviews the steps necessary to enter WinSLAMM land use and drainage system information into a file. The first sub-section reviews the land use area information, the second sub-section reviews the catchbasin and drainage control information, and the final sub-section reviews the outfall control information.

Land Use and Source Area Information

Characterize the six land uses described in Table C-2 by defining source areas. Enter source areas for each land use by selecting, from the main menu, "File/{Land Use}". A data entry spreadsheet, shown below, for the land use will appear on the "Main Data Entry" form. This spreadsheet lists all the available source areas for the land use, the area of the source area, the available controls, and the source area parameters. To enter an area, double-click on the area column box in the row of the desired land use. You will be prompted to enter the area of the source area as well as the required source area parameter information. To enter a control for the source area, double-click on the desired control box in the row of the selected source area. Land use areas 1 to 5 each have 30 source areas listed in Table C-5. Land use 6 (Freeways) has 10 source areas.

Source Area No.	Source Area	Area (acres)	I	W	P	O	S	Source Area Parameters
1	Roofs 1	[illegible]						Entered
2	Roofs 2	12.23						Entered
3	Roofs 3							
4	Roofs 4							
5	Roofs 5							
6	Paved Parking/Storage 1							
7	Paved Parking/Storage 2							
8	Paved Parking/Storage 3							
9	Unpaved Prkng/Storage 1							
10	Unpaved Prkng/Storage 2							
11	Playground 1							
12	Playground 2							
13	Driveways 1	5.14						Entered
14	Driveways 2	1.01						Entered
15	Driveways 3							
16	Sidewalks/Walks 1	3.73						Entered
17	Sidewalks/Walks 2							
18	Street Area 1	3.92					S	Entered
19	Street Area 2	[illegible]					S	Entered
20	Street Area 3	7.49					S	Entered
21	Large Landscaped Area 1							
22	Large Landscaped Area 2							
23	Undeveloped Area							
24	Small Landscaped Area 1	63.09						Entered
25	Small Landscaped Area 2							
26	Small Landscaped Area 3							
27	Isolated Area							
28	Other Pervious Area							
29	Other Dir Cnctd Imp Area							
30	Other Part Cnctd Imp Area							

Table C-5 is a list of the source areas WinSLAMM uses. If a control option has been activated, the code letter for that control option will appear in the column. For example, in the data grid above, street sweeping has been activated, as indicated by the three S's in the S column. The control options available for each source area are illustrated in Figure C-1. The information needed for each control option and the procedure to enter this information in a WinSLAMM data file is listed at the end of this section.

Table C-5. SLAMM Source Areas

Roofs	Sidewalks/Walks	Other Impervious Areas
Paved Parking/Storage	Streets/Alleys	Freeway Lanes/Shoulders
Unpaved Parking/Storage	Undeveloped Areas	Large Turf Areas
Playgrounds	Small Landscaped Areas	Large Landscaped Areas
Driveways	Other Pervious Areas	

Each source area listed in Table C-5 has specific data requirements that depend upon the characteristics of the source area and upon the source area's land use. These requirements are listed in Table C-6 and C-7, which are coding forms that list the land use and control practice information requirements. These sheets should be filled out before the data file is created.

Streets and alleys in land uses 1 through 5 require somewhat different characteristic information than freeway (Land Use 6), paved lane, and shoulder areas. To enter a user defined street dirt accumulation equation for a street area in land uses 1 through 5, the equation must be in the form of a quadratic equation, $Ax^2 + Bx + C$, where A is greater than 0, B is greater than 0, and C is less than or equal to 0.

....

Isolated areas, or disconnected areas, are areas within a land use that do not contribute runoff to the land use outfall. Isolated areas could be constructed, e.g. swimming pools, or natural land features such as kettle ponds. Source controls are not applicable to isolated areas.

The source areas in the Freeway land use include Paved Land and Shoulder Areas, Large Turf Areas, an Undeveloped Area, an Other Pervious Area, an Other Directly Connected Impervious Area, and an Other Partially Connected Impervious Area. A paved lane and shoulder area requires somewhat different source area data requirements than street and alley source.

Catchbasin and Drainage Control Information

Enter catchbasin and drainage control information by selecting, from the main menu, "Land Use/Catchbasin" or "Drainage Control". The available options for catchbasins or drainage control are listed in Figure C-1. The data requirements for each of these options is shown on Table C-8 and are listed in a later section.

Outfall Control Information

Enter outfall control information by selecting , from the main menu, "Land Use/Outfall". The available options for outfall controls are listed in Figure C-1. The data requirements for each of these options is shown on Table C-7 and are listed in the following section.

Source Area Control Device Information

This section describes the information necessary to apply a pollutant control device to a source area or outfall. Figure C-1 lists the control devices applicable to a specific source area, the entire drainage area, or to the outfall. The control device options for each source area are also listed on the source area screen in the program under the column heading "Control Options Available." To select a control option for a source area, follow the steps listed below upon entering a source area menu:

1. Enter the source area number.

2. Enter the area, in acres, of the source area.

3. Enter the source area characteristics. The model will request all parameters necessary for each source area, as described in Tables C-6 and C-7.

4. Enter the source area option letter to use a control device to reduce the runoff volume or pollutant

loading coming from a source area. The letter for each control option is listed on Figure C-1 and at the bottom of each source area menu in the program.

Figure C-1. Source area, drainage system, and outfall control options available in SLAMM. [(1)]

	Infiltration device	Wet detention pond	Grass drainage swale	Street cleaning	Catchbasin cleaning	Porous pavement	Other
Roof	X	X					X
Paved parking/storage	X	X				X	X
Unpaved parking/storage	X	X					X
Playgrounds	X	X				X	X
Driveways						X	X
Sidewalks/walks						X	X
Streets/alleys				X			X
Undeveloped areas	X	X					X
Small landscaped areas	X						X
Other pervious areas	X	X					X
Other impervious areas	X	X				X	X
Freeway lanes/shoulders	X	X					X
Large turf areas	X	X					X
Large landscaped areas	X	X					X
Drainage system			X		X		X
Outfall	X	X					X

(1) Development characteristics affecting runoff, such as roof and pavement draining to grass instead of being directly connected to the drainage system, are included in the individual source area descriptions.

A description of the data necessary for each control device option is listed below.

Infiltration Devices

- Water percolation rate (in/hr).
- Area served by device (acres).
- Surface area of the device (square feet).
- Width to Depth ratio of the device. If the device is a spreading area, press ENTER.

Street Cleaning

The street cleaning control option can be applied to streets and alleys in land uses 1 through 5. No more than ten street cleaning schedule changes are allowed for each street or alley source area. Below is a description of the information requirements necessary to implement street cleaning.

- Street cleaning starting date (date format: MM/DD/YY).
- Street cleaning ending date (date format: MM/DD/YY).
- Street cleaning schedule. The cleaning frequency options range from none to daily.
- Street cleaning productivity. Select the default productivity by entering the parking density and the parking control status. The parking density options are:
    1. None
    2. Light
    3. Medium
    4. Extensive (short term)
    5. Extensive (long term)

- The parking control status indicates whether parking options such as limited parking hours or alternate side-of-the-street parking have been regulated by the municipality. If they have, answer “YES” to indicate that parking controls are imposed.

• Street sweeper productivity can also be described by entering the equation coefficients for the linear street cleaning equation, Y = mx + b, where is Y is the residual street dirt loading after street cleaning and x is the before street cleaning load (in lbs/curb-mile). Enter values for:

m (slope, less than 1)
b (intercept, greater than or equal to 1)

Porous Pavement

• Infiltration rate of pavement, base, or soil, whichever is the least (in/hr).
• Porous pavement area (acres).

Wet Detention Ponds

The wet detention pond algorithm in SLAMM is developed from the program DETPOND, a detention pond water quality analysis program developed by Pitt and Voorhees (1992). It uses the modified Puls hydraulic routing method and the surface overflow rate method for particulate sedimentation. The pond must have at least 3 feet of standing water below the lowest invert for these removal equations to be valid. Evaluate the pollutant removal capabilities of a wet detention pond either in specific source areas or at the outfall. The wet detention pond data requirements for SLAMM include:

• The particle size distribution in the pond influent.
• The initial stage elevation of the pond.
• The pond stage - area relationship.
• The pond outlet characteristics.

The input module creates a separate detention pond data file if one or more detention ponds are selected as a control device. The detention pond data file name is the same as the name of the SLAMM data file in the Site and File Information menu, but with the file extension ".PND." If the detention pond data file name is changed, the SLAMM data file name must also be changed to match it.

The model requires a particle size distribution file to evaluate the pollutant removal abilities of detention ponds. To create a particle size distribution file, use the SLAMM Parameter module discussed later. The model also requires the initial stage elevation of the pond and the pond stage - area relationship. The units for these values are in feet and, for the pond area, acres. The area of the pond at the datum (lowest) elevation must be zero. Enter at least five reasonably spaced stage increments. The increments can either be enter variably spaced, or at constant intervals.

SLAMM has the ability to characterize each detention pond with as many as ten different outlets. The pond outlet options are described below.

Rectangular Weir Characteristics:

1. Weir length (ft).
2. Height from bottom of weir opening (invert) to top of weir.
3. Height from datum (low elevation of pond) to bottom of weir opening (invert) (ft).

V-Notch Weir Characteristics

A) Weir angle:
   1. 22.5 degrees.
   2. 30 degrees.
   3. 45 degrees.
   4. 60 degrees.
   5. 90 degrees.
   6. 120 degrees.

B) Height from bottom of weir opening (invert) to top of weir.
C) Height from datum to bottom of weir opening (invert) (ft).

Orifice Characteristics:

1. Orifice diameter (ft).
2. Invert elevation above datum (ft).

Seepage Basin Characteristics:

1. Infiltration rate (inches/hr).
2. Width of device (ft).
3. Length of device (ft).
4. Invert elevation of seepage basin inlet above datum (ft).

Natural Seepage Infiltration Rates:
These stage elevations must correspond to the stage elevations entered for the pond stage - area elevations. The seepage rates are expressed in inches per hour. Enter 0 inches per hour for entry 0, stage 0.

Monthly Evaporation Rate
Enter the average pond surface evaporation rate, in inches per day, for each month of the year.

Other Outlet Characteristics:
This option allows you to describe a stage - discharge relationship that is independent of any other outlet discharge characteristics. The stage elevations must correspond to the pond stage - area elevations. Enter outflow values from zero stage level (datum), and enter 0 discharge at the 0 stage. I

Catchbasin Cleaning

- Total sump volume (cubic feet) in the drainage area.
- Area served by catchbasins control (acres).
- Percentage of the sump volume which is full at the beginning of the study period (0 to 100).
- Number of times the catchbasin is cleaned during the study period (cleaning up to 5 times is allowed).
- Date for each time the catchbasin is cleaned. The dates must be consecutive, within the study time period, and in the format “MM/DD/YY.”

Other Flow or Pollutant Reduction Control

- Pollutant concentration reduction (fraction).
- Water volume (flow) reduction (fraction).
- Area served by other control (acres).

Grass Swales

- Swale infiltration rate (in/hr). This is typically about one-half of the infiltration rate as measured using a double-ring infiltrometer.
- Swale density (ft/acre).
- Wetted swale width (ft).
- Enter the area served by swales (acres).

Table C-6a. Blank Coding Forms for SLAMM Source Areas

SLAMM Site Characterization Data Sheet

Land Use: Residential / Institutional / Commercial / Industrial / Open Space

Source Area	Area (ac)						
Roofs 1	______	Flat/Pitched	Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Roofs 2	______	Flat/Pitched	Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Roofs 3	______	Flat/Pitched	Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Roofs 4	______	Flat/Pitched	Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Roofs 5	______	Flat/Pitched	Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Paved Parking 1	______		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Paved Parking 2	______		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Paved Parking 3	______		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Unpaved Parking 1	______		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Unpaved Parking 2	______		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Playground 1	______		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Playground 2	______		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Driveways 1	______		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Driveways 2	______		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Driveways 3	______		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Sidewalks 1	______		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Sidewalks 2	______		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Strts/Alleys 1	______	____curb-miles	Texture: Smth/Int/Rough/ V Rough	Accum: Default/A:__ B:__ C:__	Init Load: Default/ ___ lbs		S
Strts/Alleys 2	______	____curb-miles	Texture: Smth/Int/Rough/ V Rough	Accum: Default/A:__ B:__ C:__	Init Load: Default/ ___ lbs		S
Strts/Alleys 3		curb-miles	Texture: Smth/Int/Rough/ V Rough	Accum: Default/A: B: C:	Init Load: Default/ lbs		S
Lrg Landscapes 1	______			Soil: Sandy/Clayey			IWO
Lrg Landscapes 2	______			Soil: Sandy/Clayey			IWO
Undvlpd Area				Soil: Sandy/Clayey			IWO
Sml Landscapes 1	______			Soil: Sandy/Clayey			IO
Sml Landscapes 2	______			Soil: Sandy/Clayey			IO
Sml Landscapes 3				Soil: Sandy/Clayey			IO
Isolated Area							
Other Pervious Area	______			Soil: Sandy/Clayey			IWO
Other Directly Conncted Area	______						IWPO
Other Disconnected Area	______			Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO

Page 1 of 2

Table C-6b. Blank Coding Forms for SLAMM Source Areas

SLAMM Site Characterization Data Sheet

Land Use: Freeways

Source Area	Area (ac)					
Paved Lanes/Shoulders 1	______	Texture: Smth/Int/Rough/ V Rough	ADT: ______ veh/day	Highway Length: ____ miles	Init Load: Default/ ___ lbs	IWO
Paved Lanes/Shoulders 2	______	Texture: Smth/Int/Rough/ V Rough	ADT: ______ veh/day	Highway Length: ____ miles	Init Load: Default/ ___ lbs	IWO
Paved Lanes/Shoulders 3	______	Texture: Smth/Int/Rough/ V Rough	ADT: ______ veh/day	Highway Length: ____ miles	Init Load: Default/ ___ lbs	IWO
Paved Lanes/Shoulders 4	______	Texture: Smth/Int/Rough/ V Rough	ADT: ______ veh/day	Highway Length: ____ miles	Init Load: Default/ ___ lbs	IWO
Paved Lanes/Shoulders 5	______	Texture: Smth/Int/Rough/ V Rough	ADT: ______ veh/day	Highway Length: ____ miles	Init Load: Default/ ___ lbs	IWO
Large Turf Areas	______	Soil: Sandy/Clayey				IWO
Undeveloped Areas	______	Soil: Sandy/Clayey				IWO
Other Pervious Area	______	Soil: Sandy/Clayey				IWO
Other Directly Conncted Area	______					IWPO
Other Disconnected Area	______	Soil: Sandy/Clayey		Density: Low/Med or High	Alleys: Yes/No	IWPO

Model Run Starting Date : ____ /____ /____

Model Run Ending Date: ____ /____ /____

Parameter File Names:

Rain File: ______________ .RAN

Runoff Coefficient File: ______________ .RSV

Particulate Solids Concentration File: ______________ .PSC

Pollutant Relative Concentration File: ______________ .PPD

Seed: 0 / ______

Particulate Residue Delivery File: ______________ .PRR

[SLMFORM1.]

Page 2 of 2

Table C-7a. Blank Coding Forms for SLAMM Control Practices

SLAMM Control Device Data Sheet

Control Device for Land Use :________________; Source Area: ______________

File name: _____________ .DAT

Infiltration Area or Trench: I

1. Water percolation rate (in/hr): ___________
2. Area served by device (acres): ___________
3. Surface area of the device (ft^2): ___________
4. Width to Depth Ratio of the Device: ___________

Street Cleaning S

1. Number of Street Cleaning Schedule Changes:
2. Start Cleaning Date / Cleaning Schedule No.

	Start Cleaning Date	Cleaning Schedule No.
1	___/___/___	________________
2	___/___/___	________________
3	___/___/___	________________
4	___/___/___	________________
5	___/___/___	________________
6	___/___/___	________________
7	___/___/___	________________
8	___/___/___	________________
9	___/___/___	________________
10	___/___/___	________________

Cleaning Schedule Code

1. None
2. 7 Passes/wk
3. All weekdays
4. 4 Passes/wk
5. 3 Passes/wk
6. 2 Passes/wk
7. 1 Pass/wk
8. Every two weeks
9. Every 4 weeks
10. Every 8 weeks
11. Every 12 weeks

3. Final Street Cleaning Date: ___/___/___
4. Overall Street Cleaning Productivity:

   Default Cleaning Productivity:

   1. Parking Density
      1. None
      2. Light
      3. Medium
      4. Extensive (short term)
      5. Extensive (long term)
   2. Parking Controls: Yes / No

   User Defined Cleaning Productivity:

   m Slope (less than 1): _________

   b Intercept (greater than or equal to 1): _________

Porous Pavement P

1. Infiltration rate of pavement, base, or soil, whichever is the least (in/hr): _______
2. Porous Pavement Area (acres): ___________

Other Flow or Pollutant Reduction Control O

1. Pollutant concentration reduction (fraction): ________________
2. Water volume (flow) reduction (fraction): ________________
3. Area served by other control (acres): ________________

Table C-7b. Blank Coding Forms for SLAMM Control Practices

SLAMM Control Device Data Sheet

Catchbasin Cleaning C

1. Total sump volume (ft^3): ______________
2. Area served by other control (acres): ______________
3. Percentage of sump volume which is full at beginning of study period (0 to 100) ______________
4. Number of times catchbasin cleaned during study period (0 - 5 times): ______________
5. Date each time catchbasin is cleaned:
   1 ___/____/____
   2 ___/____/____
   3 ___/____/____
   4 ___/____/____
   5 ___/____/____

Grass Swales G

1. Swale infiltration rate (in/hr): ______________
2. Swale density (ft/acre): ______________
3. Wetted swales width (ft): ______________
4. Area served by swales (acres): ______________

Other Flow or Pollutant Reduction Control at the Outfall O

1. Particulate Residue Reduction due to rainfall delivery (fraction)

Rain (mm)	Particulate Reduction	Rain (mm)	Particulate Reduction
1	______________	25	______________
2	______________	30	______________
3	______________	40	______________
5	______________	50	______________
10	______________	60	______________
15	______________	70	______________
20	______________	80	______________

2. Water volume (flow) reduction (fraction): ______________
3. Area served by other control (acres): ______________

Drainage System Type — Fraction of Total Area

1. Grass Swales: ______________
2. Undeveloped roadside: ______________
3. Curbs and gutters in poor condition (or flat): ______________
4. Curbs and gutters in fair condition: ______________
5. Curbs and gutters in good condition (or steep): ______________

Page 2 of 4

Table C-7c. Blank Coding Forms for SLAMM Control Practices

SLAMM Control Device Data Sheet

Wet Detention Ponds **D**

Diagram Outlet Structure in Space Below

1. Initial Stage Elevation (feet) above datum: ____________
2. Number of stage elevation increments required: ____________
3. Total number of outlets (maximum: 10): __________
4. Stage, pond area, seepage, and other outlet information:

Entry Number	Stage (ft)	Pond Area (acres)	Natural Seepage (cfs)	Other Outflow (cfs)
0	0.0	0.0	0.0	0.0
1	________	________	________	________
2	________	________	________	________
3	________	________	________	________
4	________	________	________	________
5	________	________	________	________
6	________	________	________	________
7	________	________	________	________
8	________	________	________	________
9	________	________	________	________
10	________	________	________	________
11	________	________	________	________
12	________	________	________	________
13	________	________	________	________
14	________	________	________	________
15	________	________	________	________
16	________	________	________	________
17	________	________	________	________
18	________	________	________	________
19	________	________	________	________
20	________	________	________	________
21	________	________	________	________
22	________	________	________	________
23	________	________	________	________
24	________	________	________	________
25	________	________	________	________
26	________	________	________	________
27	________	________	________	________
28	________	________	________	________
29	________	________	________	________
30	________	________	________	________

Table C-7d. Blank Coding Forms for SLAMM Control Practices

SLAMM Control Device Data Sheet

Wet Detention Ponds (continued)

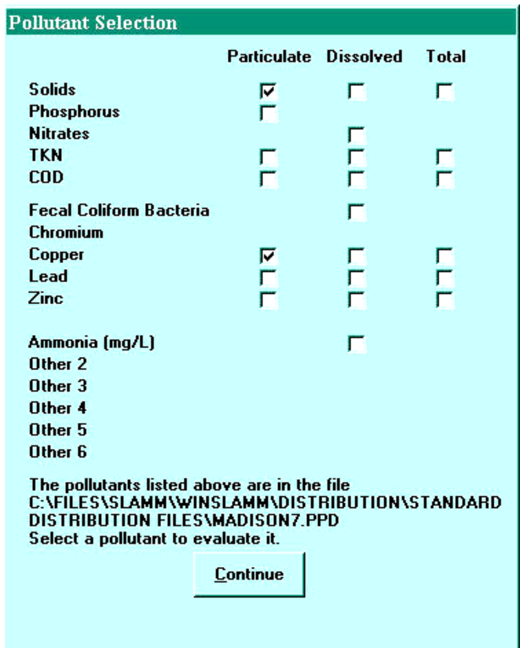
5. Outlet Characteristics
   1. Rectangular Weir
      1. Weir length (ft)
      2. Height from bottom of weir opening (invert) to top of weir: ________
      3. Height from datum to bottom of weir opening (invert) (ft): ________
   2. V-Notch Weir
      A) Weir angle
         1. 22.5 degrees
         2. 30 degrees
         3. 45 degrees
         4. 60 degrees
         5. 90 degrees
         6. 120 degrees
      B) Height from bottom of weir opening (invert) to top of weir: ________
      C) Height from datum to bottom of weir opening (invert) (ft): ________
   3. Orifice
      1. Orifice diameter (ft): ________
      2. Invert elevation above datum (ft): ________
   4. Seepage Basin characteristics
      1. Infiltration rate (in/hr): ________
      2. Width of device (ft): ________
      3. Length of device (ft): ________
      4. Invert elevation of seepage basin inlet above datum (ft): ________
   5. Monthly Evaporation Rate

Month Number	Month	Evaporation (in/day)
1	January	________
2	February	________
3	March	________
4	April	________
5	May	________
6	June	________
7	July	________
8	August	________
9	September	________
10	October	________
11	November	________
12	December	________

[SLMCONTR.]

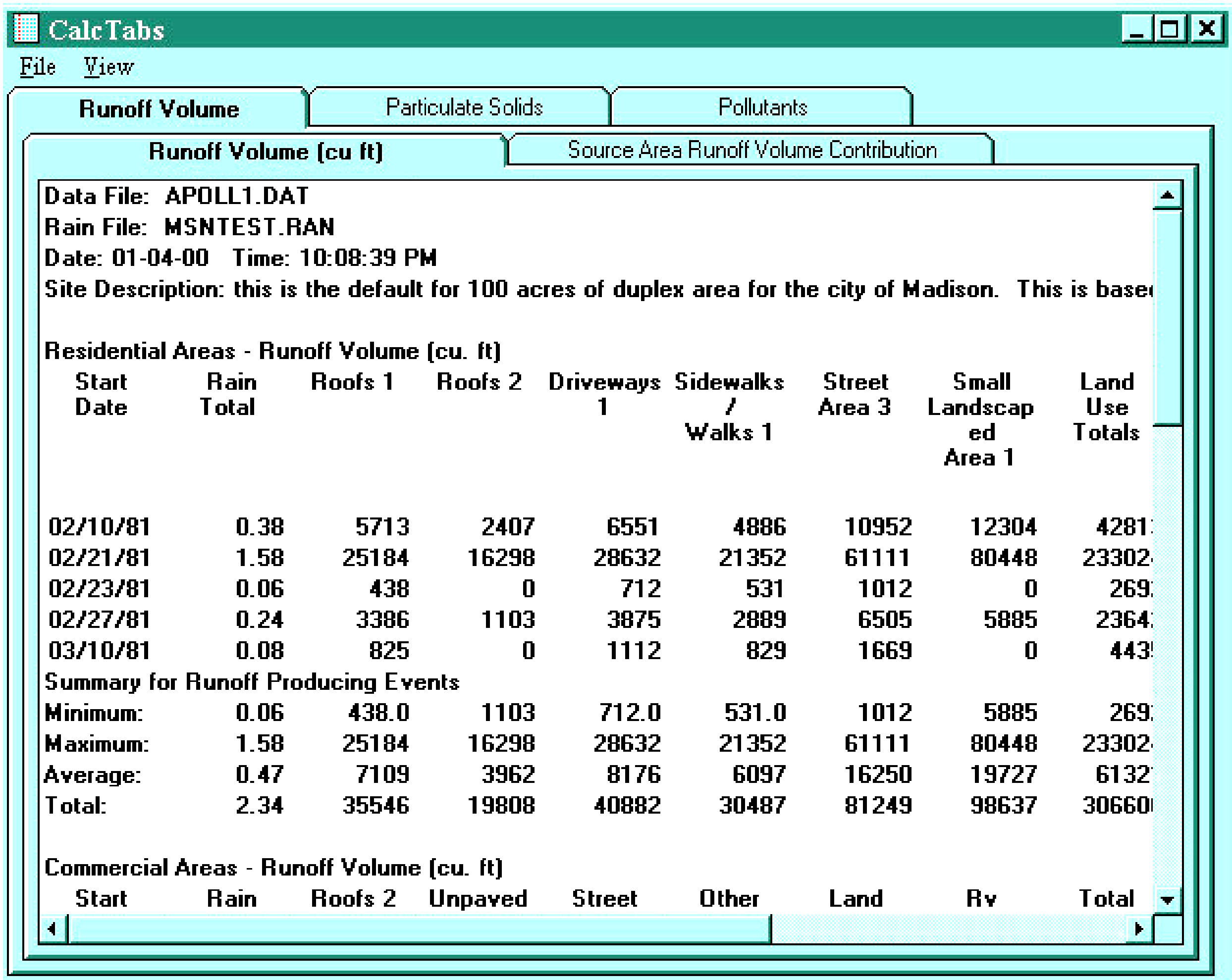
Pollutant Analysis Selection Information
Select “Pollutants” in the “Main Menu” to analyze pollutants in a WinSLAMM model run. It is necessary to enter the name of the pollutant probability distribution file before selecting the pollutants, as the model must examine this file to show which pollutants are available. To enter the name of the pollutant probability distribution file, select the “Current File Data” button.

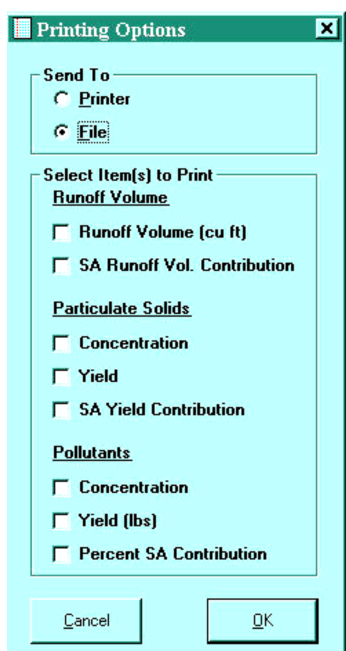
The pollutant selection box lists all of the available pollutants in the pollutant probability distribution file. To select a pollutant for analysis, click on its check box. To remove a checked box, simple click on it again. An example of the “Pollutant Selection” box is shown below, indicating that suspended solids (particulate solids) and particulate forms of copper are to be evaluated. Suspended solids are always evaluated and cannot be removed from the analysis.



Saving the Data File
To save a data file, from the main menu, select “File/Save”. You will be prompted for a file name if you haven’t already entered one. You may change the name of the file by selecting “File/Save As/Current Version”. An example data.DAT file is also included on the distribution disk. This “new mdr.dat” file is a medium density residential land use file.

Creating WinSLAMM Output
To Run a WinSLAMM data.dat model, select the “Windows Calculation Module” menu item to create model output based upon the input data currently loaded in the WinSLAMM interface. You will be asked whether you want to save the input file. If you select “yes”, the standard Windows “Save” dialog box will appear; enter the desired path and file name and press “OK”. The program will then run and create the output in the format selected in the “File / Output Format Options” submenu. A typical calculation tabulation of the output is listed below. The “Print Option” in the file drop down menu item allows the user to select which of the outputs to print. The user must also elect to print the output to either a file, in Comma Separated Value (or .CSV) format, or directly to a printer. The printing options listing is also shown below.


CalcTabs
File View
Runoff Volume
Particulate Solids
Pollutants
Runoff Volume (cu ft)
Source Area Runoff Volume Contribution
Data File: APOLL1.DAT
Rain File: MSNTEST.RAN
Date: 01-04-00 Time: 10:08:39 PM
Site Description: this is the default for 100 acres of duplex area for the city of Madison. This is base
Residential Areas - Runoff Volume (cu. ft)
Start Date | Rain Total | Roofs 1 | Roofs 2 | Driveways 1 | Sidewalks / Walks 1 | Street Area 3 | Small Landscaped Area 1 | Land Use Totals
02/10/81 0.38 5713 2407 6551 4886 10952 12304 4281
02/21/81 1.58 25184 16298 28632 21352 61111 80448 23302
02/23/81 0.06 438 0 712 531 1012 0 269
02/27/81 0.24 3386 1103 3875 2889 6505 5885 2364
03/10/81 0.08 825 0 1112 829 1669 0 443
Summary for Runoff Producing Events
Minimum: 0.06 438.0 1103 712.0 531.0 1012 5885 269
Maximum: 1.58 25184 16298 28632 21352 61111 80448 23302
Average: 0.47 7109 3962 8176 6097 16250 19727 6132
Total: 2.34 35546 19808 40882 30487 81249 98637 30660
Commercial Areas - Runoff Volume (cu. ft)
Start Rain Roofs 2 Unpaved Street Other Land Rv Total


Printing Options
Send To
Printer
File
Select Item(s) to Print
Runoff Volume
Runoff Volume (cu ft)
SA Runoff Vol. Contribution
Particulate Solids
Concentration
Yield
SA Yield Contribution
Pollutants
Concentration
Yield (lbs)
Percent SA Contribution
Cancel
OK

Parameter Module Description

Introduction

The parameter module contains five subprograms that create the parameter files needed to run WinSLAMM. A brief discussion of the subprograms is listed below, and is followed by a detailed description of each subprogram.

1. Rain Data: Creates files listing rainfall depths, durations, and interevent time periods from actual or stochastically generated rainfall data.

2. Runoff Coefficient Data: Creates files containing the data needed to calculate runoff from specific urban source areas.

3. Particle Size Data: Creates files describing the particle size distribution of sediment in urban runoff entering detention ponds.

4. Particulate Solids Concentration Data: Creates files containing the particulate solids concentration data needed by WinSLAMM to predict particulate solids loadings in urban source areas and land uses.

5. Particulate Residue Reduction Data: Creates files that determine the particulate residue loading remaining in curb and gutter delivery systems after a storm event.

6. Pollutant Probability Distribution Data: Creates files describing pollutant (*e.g.* lead, zinc, etc.) concentrations from WinSLAMM source areas and land uses.

Rain Input Subprogram

Both WinSLAMM and WinDETPOND need rain depths, rain durations, and interevent time periods to calculate runoff volume and pollutant loadings. The rain input parameter subprogram records this rain information in a format the models can use. This information can be recorded from rainfall records or generated stochastically from rainfall statistics. Both forms of this data are discussed below.

There are eleven options in the rain input Module menu. They are listed in Table C-8.

Table C-8. Rain Input Module Menu

1. Create a Rain File
2. Review or edit a rain file
3. Print a rain file
4. Save a rain file with duration calculations
5. View rain file input instruction
6. Create a generated rain file
7. Calculate the Depth-Duration Rank Correlation
8. Create a Rainfile from Standard Format Data
9. Create a Rainfile from Standard Format Data with
   Duration and Rainfall Erosive Capacity Data
10. Create a Rainfile from Data Base Formatted Data
11. Leave Rain input Program

Select options 1, 2, or 3 to create, edit, and print a rain file containing rainfall data from recorded rainfall records. The only rain information needed by WinSLAMM is the starting and ending times of each rain and the total rain depth (in inches) of each rain. A rain file therefore consists of rainfall starting and ending dates and times, and rainfall depths. Hourly rainfall data is available from National Oceanic and Atmospheric Administration records. However, the rainfall data must be in the format described below. It will be necessary to examine the hourly rain data and determine the beginning and ending times of each rain event. It is conventional to select 6 hours of no rain as the separating time between adjacent rains for most urban areas.

Rainfall date and time.
The dates must be in the form MM/DD/YY or MM.DD.YY. A date entered as 1/4/88 is unacceptable; it must be entered as 01/04/88. Time must be in the form HH:MM or HH.MM. A time entered as 6:30 is unacceptable; it must be entered as 06:30. Time is entered in 24 hour increments, so afternoon or evening times must be entered as, for example, 18:15, not 06:15. The data entry process in this subprogram is designed to speed data input, and is described below. The process applies to both creating a new rain file and editing an existing file. When editing a file, if an entry is correct, press ENTER; and the existing value will remain unchanged. An analysis cannot currently contain rains from 1999 to 2000. If all the rains selected for analysis are before 2000, or all are after 2000, then there is no problem.

Entering Date and Time Information (Shortcut method):

- Before entering rainfall data, enter the number of distinct rainfall events.
- Before entering rainfall data, enter the last two digits of the year of the first rainfall. For example, type "89" for 1989.
- Enter the beginning date of the rainfall by entering two digits for the month and two digits for the day. Do not separate the two sets of digits with another character or a space.
- Enter the beginning time of the rainfall by entering two digits for the hour. If the rainfall started on the hour, press ENTER. If not, also enter two digits for the minutes. Do not separate the two sets of digits with another character or a space.
- Enter the ending date of the rainfall, if the date is different from the starting date, by entering two digits for the month and two digits for the day. If the ending date is the same as the starting date, press ENTER. Do not separate the two sets of digits with another character or a space. If the ending year is different that the starting year, enter the month, the day, and the new year in the following format: MMDDYY.
- Enter the ending time of the rainfall by entering two digits for the hour. If the rainfall started on the hour, press ENTER. If not, also enter two digits for the minutes.

Entering Rainfall Depth information:
The rain depth must be entered in units of hundredths of inches. For example, if the rainfall depth was 0.09 inches, enter "9." If the rainfall depth was 1.25 inches, enter "125." Rain files created with this module will have the extension ".RAN."

Select option 4 to export rain depths, durations, and times between rains to a file in a comma separated value data format. This option has been provided so that these values can be exported to a spreadsheet to calculate mean rain depths, mean durations, and mean interevent periods that may be used to generate rain events statistically. The format of this export file is listed later. It has the extension ".RES."

Option 5 is a help screen. It lists the data input and editing shortcuts available for entering the rain data. The help screen is listed in Table C-9.

Table C-9. Rainfall Input and Edit Help Screen

1. In the create rain file option, to avoid entering the year each time you enter a date, type before entering any data the last two digits of the year (*e.g.*, 89 for 1989) as a beginning rain data. Press ENTER and then enter all dates with just the month and the date.
2. Do not use "/" (slash) marks when entering dates. Use "0506" or "050689" for 05/06/89.
3. If the times have no minutes, do not add ":00" when entering a time. Enter the two hour digits only.
4. If the ending date is the same as the beginning date, press ENTER.
5. In the create rain file option, enter integers for rain depths. The program will change them to hundredths of an inch.
6. When editing a rain file, if a part of a data line is correct, press ENTER. The current value will be retained.

Select option 6 to create a stochastically generated rain file. This set of subroutines creates rain depths, rain durations, and interevent periods by assuming that the distribution of these parameters closely matches an exponential probability distribution. This assumption is reasonably valid for the small and medium sized rain events (Voorhees 1989) that cause most of the urban nonpoint source pollution problems (Pitt 1987). The rainfall duration can be modeled using either the exponential probability distribution or the gamma probability distribution. The output from this option can be entered into SLAMM or DETPOND as a rain file. To create a stochastically generated rain file, enter the information listed in Table C-10.

Table C-10. Information Needed to Create a Stochastically Generated Rain File

1. Generator data file name.
2. Mean rain depth (inches).
3. Minimum recorded rain depth (inches). This is zero unless there is a lower limit (arbitrary or established by data limitations) in the rainfall data.
4. Mean rain duration (hours). Also enter the duration variance to model the duration using the gamma distribution.
5. Mean time between rains (hours).
6. Minimum time between rains (hours; must be an integer). For example, if an interevent period is defined as being greater than three hours, enter 3.
7. Number of events to be generated.
8. Seed. This value initializes the random number generator. Select "0" to use a random seed taken from the computer's internal clock.
9. Enter the rank correlation coefficient for the rainfall depths and rainfall durations in the data. The rank correlation is found by ranking the depths and durations of the data and calculating the correlation of the ranks. Option 7 in this module will calculate this.
10. Rain file start date. The date must be in the form “MM/DD/YY.”
11. Number of years of rainfall data. This value is altered by changing the mean time between rains, mean rain duration, or the number of events to be generated.

Option 7 is a two variable Spearman Rank Correlation program. It will calculate both the correlation coefficient (r) and the Spearman rank correlation coefficient for two variables. The data must be in one of three formats that are described later. The output from this option includes the file rain depth, duration, and interevent period averages and maximum values. The output is sent to a file with the extension “COR.”

Option 8 is a subroutine that converts hourly rain data into a WinSLAMM rainfall file. The standard format with hourly data is in a comma separated value ASCII file. Each row in the file represents one day of rainfall data. The first value in each row is the date, in the form MM/DD/YY. The next twenty-four values in each row, each separated by a comma, represent hourly rainfall data. Zero rainfall values are acceptable. The user must also enter the minimum number of hours between rains and the minimum rainfall depth to define a rainfall event.

Option 9 evaluates the erosion potential of different rains through an energy equation that evaluates the erosive power of each rainfall event. This option was included in the parameter module to evaluate the usefulness of the energy algorithm; WinSLAMM currently does not use the information.

Option 10 is another subroutine that converts hourly rain data into a WinSLAMM rainfall file. The database file format is also a comma separated value file with three columns. The first column is the date in the form MM/DD/YY. The second column is the time, in hours, in the form 0100 for 1:00 AM, 1300 for 1:00 PM, and so on. The subroutine ignores any 2500 values that are often used to summarize the daily rainfall totals. The third column is the rainfall for the hour. The user must also enter the minimum number of hours between rains and the minimum rainfall depth to define a rainfall event.

Description of Selected Rainfiles Included With The Program

• BHAM76.RAN file contains all of the rains from 1976, as recorded at the Birmingham, AL, airport. The BHAM76.RAN file was selected to represent a typical Birmingham rain year.

• BHAM77 through BHAM88 rain files for other recent rain years as recorded at the Birmingham, AL, airport.

• BHAMFLOD.RAN contains all of the drainage design storms, having reoccurrence frequencies from one to 100 years, with rain durations from 0.5 to 24 hours for the Jefferson County, Alabama area. The rain dates are arbitrary (all dated for 1990) and are spaced about 1/2 week apart to minimize inter-event interference, especially for evaluating wet detention ponds.

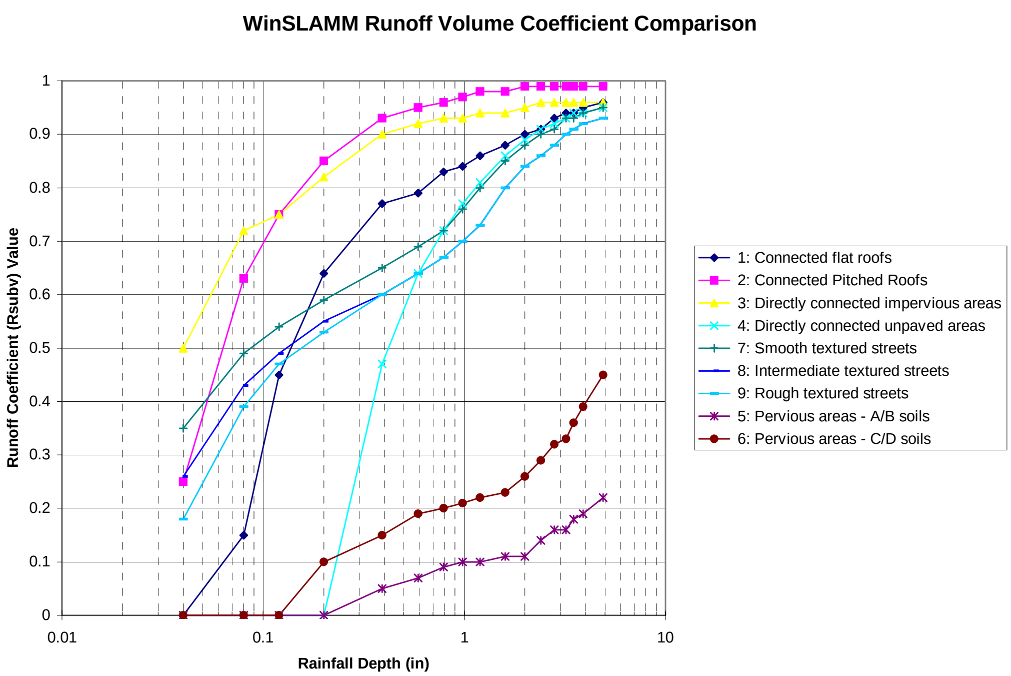
• RAIN81.RAN and RAIN83.RAN contain all of the 1981 and 1983 rains observed at the Milwaukee Nationwide Urban Runoff Project (NURP) sampling locations. These files were used for the verification of the runoff volume and pollutant discharges using the observed NURP data. MILWFLOD.RAN contains drainage design storms for Milwaukee. RAIN88.RAN represents the 1988 rain year for Madison, Wisconsin.

Runoff Coefficient Subprogram

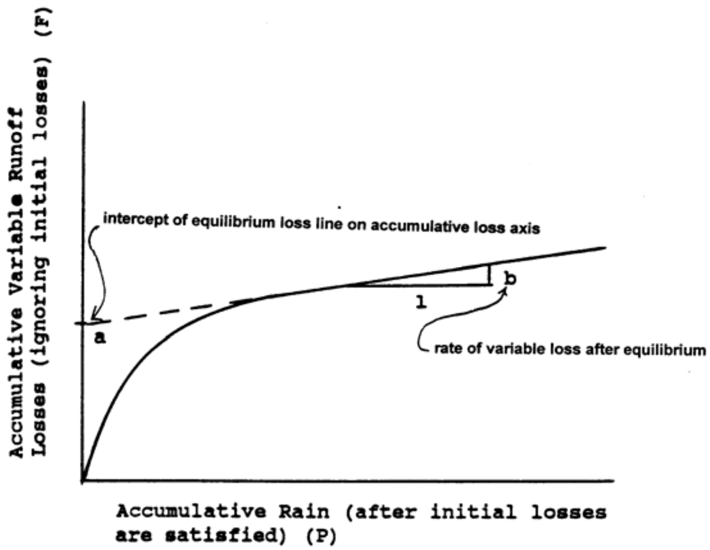
Runoff volume generation in WinSLAMM is accomplished with an RSV file. The included runoff.RSV file, named RUNOFF.RSV has undergone extensive calibration and verification and should not be destroyed. The runoff coefficients were calculated using general impervious and pervious area models. These models were then calibrated based on extensive Toronto data and were then verified using additional independent Toronto data, along with numerous Milwaukee and Madison data for a wide variety of land development and rain conditions. However, WinSLAMM was designed to allow the use of alternative runoff models, as desired. Alternative runoff coefficients for each source area type can be calculated using other models and saved as a different runoff.RSV file name.

Runoff coefficients, when multiplied by rain depths, land use source areas, and a conversion factor, determine the runoff volumes needed by SLAMM. The runoff coefficient subprogram creates the runoff coefficient file used in SLAMM and DETPOND. All runoff coefficient files have the extension ".RSV." Coefficients are required for nine area types which are listed in Table C-11. Each area type requires a value for the 17 different rainfall depths listed in Table C-12. The runoff coefficients are further reduced when the runoff from the areas drain across soils instead of being directly connected to the storm drainage system. These reduction factors are expressed as drainage efficiency factors (DEF). Table C-13 lists the drainage efficiency factors. Disconnected paved area runoff coefficients in low density areas are similar to the runoff coefficients for the landscaped areas. All coefficient values must be less than 1.0.

The RUNOFF.RSV file contains the verified runoff coefficients, based on the small storm hydrology model. A typical runoff coefficient file is plotted below.



These data fit the general infiltration rate model developed by Pitt (1987) as follows:



$F = bP + a(1 - e^{-gP})$

where F = accumulative variable losses

g = exponential coefficient

P = accumulated rainfall

If b = 0, then a = total losses and no steady state losses occur (equivalent to SCS model)

Note: time since runoff started is not a factor (as implied by most users of Horton equation).

This figure plots cumulative variable runoff losses (F, inches or mm), ignoring the initial losses, versus cumulative rain (P, inches or mm), after runoff begins. The slope of this line is the instantaneous variable runoff loss (infiltration) occurring at a specific rain depth after runoff starts. A simple nonlinear model can be used to describe this relationship which is similar to many other infiltration models. For a constant rain intensity (i), total rain depth since the start of runoff (P), equals intensity times the time since the start of runoff (t). The small storm hydrology nonlinear model for this variable runoff loss (F) is therefore:

$$F = bit + a(1 - e^{-git}) \quad \text{or} \quad F = bP + a(1 - e^{-gP})$$

Three basic model parameters were used to define the model behavior, in addition to initial runoff losses and rain depth: “a”, the intercept of the equilibrium loss line on the cumulative variable loss axis; “b”, the rate of the variable losses after equilibrium; and “g”, an exponential coefficient. If variable losses are zero at equilibrium, then “b” would be zero. Because this plot does not consider initial runoff losses, the variable loss line must pass through the origin. This model reduces to the SCS model when the “b” value is zero and “a” is S’, and when Ia is 0.16 (80% of 0.2) of “a”. This general model also reduces to the Horton equation when cumulative rain depth since the start of the event is used instead of just time since the start of rain. Observed runoff data from both small- and large-scale tests were fitted to this equation to determine the values for a, b, and g for observed i and t (or P), and F values. In addition, outfall runoff observations from many different heterogeneous land uses were used to verify the calibrated model (Pitt 1987). Below is a table showing the relationship between this model and the SCS and Horton parameters:

Curve Number	Fitted g from hypo-thesized model	SCS S' Value (ignores Ia) (mm)[1]	Initial Horton Infiltration Rate (Fo) (mm/hr)[2]	Horton Equation Decay Coefficient (k)[3] (1/hr)
99	0.22	2.03	0.45i	0.22i
95	0.042	10.7	0.45i	0.042i
90	0.022	22.6	0.50i	0.022i
85	0.016	35.8	0.57i	0.016i
80	0.012	50.8	0.61i	0.012i
75	0.010	67.8	0.67i	0.010i
70	0.0081	87.4	0.71i	0.0081i
60	0.0057	136	0.78i	0.0057i
50	0.0041	203	0.83i	0.0041i
40	0.0029	305	0.88i	0.0029i

(1) S' = 0.8S assumed by SCS. S' also equals a.
(2) Fo = S'gi, where i equals rain intensity (mm/hr).

Note: The SCS curve number procedure assumes that the final infil tration rate (Fc) is zero.

(3) K = gi, or Fo/S'

Table C-11. Runoff Coefficient Area Types

1. Connected flat roofs
2. Connected pitched roofs
3. Directly connected impervious areas
4. Directly connected unpaved areas
5. Pervious area - sandy (A/B) soils
6. Pervious area - clayey (C/D) soils
7. Smooth textured streets
8. Intermediate textured streets
9. Rough textured streets

Table C-12. Rain Depths Needed for Each Area Type

in:	0.04	0.08	0.12	0.20	0.39	0.59	0.79	0.98	1.2
mm:	1	2	3	5	10	15	20	25	30
in:	1.6	2.0	2.4	2.8	3.2	3.5	3.9	4.9	
mm:	40	50	60	70	80	90	100	125	

Table C-13. Drainage Efficiency Factors

1. w/o alleys, medium to high density land use
2. w/ alleys, medium to high density land use
3. strip commercial and shopping center land use

Critical Particle Size Subprogram

The particle size distribution option prepares files containing the runoff particle size distribution for wet detention pond analyses. This information describes the size distribution of urban runoff particulates that enter a detention pond. These files have the extension ".CPZ." The particle size range is from 0 to 2000 microns.

To create a particle size file, enter the percentage of the particles in the runoff that are greater than the corresponding particle size for each particle size. The program will scroll from a particle size of 1 micron to a particle size of 2000 microns. The program will beep if a percentage value greater than the previous value is entered. Correct the error with the file-editor option.

Table C-14 lists the particle sizes needed for a distribution. By definition, 100% of the particles are greater than 0 micrometers (μm) in size, and 0% of the particles are greater than 2000 μm. Data for each size can be easily determined from a standard particle size distribution plot developed from laboratory settling column tests or particle size analyses.

Table C-14. Critical Particle Sizes for Detention Pond Analysis (μm)

0	6	12	30	100	1000
1	7	13	35	150	2000
2	8	14	40	200	
3	9	15	50	300	
4	10	20	60	500	
5	11	25	80	800	

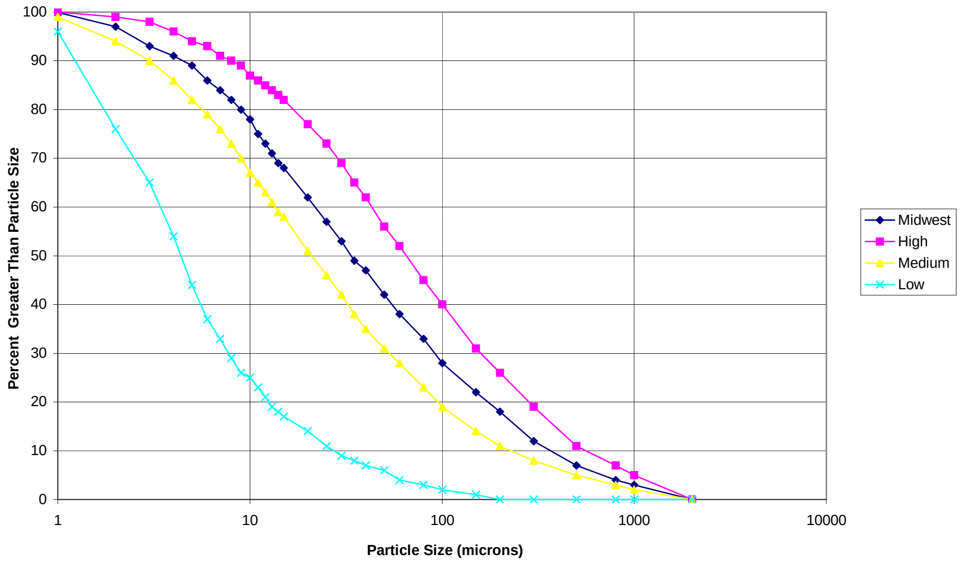
Description of Selected Critical Particle Size Files Included With The Program

The example size.CPZ files for wet detention analysis included in the disk were constructed using extensive urban runoff particle size data. However, these different size.CPZ files result in a wide range of potential wet detention pond performance (suspended solids percentage reduction) measurements. The particle size distributions for various source areas where wet detention ponds may be used can be expected to also vary widely. These size.CPZ files should therefore be used with caution, but they are expected to generally bracket particle size distributions in stormwater.

- LOW.CPZ is a particle size distribution corresponding to an urban runoff flow containing low concentrations of particulate residue (such as for roof runoff).
- MEDIUM.CPZ is a particle size distribution file for runoff containing "medium" particulate residue concentrations (such as for outfall locations).
- HIGH.CPZ is a particle size distribution file for runoff containing high concentrations of particulate residue (such as for construction sites).
- NURP.CPZ is an average of the available outfall particle size distribution data for all of the NURP projects.
- MIDWEST.CPZ summarizes the upper Midwest and Toronto outfall particle size data.

Below is a plot of the data in each of these files.

Particle Size Distribution File Comparison



Particulate Solids Concentration Module

Particulate solids concentration values, when multiplied by source area runoff volumes and a conversion factor, calculate particulate solids loadings (lbs) in WinSLAMM. The particulate solids concentration subprogram creates the particulate solids concentration file used in WinSLAMM. All particulate solids concentration files have the extension ".PSC." Concentrations are required for thirteen area types in six land uses in WinSLAMM. These are listed in Table C-15. Street areas are not included because WinSLAMM calculates street source area washoff directly. Each area type requires a value for the 14 different rain depths listed in Table C-16.

Table C-15. SLAMM Land Uses And Source Areas Listed In The Particulate Solids Concentration Subprogram

Land Uses:	Residential	Institutional
	Commercial	Industrial
	Open Spaces	Freeways

Source Areas:

Roofs	Undeveloped Areas
Paved Parking/Storage	Small Landscaped Areas
Unpaved Parking/Storage	Large Turf Areas
Playgrounds	Other Pervious Areas
Driveways	Other Impervious Areas
Sidewalks/Walks	Freeway Lanes/Shoulders
Large Landscaped Areas	

Table C-16. Rain Depths Listed In The Particulate Solids Concentration Subprogram

in:	0.04	0.08	0.12	0.20	0.39	0.59	0.79	0.98	1.2
mm:	1	2	3	5	10	15	20	25	30
in:	1.6	2.0	2.4	2.8	3.2				
mm:	40	50	60	70	80				

The distribution disk contains a particulate residue (suspended solids) description file, MADISON.PSC. This file contains the summary of the calibrated and verified runoff particle solids concentration conditions found during Madison, Toronto, Birmingham and Milwaukee urban runoff research.

Particulate Residue Reduction Subprogram

SLAMM uses the particulate residue reduction subprogram to create parameter files that describe the fraction of total particulates that remains in the drainage system (curbs and gutters, grass swales, and storm drainage) after rain events end due to deposition. The reduction of particulate residue at the outfall due to the delivery system is a function of the type of drainage system and rainfall depth. SLAMM calculates this deposition effect for three different drainage systems, based on the condition of the curb and gutter. The three drainage delivery systems are:

1. Grass swales
2. Undeveloped roadside
3. Curb and gutters, “valleys,” or sealed swales

The three condition options for curbs and gutters are:

1. Poor condition (or very flat)
2. Fair condition
3. Good condition (or very steep)

To create a particulate residue delivery reduction parameter file, enter the particulate residue reduction fraction for each of the drainage delivery types and, for curb and gutter system, conditions, described above. Enter a fractional value for each rainfall depth listed in Table C-16. To edit a file, select a delivery system type, and condition option for curb and gutter systems, and the rain number. Enter the new fractional value at the prompt after entering the rain number. Particulate residue reduction parameter files have the extension “.PRR.”

Pollutant Probability Distribution Subprogram

Data from a pollutant value file determine, when multiplied by either a source area runoff volume or source area particulate loading, the pollutant loading from a source area. This subprogram creates files that describe pollutant concentrations or loadings that are from source areas and land uses used in SLAMM. This data is generally based upon pollutant loading and concentration source area and land use data collected from the study area or region. For example, particulate phosphate source data, in units of milligrams of phosphate per kilogram of suspended solids loading in the runoff, must be entered for each source area and land use of concern. The land uses and source areas are described in Table C-17.

To enter pollutant data in a new file, select the pollutant of concern from the “Pollutant Concentration Relative Values” menu. Then enter the geometric mean relative concentration value and the coefficient of variation of the selected pollutant for each source area and land use. To edit an existing pollutant parameter file, the user may either edit pollutant values for an entire source area, edit only a specified land use-source area pollutant value, or enter a multiplier factor for the mean pollutant value and coefficient of variation value of each of the source areas in a land use.

Table C-17. SLAMM Land Uses and Source Areas Listed in the Pollutant Probability Distribution Subprogram

Land Uses:

Residential	Institutional	Commercial
Industrial	Open Spaces	Freeways

Source Areas:

Roofs	Undeveloped Areas
Paved Parking/Storage	Small Landscaped Areas
Unpaved Parking/Storage	Other Pervious Areas

Playgrounds	Other Impervious Areas
Driveways	Freeway Lanes/Shoulders
Sidewalks/Walks	Large Turf Areas
Street Areas	Large Landscaped Areas

The MADISON7.PPD file contains the filterable residue (dissolved solids) concentrations for each source area and for several pollutants. This file also contains COV values needed for the Monte Carlo evaluations. Table C-18 shows the complete listing of pollutants available in SLAMM. In addition, the user may define up to six other pollutants in both particulate and filterable forms.

Table C-18. Pollutants Available in SLAMM

Particulate Forms	Filterable Forms
Particulate Solids (kg/kg) (1)	Filterable Solids (mg/L)
Phosphorus (mg/kg)	Phosphate (mg/L)
	Nitrates (mg/L)
	Ammonia (mg/L)
Total Kjeldahl Nitrogen (mg/kg)	Total Kjeldahl Nitrogen (mg/L)
Chemical Oxygen Demand (mg/kg)	Chemical Oxygen Demand (mg/L)
Chromium (micrograms/kg)	Chromium (micrograms/L)
Copper (micrograms/kg)	Copper (micrograms/L)
Lead (micrograms/kg)	Lead (micrograms/L)
Zinc (micrograms/kg)	Zinc (micrograms/L)
	Fecal Coliform Bacteria (#/100 ml) (2)
Other pollutant #1	Other pollutant #1
Other pollutant #2	Other pollutant #2
Other pollutant #3	Other pollutant #3
Other pollutant #4	Other pollutant #4
Other pollutant #5	Other pollutant #5
Other pollutant #6	Other pollutant #6

(1) The particulate solids (suspended solids) data is obtained in the Particulate Solids Concentration subprogram described below.

(2) Fecal Coliform are retained on 0.45 micrometer filters, but generally behave like filterable pollutants in most urban runoff control practices.

Table C-19. Units Available for Other Pollutants

Particulate Pollutant Units	Filterable Pollutant Units
1. nanograms/kg	1. nanograms/L (ng/L)
2. micrograms/kg	2. micrograms/L (μg/L)
3. milligrams /kg	3. milligrams /L (mg/L)
	4. #/100 ml (# ==> bacteria count)

To enter pollutants that are not listed in Table C-18, select pollutants 11 -16 (Other particulate pollutants) or pollutants 27 - 32 (Other filterable pollutants). Enter the name of the pollutant and the units of the pollutant. Table C-19 lists the available units. Apply the same procedures used to enter pollutants listed in Table C-18 when entering "Other Pollutant" values. Table C-20 is a blank coding form to organize the pollutant values.

Table C-20. Blank Coding Form for Pollutant Probability Concentration File

Pollutant Probability Relative Concentration File (file.ppd)												
File name:												
Pollutant:												
filterable form (mg/L for COD, ug/L for nutrients and metals, and #/100 mL for bacteria)												
	Residential		Institutional		Commercial		Industrial		Open Space		Freeways	
	mean	COV	mean	COV	mean	COV	mean	COV	mean	COV	mean	COV
1. Roofs											n/a	n/a
2. Paved parking/storage											n/a	n/a
3. Unpaved parking/storage											n/a	n/a
4. Paved playground											n/a	n/a
5. Paved driveways											n/a	n/a
6. Paved walks											n/a	n/a
7. Paved streets											n/a	n/a
8. Large landscaped areas											n/a	n/a
9. Undeveloped areas											n/a	n/a
10. Small landscaped areas											n/a	n/a
11. Isolated areas	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
12. Other pervious areas												
13. Other directly connected impervious areas												
14. Other partially connected impervious areas												
15. Paved freeway lane and shoulder areas	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a		
16. Large turf areas												
particulate form (mg/kg)	Residential		Institutional		Commercial		Industrial		Open Space		Freeways	
	mean	COV	mean	COV	mean	COV	mean	COV	mean	COV	mean	COV
1. Roofs											n/a	n/a
2. Paved parking/storage											n/a	n/a
3. Unpaved parking/storage											n/a	n/a
4. Paved playground											n/a	n/a
5. Paved driveways											n/a	n/a
6. Paved walks											n/a	n/a
7. Paved streets											n/a	n/a
8. Large landscaped areas											n/a	n/a
9. Undeveloped areas											n/a	n/a
10. Small landscaped areas											n/a	n/a
11. Isolated areas	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
12. Other pervious areas												
13. Other directly connected impervious areas												
14. Other partially connected impervious areas												
15. Paved freeway lane and shoulder areas	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a		
16. Large turf areas												

Example Input and Output Files

Printouts of the following example WinSLAMM files described below are presented in this section:

- NEWRES.DAT. This is an example input file summarizing the characteristics of the area to be simulated. This file shows the areas for each source area, along with the associated "parameter" files also used. The rain simulation period examined, plus the source area and outfall controls are also shown.

- BHAM76.RAN. This is the 1976 rain file for Birmingham, AL. It contains 112 rains, although the example output file only includes a simulation for January. This file shows the beginning and end dates and times of the individual rains, plus the rainfall depth, the rainfall duration, the average rainfall intensity, and the interevent duration between the end of the indicated event and the following event.

- RUNOFF.RSV. This is the general runoff coefficient description file. The file is set up as a table of varying volumetric runoff coefficients for different rains and source areas.

- BHAM.PSC. This is the suspended solids concentration file showing changes in SS concentrations for different rains and source areas (except for streets and freeway lanes which area calculated internally by WINSLAMM).

- DELIVERY.PRR. This is the suspended solids "delivery" file reflecting the SS fractions that are trapped in the surface drainage system (swales and curbs) and in the sewerage. These values are quite large for small rains where sufficient energy is available to dislodge particulates from paved surfaces, but is insufficient to transport the solids to the outfall.

- MEDIUM.CPZ. This is an example particle size file needed if wet detention ponds are included in the simulation. None are used in this example.

- POLL.POL. This is the pollutant relative concentration file that describes the sheetflow concentrations of pollutants (other than suspended solids). Both particulate fractions (usually in mg/kg of SS) and filtered concentrations (usually in mg/L) are given for each source area and land use.

- NEWRES.OUT. This file is an example WINSLAMM output file for the above NEWRES.DAT input file and the associated parameter files. Summary tables are shown for runoff volume and suspended solids.

```
Data file name:  E:\slamm803\Newres.dat                      SLAMM Version V8.0
    Rain file name:  E:\SLAMM803\BHAM76.RAN                      Particulate Solids Concentration file name:  E:\SLAMM803\BHAM.PSC
    Runoff Coefficient file name:  E:\SLAMM803\RUNOFF.RSV        Particulate Residue Delivery file name:  E:\SLAMM803\DELIVERY.PRR
    Pollutant Relative Concentration file name:  E:\SLAMM803\POLL.PPD
                                                                 Seed for random number generator:   5
    Study period starting date:  01/02/76                        Study period ending date:  01/31/76
    Date:  03-08-1999                                            Time:  20:30:40
    Fraction of each type of Drainage System serving study area:
      1. Grass Swales 0
      2. Undeveloped roadside 0
          Curb and Gutters, `valleys', or sealed swales in:
           3. Poor condition (or very flat) 0
           4. Fair condition 1
           5. Good condition (or very steep) 0
    Site information:  MEDIUM DENSITY RESIDENTIAL 1961-1980, CURBS AND GUTTERS, CLAYEY SOILS, BASELINE CONTROLS (NONE)
```

Source Area	Residential Areas	Institutional Areas	Commercial Areas	Industrial Areas	Open Spaces Areas
	|<===== Areas for each Source (acres) =====>|				
Roofs 1	2.60	0.00	0.00	0.00	0.00
Roofs 2	6.05	0.00	0.00	0.00	0.00
Roofs 3	0.00	0.00	0.00	0.00	0.00
Roofs 4	0.00	0.00	0.00	0.00	0.00
Roofs 5	0.00	0.00	0.00	0.00	0.00
Paved Parking/Storage 1	0.00	0.00	0.00	0.00	0.00
Paved Parking/Storage 2	0.00	0.00	0.00	0.00	0.00
Paved Parking/Storage 3	0.00	0.00	0.00	0.00	0.00
Unpaved Prkng/Storage 1	0.00	0.00	0.00	0.00	0.00
Unpaved Prkng/Storage 2	0.00	0.00	0.00	0.00	0.00
Playground 1	0.00	0.00	0.00	0.00	0.00
Playground 2	0.00	0.00	0.00	0.00	0.00
Driveways 1	1.19	0.00	0.00	0.00	0.00
Driveways 2	1.18	0.00	0.00	0.00	0.00
Driveways 3	0.00	0.00	0.00	0.00	0.00
Sidewalks/Walks 1	0.00	0.00	0.00	0.00	0.00
Sidewalks/Walks 2	0.00	0.00	0.00	0.00	0.00
Street Area 1	6.58	0.00	0.00	0.00	0.00
Street Area 2	0.65	0.00	0.00	0.00	0.00
Street Area 3	0.00	0.00	0.00	0.00	0.00
Large Landscaped Area 1	0.00	0.00	0.00	0.00	0.00
Large Landscaped Area 2	0.00	0.00	0.00	0.00	0.00
Undeveloped Area	4.59	0.00	0.00	0.00	0.00
Small Landscaped Area 1	50.94	0.00	0.00	0.00	0.00
Small Landscaped Area 2	26.22	0.00	0.00	0.00	0.00
Small Landscaped Area 3	0.00	0.00	0.00	0.00	0.00
Isolated Area	0.00	0.00	0.00	0.00	0.00
Other Pervious Area	0.00	0.00	0.00	0.00	0.00
Other Dir Cnctd Imp Area	0.00	0.00	0.00	0.00	0.00
Other Part Cnctd Imp Area	0.00	0.00	0.00	0.00	0.00
	--------	--------	--------	--------	--------
Total	100.00	0.00	0.00	0.00	0.00

Freeway Source Area	Area (acres)
Pavd Lane & Shldr Area 1	0.00
Pavd Lane & Shldr Area 2	0.00
Pavd Lane & Shldr Area 3	0.00
Pavd Lane & Shldr Area 4	0.00
Pavd Lane & Shldr Area 5	0.00
Large Turf Areas	0.00
Undeveloped Areas	0.00
Other Pervious Areas	0.00
Other Directly Conctd Imp	0.00
Other Partially Conctd Imp	0.00

Total	0.00

Total of All Source Areas 100.00

Total of All Source Areas
less All Isolated Areas 100.00

Source Area Control Practice Information

Land Use: Residential
- Roofs 1 Source area number: 1
  - The roof is pitched
  - The Source Area is directly connected or draining to a directly conntected area
- Roofs 2 Source area number: 2
  - The roof is pitched
  - The Source Area is draining to a pervious area (partially connected impervious area)
  - The SCS Hydrologic Soil Type is Clayey
  - The building density is medium or high
  - Alleys are not present
- Driveways 1 Source area number: 13
  - The Source Area is directly connected or draining to a directly conntected area
- Driveways 2 Source area number: 14
  - The Source Area is draining to a pervious area (partially connected impervious area)

```
         The SCS Hydrologic Soil Type is Clayey
         The building density is medium or high
         Alleys are not present
   Street Area 1    Source area number:  18
            1. Street Texture:  intermediate
            2. Total study area street length (curb-miles):  2.73
            3. Initial Street Dirt Loading (lbs/curb-mi):  default value
            4. Street Dirt Accumulation:
                  Default value used
   Street Area 2    Source area number:  19
            1. Street Texture:  rough
            2. Total study area street length (curb-miles):  0.27
            3. Initial Street Dirt Loading (lbs/curb-mi):  default value
            4. Street Dirt Accumulation:
                  Default value used
   Undeveloped Area    Source area number:  23
         The SCS Hydrologic Soil Type is Clayey
   Small Landscaped Area 1    Source area number:  24
         The SCS Hydrologic Soil Type is Clayey
   Small Landscaped Area 2    Source area number:  25
         The SCS Hydrologic Soil Type is Clayey

Pollutants to be Analyzed and Printed:
         Pollutant Name               Pollutant Type
         --------------               --------------
          Solids                      Particulate
          Chemical Oxygen Demand
```

Rain File name: bham76.RAN
Printout Date: 03-08-1999

Rain Number	Beginning Rain Date	Beginning Rain Time	Ending Rain Date	Ending Rain Time	Rainfall Depth (in)	Rainfall Duration (days)	Intensity (in/hr)	Interevent Duration (days)
1	01/02/76	22:00	01/03/76	07:00	0.46	0.3750	0.0511	3.7917
2	01/07/76	02:00	01/08/76	13:00	0.58	1.4583	0.0166	2.8333
3	01/11/76	09:00	01/11/76	21:00	0.25	0.5000	0.0208	1.1667
4	01/13/76	01:00	01/13/76	03:00	0.03	0.0833	0.0150	0.2500
5	01/13/76	09:00	01/13/76	21:00	0.39	0.5000	0.0325	2.8333
6	01/16/76	17:00	01/17/76	03:00	0.01	0.4167	0.0010	3.2083
7	01/20/76	08:00	01/20/76	14:00	0.05	0.2500	0.0083	3.7500
8	01/24/76	08:00	01/24/76	19:00	0.03	0.4583	0.0027	0.7083
9	01/25/76	12:00	01/26/76	22:00	2.33	1.4167	0.0685	5.4167
10	02/01/76	08:00	02/01/76	10:00	0.01	0.0833	0.0050	0.3333
11	02/01/76	18:00	02/01/76	20:00	0.01	0.0833	0.0050	3.5417
12	02/05/76	09:00	02/06/76	10:00	0.51	1.0417	0.0204	4.8750
13	02/11/76	07:00	02/11/76	18:00	0.01	0.4583	0.0009	6.0000
14	02/17/76	18:00	02/17/76	19:00	0.01	0.0417	0.0100	0.3750
15	02/18/76	04:00	02/18/76	12:00	0.67	0.3333	0.0837	3.0833
16	02/21/76	14:00	02/21/76	23:00	0.61	0.3750	0.0678	0.5000
17	02/22/76	11:00	02/22/76	14:00	0.01	0.1250	0.0033	12.0000
18	03/05/76	14:00	03/06/76	15:00	0.85	1.0417	0.0340	1.5417
19	03/08/76	04:00	03/08/76	08:00	0.01	0.1667	0.0025	0.4583
20	03/08/76	19:00	03/09/76	14:00	1.02	0.7917	0.0537	0.2500
21	03/09/76	20:00	03/09/76	23:00	0.01	0.1250	0.0033	2.2917
22	03/12/76	06:00	03/12/76	23:00	1.48	0.7083	0.0871	0.6250
23	03/13/76	14:00	03/13/76	15:00	0.01	0.0417	0.0100	0.5000
24	03/14/76	03:00	03/14/76	13:00	0.01	0.4167	0.0010	0.5000
25	03/15/76	01:00	03/16/76	12:00	3.64	1.4583	0.1040	3.7083
26	03/20/76	05:00	03/20/76	13:00	0.04	0.3333	0.0050	0.2500
27	03/20/76	19:00	03/21/76	05:00	1.14	0.4167	0.1140	3.5417
28	03/24/76	18:00	03/25/76	09:00	0.04	0.6250	0.0027	0.9167
29	03/26/76	07:00	03/27/76	06:00	1.54	0.9583	0.0670	2.4167
30	03/29/76	16:00	03/30/76	04:00	2.20	0.5000	0.1833	0.3333
31	03/30/76	12:00	03/31/76	15:00	2.08	1.1250	0.0770	3.8333
32	04/04/76	11:00	04/04/76	12:00	0.01	0.0417	0.0100	7.3333
33	04/11/76	20:00	04/11/76	25:00	0.21	0.2083	0.0420	1.9167
34	04/13/76	23:00	04/14/76	13:00	0.04	0.5833	0.0029	6.8333
35	04/21/76	09:00	04/21/76	11:00	0.01	0.0833	0.0050	3.1250
36	04/24/76	14:00	04/25/76	07:00	0.84	0.7083	0.0494	4.2500
37	04/29/76	13:00	05/01/76	05:00	1.03	1.6667	0.0258	5.4583

38	05/06/76	16:00	05/07/76	19:00	1.71	1.1250	0.0633	0.2500
39	05/08/76	01:00	05/08/76	12:00	0.30	0.4583	0.0273	2.0417
40	05/10/76	13:00	05/11/76	15:00	0.26	1.0833	0.0100	1.7917
41	05/13/76	10:00	05/14/76	24:00	3.84	1.5833	0.1011	0.4583
42	05/15/76	11:00	05/15/76	13:00	0.01	0.0833	0.0050	0.7917
43	05/16/76	08:00	05/16/76	11:00	0.07	0.1250	0.0233	1.6667
44	05/18/76	03:00	05/18/76	05:00	0.01	0.0833	0.0050	4.6250
45	05/22/76	20:00	05/24/76	02:00	2.31	1.2500	0.0770	2.5833
46	05/26/76	16:00	05/28/76	13:00	0.27	1.8750	0.0060	0.4583
47	05/28/76	24:00	05/29/76	07:00	0.05	0.2917	0.0071	3.1667
48	06/01/76	11:00	06/01/76	22:00	0.48	0.4583	0.0436	0.3333
49	06/02/76	06:00	06/02/76	14:00	0.01	0.3333	0.0012	2.3750
50	06/04/76	23:00	06/05/76	02:00	0.01	0.1250	0.0033	4.6667
51	06/09/76	18:00	06/09/76	20:00	0.01	0.0833	0.0050	6.7917
52	06/16/76	15:00	06/16/76	19:00	0.01	0.1667	0.0025	1.7083
53	06/18/76	12:00	06/18/76	19:00	0.03	0.2917	0.0043	0.3750
54	06/19/76	04:00	06/20/76	06:00	1.78	1.0833	0.0685	7.3333
55	06/27/76	14:00	06/27/76	15:00	0.01	0.0417	0.0100	2.6250
56	06/30/76	06:00	06/30/76	10:00	0.46	0.1667	0.1150	3.5417
57	07/03/76	23:00	07/04/76	24:00	1.17	1.0417	0.0468	8.6250
58	07/13/76	15:00	07/13/76	16:00	0.26	0.0417	0.2600	3.0000
59	07/16/76	16:00	07/17/76	08:00	0.03	0.6667	0.0019	0.3333
60	07/17/76	16:00	07/17/76	17:00	0.01	0.0417	0.0100	3.9167
61	07/21/76	15:00	07/21/76	17:00	0.09	0.0833	0.0450	1.9583
62	07/23/76	16:00	07/23/76	18:00	0.26	0.0833	0.1300	3.7083
63	07/27/76	11:00	07/27/76	24:00	1.01	0.5417	0.0777	0.4167
64	07/28/76	10:00	07/28/76	17:00	1.63	0.2917	0.2329	1.0000
65	07/29/76	17:00	07/29/76	20:00	0.17	0.1250	0.0567	0.4167
66	07/30/76	06:00	07/30/76	12:00	0.23	0.2500	0.0383	1.0000
67	07/31/76	12:00	07/31/76	14:00	0.07	0.0833	0.0350	5.9583
68	08/06/76	13:00	08/06/76	20:00	0.30	0.2917	0.0429	0.7500
69	08/07/76	14:00	08/07/76	16:00	0.54	0.0833	0.2700	8.0000
70	08/15/76	16:00	08/15/76	19:00	0.06	0.1250	0.0200	0.7917
71	08/16/76	14:00	08/16/76	17:00	0.93	0.1250	0.3100	7.9167
72	08/24/76	15:00	08/25/76	04:00	0.86	0.5417	0.0662	1.1667
73	08/26/76	08:00	08/26/76	14:00	0.01	0.2500	0.0017	0.6667
74	08/27/76	06:00	08/27/76	20:00	0.34	0.5833	0.0243	0.2500
75	08/28/76	02:00	08/28/76	15:00	0.28	0.5417	0.0215	2.8333
76	08/31/76	11:00	08/31/76	13:00	0.01	0.0833	0.0050	0.4167
77	08/31/76	23:00	09/01/76	20:00	1.41	0.8750	0.0671	1.3333
78	09/03/76	04:00	09/03/76	07:00	0.01	0.1250	0.0033	0.2500
79	09/03/76	13:00	09/03/76	24:00	0.25	0.4583	0.0227	0.2500
80	09/04/76	06:00	09/04/76	14:00	0.04	0.3333	0.0050	0.2917
81	09/04/76	21:00	09/05/76	18:00	0.44	0.8750	0.0210	0.9167

82	09/06/76	16:00	09/06/76	20:00	0.04	0.1667	0.0100	0.7083
83	09/07/76	13:00	09/07/76	17:00	0.11	0.1667	0.0275	1.8750
84	09/09/76	14:00	09/09/76	15:00	0.01	0.0417	0.0100	0.4167
85	09/10/76	01:00	09/10/76	03:00	0.01	0.0833	0.0050	6.8333
86	09/16/76	23:00	09/16/76	24:00	0.01	0.0417	0.0100	3.9583
87	09/20/76	23:00	09/21/76	06:00	0.06	0.2917	0.0086	4.8333
88	09/26/76	02:00	09/26/76	03:00	0.01	0.0417	0.0100	0.3333
89	09/26/76	11:00	09/26/76	15:00	0.12	0.1667	0.0300	0.6667
90	09/27/76	07:00	09/27/76	09:00	0.03	0.0833	0.0150	0.2500
91	09/27/76	15:00	09/27/76	18:00	0.01	0.1250	0.0033	1.1250
92	09/28/76	21:00	09/29/76	22:00	2.39	1.0417	0.0956	6.1250
93	10/06/76	01:00	10/07/76	05:00	0.05	1.1667	0.0018	0.7083
94	10/07/76	22:00	10/08/76	24:00	0.16	1.0833	0.0062	7.7500
95	10/16/76	18:00	10/17/76	03:00	0.05	0.3750	0.0056	2.9583
96	10/20/76	02:00	10/20/76	06:00	0.15	0.1667	0.0375	4.0000
97	10/24/76	06:00	10/24/76	17:00	0.01	0.4583	0.0009	0.2500
98	10/24/76	23:00	10/25/76	22:00	0.64	0.9583	0.0278	3.9167
99	10/29/76	20:00	10/30/76	16:00	0.54	0.8333	0.0270	11.8333
100	11/11/76	12:00	11/12/76	02:00	0.23	0.5833	0.0164	1.9583
101	11/14/76	01:00	11/15/76	05:00	0.96	1.1667	0.0343	4.3750
102	11/19/76	14:00	11/19/76	19:00	0.01	0.2083	0.0020	0.5833
103	11/20/76	09:00	11/20/76	19:00	0.22	0.4167	0.0220	5.4167
104	11/26/76	05:00	11/26/76	18:00	0.12	0.5417	0.0092	0.6667
105	11/27/76	10:00	11/27/76	15:00	0.02	0.2083	0.0040	0.4167
106	11/28/76	01:00	11/29/76	12:00	0.72	1.4583	0.0206	6.9583
107	12/06/76	11:00	12/07/76	15:00	0.57	1.1667	0.0204	2.5833
108	12/10/76	05:00	12/11/76	20:00	1.09	1.6250	0.0279	3.0417
109	12/14/76	21:00	12/15/76	05:00	0.25	0.3333	0.0312	4.5417
110	12/19/76	18:00	12/20/76	13:00	0.87	0.7917	0.0458	4.7917
111	12/25/76	08:00	12/25/76	24:00	1.35	0.6667	0.0844	4.5000
112	12/30/76	12:00	12/31/76	06:00	0.20	0.7500	0.0111	**

Runoff Coefficient file name: RUNOFF.RSV
Runoff Coefficient file description: CALIBRATED RUNOFF COEFFICIENT FILE
Date: 03-08-1999

Area Types:
1: Connected flat roofs
2: Connected Pitched Roofs
3: Directly connected impervious areas
4: Directly connected unpaved areas
5: Pervious areas - A/B soils
6: Pervious areas - C/D soils
7: Smooth textured streets
8: Intermediate textured streets
9: Rough textured streets

Drainage efficiency coefficients (fractions)
10: C/D soils, w/o alleys, medium to high density land use
11: C/D soils, w/ alleys, medium to high density land use
12: C/D soils for strip commercial and shopping center land use

Volumetric Runoff Coefficients for Rains (in & mm)

Area Type No																		
	in:	.01	.08	.12	.20	.39	.59	.79	.98	1.2	1.6	2.0	2.4	2.8	3.2	3.5	3.9	4.9
	mm:	1	2	3	5	10	15	20	25	30	40	50	60	70	80	90	100	125
	Rain #:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 :		0.00	0.00	0.30	0.54	0.72	0.79	0.83	0.84	0.86	0.88	0.90	0.91	0.93	0.94	0.94	0.95	0.96
2 :		0.25	0.63	0.75	0.85	0.93	0.95	0.96	0.97	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99
3 :		0.93	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99
4 :		0.00	0.00	0.00	0.00	0.47	0.64	0.72	0.77	0.81	0.86	0.89	0.91	0.92	0.93	0.94	0.94	0.95
5 :		0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.02	0.03	0.04	0.07	0.10	0.13	0.15	0.20	0.22	0.25
6 :		0.00	0.00	0.00	0.10	0.15	0.19	0.20	0.21	0.22	0.23	0.26	0.29	0.32	0.33	0.36	0.39	0.45
7 :		0.35	0.49	0.54	0.59	0.65	0.69	0.72	0.76	0.80	0.85	0.88	0.90	0.91	0.93	0.93	0.94	0.95
8 :		0.26	0.43	0.49	0.55	0.60	0.64	0.67	0.67	0.73	0.80	0.84	0.86	0.88	0.90	0.91	0.92	0.93
9 :		0.18	0.39	0.47	0.53	0.60	0.64	0.67	0.70	0.73	0.80	0.84	0.86	0.88	0.90	0.91	0.92	0.93
Drainage efficiency coefficients (fractions):																		
10 :		0.00	0.00	0.00	0.11	0.16	0.20	0.21	0.22	0.22	0.24	0.27	0.30	0.33	0.34	0.37	0.40	0.46
11 :		0.00	0.05	0.08	0.11	0.16	0.20	0.29	0.38	0.46	0.64	0.81	0.93	0.99	0.99	0.99	0.99	0.99
12 :		0.00	0.00	0.00	0.47	0.90	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99

Particulate Solids Concentration file name: BHAM.PSC
Particulate Solids Concentration file description: Particulate residue concentrations for source areas.
Date: 03-08-1999

Area Types:
A : Roofs
B : Paved Parking
C : Unpaved parking, driveways, and walkways
D : Paved playgrounds
E : Paved driveways
F : Paved sidewalks and walks
G : Large landscaped areas
H : Small landscaped areas
I : Undeveloped areas
J : Other pervious areas
K : Other directly connected impervious areas
L : Other partially connected impervious areas
M : Paved lane and shoulder areas

Particulate Solids (mg/l) for Rains (in & mm)

Row No	Area Type	.04	.08	.12	.20	.39	.59	.79	.98	1.2	1.6	2.0	2.4	2.8	3.2	:in
		1	2	3	5	10	15	20	25	30	40	50	60	70	80	:mm
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	:Rain #
Residential Areas																
1	A	5	5	5	5	5	5	5	5	5	5	5	5	5	5	
2	B	1030	550	370	210	80	60	60	60	60	60	60	60	60	60	
3	C	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600	
4	D	1030	550	370	210	80	60	60	60	60	60	60	60	60	60	
5	E	1030	550	370	210	80	60	60	60	60	60	60	60	60	60	
6	F	1030	550	370	210	80	60	60	60	60	60	60	60	60	60	
7	G	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600	
8	H	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600	
9	I	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600	
10	J	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600	
11	K	1030	550	370	210	80	60	60	60	60	60	60	60	60	60	
12	L	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600	

Institutional Areas

13	A	5	5	5	5	5	5	5	5	5	5	5	5	5	5
14	B	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
15	C	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
16	D	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
17	E	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
18	F	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
19	G	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
20	H	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
21	I	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
22	J	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
23	K	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
24	L	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600

Commercial Areas

25	A	5	5	5	5	5	5	5	5	5	5	5	5	5	5
26	B	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
27	C	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
28	D	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
29	E	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
30	F	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
31	G	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
32	H	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
33	I	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
34	J	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
35	K	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
36	L	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600

Industrial Areas

37	A	5	5	5	5	5	5	5	5	5	5	5	5	5	5
38	B	300	200	150	100	100	100	100	100	100	100	100	100	100	100
39	C	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
40	D	300	200	150	100	100	100	100	100	100	100	100	100	100	100
41	E	300	200	150	100	100	100	100	100	100	100	100	100	100	100
42	F	300	200	150	100	100	100	100	100	100	100	100	100	100	100
43	G	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
44	H	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
45	I	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
46	J	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
47	K	300	200	150	100	100	100	100	100	100	100	100	100	100	100
48	L	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600

Open Space Areas

49	A	5	5	5	5	5	5	5	5	5	5	5	5	5	5

50	B	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
51	C	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
52	D	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
53	E	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
54	F	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
55	G	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
56	H	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
57	I	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
58	J	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
59	K	1030	550	370	210	80	60	60	60	60	60	60	60	60	60
60	L	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600

Freeways

61	M	5800	4200	3100	2000	1200	1100	1100	1100	1100	1100	1100	1100	1100	1100
62	G	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
63	I	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
64	J	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600
65	K	1030	550	370	210	100	100	100	100	100	100	100	100	100	100
66	L	5000	4000	3300	2200	1100	700	600	600	600	600	600	600	600	600

Particulate Residue Reduction due to Delivery file name: DELIVERY.PRR
Size distribution file description: PARTICULATE REDUCTIONS DUE TO SEDIMENTATION IN DRAINAGE SYSTEMS
Date: 03-08-1999

Particulate Residue Reduction due to Delivery (fraction) for Rains (in & mm)

Rain (in) :	.04	.08	.12	.20	.39	.59	.79	.98	1.2	1.6	2.0	2.4	2.8	3.2
Rain (mm) :	1	2	3	5	10	15	20	25	30	40	50	60	70	80
For 1. Grass Swales:	0.99	0.98	0.97	0.94	0.85	0.74	0.61	0.44	0.25	0.07	0.02	0.00	0.00	0.00
For 2. Undeveloped roadside:	0.99	0.98	0.97	0.94	0.85	0.74	0.61	0.44	0.25	0.07	0.02	0.00	0.00	0.00
For 3. Curb and Gutters, `valleys', or sealed swales in poor condition (or very flat):	0.98	0.96	0.92	0.85	0.61	0.46	0.31	0.22	0.13	0.04	0.01	0.00	0.00	0.00
For 3. Curb and Gutters, `valleys', or sealed swales in fair condition:	0.98	0.95	0.90	0.80	0.48	0.32	0.16	0.11	0.07	0.02	0.00	0.00	0.00	0.00
For 3. Curb and Gutters, `valleys', or sealed swales in good condition (or very steep):	0.98	0.95	0.88	0.75	0.36	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Size distribution file name: MEDIUM.CPZ
Size distribution file description: PARTICLE SIZE DISTRIBUTION FOR URBAN RUNOFF HAVING MEDIUM TOTAL RESIDUE CONCENTRATIONS
Date: 03-08-1999

Entry Number	Critical Size (microns)	Percent > Critical Size
0	0	100.0
1	1	99.0
2	2	94.0
3	3	90.0
4	4	86.0
5	5	82.0
6	6	79.0
7	7	76.0
8	8	73.0
9	9	70.0
10	10	67.0
11	11	65.0
12	12	63.0
13	13	61.0
14	14	59.0
15	15	58.0
16	20	51.0
17	25	46.0
18	30	42.0
19	35	38.0
20	40	35.0
21	50	31.0
22	60	28.0
23	80	23.0
24	100	19.0
25	150	14.0
26	200	11.0
27	300	8.0
28	500	5.0
29	800	3.0
30	1000	2.0
31	2000	0.0

Pollutant Probability Relative Concentration file name: poll.PPD
File description: Basic poll. prob. file for calibration
Date: 03-08-1999

Source Areas:
1: Roofs
2: Paved Parking/Storage
3: Unpaved Parking/Storage
4: Playground
5: Driveways
6: Sidewalks/Walks
7: Street Area
8: Large Landscaped Area
9: Undeveloped Area
10: Small Landscaped Area
11: Isolated Area
12: Other Pervious Area
13: Other Dir Conctd Imperv Area
14: Othr Partially Conctd Imperv Area
15: Paved Lane & Shoulder Area
16: Large Turf Areas

Particulate Pollutant: Copper (mg/kg)

Source Area #	Residential Land Uses	Institutional Land Uses	Commercial Land Uses	Industrial Land Uses	Open Spcs Land Use	Freeway Land Use
1-AVE :	4334	4247	4247	28579	4247	0
1-COV :	1.38	1.49	1.49	1.26	1.49	0.00
2-AVE :	17086	693	878	1062	693	0
2-COV :	0.23	1.06	0.74	0.42	1.06	0.00
3-AVE :	637	637	637	1748	637	0
3-COV :	0.86	0.86	0.86	1.12	0.86	0.00
4-AVE :	693	693	693	693	693	0
4-COV :	1.06	1.06	1.06	1.06	1.06	0.00
5-AVE :	693	693	693	693	693	0
5-COV :	1.06	1.06	1.06	1.06	1.06	0.00
6-AVE :	693	693	693	693	693	0
6-COV :	1.06	1.06	1.06	1.06	1.06	0.00
7-AVE :	693	797	693	5272	693	0
7-COV :	1.06	0.69	1.06	1.16	1.06	0.00
8-AVE :	3567	3567	3567	3567	3567	3567
8-COV :	1.10	1.10	1.10	1.10	1.10	1.10
9-AVE :	3567	3567	3567	3567	3567	150
9-COV :	1.10	1.10	1.10	1.10	1.10	1.10
10-AVE :	3567	3567	3567	3567	3567	150
10-COV :	1.10	1.10	1.10	1.10	1.10	1.10
11-AVE :	0	0	0	0	0	0
11-COV :	0.00	0.00	0.00	0.00	0.00	0.00
12-AVE :	3567	3567	3567	3567	3567	82
12-COV :	1.10	1.10	1.10	1.10	1.10	1.10
13-AVE :	693	693	7410	425	693	165
13-COV :	1.06	1.06	2.02	0.88	1.06	1.06
14-AVE :	693	693	7410	425	693	165
14-COV :	1.06	1.06	2.02	0.88	1.06	1.06
15-AVE :	0	0	0	0	0	1100
15-COV :	0.00	0.00	0.00	0.00	0.00	1.06
16-AVE :	3567	3567	3567	3567	3567	150
16-COV :	1.10	1.10	1.10	1.10	1.10	1.10

Filterable Pollutant: Copper (μg/L)

1-AVE :	2.820	0.850	0.850	1.600	0.850	0.000
1-COV :	1.18	0.72	0.72	0.94	0.72	0.00
2-AVE :	2.050	15.790	8.360	0.930	2.050	0.000
2-COV :	0.52	1.37	0.90	0.43	0.52	0.00
3-AVE :	2.280	2.280	2.280	154.000	2.280	0.000
3-COV :	0.20	0.20	0.20	1.64	0.20	0.00
4-AVE :	2.280	2.280	2.280	2.280	2.280	0.000
4-COV :	0.20	0.20	0.20	0.20	0.20	0.00
5-AVE :	2.280	2.280	2.280	2.280	2.280	0.000
5-COV :	0.20	0.20	0.20	0.20	0.20	0.00
6-AVE :	2.280	2.280	2.280	2.280	2.280	0.000
6-COV :	0.20	0.20	0.20	0.20	0.20	0.00
7-AVE :	1.340	1.340	1.340	4.230	1.340	0.000
7-COV :	0.39	0.39	0.39	1.16	0.39	0.00
8-AVE :	3.300	3.300	3.300	3.300	3.300	3.300
8-COV :	0.90	0.90	0.90	0.90	0.90	0.90
9-AVE :	3.300	3.300	3.300	3.300	3.300	3.300
9-COV :	0.90	0.90	0.90	0.90	0.90	0.90
10-AVE :	3.300	3.300	3.300	3.300	3.300	3.300
10-COV :	0.90	0.90	0.90	0.90	0.90	0.90
11-AVE :	0.000	0.000	0.000	0.000	0.000	0.000
11-COV :	0.00	0.00	0.00	0.00	0.00	0.00
12-AVE :	3.300	3.300	3.300	3.300	3.300	3.300
12-COV :	0.90	0.90	0.90	0.90	0.90	0.90
13-AVE :	2.280	2.280	7.000	5.940	2.280	2.280
13-COV :	0.20	0.20	1.45	1.29	0.20	0.20
14-AVE :	2.280	2.280	6.810	5.940	2.280	2.280
14-COV :	0.20	0.20	1.45	1.29	0.20	0.20
15-AVE :	0.000	0.000	0.000	0.000	0.000	1.340
15-COV :	0.00	0.00	0.00	0.00	0.00	0.39
16-AVE :	3.300	3.300	3.300	3.300	3.300	3.300
16-COV :	0.90	0.90	0.90	0.90	0.90	0.90

Data File: Newres.DAT
Rain File: BHAM76.RAN
Date: 03-08-99 Time: 8:27:46 PM
Site Description: MEDIUM DENSITY RESIDENTIAL 1961-1980, CURBS AND GUTTERS, CLAYEY SOILS, BASELINE CONTROLS (NONE)

Residential Areas - Runoff Volume (cu. ft)

Start Date	Rain Total	Roofs 1	Roofs 2	Driveways 1	Driveways 2	Street Area 1	Street Area 2	Undeveloped Area	Small Landscaped Area 1	Small Landscaped Area 2	Land Use Totals	Rv	Total Losses (in.) *	Calculated CN
01/02/76	0.46	4067	1642	1927	332	6740	666	1253	13905	7157	37689	0.23	0.36	93.6
01/07/76	0.58	5194	2392	2430	477	8837	873	1815	20147	10370	52536	0.25	0.44	92.6
01/11/76	0.25	2057	591	1048	128	3365	324	473	5247	2701	15932	0.18	0.21	95.8
01/13/76	0.03	54	0	92	0	142	10	0	0	0	297	0.03	0.03	99.0
01/13/76	0.39	3418	1265	1634	258	5580	551	969	10750	5533	29957	0.21	0.31	94.3
01/16/76	0.01	6	0	10	0	16	1	0	0	0	33	0.01	0.01	99.6
01/20/76	0.05	166	0	203	0	365	28	0	0	0	762	0.04	0.05	98.5
01/24/76	0.03	54	0	92	0	142	10	0	0	0	297	0.03	0.03	99.0
01/25/76	2.33	21771	15073	9964	2940	47771	4719	11163	123888	63768	301056	0.36	1.50	81.1
Summary for Runoff Producing Events														
Minimum:	0.01	6.00	0.00	10.00	0.00	16.00	1.00	0.00	0.00	0.00	33.00	0.01	0.01	81.1
Maximum:	2.33	21771.00	15073.00	9964.00	2940.00	47771.00	4719.00	11163.00	123888.00	63768.00	301056.00	0.36	1.50	99.6
Average:	0.46	4087.44	2329.22	1933.33	459.44	8106.44	798.00	1741.44	19326.33	9947.67	48728.78	0.31	0.33	
Total:	4.13	36787	20963	17400	4135	72958	7182	15673	173937	89529	438559			

Total Area, with Drainage and Outfall Controls - Runoff Volume (cu. ft)

Start Date	Rain Total (inches)	Total Without Drainage Controls	Total With Drainage Controls	Catch basin Volume % Full	Total With Outfall Controls	Rv	Total Losses (in) *	Calculated CN	Peak Reduction Factor	Flushing Ratio	Det. Basin Out. Struct. Failed (l.u. #-src. area #)
01/02/76	0.46	37689	37689	0.00	37689	0.23	0.36	93.6			
01/07/76	0.58	52536	52536	0.00	52536	0.25	0.44	92.6			
01/11/76	0.25	15932	15932	0.00	15932	0.18	0.21	95.8			
01/13/76	0.03	297	297	0.00	297	0.03	0.03	99.0			
01/13/76	0.39	29957	29957	0.00	29957	0.21	0.31	94.3			
01/16/76	0.01	33	33	0.00	33	0.01	0.01	99.6			
01/20/76	0.05	762	762	0.00	762	0.04	0.05	98.5			
01/24/76	0.03	297	297	0.00	297	0.03	0.03	99.0			
01/25/76	2.33	301056	301056	0.00	301056	0.36	1.50	81.1			
Summary of Runoff Producing Events											
Number of Rains:	9	9	9	9	9						
Minimum:	0.01	33	33	0.0	33	0.01	0.01	81.1			
Maximum:	2.33	301056	301056	0.0	301056	0.36	1.50	99.6			
Average:	0.46	48729	48729	0.0	48729	0.32	0.33				
Total:	4.13	438559	438559	0.0	438559						

Data File: Newres.DAT											
Rain File: BHAM76.RAN											
Date: 03-08-99 Time: 8:27:46 PM											
Site Description: MEDIUM DENSITY RESIDENTIAL 1961-1980, CURBS AND GUTTERS, CLAYEY SOILS, BASELINE CONTROLS (NONE)											
Residential - Source Area Percentage Contributio											
Start Date	Rain Total	Roofs 1	Roofs 2	Driveways 1	Driveways 2	Street Area 1	Street Area 2	Undeveloped Area	Small Landscaped Area 1	Small Landscaped Area 2	Land Use Totals
01/02/76	0.46	0.11	0.04	0.05	0.01	0.18	0.02	0.03	0.37	0.19	1.00
01/07/76	0.58	0.10	0.05	0.05	0.01	0.17	0.02	0.03	0.38	0.20	1.00
01/11/76	0.25	0.13	0.04	0.07	0.01	0.21	0.02	0.03	0.33	0.17	1.00
01/13/76	0.03	0.18	0.00	0.31	0.00	0.48	0.03	0.00	0.00	0.00	1.00
01/13/76	0.39	0.11	0.04	0.05	0.01	0.19	0.02	0.03	0.36	0.18	1.00
01/16/76	0.01	0.18	0.00	0.31	0.00	0.48	0.03	0.00	0.00	0.00	1.00
01/20/76	0.05	0.22	0.00	0.27	0.00	0.48	0.04	0.00	0.00	0.00	1.00
01/24/76	0.03	0.18	0.00	0.31	0.00	0.48	0.03	0.00	0.00	0.00	1.00
01/25/76	2.33	0.07	0.05	0.03	0.01	0.16	0.02	0.04	0.41	0.21	1.00
Summary for Runoff Producing Events											
Minimum:	0.01	0.07	0.00	0.03	0.00	0.16	0.02	0.00	0.00	0.00	1.00
Maximum:	2.33	0.22	0.05	0.31	0.01	0.48	0.04	0.04	0.41	0.21	1.00
Average:	0.46	0.14	0.02	0.16	0.01	0.31	0.03	0.02	0.21	0.11	1.00

Data File: Newres.DAT											
Rain File: BHAM76.RAN											
Date: 03-08-99 Time: 8:27:46 PM											
Site Description: MEDIUM DENSITY RESIDENTIAL 1961-1980, CURBS AND GUTTERS, CLAYEY SOILS, BASELINE CONTROLS (NONE)											
Residential Areas - Concentration of PARTICULATE SOLIDS (mg/L)											
Start Date	Rain Total	Roofs 1	Roofs 2	Driveways 1	Driveways 2	Street Area 1	Street Area 2	Undeveloped Area	Small Landscaped Area 1	Small Landscaped Area 2	Land Use Totals
01/02/76	0.46	5	5	73	73	211	97	965	965	965	616.0231
01/07/76	0.58	5	5	61	61	168	78	721	721	721	477.5421
01/11/76	0.25	5	5	175	175	449	218	1903	1903	1903	1118.625
01/13/76	0.03	4	0	785	0	3980	2838	0	0	0	2234.699
01/13/76	0.39	5	5	82	82	278	137	1121	1121	1121	705.5395
01/16/76	0.01	1	0	262	0	14780	10666	0	0	0	7481.86
01/20/76	0.05	5	0	900	0	2696	1662	0	0	0	1593
01/24/76	0.03	4	0	785	0	5106	3487	0	0	0	2793.458
01/25/76	2.33	5	5	60	60	41	20	600	600	600	406.1884
Summary for Runoff Producing Events											
Minimum:	0.01	1	0	60	0	41	20	0	0	0	406
Maximum:	2.33	5	5	900	175	14780	10666	1903	1903	1903	7482
Fl Wt Ave:	0.46	5	5	88	66	143	68	715	715	715	485

Total Area, with Drainage and Outfall Controls - Concentration of PARTICULATE SOLIDS (mg/L)											
Start Date	Rain Total (inches)	Total Without Drainage Controls	Total With Drainage Controls	Catch basin Volume % Full	Total With Outfall Controls	Flow-wtd Min. Part. Size Controlled					
01/02/76	0.46	616	354	0.00	354						
01/07/76	0.58	478	321	0.00	321						
01/11/76	0.25	1119	320	0.00	320						
01/13/76	0.03	2235	45	0.00	45						
01/13/76	0.39	706	363	0.00	363						
01/16/76	0.01	7483	150	0.00	150						
01/20/76	0.05	1593	45	0.00	45						
01/24/76	0.03	2794	56	0.00	56						
01/25/76	2.33	406	406	0.00	406						
Summary of Runoff Producing Events											
Number of Rains:	9	9	9	9	9						
Minimum:	0.01	406	45	0.0	45						
Maximum:	2.33	7483	406	0.0	406						
Fl Wt Ave:	0.46	1937	229	0.0	229						

Data File: Newres.DAT											
Rain File: BHAM76.RAN											
Date: 03-08-99 Time: 8:27:46 PM											
Site Description: MEDIUM DENSITY RESIDENTIAL 1961-1980, CURBS AND GUTTERS, CLAYEY SOILS, BASELINE CONTROLS (NONE)											
Residential Areas - Yield of PARTICULATE SOLIDS (lbs)											
Start Date	Rain Total	Roofs 1	Roofs 2	Driveways 1	Driveways 2	Street Area 1	Street Area 2	Undeveloped Area	Small Landscaped Area 1	Small Landscaped Area 2	Land Use Totals
01/02/76	0.46	1	1	9	2	89	4	75	837	431	1449
01/07/76	0.58	2	1	9	2	92	4	82	907	467	1565
01/11/76	0.25	1	0	11	1	94	4	56	623	321	1112
01/13/76	0.03	0	0	4	0	35	2	0	0	0	41
01/13/76	0.39	1	0	8	1	97	5	68	751	387	1319
01/16/76	0.01	0	0	0	0	15	1	0	0	0	15
01/20/76	0.05	0	0	11	0	61	3	0	0	0	76
01/24/76	0.03	0	0	4	0	45	2	0	0	0	52
01/25/76	2.33	7	5	37	11	123	6	418	4637	2387	7630
Summary for Runoff Producing Events											
Minimum:	0.01	0	0	0	0	15	1	0	0	0	15
Maximum:	2.33	7	5	37	11	123	6	418	4637	2387	7630
Fl Wt Ave:	0.46	5	4	25	8	112	5	319	3540	1822	5680
Total:	4.13	12	7	93	17	651	31	699	7755	3993	13259

Total Area, with Drainage and Outfall Controls - Yield of PARTICULATE SOLIDS (lbs)						
Start Date	Rain Total (inches)	Total Without Drainage Controls	Total With Drainage Controls	Catch basin Volume % Full	Total With Outfall Controls	Flow-wtd Min. Part. Size Controlled
01/02/76	0.46	1449	831	0.00	831	
01/07/76	0.58	1565	1051	0.00	1051	
01/11/76	0.25	1112	318	0.00	318	
01/13/76	0.03	41	1	0.00	1	
01/13/76	0.39	1319	678	0.00	678	
01/16/76	0.01	15	0	0.00	0	
01/20/76	0.05	76	2	0.00	2	
01/24/76	0.03	52	1	0.00	1	
01/25/76	2.33	7630	7630	0.00	7630	
Summary of Runoff Producing Events						
Number of Rains:	9	9	9	9	9	
Minimum:	0.01	15	0	0.0	0	
Maximum:	2.33	7630	7630	0.0	7630	
Fl Wt Ave:	0.46	1473	1168	0.0	1168	
Total:	4.13	13259	10512	0.0	10512	

Typical Land Use Descriptions

Residential Land Uses

High Density Residential without Alleys (HRNA): Urban single family housing at a density of greater than 6 units/acre. Includes house, driveway, yards, sidewalks, and streets.

High Density Residential with Alleys (HRWA): Same as HRNA1, except alleys exist behind the houses.

Medium Density without Alleys (MRNA): Same as HRNA except the density is between 2 - 6 units/acre.

Medium Density with Alleys (MRWA): Same as HRWA, except alleys exists behind the houses.

Low Density (LR): Same as HRNA except the density is 0.7 to 2 units/acre.

Duplexes (DUPLX): Housing having two separate units in a single building.

Multiple Family (MF): Housing for three or more families, from 1 - 3 stories in height. Units may be adjoined up-and-down, side-by-side; or front-and-rear. Includes building, yard, parking lot, and driveways.
High Rise (HIR): Same MF except buildings are

High Rise Apartments (APTS): Multiple family units 4 or more stories in height.

Trailer Parks (MOBR): A mobile home or trailer park, includes all vehicle homes, the yard, driveway, and office area.

Suburban (SUBR): Same as HRNA except the density is between 0.2 and 0.6 units/acre.

Commercial Land Uses

Strip Commercial (CST): Those buildings for which the primary function involves the sale of goods or services. This category includes some institutional lands found in commercial strips, such as post offices, court houses, and fire and police stations. This category does not include buildings used for the manufacture of goods or warehouses. This land use includes the buildings, parking lots, and streets. This land use does not include nursery, tree farms, or lumber yards.

Shopping Centers (SC): Commercial areas where the related parking lot is at least 2.5 times the area of the building roof area. The buildings in this land use are usually surrounded by the parking area. This land use includes the buildings, parking lot, and the streets.

Office Parks (OP): Land use where non-retail business takes place. The buildings are usually multi storied buildings surrounded by larger areas of lawn and other landscaping. This land use includes the buildings, lawn, and road areas. Types of establishments that may be in this category includes: insurance offices, government buildings, and company headquarters.

Downtown Central Business District (CBD): Highly impervious downtown areas of commercial and institutional land use.

Industrial Land Uses

Manufacturing Industrial (HI): Those buildings and premises which are devoted to the manufacture of products, with many of the operations conducted outside, such as power plants, steel mills, and cement plants.

Medium Industrial (MI): This category includes businesses such as lumber yards, auto salvage yards, junk yards, grain elevators, agricultural coops, oil tank farms, coal and salt storage areas, slaughter houses, and areas for bulk storage of fertilizers.

Non-Manufacturing (LI): Those buildings which are used for the storage and/or distribution of goods awaiting further processing or sale to retailers. This category mostly includes warehouses, and wholesalers where all operations are conducted indoors, but with truck loading and transfer operations conducted outside.

Institutional Land Uses

Hospitals (HOSP): Medical facilities that provide patient overnight care. Includes nursing homes, state, county, or private facilities. Includes the buildings, grounds, parking lots, and drives.

Education (SCH): Includes any public or private primary, secondary, or college educational institutional grounds. Includes buildings, playgrounds, athletic fields, roads, parking lots, and lawn areas.

Miscellaneous Institutional (MISC): Churches and large areas of institutional property not part of CST and CDT.

Open Space Land Uses

Cemeteries (CEM): Includes cemetery grounds, roads, and buildings located on the grounds.

Parks (PARK): Outdoor recreational areas including municipal playgrounds, botanical gardens, arboretums, golf courses, and natural areas.

Undeveloped (OSUD): Lands that are private or publicly owned with no structures and have a complete vegetative cover. This includes vacant lots, transformer stations, radio and TV transmission areas, water towers, and railroad rights-of-way.

Freeway Land Uses

Freeways (FREE): Limited access highways and the interchange areas, including any vegetated rights-of-ways.

WinSLAMM Calibration Procedures

The calibration and verification procedures of WinSLAMM are similar to the procedures needed to calibrate and verify any stormwater quality model. Local data should be collected, including stormwater outfall quality and quantity data and watershed information. Numerous individual rainfall-runoff events need to be sampled (using flow-weighted composite sampling). The best scenario is to collect all calibration information from one watershed and then verify the model using independent observations from another watershed. Another common approach is to collect calibration information for a series of events from one watershed, and then verify the calibrated model using additional data from other storms from the same watershed.

WinSLAMM has typically been calibrated and verified using a combination of approaches. The initial effort for the full implementation of WinSLAMM (as reported by Pitt 1987) used data from three years of monitoring of eight watersheds in Milwaukee and data from one year of monitoring two additional watersheds in Toronto. These data represented a broad range of land uses (residential, commercial, and industrial uses), a wide range of hydraulic complexity (from having mostly connected impervious areas to having much landscaped areas and grass drainages), and widely varying rain conditions (from 0.01 to over 3 inches). The data was supplemented with source area data collected elsewhere (as referenced later) and with small-scale washoff tests conducted in Toronto. These data (from several hundred independent rainfall-runoff events) enabled the basic processes contained within WinSLAMM to be rigorously tested and allowed for a comprehensive set of initial calibration conditions to be developed. With additional site-specific data, these calibration conditions should be modified to consider specific situations not contained in the initial data set. This has been especially important for organic toxicants and for source areas not well represented in the initial data set.

This section describes a general approach to calibrate WinSLAMM and describes the data sources for the additional parameter files used in WinSLAMM. The order for calibrating WinSLAMM is:

1) Runoff quantity
2) Annual suspended solids loading (and event mean concentration)
3) Event suspended solids loadings and concentrations
4) Annual total pollutant loadings (and event mean concentrations)
5) Partitioning of pollutants between particulate and filterable phases
6) Variations in pollutant concentrations

It is very important that the user start with runoff quantity and be completely satisfied with the calibration of each step before proceeding to the next step. Much wasted effort will occur if one skips around in the order of the calibration.

Runoff Coefficients

The mandatory *.RSV file contains volumetric runoff coefficients (the ratio of runoff quantity to rain quantity: Rv) for each surface type for various rain depths. The runoff coefficients were calculated using general impervious and pervious area models. These models were then calibrated based on extensive Toronto data and were then verified using additional independent Toronto data, along with numerous Milwaukee data for a wide variety of land development and rain conditions. However, WinSLAMM was designed to allow the use of alternative runoff models, as desired. Alternative runoff coefficients for each source area type can be calculated using other models and saved under other runoff volume file names.

The *.RSV file must be calibrated before any of the other parameter files are examined. After this file is modified, as needed, the suspended solids files must be calibrated. Finally, the file describing the other pollutants is examined and modified last.

Initial Data Sources

The RUNOFF.RSV file contains the verified runoff coefficients, based on the small storm hydrology model described in:

R. Pitt. *Small Storm Urban Flow and Particulate Washoff Contributions to Outfall Discharges*. Ph.D. Dissertation, Civil and Environmental Engineering Department, University of Wisconsin, Madison, WI, November 1987.

This file was developed using data from eight study sites in Milwaukee (having generally clayey soils) and two study sites in Toronto (having generally sandy soils). The published data are contained in the following reports:

Bannerman, R., K. Baun, M. Bohn, P.E. Hughes, and D.A. Graczyk. *Evaluation of Urban Nonpoint Source Pollution Management in Milwaukee County, Wisconsin*, Vol. I. Grant No. P005432-01-5, PB 84-114164. US Environmental Protection Agency, Water Planning Division, November 1983.

R. Pitt and J. McLean. *Humber River Pilot Watershed Project*. Ontario Ministry of the Environment, Toronto, Canada, December 1984.

Calibration Steps

The runoff file should be modified based on correctly collected rainfall and runoff data. It is very important that adequate QA/QC procedures be used to insure the accuracy and suitability of the data. Common problems are associated with unrepresentative rainfall data (too few rain gauges and not correctly located in the watershed), incorrect rain gauge calibrations, poor flow monitoring conditions (surcharged flows, relying on Manning’s equation for V and Q, poor conditions at the monitoring location), etc. The use of a calibrated flume or simultaneous use of velocity and depth sensors is preferred, for example. Other common errors are associated with inaccurate descriptions of the watershed (incorrect area, amount of impervious areas, understanding of drainage efficiency, soil characteristics, etc.).

Few people appreciate the inherent errors associated with measuring rainfall and runoff. Most monitoring programs are probably no more than ± 25% accurate for each event. It is very demanding to obtain rainfall and runoff data that is only 10% in error. This is most evident when highly paved areas (such as shopping centers or strip commercial areas) are monitored and the volumetric runoff coefficients are examined. For these areas, it is not uncommon for many of the events to have Rv values greater than 1.0 (implying more runoff than rainfall). Similar errors occur with other sites, but are not as obvious.

The first calibration steps are therefore associated with observing the watershed and rainfall - runoff data, followed by changing the RUNOFF.RSV file, as necessary:

1. Confirm that the watershed areas and development characteristics are correctly described. Urban drainage areas generally follow the topographic divide, but it is not unusual for storm drainage to cross-over surface topographic divides for a block, or more. If the area is very large (hundreds to thousands of acres), these deviations will tend to cancel out, with minimal detrimental effect. However, for calibration and verification studies, the drainage area should be as precisely defined as possible, especially for small drainage areas (tens to hundreds of acres). Therefore, confirm all storm drainage locations and storm drain inlets affecting the outfall monitoring location. For each inlet, identify the precise watershed divide, if at all possible. This includes examining all buildings located close to the divide and determining where the actual divide is located, including splitting roofs or paved areas, as necessary.

Another important aspect is correctly identifying the development characteristics for the watershed area. The most important attribute that affects runoff quantity (and quality) is the drainage efficiency of the area. This includes understanding where the paved areas drain. Are they directly connected to the storm drainage system, or do they drain across substantial distances of unpaved areas before reaching the drainage system? Each type of paved area (roofs, parking/storage areas, play grounds, driveways, sidewalks, etc.) needs to be divided to “directly-connected” and “disconnected” portions, usually through site investigations. Streets are assumed to be directly connected, as they are adjacent to the drainage system. Be careful of roof drains that are to lawns, but only provide a few feet of overland flow before paved areas. These are effectively directly connected areas. Similar problems arise with relatively large paved or roof areas that drain to relatively small unpaved areas (especially in multi-family residential, commercial and industrial areas). Other factors affecting drainage efficiency is the presence of grass swales, or other types of stormwater management devices (dry or wet ponds, porous pavements, infiltration areas, etc.) that may occur in the area. These need to be carefully described and considered in the calibration and verification process.

2. Calculate the Rv for each event and observe the pattern. Plot rainfall depth vs. runoff depth and plot Rv vs. rainfall depth. The Rv values should be small for small rains and steadily increase as the rains increase. The Rv differences will not be great for mostly directly connected impervious areas (either paved or roofed areas), but the trend should be quite dramatic for areas having substantial unpaved areas, if a wide range of rains were monitored. The Rv values should look reasonable for moderate rains (0.25 to 0.5 inch rains): about 0.3 for medium density residential areas, about 0.8+ for commercial areas, etc. If the Rv values all appear to be too small or too large, suspect an error in the drainage area, or an error in the rainfall or flow monitoring calibrations. If several individual events look strange and the others appear to follow a reasonable trend, then investigate specific circumstances for the odd events. Unusual rain intensities, snow/icing problems, debris at flow monitoring station, etc. are all transient problems that may periodically occur. If the unusual conditions cannot be explained, then a decision will have to be made concerning eliminating the data, or keeping it in the data set.

3. Hopefully, data from several watersheds are available for the calibration and verification process. If so, start with data from the simplest area (mostly directly connected paved areas and roofs, with little unpaved areas). This area probably represents commercial roofs and parking/storage areas alone. Therefore, these areas will be calibrated first, before moving on to more complex areas. The most complex areas, such as typical residential areas having large

expanses of landscaped areas and most of the roofs being disconnected from the drainage areas, should be examined last.

4. Carefully prepare the WinSLAMM input file describing the watershed area and a rain file for the specific rains that occurred during the monitoring period. If rains occurred during the monitoring period that were not monitored, they must also be included in the rain file. It would be a good idea to include rains for about a month preceding the first monitored event because WinSLAMM is a quasi-continuous model and some preceding time is needed to reach equilibrium conditions before the first monitored event. It will also be helpful to prepare another special rain file to be used in determining the relative sources of runoff (and pollutants). This rain file (could be named SOURCE.RAN) should include about 12 rains spaced about two weeks apart, containing the following rain depths (sorted from small to large rains) and durations (modify durations based on typical durations for these rain depths for the area of interest):

0.01 inches	3 hours
0.05	7
0.10	8
0.25	10
0.50	12
0.75	14
1.0	14
1.5	14
2.0	14
2.5	14
3.0	14
4.0	14

5. Run the created watershed file for the two rain files, without any additional pollutants selected, using the available RUNOFF.RSV file and using the outfall total (at least) output option for the actual rains and the source area, by rains, output option for the source rain file. Compare the predicted runoff depths (in inches) with the measured runoff depths (in inches) for the monitored events by creating a scatter plot of observed vs. predicted runoff values. Calculate the percentage runoff depth errors: 100 x (observed-predicted)/observed, and plot these against the observed rain depths. The desired pattern for the observed vs. predicted runoff depth plot is a 45 degree line, with little deviation. The desired pattern for the residual error plot is an even, narrow band over the range of observed rain depths, centered on the zero residual error horizontal line. Also calculate the sum of the observed and predicted runoff depths for all monitored events. The percentage difference in the sum of depths should be small.

If you are satisfied with these analyses, then no changes are to be made to the RUNOFF.RSV file. However, some improvement is usually possible. The overall sum runoff error indicated the general severity of the problem, but other information needs to be used to identify which source areas for which rains need to have their Rv values modified.

The model run using the SOURCE.RAN file is important in directing where the changes should be made. This run contains the percentage contribution of runoff for each rain, for each source area. This shows where WinSLAMM is generating the runoff for the different rain depths. It is doubtful if the monitored events cover the wide range of rains contained in this special rain file. Therefore, only look at the range of predicted data covering the actual monitored rains.

If a constant percentage bias occurs (unlikely) over the range of events monitored, then modify the Rv values in the RUNOFF.RSV file for the contributing source areas for the range of rains monitored. However, the residual error plot probably shows a bias, with some portions of the rain distribution having greater problems than others. It is therefore possible to divide the residual error plot into different rain depth ranges, corresponding to different amounts of correction needed. Each rain depth range also has different source contributions. Therefore, Rv corrections can be made to each source area for different rain ranges. It is probably best to start with the smallest rains where the directly connected impervious areas have the greatest influence, then go to the largest rains where runoff from the soil dominates. It is possible to create a simple series of simultaneous equations to solve for the changes to be concurrently made, but manual changes are typically adequate. After the changes are made, it is necessary to plot the new Rv values for each source area against rain depth and to smooth the resulting relationships to remove any discontinuities. After these smoothing changes are made, then re-run the program using the new *.RSV file and review the results. It may be necessary to repeat this process a few times to become satisfied that no further improvements are possible or necessary.

6. The above process is difficult if only one watershed is available for study and if the watershed area has much disconnected paved/roof areas. The preferred approach would be to start by evaluating an area having all directly connected impervious areas and making the basic changes in the Rv values for each source area and rain, as needed. Another area (preferably similar in character) having disconnected impervious areas would then be used to verify (or change) the coefficients in the RUNOFF.RSV that reduces the Rv values if the impervious areas are disconnected. The ten different watersheds used in preparing the initial RUNOFF.RSV file allowed this more rigorous approach.

Assuming the RUNOFF.RSV file Rv values are acceptable, the disconnection coefficients can be adjusted in a similar manner using the above described residual analysis: the runoff residual errors are plotted against rain depth and changes are made to the disconnection coefficients to minimize the total and individual errors.

Particulate Solids Concentrations

The mandatory *.PSC file describes the particulate residue (suspended solids) concentrations for each source area (except for roads and freeway lanes, which are included in the build-up and washoff algorithms of WinSLAMM) and land use, for several rain categories. The PART.PSC file was developed and verified using source area data mostly from Toronto, Milwaukee and Birmingham during specific field tests.

SLAMM uses another file (*.PRR) to calibrate the source predictions to outfall observations because the *.PSC file contains suspended solids data for only some of the source areas, while the streets and highway lanes are directly predicted. The mandatory delivery.PRR file accounts for the deposition of particulate pollutants in the storm drainage system, before the outfall, or before outfall controls. The DELIVERY.PRR file was originally calibrated for swales, curb and gutters, undeveloped roadsides, or combinations of drainage conditions.

Initial Data Sources

The following list shows the major published sources of the particulate residue (suspended solids) data used in developing the original PART.PSC and DELIVERY.PRR files:

Bannerman, R., K. Baun, M. Bohn, P.E. Hughes, and D.A. Graczyk. *Evaluation of Urban Nonpoint Source Pollution Management in Milwaukee County, Wisconsin*, Vol. I. Grant No. P005432-01-5, PB 84-114164. US Environmental Protection Agency, Water Planning Division, November 1983. SS and pollutants from streets, commercial roofs and parking areas - Milwaukee

R. Pitt and G. Shawley. *Demonstration of Nonpoint Pollution Management on Castro Valley Creek*. Environmental Protection Agency, Water Planning Division, Washington, D.C., June 1981. SS and pollutants from many source areas - Castro Valley, CA

R. Pitt. *Urban Bacteria Sources and Control in the Lower Rideau River Watershed*, Ottawa, Ontario. Ontario Ministry of the Environment, May 1982. SS and some pollutants from some source areas- Ottawa

Pitt, R. and M. Bozeman. *Sources of Urban Runoff Pollution and Its Effects on an Urban Creek*. EPA-600/S2-82-090, U.S. Environmental Protection Agency, Cincinnati, Ohio, December 1982. SS and pollutants from many source areas - San Jose, CA

R. Pitt and J. McLean. *Humber River Pilot Watershed Project*. Ontario Ministry of the Environment, Toronto, Canada, December 1984. SS and pollutants from many source areas - Toronto

Shelley, P.E. and D.R. Gaboury. "Estimation of Pollution from Highway Runoff - Initial Results," *Conference on Urban Runoff Quality - Impact and Quality Enhancement Technology*, Henniker, New Hampshire, Edited by B. Urbonas and L.A. Roesner, Proceedings published by the American Society of Civil Engineering, New York, June 1986. SS and pollutants from highways - nationwide

Calibration Steps

The suspended solids files can only be examined and modified after the runoff file is acceptable. The *.PSC file contains suspended solids concentrations (in mg/L) for each source area and land use for different rains, except for the street areas that use explicit accumulation and washoff algorithms based on land use, street texture, and rain conditions. Highway paved lane and shoulder areas also have explicit algorithms that calculate accumulation and washoff of suspended solids based on traffic volume and rains. Both of these areas have a great deal of research information available, allowing these direct calculations. Unfortunately, other source areas have little research data available to allow direct predictions of suspended solids runoff concentrations. This file is therefore used to account for the "first-flush" effects observed at specific source areas. Concentrations of suspended solids at the very beginning of rains at some paved areas (especially paved parking areas) are much greater than later in the same rain. This variation is highly dependent on rain energy and SLAMM uses a similar relationship to describe suspended solids variations for different rain depths. These data are based on observed conditions at the source areas. Runoff from some source areas (especially roofs and landscaped areas) typically do not indicate major concentration changes for different rains.

The first calibration steps are associated with QA/QC checks and observing trends in predicted vs. observed outfall suspended solids concentrations, and then making needed changes:

1. This step is used if local source area data for suspended solids is available. If this data is not available, then start with the PART.PSC file and step 2.

The first step is to look at the data and see if it seems reasonable. The collected source area suspended solids concentrations need to be divided into separate categories for each source area and land use. These categories should be tested to determine if the categories are significantly different from each other. The easiest way to visualize these relationships is by using grouped boxed plots, sorted by median concentrations. If the boxes are offset by at least the 25% and 75% values, then they are generally significantly different at the 95% confidence level. What is likely, however, is that the groups show a gradual trend, with extreme groups different from each other and the other central groups showing generally overlapping distributions. The extreme groups may be roof runoff (for the low concentrations) and landscaped area runoff (for the high concentrations). The other groups (parking areas, streets, walks, etc.) area probably have more closely related suspended solids concentrations.

A two-way ANOVA test can be conducted to determine if there is any significant difference between the source area categories or between the land use categories. The test also determines if the combination of source area and land use combined affects the categories. ANOVA doesn't specifically identify which sets of data are different from any other. A multiple comparison procedure (such as the Bonferroni *t*-test) can be used to identify significant differences between all cells in the 2-way matrix if the ANOVA finds that a significance difference exists. Both of these tests are parametric tests and require that the data be normally distributed. It may therefore be necessary to perform a log-transformation on the raw suspended solids data. These tests will identify differences in sample groupings, but similarities (to combine data) are probably more important to know. The grouped box plots, again, will be most helpful, in addition to possibly conducting a cluster analysis to identify natural groupings of the data.

Combine the data into fewer groupings (such as all paved parking areas for commercial and industrial areas, another group for all roofs, regardless of land use, and another for all landscaped area runoff). The data in each of these new groups should be plotted as suspended solids concentrations vs. rain depth. The resulting suspended solids concentrations for each rain depth should be included in the construction of a new *.PSC file, duplicating values for all land uses and source areas that were combined based on the statistical tests. If all land uses and source areas are not included in the local monitoring data, then data (unmodified) from elsewhere (including the existing PART.PSC file) can be used with caution.

2. Run the watershed description SLAMM file prepared previously, using the DELIVERY.PRR file, the calibrated *.RSV file and the two rain files (one containing the monitored events and the other being the source.RAN file) without any additional pollutants selected. Select the output option giving results for each rain, by source area. Compare the predicted to the observed suspended solids concentrations for the monitored events by creating a scatter plot of observed vs. predicted runoff values. Calculate the percentage suspended solids concentration errors: 100 x (observed-predicted)/observed, and plot these against the observed suspended solids concentrations and against rain depth for the monitored events. The residual patterns desired are as described above for the runoff calibration. Also calculate the sum of the observed and predicted suspended solids loadings (in lbs) for all monitored events. The percentage difference in the sum of loadings should be small and will indicate the general magnitude of the changes needed. It is likely that the largest discrepancies in suspended solids concentrations will be associated with small rain depths (SLAMM will probably over-estimate the concentrations), while the differences for the larger rains will be smaller.

The calibration of WinSLAMM for the suspended solids concentrations and loadings will mostly be accomplished by modifying the DELIVERY.PRR file. This file accounts for the reduction of suspended solids concentrations for small rains because of deposition of these solids along the drainage path, from the source area (where the *.PSC associated concentrations were measured) to the outfall. Grass swales, undeveloped roadsides, and flat curbs and gutters have relatively slow runoff velocities and lower carrying capacities of sediment than flows in steeper areas and smoother gutters. The differences are most pronounced for the smaller rains than for larger rains where the velocities are all much greater, corresponding to much greater sediment carrying capacities.

Since the *.PRR file adjusts the delivery of the suspended solids for the whole watershed combined (for the drainage system type) the SOURCE.RAN file results won't be helpful in making changes to this files. However, if changes need to be made to the *.PSC file, the results from the model run using this rain file will be very helpful. This run contains the percentage contribution of suspended solids for each rain, for each source area. This shows where SLAMM is generating the suspended solids for the different rain depths. Again, only look at the range of predicted data covering the actual monitored rains.

If a constant percentage bias occurs (unlikely) over the range of events monitored, then modify all of the delivery fractions by the same amount. However, the residual error plot probably shows a bias, with some portions of the rain distribution having greater problems than others. As with the runoff calibration, it is possible to divide the residual error plot into different rain depth ranges, corresponding to different amounts of correction needed for suspended solids loads. Each rain depth range also has different source contributions. Therefore, the delivery corrections can be made to each source area for different rain ranges. After the changes are made, it is necessary to plot the new delivery values for each rain depth and to smooth the resulting relationships to remove any discontinuities. After these smoothing changes are made, re-run the program using the new *.PRR file and review the results. It may be necessary to repeat this process a few times to become satisfied that no further improvements are possible.

Pollutant Concentrations

The optional pollutant.PPD file describes the particulate pollutant strengths related to particulate residue and describes the filterable pollutant concentrations for each source area for each land use. This file is not needed if only runoff volume and particulate residue calculations are desired. This file also contains the COV values for each pollutant for Monte Carlo simulation in SLAMM. The POLL.PPD file was developed and verified using source area data from Toronto, Milwaukee and Birmingham during specific field tests. The following list shows the major published sources of the pollutant characteristic data used in developing this file:

Bannerman, R., K. Baun, M. Bohn, P.E. Hughes, and D.A. Graczyk. *Evaluation of Urban Nonpoint Source Pollution Management in Milwaukee County, Wisconsin*, Vol. I. Grant No. P005432-01-5, PB 84-114164. US

Environmental Protection Agency, Water Planning Division, November 1983. SS and pollutants from streets, commercial roofs and parking areas - Milwaukee

Pitt, R. and G. Amy. *Toxic Materials Analysis of Street Surface Contaminants*. EPA-R2-73-283, U.S. Environmental Protection Agency, Washington, D.C., August 1973. SS quality from street dirt - nationwide

Pitt, R. *Demonstration of Nonpoint Pollution Abatement Through Improved Street Cleaning Practices*. EPA-600/2-79-161, U.S. Environmental Protection Agency, Cincinnati, Ohio, August 1979. SS and pollutants from streets - San Jose, CA

R. Pitt and G. Shawley. *Demonstration of Nonpoint Pollution Management on Castro Valley Creek*. Environmental Protection Agency, Water Planning Division, Washington, D.C., June 1981. SS and pollutants from many source areas - Castro Valley, CA

R. Pitt. *Urban Bacteria Sources and Control in the Lower Rideau River Watershed*, Ottawa, Ontario. Ontario Ministry of the Environment, May 1982. SS and some pollutants from some source areas- Ottawa

Pitt, R. and R. Sutherland. *Washoe County Urban Stormwater Management Program; Volume 2, Street Particulate Data Collection and Analyses*. Washoe Council of Governments, Reno, Nevada, August 1982. SS and pollutants from streets - Reno, NV

Pitt, R. and M. Bozeman. *Sources of Urban Runoff Pollution and Its Effects on an Urban Creek*. EPA-600/S2-82-090, U.S. Environmental Protection Agency, Cincinnati, Ohio, December 1982. SS and pollutants from many source areas - San Jose, CA

Pitt, R. *Characterization, Sources, and Control of Urban Runoff by Street and Sewerage Cleaning*. Contract No. R-80597012, U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, Ohio, 1984. SS and pollutants from streets - Bellevue, WA

R. Pitt and J. McLean. *Humber River Pilot Watershed Project*. Ontario Ministry of the Environment, Toronto, Canada, December 1984. SS and pollutants from many source areas - Toronto

Sartor, J.D. and G.B. Boyd. *Water Pollution Aspects of Street Surface Contaminants*. EPA-R2-72-081, U.S. Environmental Protection Agency, November 1972. SS and pollutants from streets - nationwide

Shaheen, D.G. *Contributions of Urban Roadway Usage to Water Pollution*. 600/2-75-004, U.S. Environmental Protection Agency, April 1975. SS and pollutants from streets - Washington, D.C.

Shelley, P.E. and D.R. Gaboury. “Estimation of Pollution from Highway Runoff - Initial Results,” *Conference on Urban Runoff Quality - Impact and Quality Enhancement Technology*, Henniker, New Hampshire, Edited by B. Urbonas and L.A. Roesner, Proceedings published by the American Society of Civil Engineering, New York, June 1986. SS and pollutants from highways - nationwide

Terstriep, M.L., G.M. Bender, and D.C. Noel. *Final Report - NURP Project, Champaign, Illinois: Evaluation of the Effectiveness of Municipal Street Sweeping in the Control of Urban Storm Runoff Pollution*. State Water Survey Division, Illinois Dept. of Energy and Natural Resources, Champaign-Urbana, Illinois, December 1982. SS and pollutants from streets - Champaign, IL

WinSLAMM Algorithm Documentation
Introduction

This discussion describes how the program is structured. The following subsection discusses the input data requirements of the program. The last two subsections describe how the model calculates runoff and pollutant loadings, and the output formats available.

Data Entry

The graphical user interface allows you to create, edit, and print WinSLAMM data files. This subsection discusses the kinds of information needed to create a WinSLAMM data file. This includes information on both the different source area parameters, as well as a brief discussion of the control devices available in the model. Five main areas of data are needed to run WinSLAMM. They are the “Land Uses”, the “Catchbasin or Drainage Controls”, the “Outfall Controls”, the “Other Pollutant Analysis Selection”, and the “File Name Information”, and are described in the following discussion.

Table C-21 lists the six land uses. Each one of these land uses, except Freeways, contains 14 source area types. Most of the source area types are listed more than once to account for different characteristics in a land use. The Freeways land use description has six source area types and a total of 10 available source areas. Table C-22 lists the source areas and the number of each of the source areas available in each land use.

Table C-21. SLAMM5 Land Uses

1. Residential Areas
2. Institutional Areas
3. Commercial Areas
4. Industrial Areas
5. Open Space Areas
6. Freeways

Table C-22. Source Areas

Source Area	Number Available in Each Land Use
Roofs	5
Paved Parking/Storage	3
Unpaved Parking/Storage	2
Playgrounds	2
Driveways	3
Sidewalks	2
Street Areas/Alleys	3
Large Landscaped Areas	2
Undeveloped Areas	1
Small Landscaped Areas	3
Isolated Areas	1
Other Pervious Area	1
Other Directly Connected Impervious Area	1
Other Partially Connected Impervious Area	1
Paved Freeway and Shoulder Area (F)	5
Large Turf Area (F)	1

(F) indicates available in Freeway Land Use area only

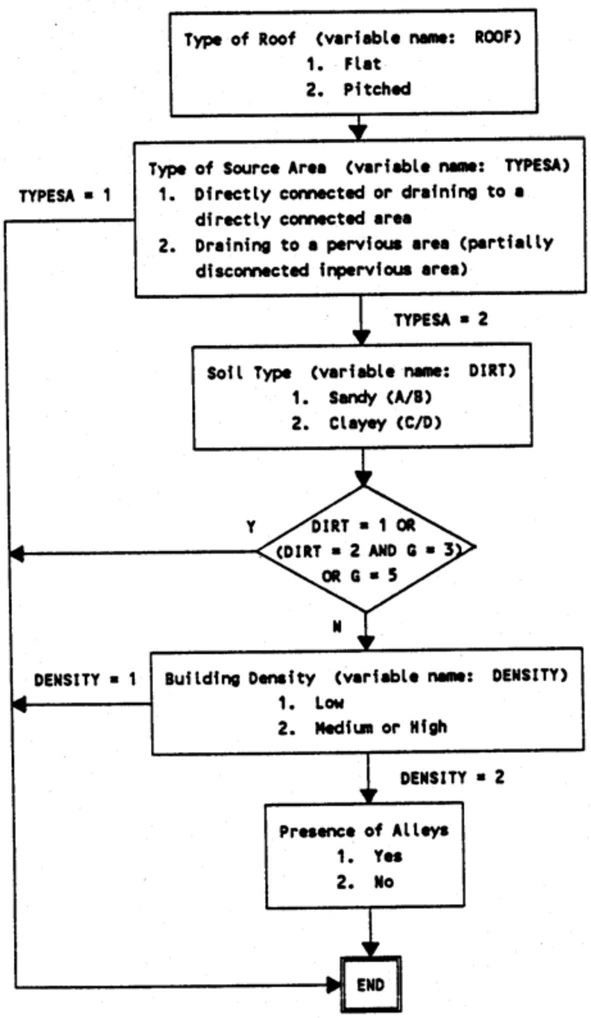
There are two kinds of information required for each source area: the source area (in acres), and specific information about the characteristics, or parameters, of the source area. The various parameters are listed in Table C-23. Each source area might need none, some, or all of this information. Figures C-2 to C-7 are flow charts that completely describe which parameters the model needs for each source area. The directly connected impervious areas are completely described by the name and no other information is required by the model for those source areas.

Table C-23. "Other Information" Needed in a Source Area

1. Type of roof - pitched or flat
2. Source area connection to pavement drainage – directly connected, or unconnected/draining to a pervious area
3. Soil type - Sandy (A/B) or Clayey (C/D)
4. Building density - low or medium/high
5. Presence of alleys - yes or no
6. Pavement texture - smooth to very rough
7. Total street length - curb-miles
8. Street dirt accumulation equation coefficients (or let SLAMM5 determine based on land use)
9. Initial street dirt loading (or let SLAMM5 determine based on street texture and street cleaning frequency)
10. Average daily traffic - vehicles/day (freeway source area only)

"Catchbasin or Drainage Controls" are runoff and particulate residue loading control devices, and include infiltration devices, grass swales, and catchbasins. These devices modify the quantity of runoff and particulate residue after they are calculated for each source area and combined, but before they reach the outfall. "Outfall Controls" are runoff and suspended solids reduction devices. They are used to reduce runoff volumes and loadings at the outfall. These devices include wet detention ponds and infiltration devices. The "Other Pollutant Analysis" section allows the user to identify the other pollutants that are evaluated by WinSLAMM.

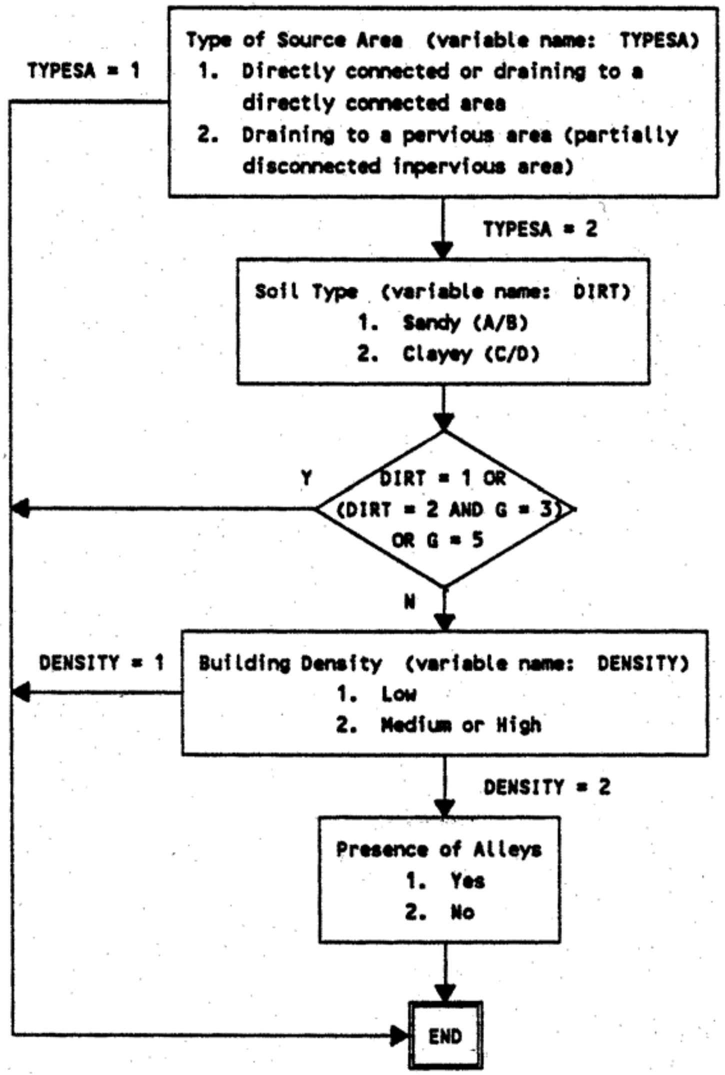
Figure C-2. Source Area Information: Roofs



G: Land Use Numbers

1. Residential Areas
2. Institutional Areas
3. Commercial Areas
4. Industrial Areas
5. Open Space Areas
6. Freeways

Figure C-3. Source Area Information: Paved parking/storage; unpaved parking/storage; playgrounds; driveways; and sidewalks



G: Land Use Numbers

1. Residential Areas
2. Institutional Areas
3. Commercial Areas
4. Industrial Areas
5. Open Space Areas
6. Freeways

Figure C-4. Source Area Information: Streets and alleys

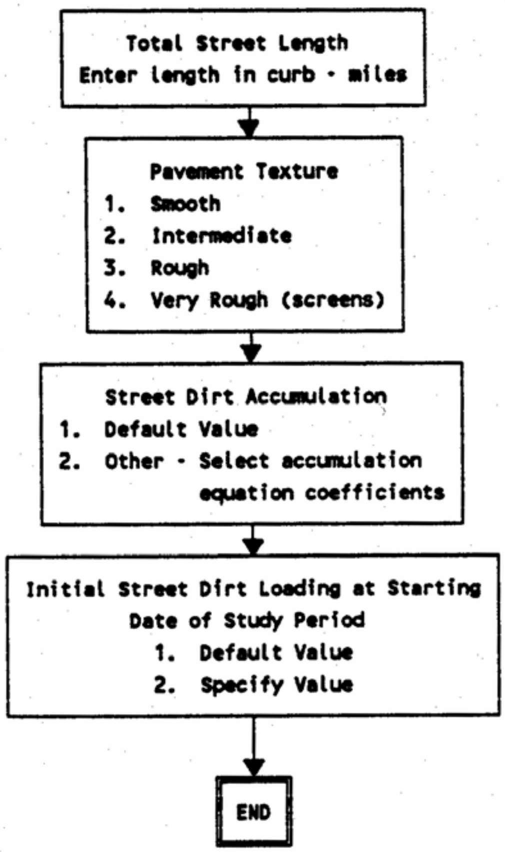


Figure C-5. Source Area Information: Unpaved areas; other pervious areas; large landscaped areas; large turf areas; and undeveloped areas

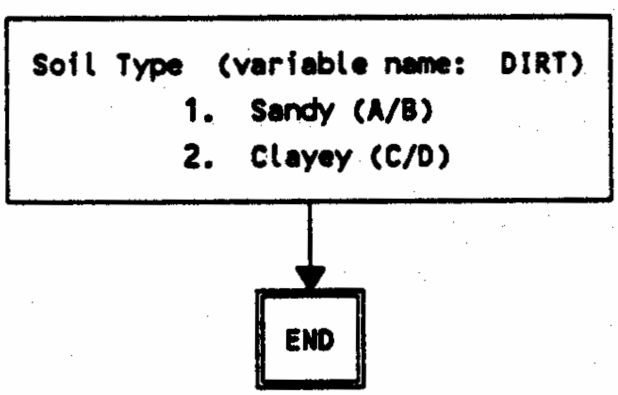


Figure C-6. Source Area Information: Other area: partially connected impervious areas

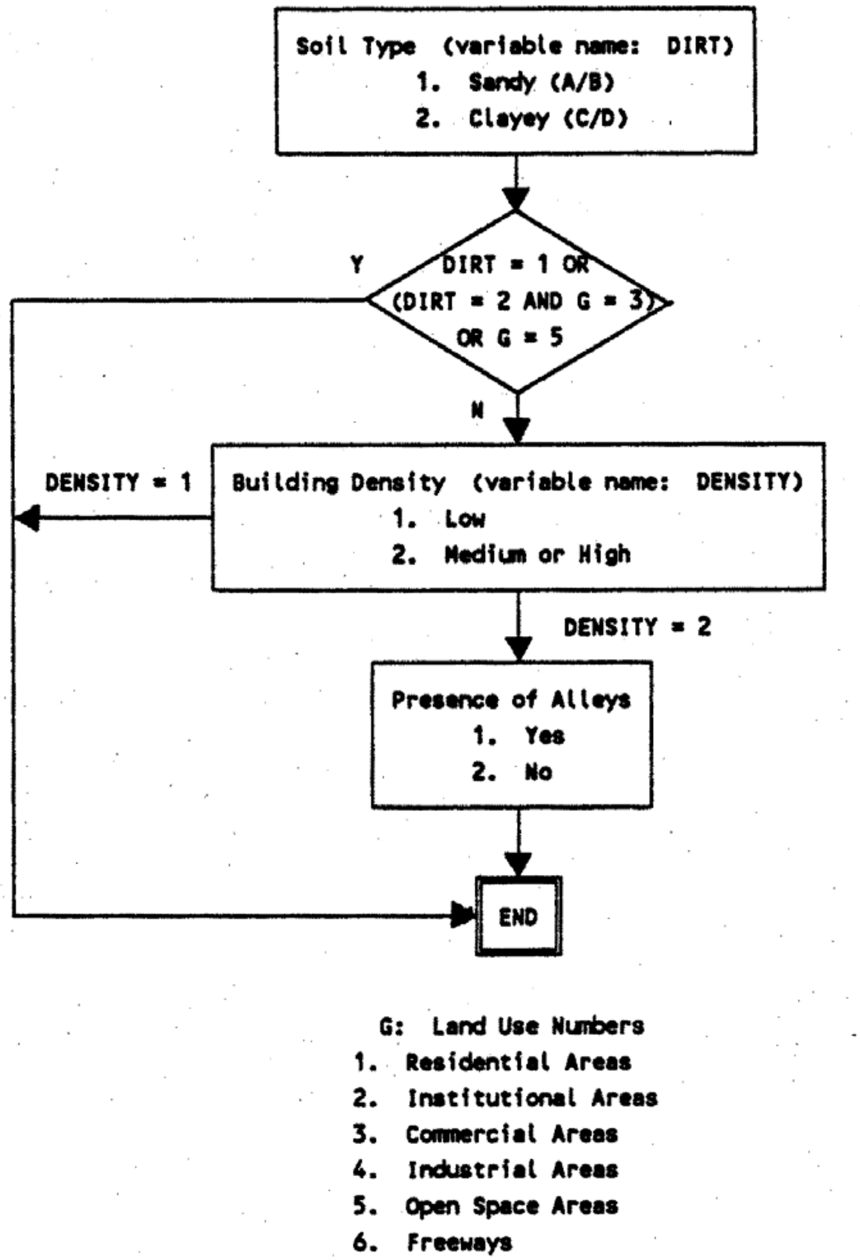
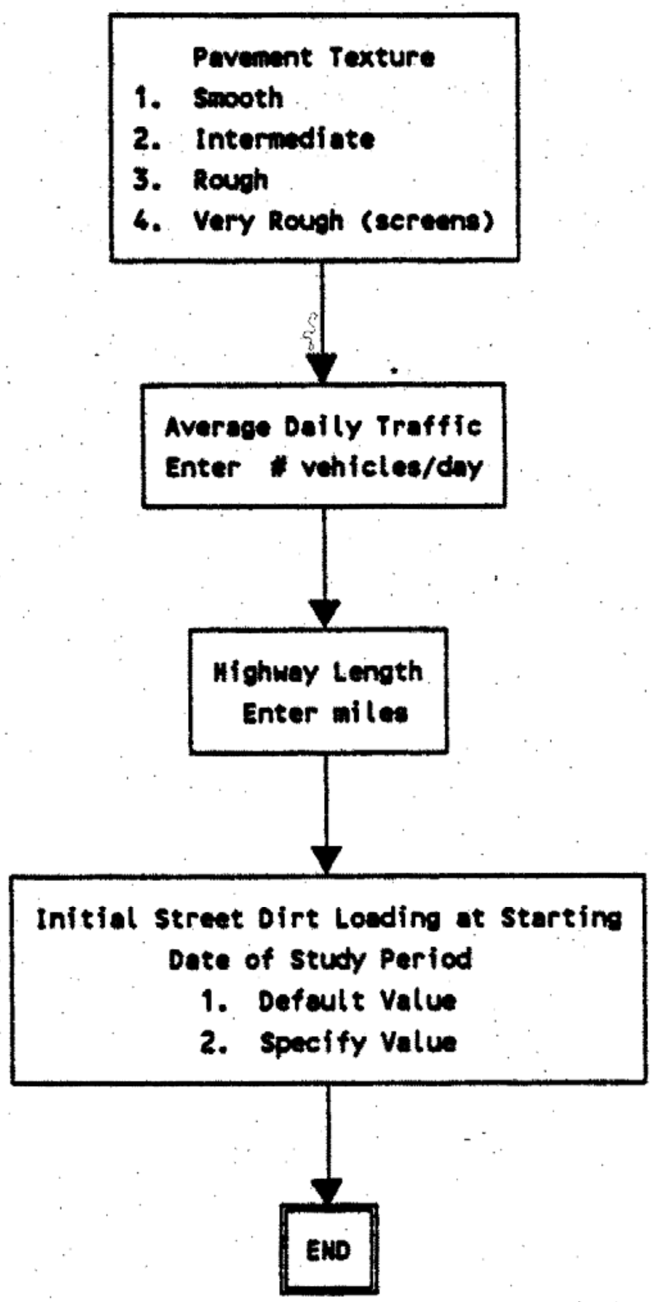


Figure C-7. Source Area Information: Paved lane and shoulder areas (freeways)



Control Devices
There are seven different major categories of control devices available within SLAMM5 to reduce runoff volume and pollutant loadings. The following paragraphs describe each device. The algorithms for each device are described in detail later in this section and summarized in Appendix D. The control devices included in SLAMM5 are:

1. Wet Detention Ponds
2. Porous Pavement
3. Infiltration Devices
4. Other Devices (source areas)
5. Street Cleaning
6. Catchbasin Cleaning
7. Grass Swales
8. Other Devices (outfall)

Wet detention ponds. The wet detention ponds are the most complex control devices in the model. The design for each pond includes an outlet device description and a stage-area curve describing the incremental pond volume. The algorithm is based on the storage-indication reservoir routing subroutine in HEC-1 and in TR-20 and is summarized by McCuen (1982). The governing storage equation is:

Inflow - Outflow = Change in Storage/Change in Time

The inflow is calculated from a triangular hydrograph developed from the depth and duration of the runoff from each rain. The outflow is calculated from the outfall structure and the combined rating curve. The connection between the two is made through a storage indication curve.

The incremental upflow velocities are calculated from the incremental pond area and outflow values. These velocities are then used to find the quantity of particulates which settle in the pond. These values are based on the particle sizes entered in the critical particle size parameter file using the Parameter Module. If any detention pond should overflow ("fail") during a rain event, the output will list the land use and source area where the overflow occurred.

Porous pavement. Porous Pavement flow volume reductions are based solely on the infiltration rate through the pavement times the duration of the event (compared to the rain intensity). The algorithm calculates the fraction of the total rain which is infiltrated into the ground by the pavement.

Infiltration devices. Infiltration device flow volume reductions are due to infiltration from both the bottom and sides of an infiltration device. The amount of infiltration is a function of the device area and the runoff volume and duration.

Other controls. The "Other" volume and loading reduction device only allows the user to enter a fixed fraction (from 0 to 1) as a runoff volume or particulate reduction value. This fraction is not a function of any other parameter except at the outfall, where the loading reduction may be entered as a function of rain depth.

Street cleaning. Street cleaning is part of the street loading subroutine. It is applied by setting street cleaning frequencies and durations in the input module for each street source area. The subroutine assumes that there are two possible street events which could occur over time: 1) street cleaning, and 2) washoff. Street dirt accumulates during the time between each street event. Then, when the time period between any two street events is up, the algorithm makes the appropriate street cleaning or street washoff event calculation.

Catchbasin cleaning. The catchbasin cleaning routine is used immediately before the outfall calculations and removes particulate loadings from the runoff. The user must enter the size of the basin as well as cleaning dates. The device will remove solids from the indicated source areas until it is full. At that point, no more solids are removed until the device is cleaned. The solids removal process then begins again.

Grass swales. Grass swales reduce runoff through infiltration. The reduction is a function of the dynamic percolation rate, the rain duration, the volume of runoff entering the swale, and the area of the swale .

Data File Format
WinSLAMM Version 8.0 creates either one or two input data files for use in the calculation module. It will always create a file with the extension .DAT. This file includes the source area, control device (except detention pond), and parameter file name information. If there are any detention ponds used as control devices, it also creates another input data file with the extension . SDP. Version 8.1 will combine the two files into one .DAT file.

Calculation/Output Module – Calculations

Calculation/Output Module Overview

The subprograms for WinSLAMM calculations calculate the runoff volumes and particulate loadings for all source areas and at the outfall and evaluate the effects of any control devices at the source areas and at the outfall.

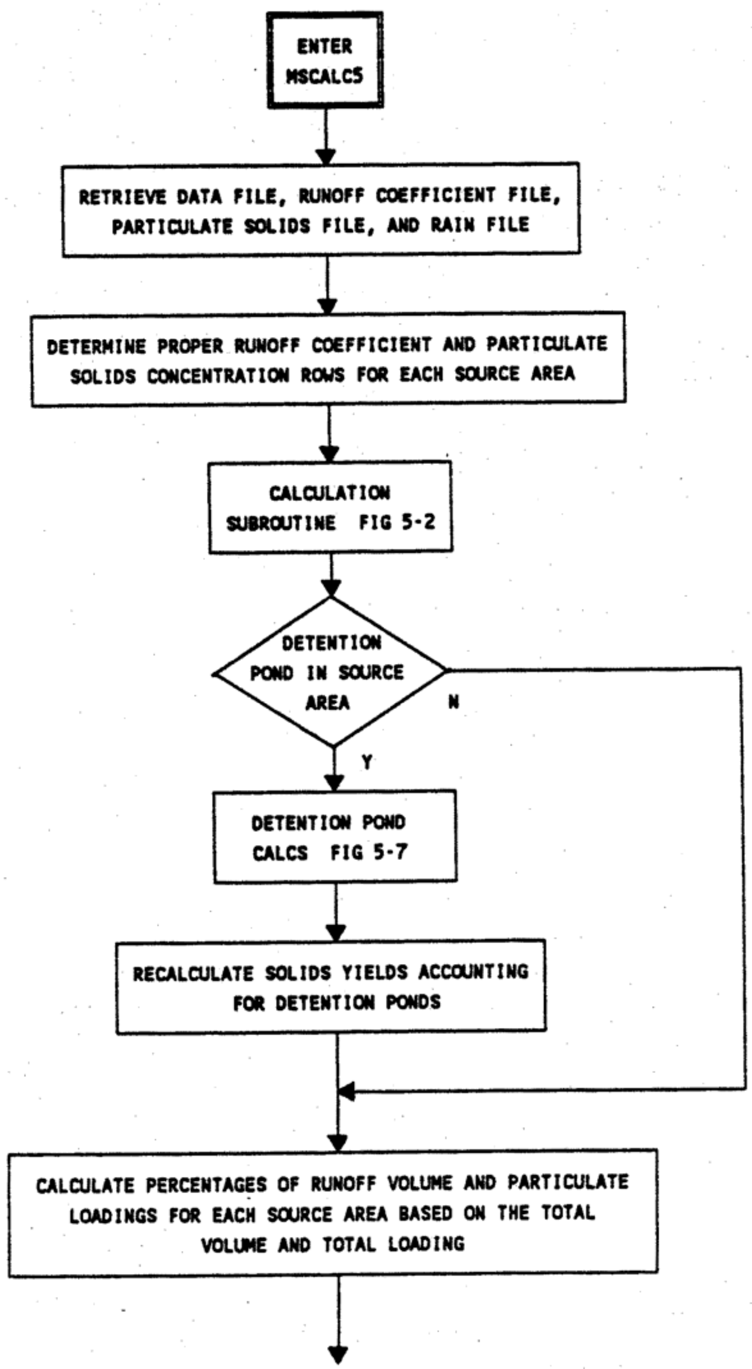
Once all calculations are completed, WinSLAMM produces a number of temporary output variables. These variables contain the runoff volumes, particulate loadings, and other information generated by the model. They are used to calculate the loadings for other pollutants (besides suspended solids) and print or save the results of the calculations in the desired format.

The following flow charts describe the calculations module algorithms and equations. Figure C-8 is the main flow chart for the calculations program of the main module. All the other flow charts in this section are connected to this main flow chart. Figure C-9 illustrates the main calculation subroutines. This subroutine calculates runoff volumes and directs the program to the appropriate control device subroutines for infiltration, porous pavement, or “other” control methods (Figures C-11 to C-13. It also routes the program to the paved lane and shoulder subroutine (Figure C-9.1) and to the street and alley loading subroutine (Figure C-9.2). The street and alley loading subroutine can route program control to either the street cleaning subroutine (Figure C-10) or the washoff subroutine (Figure C-9.4).

WinSLAMM calculates the effects of detention ponds after completing the main calculation subroutines. This process is developed as a control device in Figure C-14. After adjusting the loading results for the detention pond particulate reductions, WinSLAMM determines the effects of grass swales (Figure C-15) and catchbasins (Figure C-16). It then calculates the effects of infiltration, detention ponds, and the “other” control device (which is, for the outfall, a function of rain depth) at the outfall.

The variables in each flow chart are defined in the variable list on the facing page. The flow charts are not intended to give a detailed description of the program structure. They should, however, help the user to understand how the calculation algorithms are structured in the code. Most of the variable subscripts have been eliminated to simplify the flow chart. Double lined boxes with a RETURN inside indicate the end of a subroutine. You should return to the box that sent you to the subroutine and continue from there.

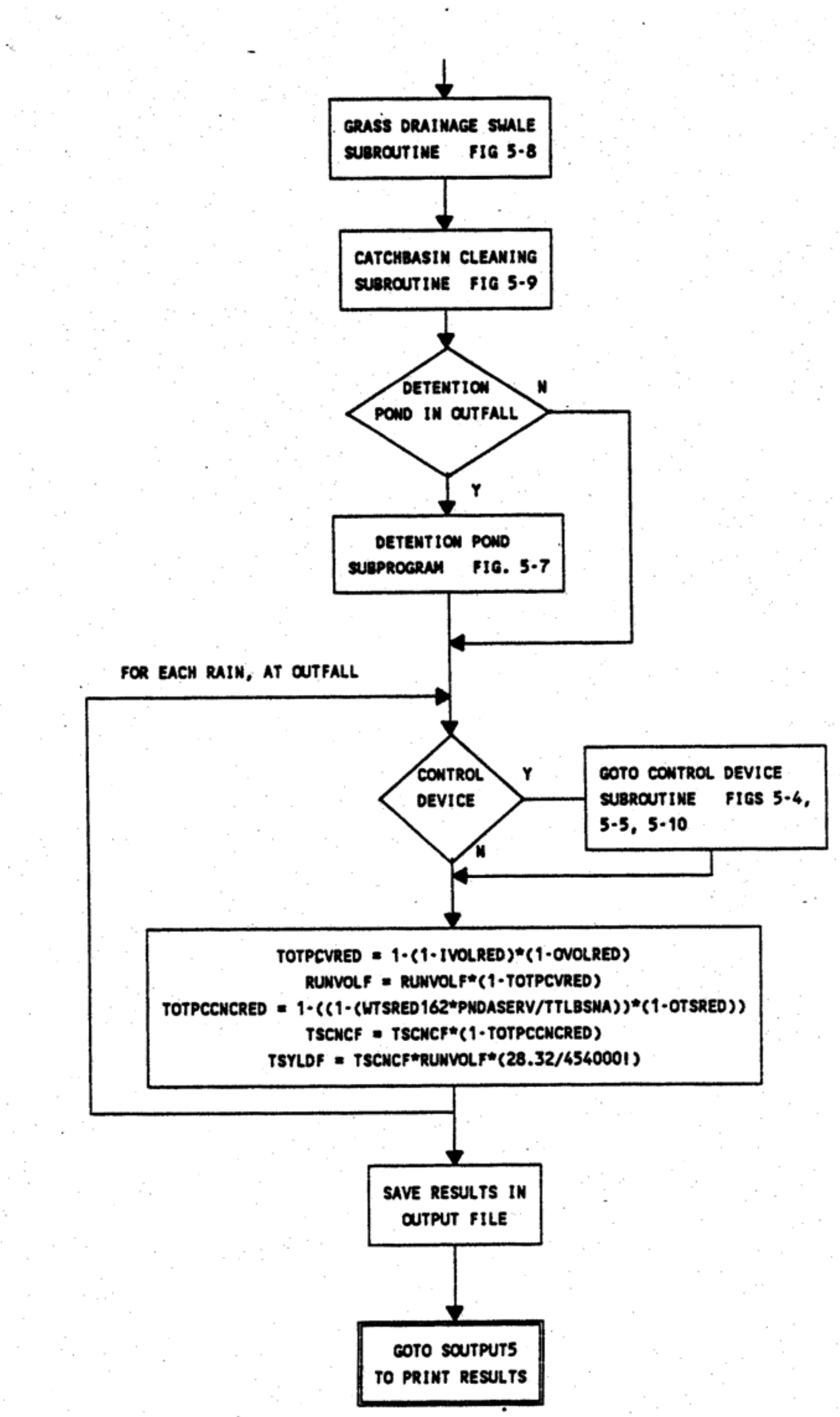
Figure C-8. MSCALC program module flow chart (referred to as Figure 5-1 in some flow charts).



Variable Definitions for Figure C-8:

IVOLRED	Infiltration device volume reduction [fraction]
OVOLRED	Other control device volume reduction [fraction]
PNDASERV	Area served by detention pond [acres]
RUNVOLF	Source area runoff volume for a rain event [cu ft]
SOUTPUT5	Output program which prints the SLAMM5 calculation module results
TOTPCCNCRED	Total percentage reduction in concentration
TOTPCVRED	Total percentage volume reduction
TTLBSNA	Total basin area, the sum of source areas 1 to 160
TSCNCF	Particulate solid concentration [mg/L]
TSYLDF	Particulate solid yield [lbs]
WTSRED162	Weighted average total particulate solid reduction at outfall. Equivalent to WTSRED(a,s) for outfall from Figure C-14

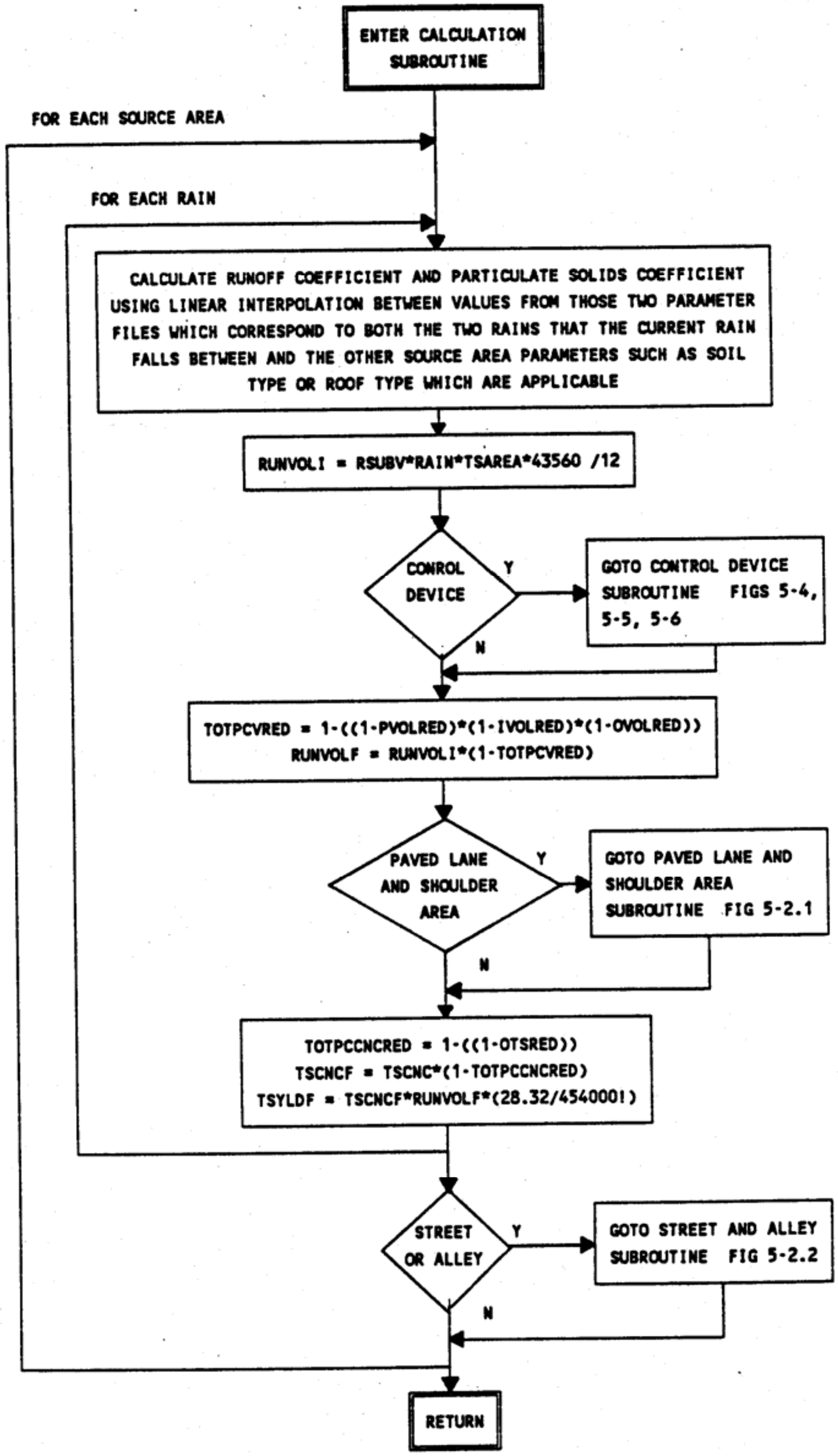
Continuation of Figure C-8 (referred to as Figure 5-1 in some flow charts).



Variable Definitions for Figure C-9:

IVOLRED	Infiltration device flow volume reduction [fraction]
OTSRED	Other control device particulate solids reduction [fraction]
OVOLRED	Other control device volume reduction [fraction]
PVOLRED	Porous pavement control device flow volume reduction [fraction]
RAIN	Rain depth [in]
RSUBV	Runoff coefficient for source area and rain depth
RUNVOLF	Source area runoff volume for a rain event [cu ft]
TOTPCCNCRED	Total percentage reduction in concentration
TOTPCVRED	Total percentage volume reduction
TSAREA	Total source area [acres]
TSCNCF	Particulate solid concentration [mg/L]
TSYLDF	Particulate solid yield [lbs]

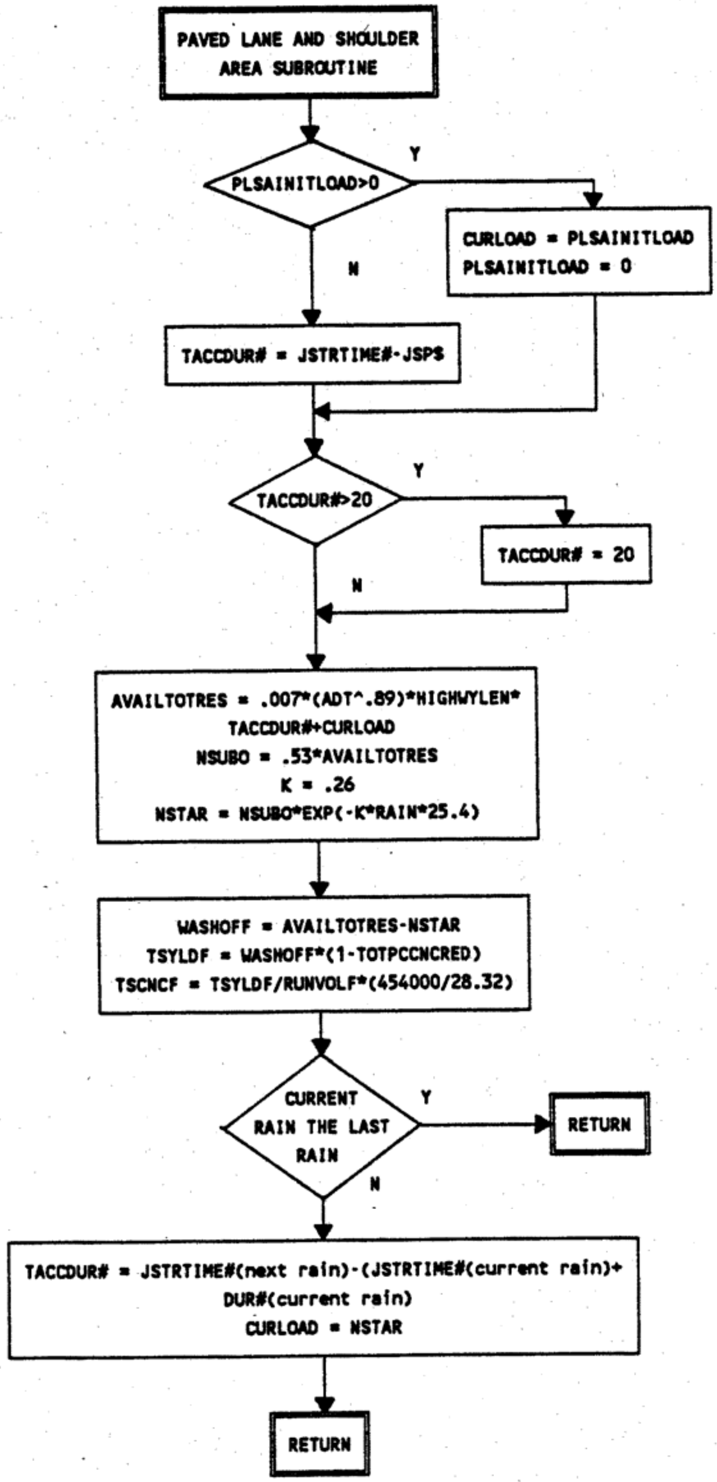
Figure C-9. Calculations subroutine (referred to as Figure 5-2 in some flow charts).



Variable Definitions for Figure C-9.1:

ADT	Average daily traffic [vehicles/day]
AVAILTOTRES	Total residue available for washoff
CURLOAD	The street loading which occurs immediately after a rain event.
DUR	Duration of rain event [days]
HIGHWYLEN	Highway length [curb miles]
JSP	The study period starting date in terms of the Julian calendar
JSTRTIME	The starting time of a rain event in terms of the Julian calendar
K	Proportionality constant used in loading calculations [l/mm]. Its a function of total street loading and rain intensity.
PLSAINITLOAD	Paved lane and shoulder area initial load [lbs]
RAIN	Rain event depth [in].
RUNVOLF	Source area runoff volume for a rain event [cu ft]
TACCDUR	Street loading accumulation time: the time between the end of one rain and the beginning of the next.
TOTPCCNCRED	Total percentage reduction in concentration
TSCNCF	Source area particulate solids concentration [mg/L]
TSYLDF	Source area particulate solids yield [lbs].
UNAVAILAFTRAIN	Total loading unavailable for washoff after a rain
WASHOFF	Street dirt contained in runoff.

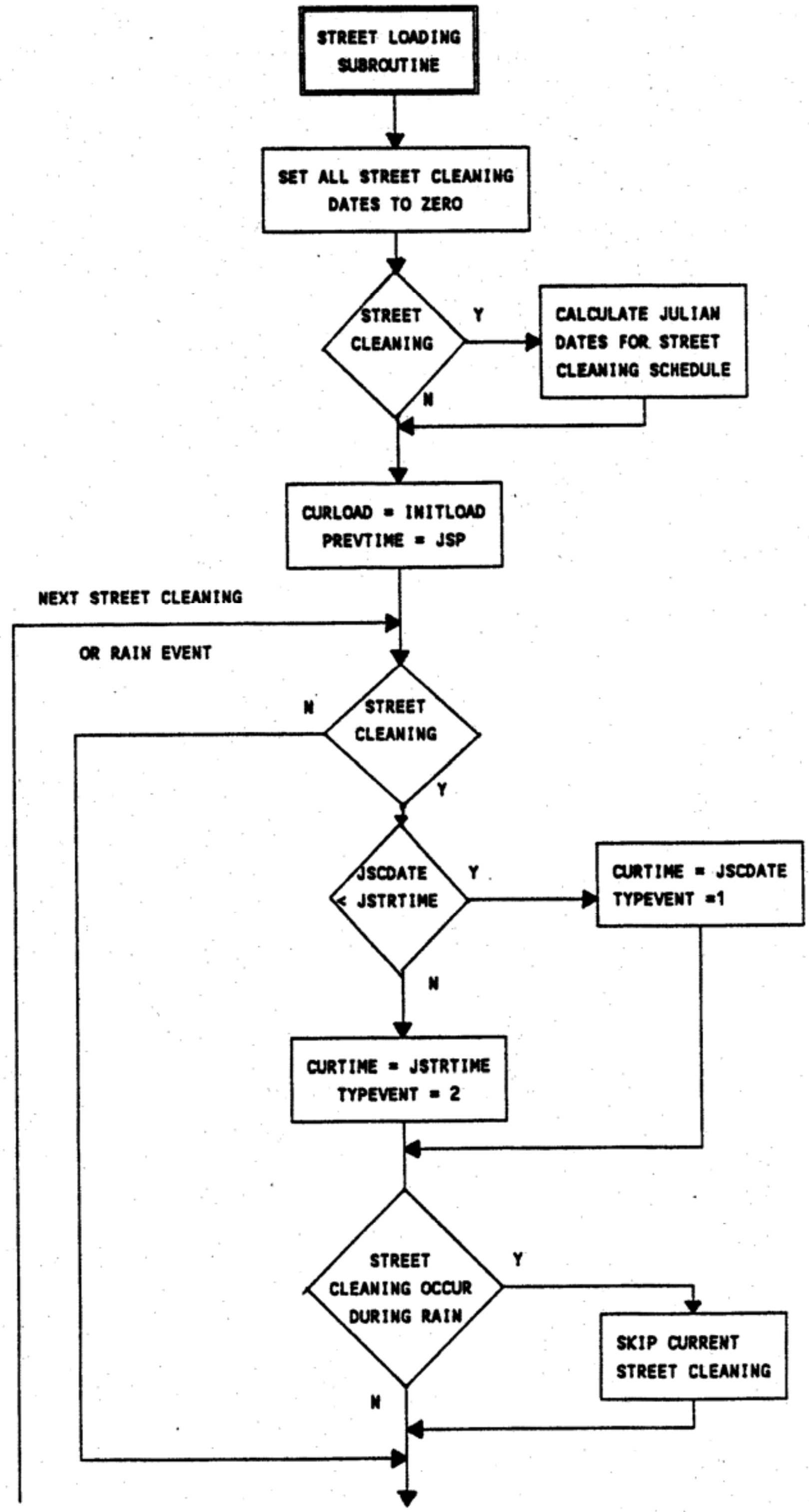
Figure-C-9.1 Paved lane and shoulder area flow chart (referred to as Figure 5-2.1 in some flow charts).



Variable Definitions for Figure C-9.2:

CURLOAD	The street loading which occurs immediately after a rain event.
CURTIME	The time of the current rain event
INITLOAD	Initial street dirt loading value [lbs/curb mi].
JSCDATE	The time a street cleaning event occurs in terms of the Julian calendar.
JSP	The study period starting date in terms of the Julian calendar.
JSTRTIME	The starting time of a rain event in terms of the Julian calendar.
PREVTIME	Julian date of the event before the current event.
RAIN	Rain event depth [in] .
TYPEVENT	Marker to indicate type of event. 1: street cleaning; 2: rain event

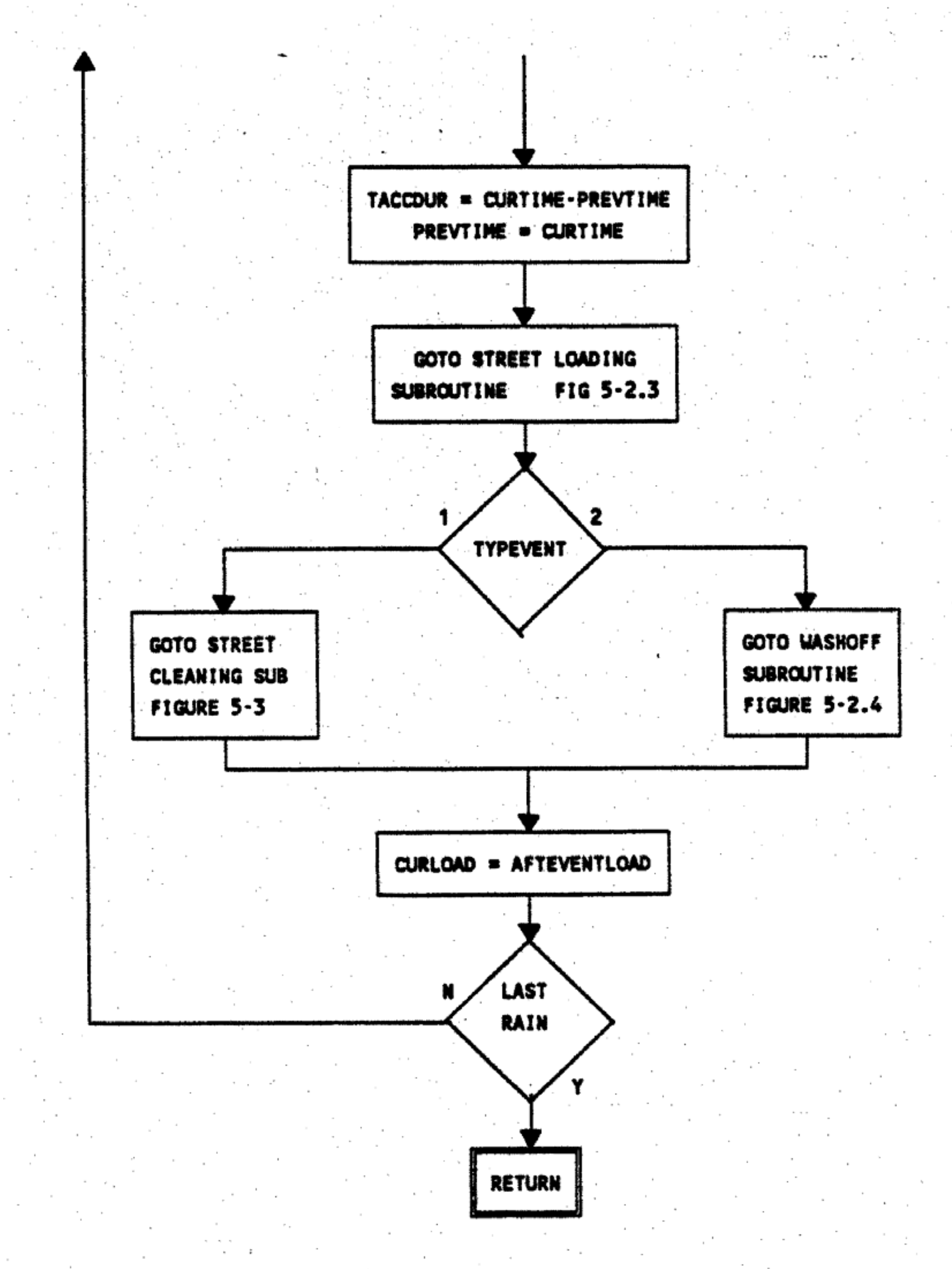
Figure C-9.2. Street and alley subroutine flow chart (referred to as Figure 5-2.2 in some flow charts).



Variable Definitions for Figure C-9.2 (Continued):

AFTFVENTLOAD	Total loading after the event [lbs].
CURLOAD	The street loading which occurs immediately after a rain event.
CURTIME	The time of the current rain event.
INITLOAD	Initial street dirt loading value [lbs/curb mi].
PREVTIME	Julian date of the event before the current event.
RAIN	Rain event depth [in].
TACCDUR	Street loading accumulation time: the time between the end of one rain and the beginning of the next.
TYPEVENT	Marker to indicate type of event. 1: street cleaning: 2: rain event.

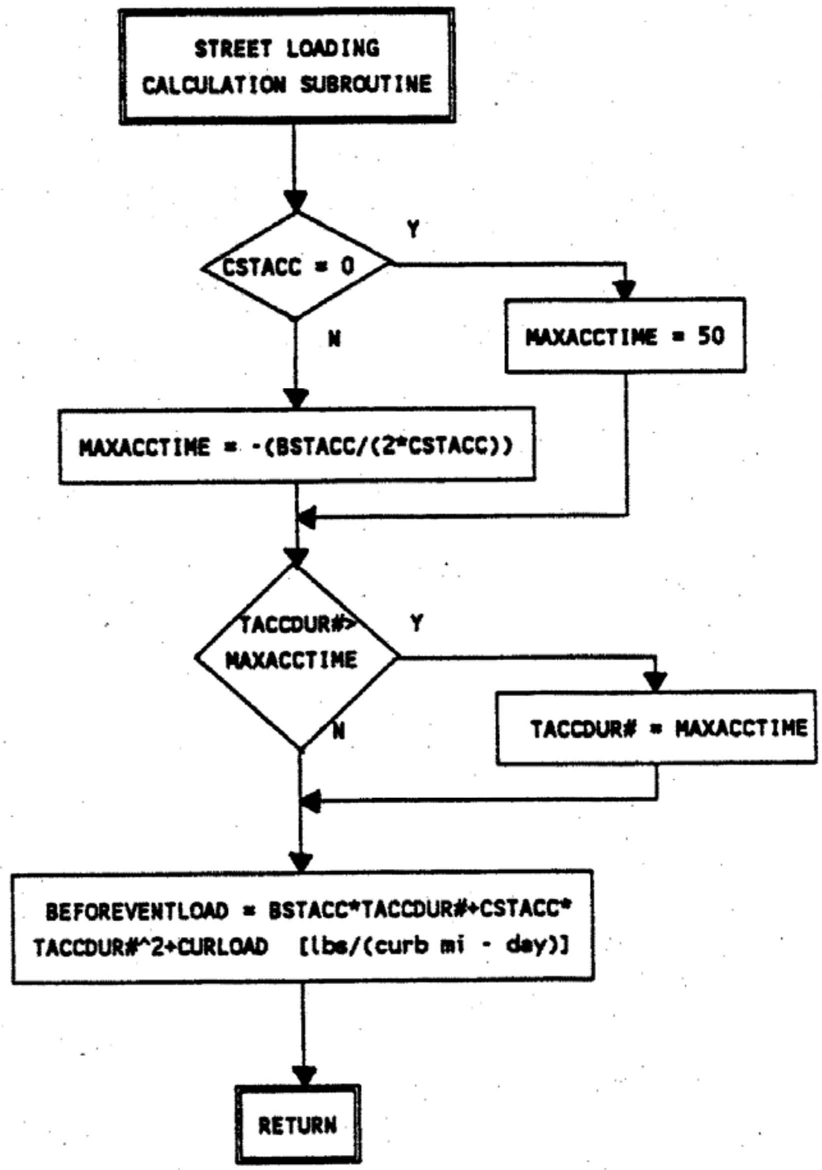
Continuation of Figure C-9.2 (referred to as Figure 5-2.2 in some flow charts).



Variable Definitions for Figure C-9.3:

BEFOREVENTLOAD	Street dirt loading [lbs/curb-mi - day] on the street immediately before the rain or street cleaning event.
BSTACC	First order coefficient in quadratic equation describing street dirt accumulation (y=ASTACC + BASTACC*x + CASTACC *x*x)
CSTACC	Second order coefficient in quadratic equation describing street dirt accumulation (y=ASTACC + BASTACC*x + CASTACC *x*x)
CURLOAD	The street loading which occurs immediately after a rain event.
MAXACCTIME	Maximum allowable time for street dirt loading accumulation. Equation is the derivative of the loading equation that calculated BEFORAINLOAD.
TACCDUR	Street loading accumulation time: the time between the end of one rain and the beginning of the next.

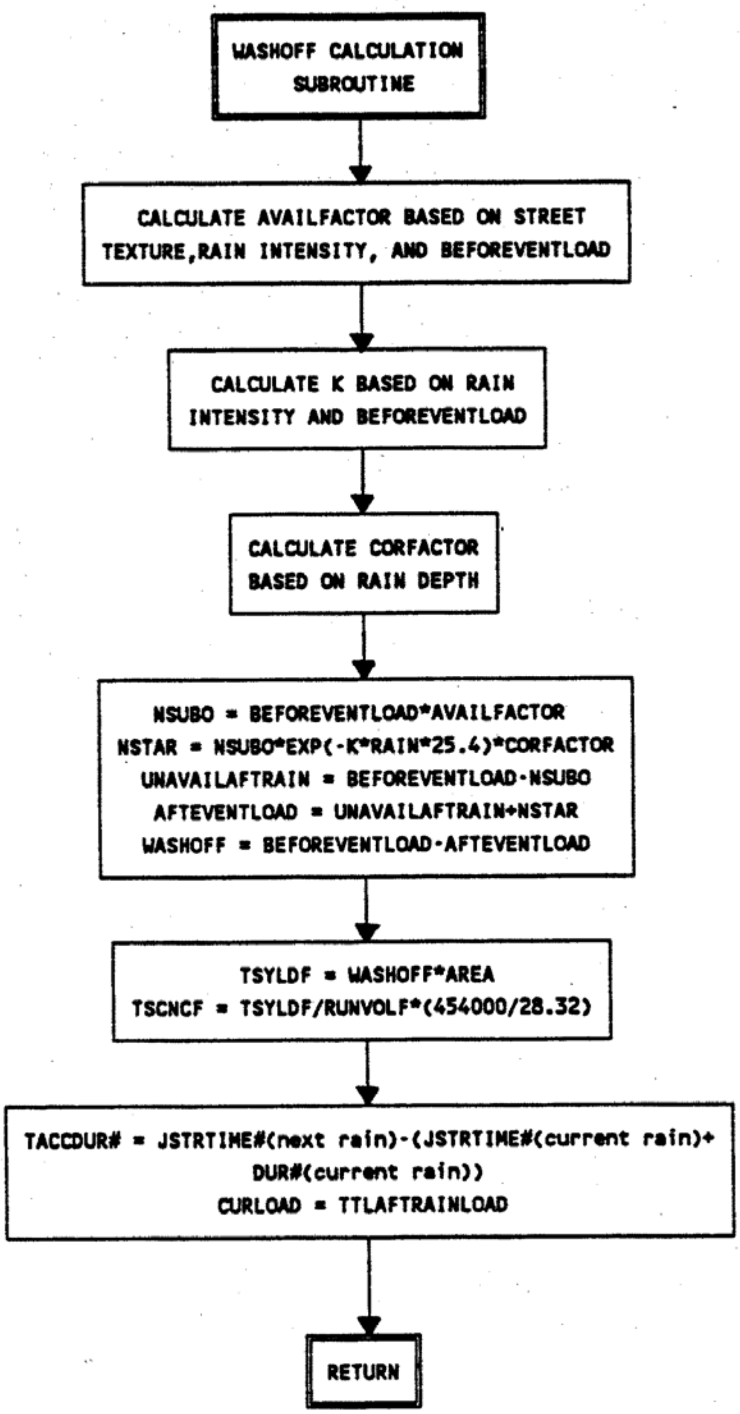
Figure C-9.3. Street dirt loadings calculation subroutine (referred to as Figure 5-2.3 in some flow charts).



Variable Definitions for Figure C-9.4:

AFTEVENTLOAD	Total loading on the street after the event [lbs].
AREA	The length of curb in a street (curb-mi/acre). If there are 2 miles of street per acre of land, then there are 4 curb-miles per acre. If the street is divided by an island, then there area 8 curb-miles per acre.
AVAILFACTOR	Availability factor which makes the initial adjustment on the street loading value immediately before the rain. It is calculated as a function of street texture, rain intensity, and street loading.
BEFOREVENTLOAD	Street dirt loading [lbs/(curb-mi)] on the street immediately before the rain or street cleaning event.
CORFACTOR	Correction factor to adjust street dirt washoff for short rains of relatively high duration. It is a function of street texture, rain depth, rain intensity, and street loading.
CURLOAD	The street loading which occurs immediately after a rain event.
DUR	Rain duration [days]
JSTRTIME	The starting time of a rain event in terms of the Julian calendar.
K	Proportionality constant used in loading calculations [l/mm]. Its a function of total street loading and rain intensity.
RAIN	Rain event depth [in].
RUNVOLF	Source area runoff volume for a rain event [cu ft]
TACCDUR	Street loading accumulation time: the time between the end of one rain and the beginning of the next.
TSCNCF	Source area particulate solids concentration [mg/L]
TSYLDF	Source area particulate solids yield [lbs].
UNAVAILAFTRAIN	Total loading unavailable for washoff after a rain
WASHOFF	Street dirt contained in runoff.

Figure C-9.4. Washoff calculation subroutine (referred to as Figure 5-2.4 in some flow charts).



Variable Definitions for Figure C-10:

AFTEVENTLOAD	Total loading after the event [lbs].
B	Y intercept term in first order equation describing street cleaning (y = m*x + B).
BEFOREVENTLOAD	Street dirt loading [lbs/(curb-mi)] on the street immediately before the rain or street cleaning event.
M	Slope term in first order equation describing street dirt cleaning (y = M *x + b).

Variable Definitions for Figure C-11:

DUR	Rainfall duration [days]
IDAREA	Infiltration device area [sq ft]
IDASERV	Area served by infiltration device [acres]
IDPRATE	Infiltration device percolation rate [in/hr]
IDWTOD	Infiltration device width to depth ratio
IVOLRED	Water volume reduction from infiltration device
RAIN	Event rain depth [in]
RSUBV	Runoff coefficient for source area and rain depth
TSAREA	Total source area [acres]

Figure C-10. Street cleaning flow chart (referred to as Figure 5-3 in some flow charts).

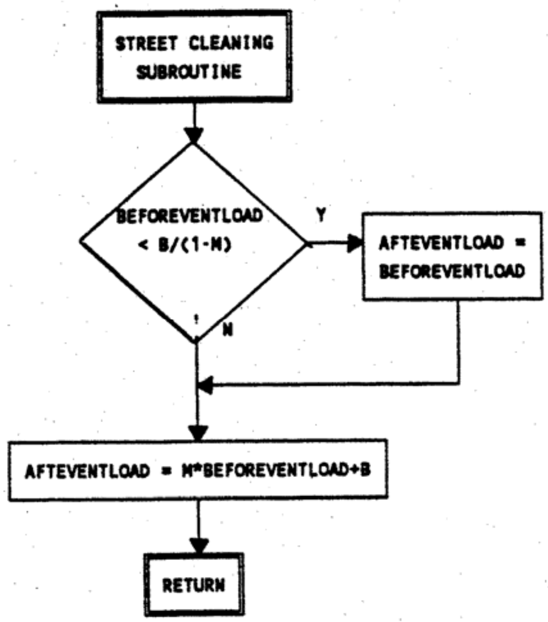
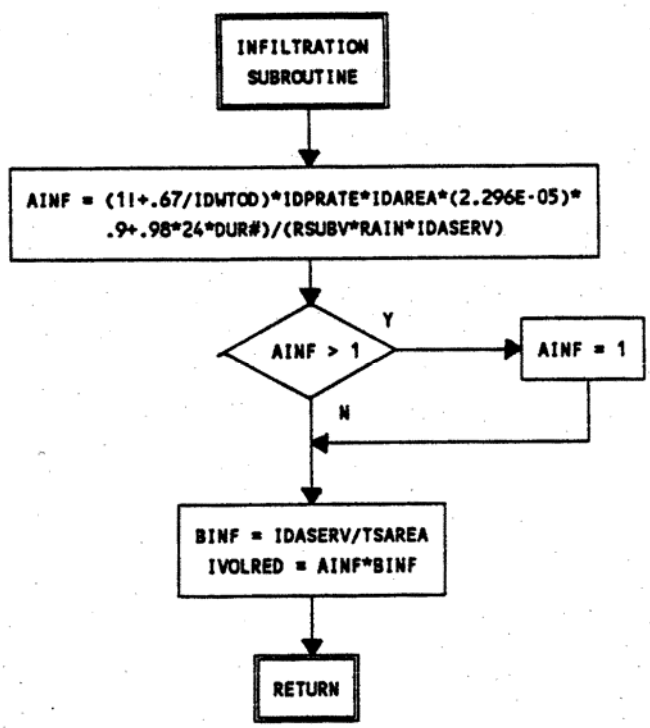


Figure C-11. Infiltration device subroutine flow chart (referred to as Figure 5-4 in some flow charts).



Variable Definitions for Figure C-12:

DUR	Rainfall duration [days]
PAVAREA	Porous pavement area [sq ft]
PAVPRATE	Porous pavement percolation rate [in/hr]
PVOLRED	Porous pavement volume reduction [fraction]
RAIN	Event rain depth [in]
TSAREA	Total source area [acres]

Variable Definitions for Figure C-13:

AOTH	Percent flow reduction for “Other” control device.
BOTH	Proportion of the total area served by the “Other” control device.
CONASERV	Area served (acres) by the “Other” control device.
FLOWRED	Percent flow reduction for “Other” control device.
OTSRED	Particulate solids reduction percentage for that part of source area served by the “Other” control device.
OVOLRED	Volume reduction percentage for the source area.
POLRED	Particulate solids reduction percentage for the source area.
TSAREA	Total source area [acres]

Figure C-12. Porous pavement subroutine flow chart (referred to as Figure 5-5 in some flow charts).

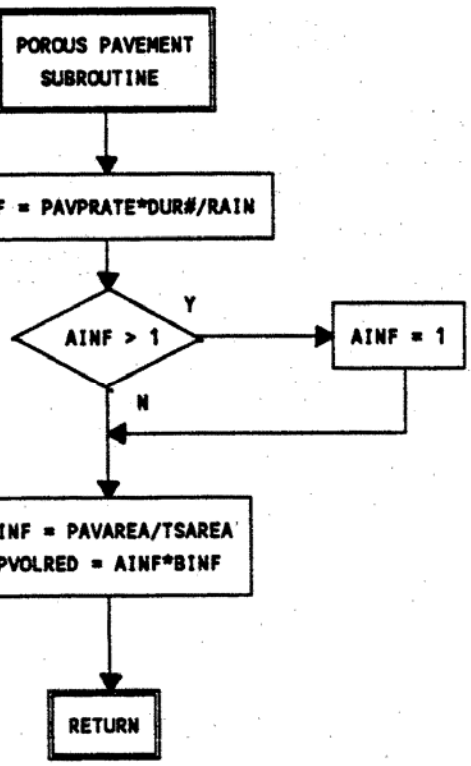
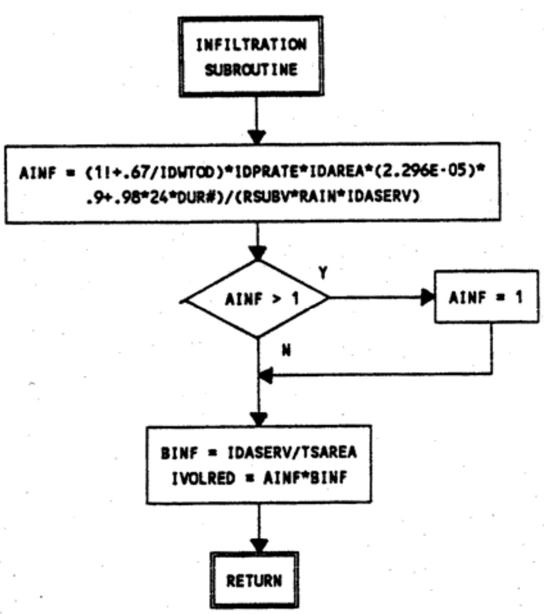


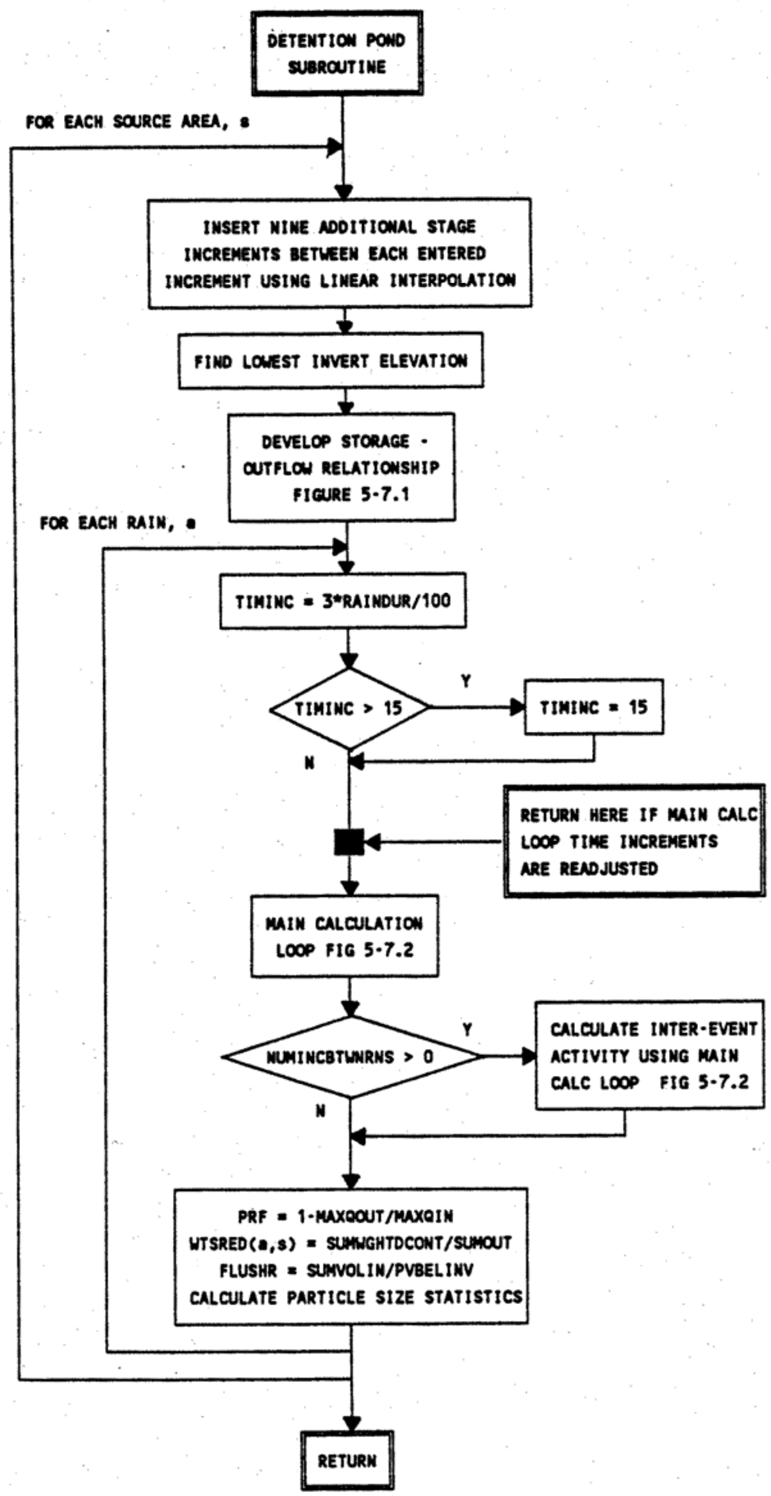
Figure C-13. Other volume and solids reduction flow chart (referred to as Figure 5-6 in some flow charts).



Variable Definitions for Figure C-14:

a	Rain number counter
FLUSHR	Flushing ratio: inflow volume/pond volume below invert
MAXQIN	Maximum event pond inflow [cfs]
MAXQOUT	Maximum event pond outflow [cfs]
NUMINCBTWNRAINS	Number of time steps for an interevent period
PRF	Peak reduction factor: 1 - (maximum pond outflow rate/maximum pond inflow rate)
PVBELINV	Pond volume below lowest invert [cu ft]
RAIN	Event rain depth [in]
RAINDUR	Event rain duration [hrs]
s	Source area number
SUMOUT	Total event outflow [cfs]
SUMVOLIN	Total event inflow volume [cu ft]
SUMWGHTDCONT	Sum of flow weighted percentage of particle sizes controlled
TIMINC	Time step increment [min]
WTSRED(a,s)	Weighted average total particulate solid reduction

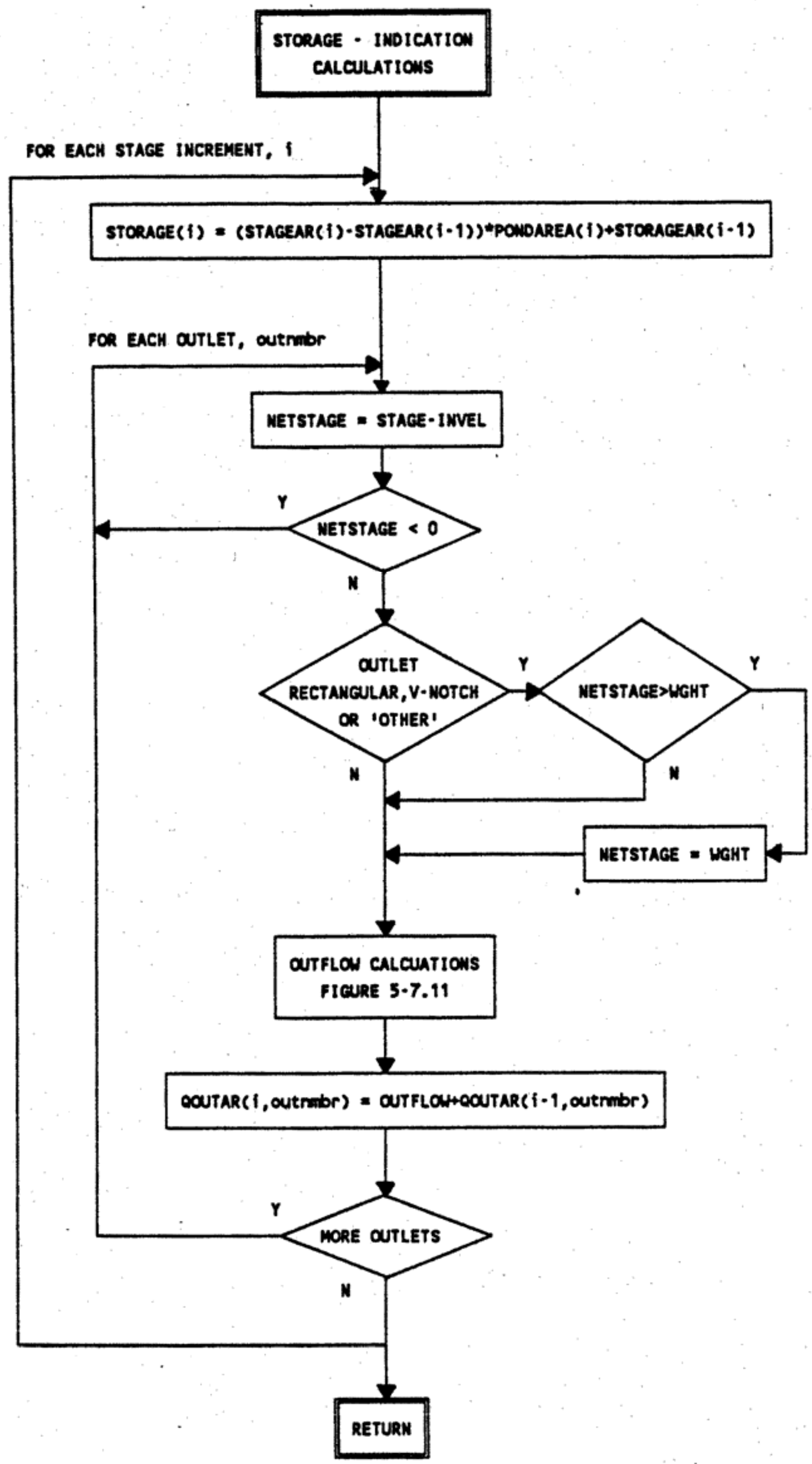
Figure C-14. Detention pond flow chart (referred to as Figure 5-7 in some flow charts).



Variable Definitions for Figure C-14.1:

i	Stage increment counter
INVEL	Invert elevation of outlet [ft]
NETSTAGE	Net stage value [ft]
OUTFLOW	Outflow [cfs]
Outnumber	Outlet number counter
PONDAREA	Pond area for a time step [sq ft]
QOUTAR	Total pond outflow from all outlets for each defined stage elevation [cfs]
STAGE	pond stage level [ft]
STAGEAR	Model or user defined stage elevation [ft]
STORAGE	Total storage volume in pond for a time step [cu ft]
STORAGEAR	Total storage volume in pond at each stage level [cu ft]
WGHT	Weir height [ft]

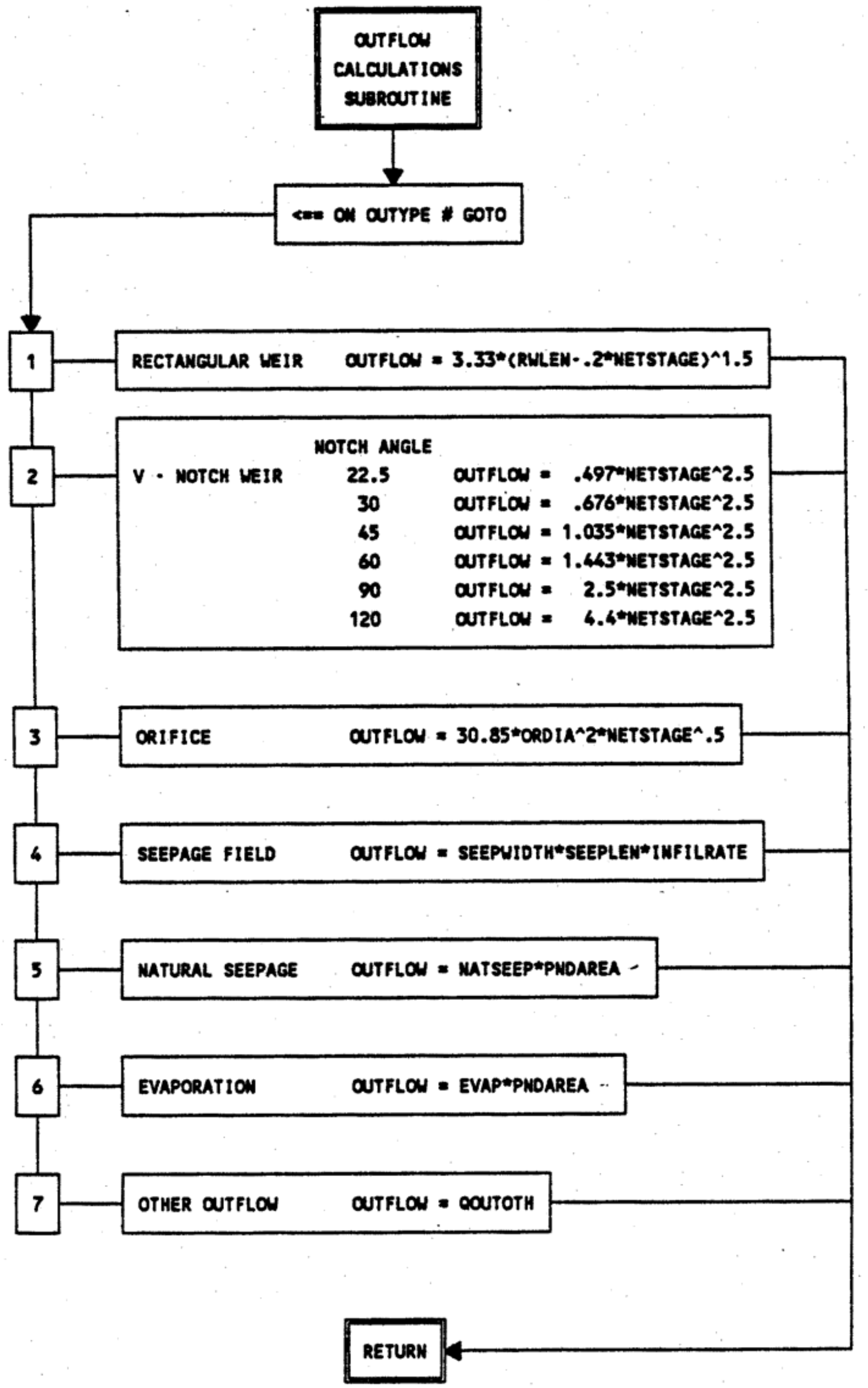
Figure C-14.1. Storage indication curve flow chart (referred to as Figure 5-7.1 in some flow charts).



Variable Definitions for Figure C-14.1.1:

EVAP	Evaporation [in/day]
INFILRATE	Seepage field infiltration rate [in/hr]
NATSEEP	Natural seepage rate for a time step [in/hr]
NETSTAGE	Net stage value [ft]
ORDIA	Orifice diameter [ft]
OUTFLOW	Outflow [cfs]
OUTYPE	Outlet type
PNDAREA	Pond area for a time step [sq ft]
QOUTOTH	User defined hydrograph outflow rate [cfs]
RWLEN	Rectangular weir length [ft]
SEEPLEN	Seepage field length [ft]
SEEPWIDTH	Seepage field width [ft]

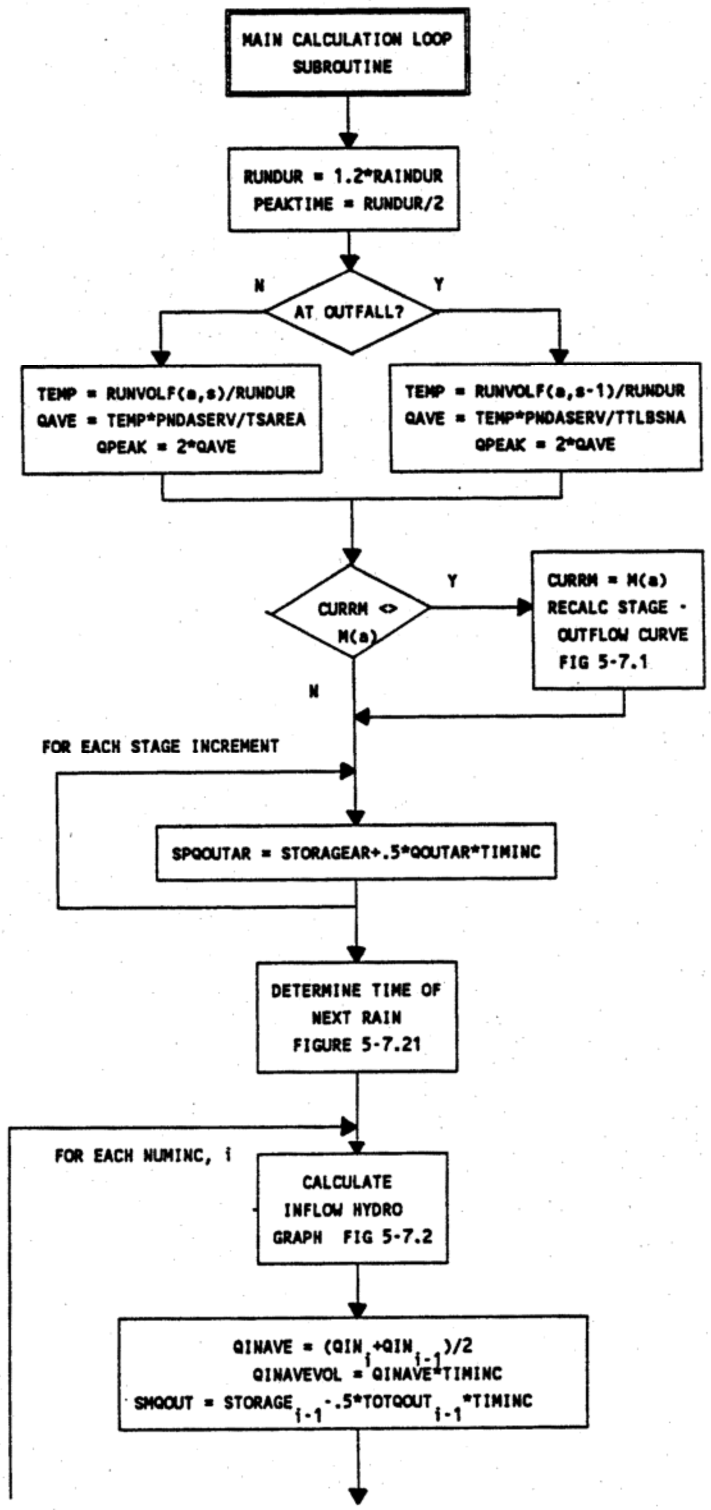
Figure C-14.1.1. Outflow calculation flow chart (referred to as Figure 5-7.11 in some flow charts).



Variable Definitions for Figure C-14.2:

a	Rain number counter
CURR	Current month
M	Month number (1 to 12)
NUMINC	Number of time step increments for an event
PEAKTIME	Time of peak inflow for an event
PNDASERV	Area served by detention pond [sq ft]
QAVE	Average event inflow rate [cfs]
QIN	Inflow for a time step [cfs]
QINAVE	Average inflow rate between two time steps [cu ft]
QINAVEVOL	Average inflow volume between two time steps [cu ft]
QOUTAR	Total pond outflow from all outlets for each defined stage elevation [cfs]
QPEAK	Peak inflow rate [cfs]
RAINDUR	Event rain duration [hrs]
RUNDUR	Event runoff duration (1.2 times rain duration)
RUNVOLF	Source area runoff volume for a rain event [cu ft]
SMQOUT	Previous time step storage volume minus previous time step outflow for current time step
SPQOUTAR	Storage plus 1/2 outflow for each stage increment
STORAGE	Total storage volume in pond for a time step [cu ft]
STORAGEAR	Total storage volume in pond at each stage level [cu ft]
TIMINC	Time step increment [min]
TOTQOUT	Total outflow per time step [cfs]
TSAREA	Total source area [acres]
TTLBSNA	Total basin area [acres]

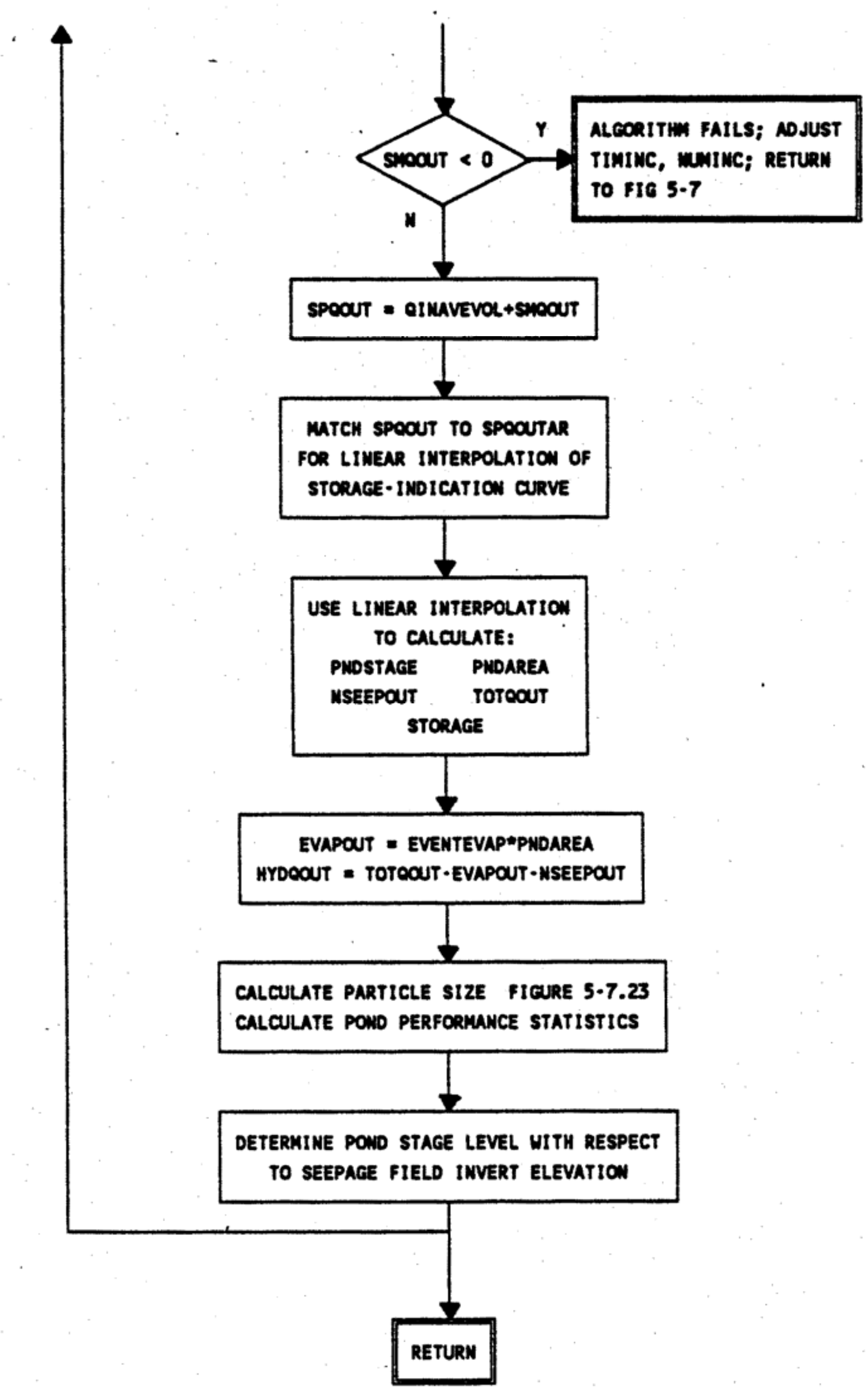
Figure C-14.2. Main calculation loop flow chart (referred to as Figure 5-7.2 in some flow charts).



Variable Definitions for Figure C-14.2 (Continued):

EVAPOUT	Outflow due to evaporation [cfs]
EVENTEVAP	Event evaporation
HYDQOUT	hydraulic outflow for a time step [cfs]
NSEEPOUT	Natural seepage for a time step [cfs]
PNDAREA	Pond area for a time step [sq ft]
PNDSTAGE	Pond stage for a time step [ft]
QINAVEVOL	Average inflow volume between two time steps [cu ft]
SMQOUT	Previous time step storage volume minus previous time step outflow for current time step
SPQOUT	Inflow volume for current time step plus SMQOUT for current time step
STORAGE	Total storage volume in pond for a time step [cu ft]
TOTQOUT	Total outflow per time step [cfs]

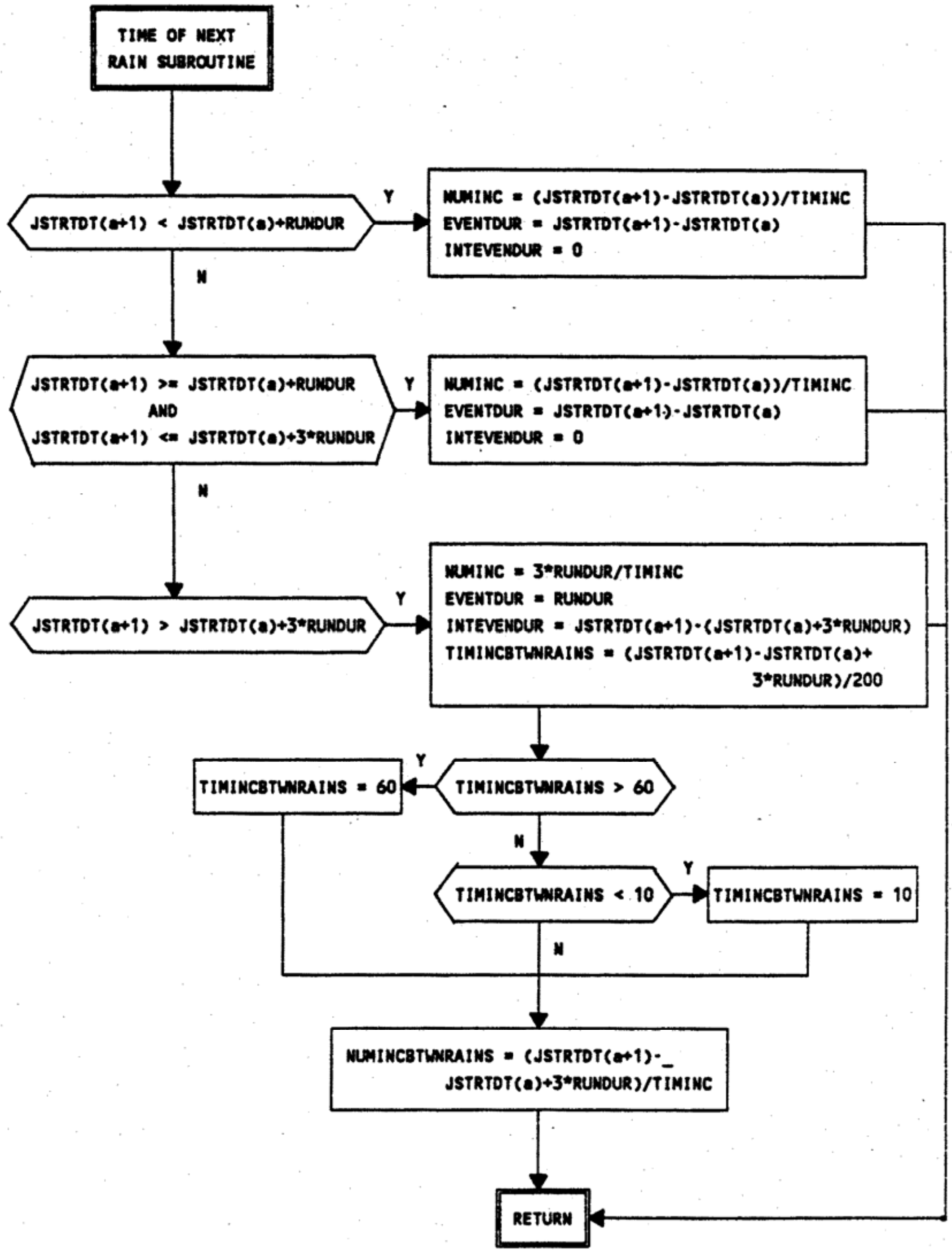
Continuation of Figure C-14.2 (referred to as Figure 5-7.2 in some flow charts).



Variable Definitions for Figure C-14.2.1:

a	Rain number counter
EVENTDUR	Event duration
INTEVENTDUR	Interevent duration time period [days]
JSTRTDT	Starting date and time for a model run (Julian calendar)
NUMINC	Number of time step increments for an event
NUMINCBTWNRAINS	Number of time steps for an interevent period
RUNDUR	Event runoff duration (1.2 times rain duration)
TIMINC	Time step increment [min]
TIMINCBTWNRAINS	Time step increment between rain events from stochastic rain file [days]

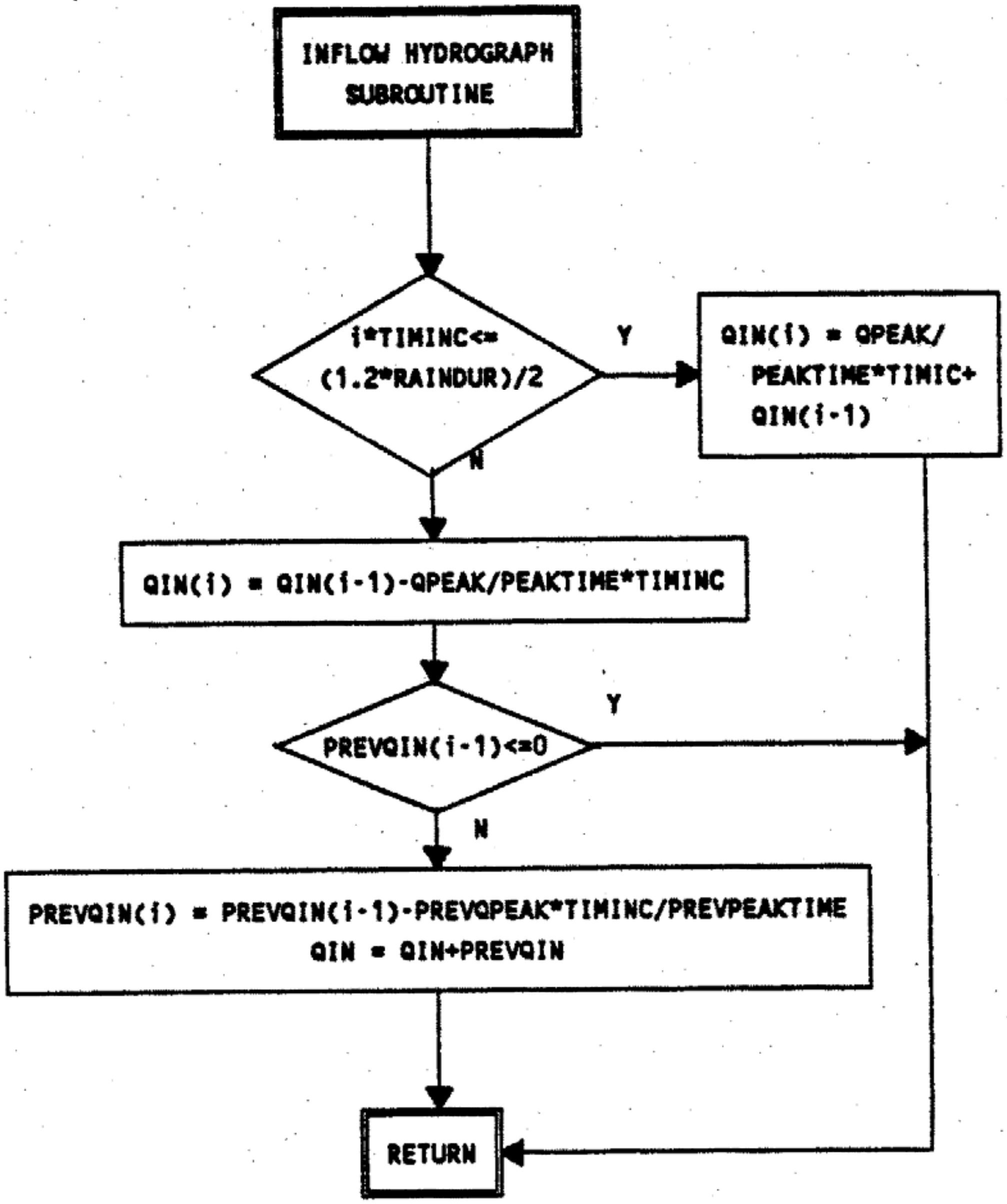
Figure C-14.2.1. Time of next rain calculation flow chart (referred to as Figure 5-7.21 in some flow charts).



Variable Definitions for Figure C-14.2.2:

i	Stage increment counter
PEAKTIME	Time of peak inflow for an event
PREVPEAKTIME	Peak inflow time used to calculate previous event inflow when a new event begins before runoff from the previous event has ended.
PREVQIN	Previous inflow value used as part of total inflow when a new event begins before runoff from the previous event has ended.
PREVQPEAK	Peak inflow value used to calculate previous event inflow when a new event begins before runoff from the previous event has ended.
QIN	Inflow for a time step [cfs]
QPEAK	Peak inflow rate [cfs]
RAINDUR	Event rain duration [hrs]
TIMINC	Time step increment [mind

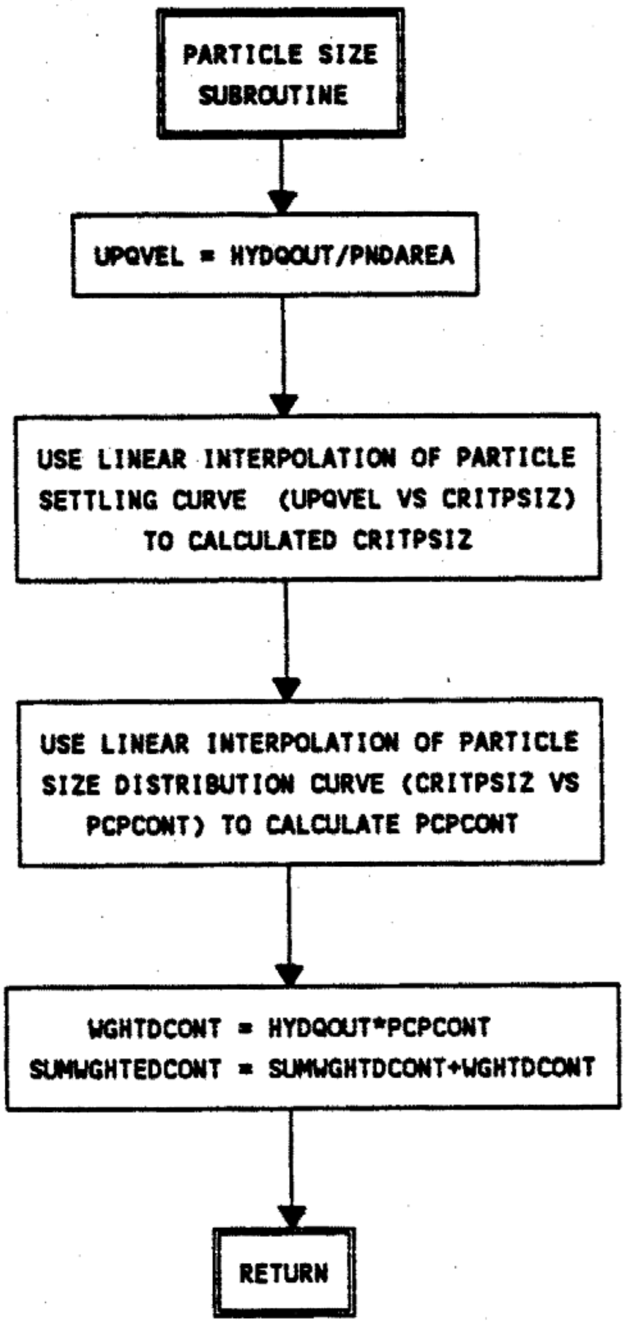
Figure C-14.2.2. Inflow hydrograph flow chart (referred to as Figure 5-7.22 in some flow charts).



Variable Definitions for Figure C-14.2.3:

CRITPSIZ	Time step critical particle size [micrometers]
HYDQOUT	hydraulic outflow for a time step [cfs]
PCPCONT	Percent particle control for a time step
PNDAREA	Pond area for a time step [sq ft]
SUMWGHTDCONT	Sum of flow weighted percentage of particle sizes controlled
UPQVEL	Upflow velocity for a time step [ft/hr]
WGHTDCONT	Flow weighted percent of particle sizes controlled for a time step

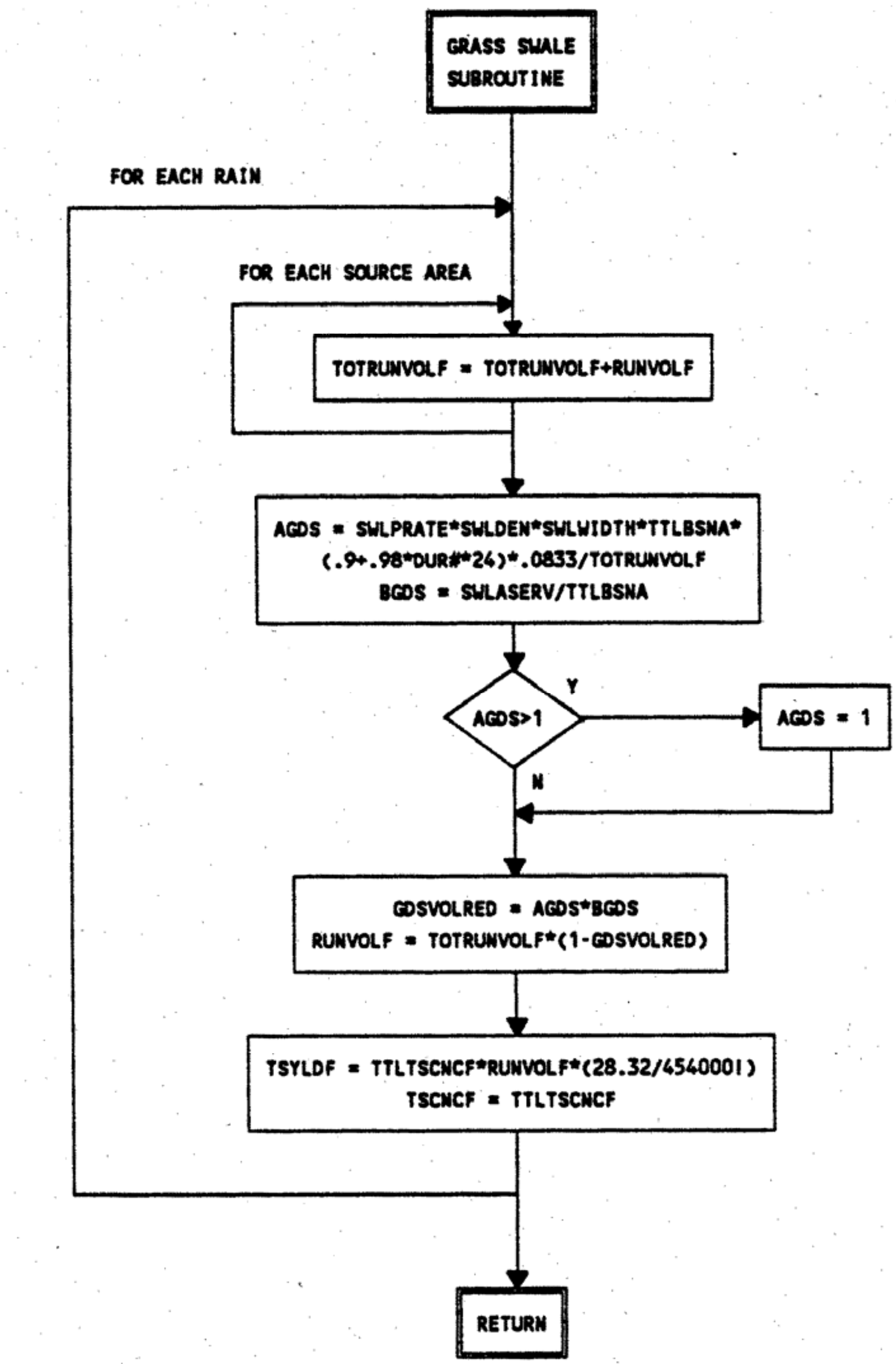
Figure C-14.2.3. Particle size calculation flow chart (referred to as Figure 5-7.23 in some flow charts)



Variable Definitions for Figure C-15:

DUR	Event duration [days]
GDSVOLRED	Grass drainage swale volume reduction [fraction]
RUNVOLF	Source area runoff volume for a rain event [cu ft]
SWLASERV	Area served by grass swales [acres]
SWLDEN	Grass swale density
SWLPRATE	Grass swale percolation rate
SWLWIDTH	Grass swale width
TOTRUNVOLF	Total runoff volume from all source areas [cu ft]
TSCNCF	Source area particulate solids concentration [mg/L]
TSYLDF	Source area particulate solids yield [lbs]
TTLBSNA	Total basin area [acres]
TTLTSCNCF	Total solids concentration from entire basin [mg/L]

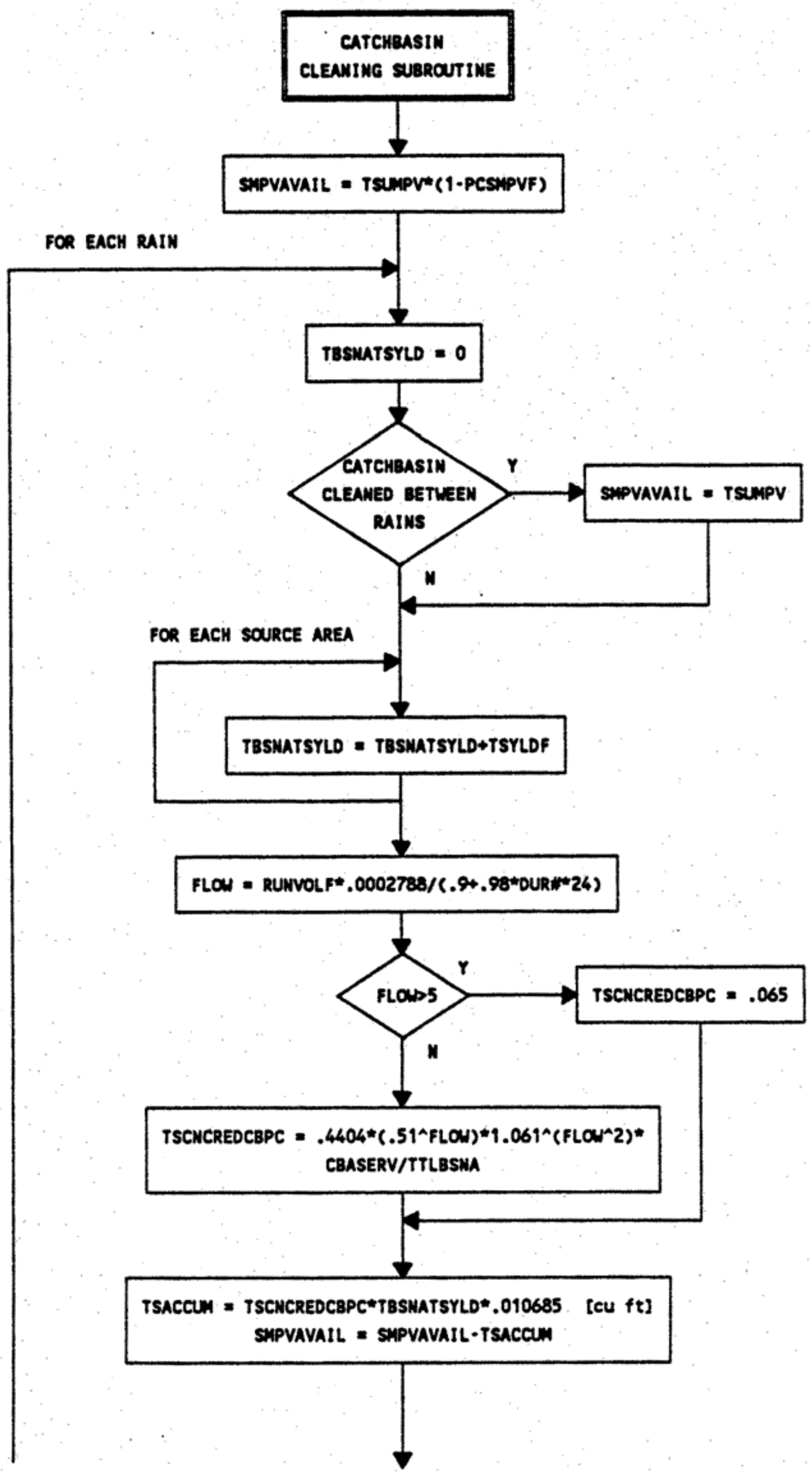
Figure C-15. Grass swale subroutine flow chart (referred to as Figure 5-8 in some flow charts).



Variable Definitions for Figure C-16:

CBASERV	Area served by catchbasin [acres]
DUR	Rain duration [days]
FLOW	Flow into catchbasin
PCSMPVF	Percent of sump volume full
RUNVOLF	Source area runoff volume for a rain event [cu ft]
SMPVAVAIL	Sump volume available for particulate solids [cu ft]
TBSNATSYLD	Total basin area particulate solids yield [lbs]
TSACCUM	Particulate solids accumulated in catchbasin [cu ft]
TSCNCREDCBPC	Percentage particulate solids reduction from catchbasin
TSUMPV	Total sump volume [cu ft]
TSYLDF	Source area particulate solids yield [lbs]
TTLBSNA	Total basin area [acres]

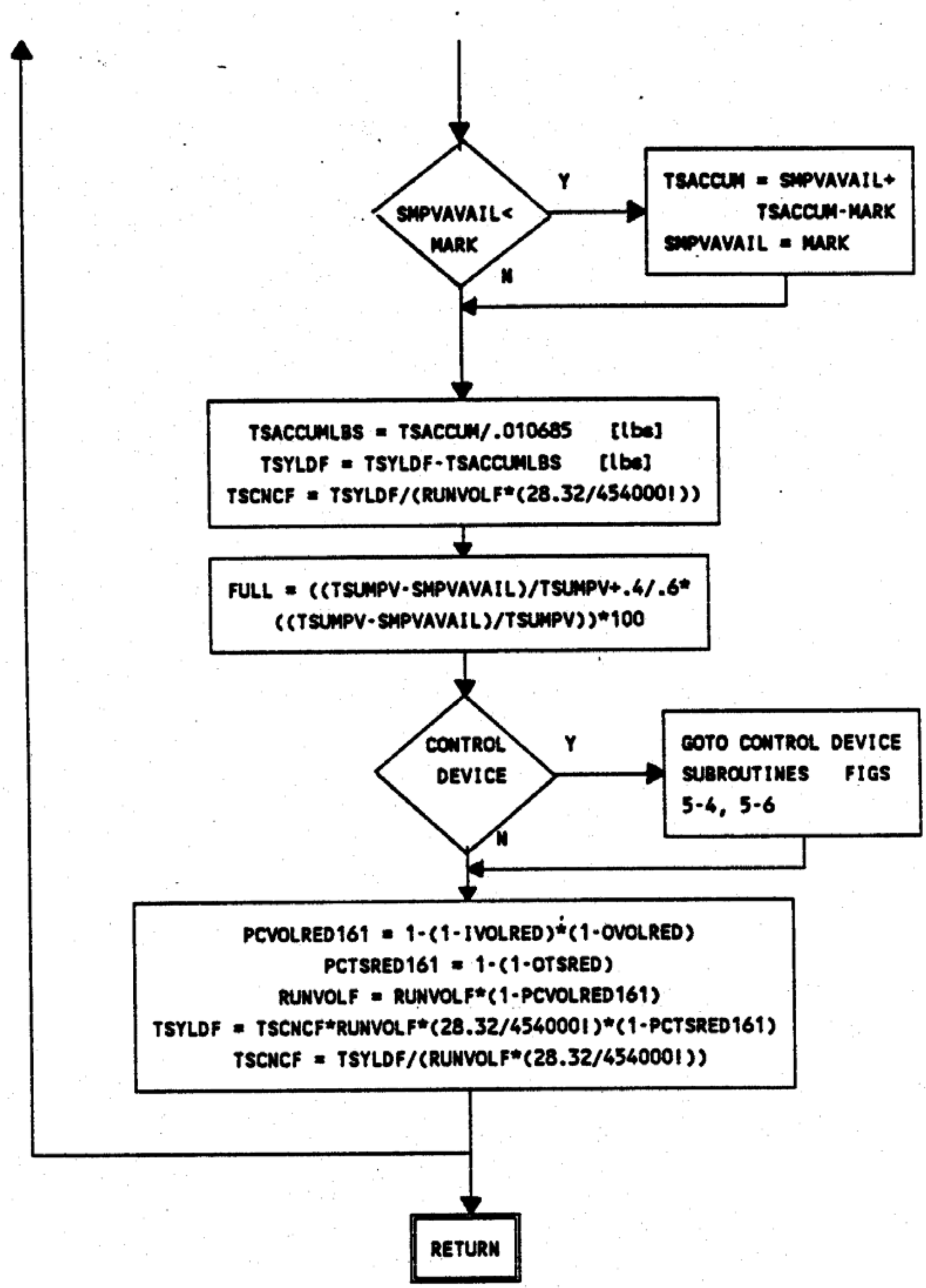
Figure C-16. Catchbasin cleaning flow chart (referred to as Figure 5-9 in some flow charts).



Variable Definitions for Figure C-16 (continued):

CBASERV	Area served by catchbasin [acres]
DUR	Rain duration [days]
FULL	Percent of catchbasin full
FLOW	Flow into catchbasin
IVOLRED	Infiltration device volume reduction [fraction]
MARK	Minimum sump volume available for solids storage (40 percent of total sump volume) [cu ft]
OVOLRED	Other control device volume reduction [fraction]
PCSMPVF	Percent of sump volume full
PCTSRED161	Percent particulate solids reduction due to drainage controls before catchbasins
PCVOLRED161	Percent flow volume reduction due to drainage controls before catchbasins
RUNVOLF	Source area runoff volume for a rain event [cu ft]
SMPVAVAIL	Sump volume available for particulate solids [cu ft] .
TBSNATSYLD	Total basin area particulate solids yield [lbs]
TSACCUM	Particulate solids accumulated in catchbasin [cu ft]
TSACCUMLBS	Particulate solids accumulated in catchbasin[lbs]
TSCNCF	Particulate solids concentration [mg/L]
TSCNCREDCBPC	Percentage particulate solids reduction from catchbasin
TSUMPV	Total sump volume [cu ft]
TSYLDF	Source area particulate solids yield [lbs].
TTLBSNA	Total basin area [acres]

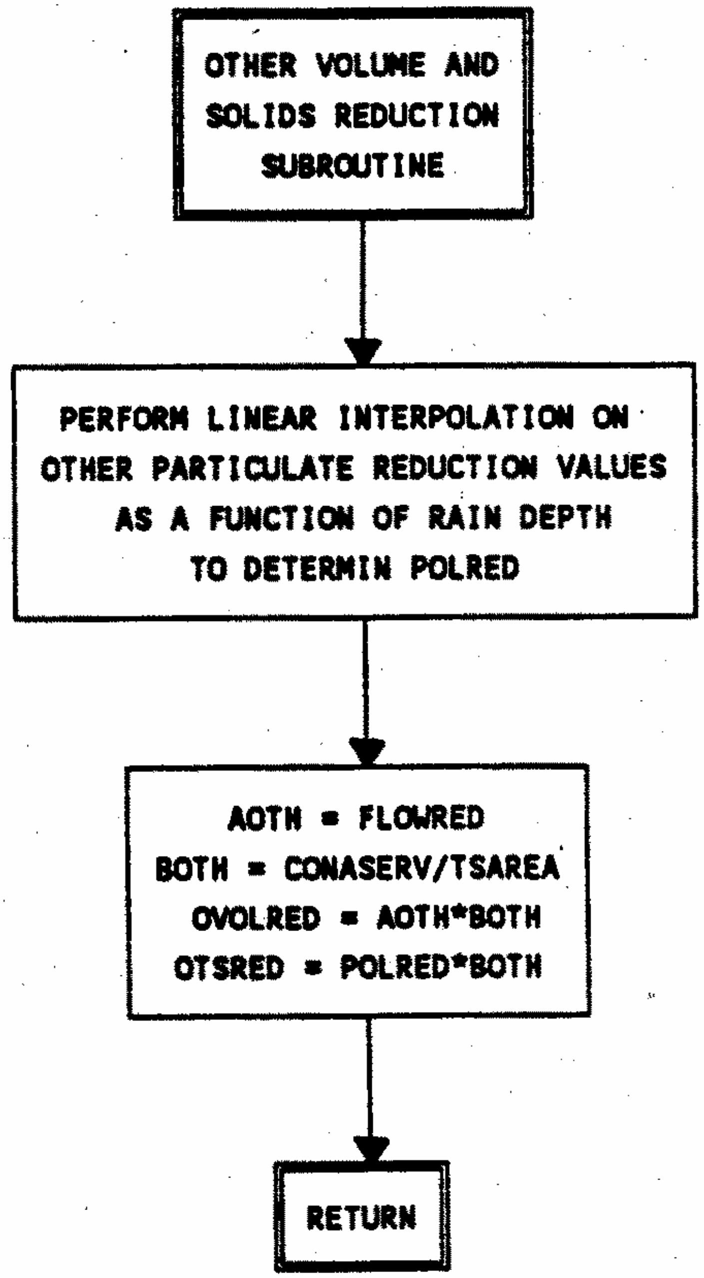
Figure C-16 continued (referred to as Figure 5-9 in some flow charts).



Variable Definitions for Figure C-17:

AOTH	Percent flow reduction for “Other” control device.
BOTH	Proportion of the total area served by the “Other” control device.
CONASERV	Area served (acres) by the “Other” control device.
FLOWRED	Percent flow reduction for “Other” control device.
OTSRED	Particulate solids reduction percentage for that part of source area served by the “Other” control device.
OVOLRED	Volume reduction percentage for the source area.
POLRED	Particulate solids reduction percentage for the source area.
TSAREA	Total source area [acres]

Figure C-17. Other volume and solids reduction flow chart (referred to as Figure 5-10 in some flow charts).



Calculation/Output Module - Output

The program uses flow volumes and particulate loadings to calculate the pollutant concentrations and loadings. Figure C-18 describes these calculations in flow chart form.

The variables in the flow chart are defined in the variable list on the facing page. The flow charts are not intended to give you a detailed description of the program structure. They should, however, help you understand how the calculations are structured in the code. To make the flow charts clearer, the variable subscripts have been eliminated.

Output from WinSLAMM is in both disk file and hard copy form. The disk file is generated in the calculations subprogram of the calculation module and has the name "datafilename.OUT." The format of the file is in Appendix A of the User's Manual. The file output is available only in version 5.0 of the Calculation Module.

There are four printing options. You select the desired option in the input module. The printing options are:

1. Print source areas by land use and outfall for each rain - complete printout. -

2. Print outfall data only for each rain.

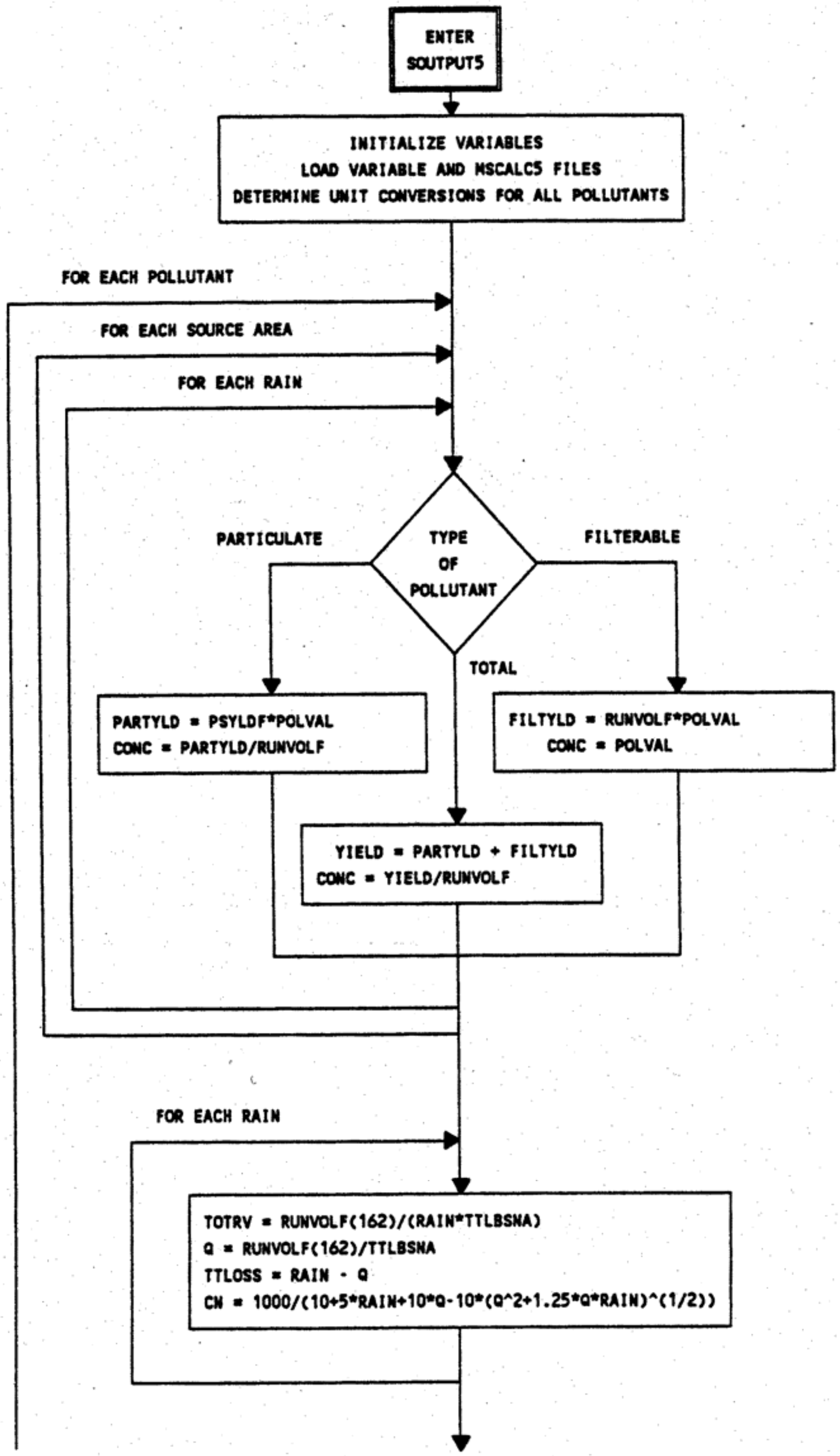
3. Print summary totals of each source area category for all land uses and print outfall data for each rain.

4. Default option - print outfall summaries only.

Variable Definitions for Figure C-18:

CONC	Concentration of a pollutant from a source area for a rain
FILTYLD	Filterable yield of a pollutant from a source area for a rain
MSCALC5	Calculation Module program which determined runoff volumes, particulate concentrations, and particulate yields for each source area for each rain
PARTYLD	Particulate yield of a pollutant from a source area for a rain
POLVAL	The concentration of a pollutant from a source area and land use. For particulate pollutants, the units are: mass of pollutant/kg particulate solids. For filterable pollutants, the units are: mass of pollutant/Liter of runoff.
PSYLDF	Particulate solids yield [lbs]. Determined for each source area for each rain in the "MSCALC5. EXE" program.
RUNOFF	Source area runoff volume for a rain event [cu ft]
s	Source area number
TTLBSNA	Total basin area [acres]

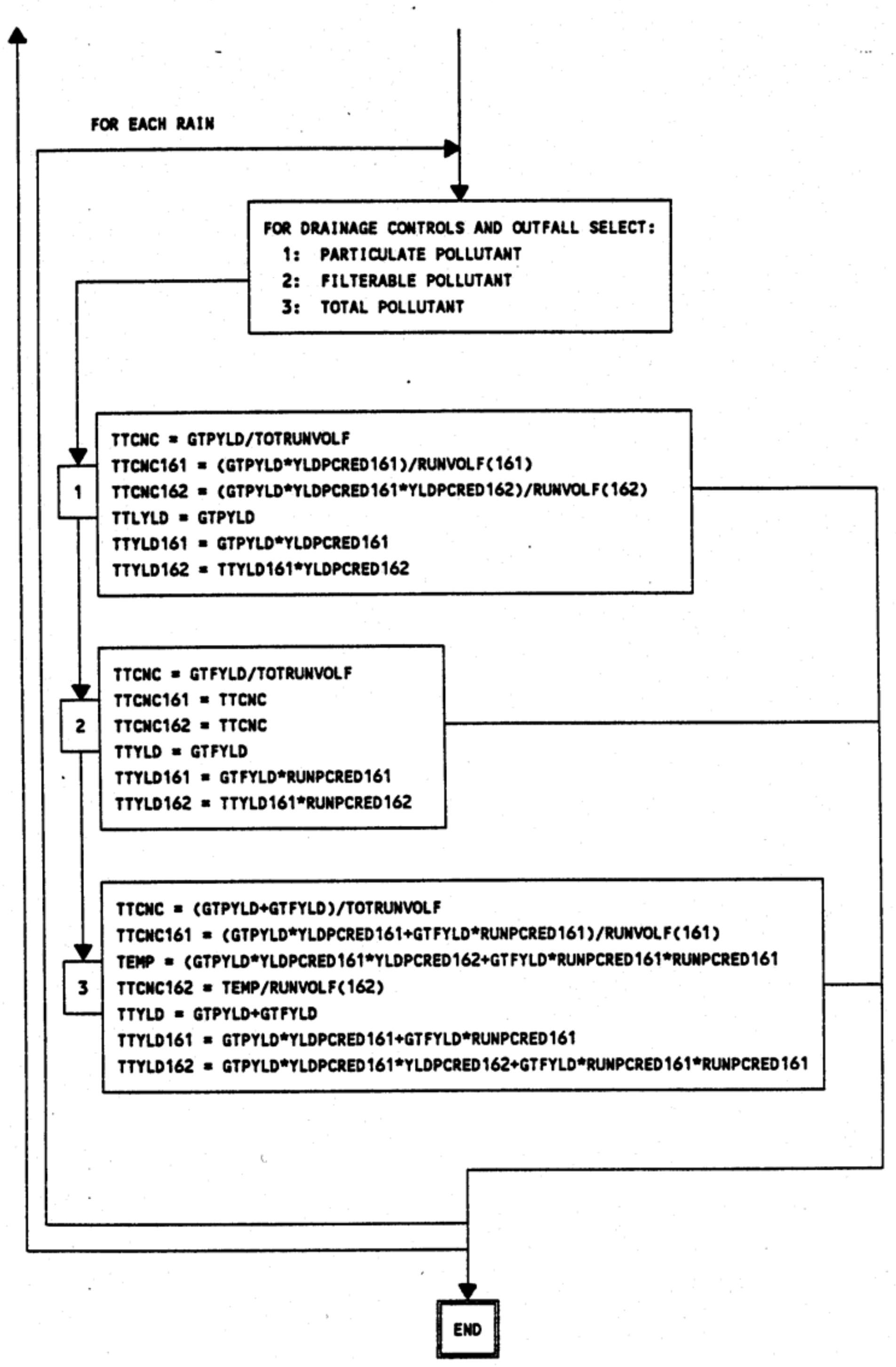
Figure C-18. Output program main flow chart.



Variable Definitions for Figure C-18 (continued):

CN	SCS Curve Number
GTFYLD	Total filterable yield of a pollutant from all source areas for a rain [lbs]
GTPYLD	Total particulate yield of a pollutant from all source areas for a rain [lbs]
PCTSRED161	Percent particulate solids reduction due to drainage controls for a rain
PCVOLRED161	Percent flow volume reduction due to drainage controls for a rain
Q	Runoff [in]
RAIN	Rain depth for an event [in]
RUNVOLF	Source area runoff volume for a rain event. (161)==> runoff volume from all source areas after drainage controls. (162)==> runoff volume from all source areas after outfall controls. [cu ft]
RUNPCRED161	Percent reduction of runoff due to drainage controls for a rain
RUNPCRED162	Percent reduction of runoff due to outfall controls for a rain
TOTRUNVOLF	Total runoff volume from all source areas for a rain
TOTRV	Ratio of runoff volume to rain volume for a rain event
TTCNC	Total concentration (particulate if yield is GTPYLD, filterable if yield is GTFYLD) from all the source areas for a rain
TTCNC161	Total concentration (particulate if yield is GTPYLD, filterable if yield is GTFYLD) from all the source areas for a rain after drainage controls
TTCNC162	Total concentration (particulate if yield is GTPYLD, filterable if yield is GTFYLD) from all the source areas for a rain after drainage and outfall controls
TTLBSNA	Total basin area t acres]
TTLOSS	Total precipitation lost due to evaporation, infiltration, and other processes
TTLYLD	Total yield (particulate if yield is GTPYLD, filterable if yield is GTFYLD) from all the source areas for a rain
TTLYLD161	Total yield (particulate if yield is GTPYLD, filterable if yield is GTFYLD) from all the source areas for a rain after drainage controls
TTLYLD162	Total yield (particulate if yield is GTPYLD, filterable if yield is GTFYLD) from all the source areas for a rain after drainage and outfall controls
YLDPCRED161	Percent reduction of yield due to drainage controls for a rain
YLDPCRED162	Percent reduction of yield due to outfall controls for a rain

Figure C-18 (continued).



Appendix D
Stormwater Quality Controls in SLAMM

Introduction

Many alternative urban runoff control practices are available at the sources where the sediment is generated (eroded) and at inputs to sewerage systems. These include infiltration devices (such as subsurface infiltration trenches, surface percolation areas, and porous pavements), grass drainage swales, grass filters, detention basins, street cleaning, and catchbasin cleaning. Other practices include those specialized for construction sites, such as site mulching and the use of filter fencing. Another important practice is the elimination of inappropriate discharges to sewerage through cross-connections. Outfall controls most commonly include wet detention ponds.

The first concern when investigating alternative treatment methods is determining the needed level of stormwater control. This determination has a great affect on the cost of the stormwater management program and needs to be carefully made. Problems that need to be reduced range from sewerage maintenance issues to protecting many receiving water uses. As an example, Laplace, *et al*. (1992) recommends that all particles greater than about 1 to 2 mm in diameter be removed from stormwater in order to prevent deposition in sewerage. The specific value is dependent on the energy gradient of the flowing water in the drainage system and the hydraulic radius of the sewerage. This treatment objective can be easily achieved using a number of cost-effective source area and inlet treatment practices. In contrast, much greater levels of stormwater control are likely needed to prevent excessive receiving water degradation. Specific treatment goals usually specify about 80% reductions in suspended solids concentrations. In most stormwaters, this would require the removal of most particulates greater than about 10 μm in diameter, about 1% of the 1 mm size to prevent sewerage deposition problems. Obviously, the selection of a treatment goal must be done with great care. The Engineering Foundation/ASCE, Mt. Crested Butte conference held in 1993 included many presentations describing receiving water impacts associated with stormwater discharges (Herricks 1995). Similarly, Pitt (1996) summarized numerous issues concerning potential groundwater impacts associated with sub-surface stormwater disposal. These references illustrate the magnitudes and variations of typical problems that can be caused by untreated stormwater. Specific control programs will therefore need to be unique for a specific area due to these variations.

There are many stormwater control practices, but all are not suitable in every situation. It is important to understand which controls are suitable for the site conditions and can also achieve the required goals. This will assist in the realistic evaluation for each practice of: the technical feasibility, implementation costs, and long-term maintenance requirements and costs. It is also important to appreciate that the reliability and performance of many of these controls have not been well established, with most still in the development stage. This is not to say that emerging controls cannot be effective, however, they do not have a large amount of historical data on which to base designs or to be confident that performance criteria will be met under the local conditions. The most promising and best understood stormwater control practices are wet detention ponds. Less reliable in terms of predicting performance, but showing promise, are stormwater filters, wetlands, and percolation basins (Roesner, *et al.* 1989). Grass swales also have shown great promise during the EPA's Nationwide Urban Runoff Program (NURP) (EPA 1983) and other research projects.

A study of 11 types of stormwater quality and quantity control practices currently being used in Prince George's County, Maryland (Metropolitan Washington Council of Governments 1992) was conducted to examine their performance and longevity. This report concluded that several types of the stormwater control practices had either failed or were not performing as well as intended. Generally, wet ponds, artificial marshes, sand filters, and infiltration trenches achieved moderate to high levels of removal for both particulate and soluble pollutants. Only wet ponds and artificial marshes demonstrated an ability to function for a relatively long time without frequent maintenance. Control practices which were found to perform poorly were infiltration basins, porous pavements, grass filters, swales, smaller “pocket” wetlands, extended detention dry ponds, and oil/grit separators. Infiltration stormwater controls had high failure rates which could often be attributed to poor initial site selection and/or lack of proper maintenance. The poor performance of some of the controls was likely a function of poor design, improper installation, inadequate maintenance, and/or unsuitable placement of the control. Greater attention to these details would probably reduce the failure rate of these practices. The wet ponds and artificial marshes were much more robust and functioned adequately under a wider range of marginal conditions. Other important design considerations include: safety for maintenance access and operations, hazards to the general public (e.g., drowning) or nuisance (e.g., mosquito breeding), acceptance by the public (e.g., enhance area aesthetics and property values).

The majority of the stormwater treatment processes are most effective for the removal of particulates only, especially the settleable solids fraction. Removal of dissolved, or colloidal, pollutants is minimal and therefore pollution prevention or control at the sources offers a more effective way to control the dissolved pollutants. Fortunately, most toxic stormwater pollutants (heavy metals and organic compounds) are mostly association with stormwater particulates (Pitt, *et. al.* 1994). Therefore, the removal of the solids will also remove much of the pollutants of interest. Notable exceptions of potential concern include: nitrates, chlorides, zinc, pathogens, 1,3-dichlorobenzene, fluoranthene, and pyrene.

A successful stormwater management program requires several components (after Field, *et al*. 1994):

• *Regulations, Local Ordinances, and Public Education.* This should be the primary component because it is likely to be the most cost effective. Mainly non-structural practices (such as simple site layout options, selection of drainage system components, etc.) and requirements for controls at new developments are particularly effective. Even though not quantified, public education to encourage careful selection of landscaping chemicals, proper disposal of household toxic substances, etc., are all important stormwater control activities.

• *Pollution Prevention.* Pollution prevention is an important component of any stormwater management program. Both non-structural and structural practices can be used to prevent pollutants from coming into contact with stormwater. These practices include:

– selection of alternative building materials (decreasing the use of galvanized metals, for example);

– flow diversion practices to keep uncontaminated stormwater from contacting contaminated surfaces, or to keep contaminated stormwater from contacting uncontaminated stormwater. This is accomplished by a variety of exposure minimization structural means, such as covering storage areas, using berms and curbs, etc.;

– management practices can include plans to recover released or spilled pollutants; and preventative practices including a variety of monitoring techniques intended to prevent releases;

– public works practices (such as catchbasin and sewerage cleaning, leaf removal, etc.) are also important pollution prevention controls;

– investigation and control of inappropriate discharges into storm drainage systems;

– controlling construction site sediment erosion by vegetative and structural means; and

– infiltration practices through site development options (direct roof and paved area runoff to lawns, use swale drainages, etc.) which infiltrate source area runoff into the groundwater, thereby reducing surface runoff during storms, recharging local groundwaters, and maintaining low flow conditions in streams.

- *Critical Source Area and Outfall Treatment.* These are mainly structural practices to provide upstream pollutant removal at the source, controlled stormwater releases to the conveyance system, outfall controls, and infiltration or reuse of the stormwater. Upstream pollutant removal at critical source areas provides treatment of stormwater at highly polluting locations (such as vehicle service facilities, storage areas, junk yards, etc.) before it enters the stormwater conveyance system. Downstream, end-of-pipe, controls may also be needed in industrial areas or at outfalls from large drainages. Large-scale infiltration, through the use of percolation ponds for example, may also be used at outfall locations, especially after pre-treatment using wet detention ponds.

Several reviews of stormwater management practices from throughout the world have recently been published. Stahre (1993) described practices in Scandinavia, Driscoll and Strecker (1993) described U.S. and Canadian practices, and Pratt (1993) described UK stormwater management activities.

The following discussion summarizes the possible levels of performance that may be achieved by various stormwater control practices. Stormwater control practices may be grouped into several general categories, including: regulations and public education, public works practices, sedimentation, infiltration, filtration and combination practices, and construction site erosion controls.

Treatment of Flows at Sources of Urban Runoff Pollution and at Outfalls

Most stormwater needs to be treated to prevent harm either to the surface waters or the groundwaters. One approach is to treat the runoff from critical source areas before it mixes with the runoff from less polluted areas. The general features of critical source areas appear to be large paved areas, heavy vehicular traffic, and outdoor use or storage of problem pollutants. The control of runoff from relatively small critical areas may be the most cost-effective approach for treatment/reduction of stormwater toxicants. However, in order for a treatment device to be useable, it must be inexpensive, both to purchase and maintain, and effective. Outfall stormwater controls, being located at the outfalls of storm drainage systems, treat all the flows that originate from the watershed. The level of treatment provided, of course, is greatly dependent on many decisions concerning the design of the treatment devices. Source area controls are, of course, physically smaller than outfall controls but may be difficult to locate on a crowded site, and there could be a great number of them located in a watershed. In all cases, questions must be answered about the appropriate level of control needed, where the control should be provided, and what controls should be used. These questions can best be answered by using a comprehensive stormwater quality management model. During this research effort, we are examining the use of the Source Loading and Management Model (SLAMM), in conjunction with the Storm Water Management Model (SWMM), to address these issues. SLAMM is unique in that it can evaluate a large number of source and outfall stormwater quality controls for a large number of rains. Table D-1 shows the stormwater control measures that are currently available in SLAMM. The results of recent research funded by the EPA are currently being used to expand SLAMM. This matrix of controls illustrates how some source area controls can be used at both source areas and at outfalls. Infiltration, filtration, and sedimentation controls can be used at both source areas and at outfalls, even though the sizes and specific designs of the specific practices must be varied to fit the site and to handle the specific flows. Therefore, the following literature review of stormwater quality management options includes practices that are usually considered as source area controls (such as street cleaning) and those that are usually considered as outfall controls (such as wet detention ponds). This review is organized into the following general categories, and topics, of control practices:

- public works practices (street cleaning, drainage inlets, oil and grease separators, and inappropriate discharges),
- sedimentation and wetlands (wet detention ponds, chemical addition, dry detention ponds, and

wetlands),
- infiltration (infiltration trenches, grass swales, grass filter strips, porous pavement, and groundwater protection), and
- filtration and combination practices (sand, activated carbon, peat moss, composted leaves, and filter fabrics).

Table D-1. Source Area, Drainage System, and Outfall Control Options Currently Available in SLAMM[1]

	Infiltration devices	Wet detention pond	Grass drainage swale	Street cleaning	Catchbasin cleaning	Porous pavement
Roof	X	X				
Paved parking/storage	X	X				X
Unpaved parking/storage	X	X				
Playgrounds	X	X				X
Driveways						X
Sidewalks/walks						X
Streets/alleys				X		
Undeveloped areas	X	X				
Small landscaped areas	X					
Other pervious areas	X	X				
Other impervious areas	X	X				X
Freeway lanes/shoulders	X	X				
Large turf areas	X	X				
Large landscaped areas	X	X				
Drainage system			X		X	
Outfall	X	X				

[1] Development characteristics affecting runoff, such as roof and pavement draining to grass instead of being directly connected to the drainage system, are included in the individual source area descriptions.

Public Works Practices

Numerous public works practices affect stormwater quality and quantity. The most significant being the design, construction, and maintenance of the stormwater drainage system. Obviously, managing stormwater quantity to provide drainage and to prevent flooding must remain the primary objective of stormwater drainage systems. Over the years, addressing this objective, while ignoring other receiving water beneficial uses, has resulted in many problems. It is now possible, as demonstrated by numerous examples from around the world, to provide stormwater drainage that addresses these numerous, and seeming conflicting objectives.

Other public works practices affecting stormwater quality may include: landscaping maintenance on public rights-of-ways, roadway and utility construction erosion controls, erosion controls at sanitary landfills, runoff control at public works garages, street cleaning, and storm drainage inlet cleaning. This section specifically addresses street and catchbasin cleaning, two commonly recommended stormwater control practices because of their apparent ease of use in existing built-up areas. Many of the on-site “ultra-urban” controls described later)filtration and combination practices) are suitable for public works facilities, such as maintenance yards.

Street Cleaning

Street cleaning was extensively studied as an urban runoff water quality control practice because of the large quantities of pollutants found on streets during early research in the U.S. (Sartor and Boyd 1972). Because streets were assumed to contribute most of the urban runoff flows and pollutants, street cleaning was assumed to be a potentially effective practice. Unfortunately, not all research has shown street cleaning to be effective because of the different sized particles that street cleaners remove compared to the particles that are mostly removed by rains. Furthermore, in many areas, rains are relatively frequent and keep the streets cleaner than typical cleaner threshold values. However, in the arid west of the U.S., rains are very infrequent, allowing streets to become quite dirty during the late summer and fall. Extensive street cleaning during this time has been shown to result in important suspended solids and heavy metal reductions in runoff (Pitt 1979, Pitt and Shawley 1982). Street cleaning should not be confused with flushing operations that really do not remove particles from the street, but simply transfer them to the sewer systems and possibly to the receiving waters. Street flushing in areas served by combined sewers, however, should be considered an alternative in areas having suitable water supplies.

Street cleaning plays an important role in most public works departments as an aesthetic and safety control measure. Street cleaning is also important to reduce massive dirt and debris buildups present in the spring in the northern regions. Leaf cleanup by street cleaning is also necessary in most areas in the fall.

Particles of different sizes "behave" quite differently on streets. Typical street dirt total solids loadings show a "saw-tooth" pattern with time between street cleaning or rain washoff events. The patterns for the separate particle sizes are considerably different than the pattern for total residue. Typical mechanical street cleaners remove much (about 70 percent) of the coarse particles in the path of the street cleaner, but they remove very little of the finer particles (Sartor and Boyd 1972; Pitt 1979). Rains, however, remove very little of the large particles, but can remove large amounts (about 50 percent) of the fine particles (Bannerman, *et al*. 1983; Pitt 1985; Pitt 1987). The intermediate particle sizes show reduced removals by both street cleaners and rain.

Factors significantly affecting street cleaning performance include particle loadings, street texture, moisture, parked car conditions, and equipment operating conditions (Pitt, *et al*. 1976; Pitt 1979). If the 500-1000 μm particle loadings are less than about 75 kg/curb-km for smooth asphalt streets, conventional street cleaning does little good. As the loadings increase, so do the removals: with loadings of about 10 kg/curb-km, less than 25 percent removals can be expected, while removals of up to about 50 percent can be expected if the initial loadings are as high as 40 kg/curb-km for this particle size. The removal performance decreases substantially for smaller particles, including those that are most readily washed off the street during rains and contribute to stormwater pollution.

Increased performance was obtained with a modified regenerative-air street cleaner, especially at low loadings during tests in Bellevue, WA (Pitt 1985). The improved performance was much greater for fine particle sizes, where the mechanical street cleaner did not remove any significant quantities of material. The larger particles were removed with about the same effectiveness for both street cleaner types. Other tests of vacuum street cleaners (Pitt 1979) and regenerative-air street cleaners (Pitt and Shawley 1982) showed very few differences in performance when compared to more standard mechanical street cleaners. These earlier tests were conducted in areas having much higher street loadings, especially for the larger particle sizes, than in Bellevue. It is expected that the high loadings of the large particles armored the small particles, so they could not be removed. For high loadings, it may be best to use a tandem operation, where the streets are first cleaned with a mechanical street cleaner to remove the large particles, followed by a regenerative-air street cleaner to remove the finer particles.

Much information concerning street cleaning productivity has been collected previously in many areas. The early tests (Clark and Cobbin 1963; and Sartor and Boyd 1972) were conducted in controlled strips using heavy loadings of simulates instead of natural street dirt at typical loadings. Later tests, from the mid 1970s to mid 1980s, were conducted in large study areas (20 to 200 ha) by measuring actual street dirt loadings on many street segments immediately before and after typical street cleaning. These large-scale tests are of most interest, as they monitored both street surface phenomena and runoff characteristics. The following list briefly describes these large-scale street cleaning performance tests:

- San Jose, California, tests during 1976 and 1977 (Pitt 1979) considered different street textures and conditions; multiple passes, vacuum-assisted, and two types of mechanical street cleaners; a wide range of cleaning frequencies; and effects of parking densities and parking controls.

• Castro Valley, California, tests during 1979 and 1980 (Pitt and Shawley 1982) considered street slopes, mechanical and regenerative-air street cleaners, and several cleaning frequencies.

• Reno/Sparks, Nevada, tests during 1981 (Pitt and Sutherland 1982) considered different land-uses, street textures, equipment speeds, multiple passes, full-width cleaning, and vacuum and mechanical street cleaners in an arid and dusty area.

• Bellevue, Washington, tests from 1980 through 1982 (Pitt 1985) considered mechanical, regenerative-air, and modified regenerative-air street cleaners, different land-uses, different cleaning frequencies, and different street textures in a humid and clean area.

• Champaign-Urbana, Illinois, tests from 1980 and 1981 (Terstriep, *et al*. 1982) examined spring clean-up, different cleaning frequencies and land-uses, and used a three-wheel mechanical street cleaner.

• Milwaukee, Wisconsin, tests from 1979 to 1983 (Bannerman, *et al*. 1983) examined various street cleaning frequencies at five study sites, including residential and commercial land-uses and large parking lots.

• Winston-Salem, North Carolina, tests during their NURP project examined different land-uses and cleaning frequencies.

Sutherland (1996, and with Jelen 1996) has conducted recent tests using a new style street cleaner that shows promise in removing large fractions of most of the street dirt particulates, even the small particles that are most heavily contaminated. The Enviro Whirl I, from Enviro Whirl Technologies, Inc. is capable of much improved removal of fine particles from the streets compared to any other street cleaner ever tested. This machine was also able to remove large fractions of the fine particles even in the presence of heavy loadings of large particles. This is a built-in tandem machine, incorporating rotating sweeper brooms within a powerful vacuum head. Model analyses for Portland, OR, indicate that monthly cleaning in a residential area may reduce the suspended solids discharges by about 50%, compared to only about 15% when using the older mechanical street cleaners that were tested during the early 1980s.

The pollutant removal benefits of street cleaning is directly dependent on the contributions of pollutants from the streets. In the Pacific Northwest region of the U.S., the large number of mild rains results in much of the runoff pollutants originating from the streets. In the Southeast, in contrast, where the rains are much larger, with greater rain intensities, the streets contribute a much smaller fraction of the annual pollutant loads for the same residential land uses. However, in heavily paved areas, such as large parking lots or paved storage areas, street cleaning of these surfaces, especially with an effective machine like the Enviro Whirl, should result in significant runoff improvements.

These many tests have examined a comprehensive selection of alternative street cleaning programs. Not all alternatives have been examined under all conditions, but sufficient information has been collectively obtained to examine many alternative street cleaning control options. Few instances of significant and important reductions in runoff pollutant discharges have been reported during these large-scale tests.

The primary and historical role of street cleaning is for litter control. Litter is also an important water pollutant in receiving waters. Litter affects the aesthetic attributes and recreation uses of waters, plus it may have direct negative biological and water quality effects. Litter has not received much attention as a water pollutant, possibly because it is not routinely monitored during stormwater research efforts. The City of New York recently conducted a special study to investigate the role of enhanced street cleaning (using intensive manual street sweeping) to reduce floatable litter entering the City's waterways (Newman, *et al.* 1996). During the summer of 1993, the City hired temporary workers to manually sweep near-curb street areas and sidewalks in a pilot watershed area having 240 km of curb face. Two levels of manual sweeping supplemented the twice per week mechanical street cleaning the area normally receives. Continuous litter monitoring was also conducted to quantify the differences in floatable litter loadings found on the streets and sidewalks. An additional four manual sweepings each week to the two mechanical cleanings reduced the litter loadings by about 64% (on a weight basis) and by about 51% (on a surface area basis). Litter loading analyses were also conducted in areas where almost continuous manual sweeping (8 to 12 daily sweeps, 7 days per week) was conducted by special business organizations. In these special areas, the litter loadings were between 73 and 82% cleaner than comparable areas only receiving the twice weekly mechanical cleaning. They concluded that manual sweeping could be an important tool in reducing floatable pollution, especially in heavily congested areas such as Manhattan. New York City is also investigating catch basin modifications and outfall netting for the control of floatable litter.

Conventional street cleaning does not have a very positive effect on stormwater quality because conventional street cleaners preferentially remove the large particles, and the smaller particles from the street that are most effectively removed during rains. Valiron (1992) confirmed the many earlier U.S. studies by showing that street cleaners only remove about 15% of the finest particles (less than 40 μm), while close to 80% of the largest particles (>2,000 μm) are removed.

Ellis (1986) concluded that street cleaning is most efficient if conventional street sweeping (using broom operated equipment) is conducted in a tandem operation with vacuuming, and if it is done three times per week. He did find that conventional tandem sweeping-vacuum machines are very sensitive to the clogging of their filters and to street moisture levels which causes particles to adhere to the street surface, preventing their efficient removal. The Enviro Whirl, mentioned above, is a new tandem machine that overcomes many of these problems. General street cleaning efficiency depends on the speed of the machines, the number of passes, the street loading and street texture, and interference from parked vehicles (Pitt 1979).

Flushing operations, using low pressure water, is more efficient than broom sweeping for the removal of fine particles. In combined sewer systems, the flushed pollutants are treated at the downstream municipal wastewater plant. However, deposition of the particulates in separate sewer systems is a potential problem, as the pollutants typically remain in the sewerage until the next storm event.

In most cases, streets are not cleaned often enough to maintain low street dirt loadings. A frequency of about 6 to 7 cleanings per week is needed to remove about 50 to 55% of the particles (Bertrand-Krajewski 1991, Valiron 1992, Vignoles and Herremans 1992). This very high cleaning frequency is typically only conducted in commercial districts of large cities.

Butler, *et al.* (1993) examined the benefits and costs of street and gully pot use for the prevention of sediments from entering combined sewerage. They compared these costs with those associated with removal of the sediment from the sewerage and removal at the sewage treatment facility. In one example, they found that the minimum total cost would be achieved with a street cleaning interval of about once every six to eight weeks, but the total costs of sediment removal would not be significantly increased if there was no street cleaning. The street cleaning costs would increase directly and linearly with increased cleaning effort, while the costs of particulate removal by the other methods would be reduced with increased street cleaning. However, the total costs would increase with increased street cleaning because the cost savings from the other treatment options were more than off-set by the increased street cleaning costs. For this combined sewerage system example, they concluded that it was more cost-effective to remove the sediment at the treatment facility. They do point out that the main requirements for street cleaning in the UK are determined by the Environmental Protection Act and stress litter removal. Sediment removal by street cleaning was never a stated objective.

Summary of Street Cleaning as a Stormwater Control Practice

Normal street cleaning operations for aesthetics and traffic safety purposes are not very satisfactory from a stormwater quality perspective. These objectives are different and the removal efficiency for fine and highly polluted particles is very low. Unless the street cleaning operations can remove the fine particles, they will always be limited in their pollutant removal effectiveness. Some efficient machines are now available to clean porous pavements and infiltration structures, and new tandem machines that incorporate both brooms and vacuums have recently been shown to be very efficient, even for the smaller particles. Conventional street cleaning operations preferentially remove the largest particles, while rain preferentially remove the smallest particles. In addition, street cleaners are very inefficient when the street dirt loadings are low, when the street texture is course, and when parked cars interfere. However, it should also be noted that streets are not the major source of stormwater pollutants for all rains in all areas. Streets are the major source of pollutants for the smallest rains, but other areas contribute significant pollutants for moderate and large rains. Therefore, the ability of street cleaning to improve runoff quality is dependent on many issues, including the local rain patterns and other sources of runoff pollutants. More research is needed to investigate newer pavement cleaning technologies in areas such as industrial storage areas and commercial parking areas which are critical pollutant sources.

Street Cleaning Effectiveness Calculations used in SLAMM

SLAMM keeps track of this street dirt accumulation, rain washoff, and street cleaner removal pattern for each street in the study area. The accumulation and washoff equations were described in the previous section. Factors significantly affecting street cleaning performance include particle loadings, street texture, moisture, parked car conditions, and equipment operating conditions (Pitt, *et al.* 1976; Pitt 1979). Figure D-1 is an example of a performance plot from a series of street cleaner tests conducted in Bellevue, Washington (Pitt 1984). It shows the dramatic effect loadings have on street cleaner performance. If the total solids loadings on the street before cleaning are less than about 300 lbs/curb-mile for smooth asphalt streets, conventional mechanical street cleaning does little good, as reflected on the data for the Mobil mechanical broom sweeper. As the loadings increase, so do the removals. With loadings approaching 700 lbs/curb-mile, removals of up to about 40 percent can be expected. The number of data observations for these higher loadings were rare for these Bellevue tests, and most of the observations were for very low loadings (75 to 400 lbs/curb-mile of total solids).

Figure D-1 also shows the improved performance obtained with a regenerative-air street cleaner, especially at low loadings, as shown for the Tymco cleaner. The improved performance was much greater at the low initial street dirt loadings, where the mechanical street cleaner did not remove any significant quantities of material. Forty percent removals occurred at about 150 lbs/curb-mile, in the lower range of observed conditions, and increased to about 60% removals at about 700 lbs/curb-mile.

Other tests of vacuum street cleaners (Pitt 1979) and regenerative-air street cleaners (Pitt and Shawley 1981) showed very few differences in performance when compared to standard mechanical street cleaners. These earlier tests were conducted in areas having much higher street loadings, especially for the larger particle sizes, than in Bellevue. It is expected that the high loadings of the large particles armored the small particles, so they could not be effectively removed. For high loadings, it may be best to first clean with a mechanical street cleaner to remove the large particles, followed by a regenerative-air street cleaner to remove the finer particles. Recent improvements in street cleaners have incorporated both technologies in the same unit, with much improved cleaning capabilities, as noted above.

SLAMM uses a series of linear first order equations describing the slope of the performance line, and the intersection of this performance line with the diagonal indicating no removal (the threshold value). No street cleaning benefit occurs if the initial street loading is less than this threshold value.

Much information concerning street cleaning productivity has been collected previously in many areas. The early tests (Clark and Cobbin 1963; and Sartor and Boyd 1972) were conducted in controlled strips using simulants instead of street dirt. The later tests were conducted in large study areas (50 to 500 acres) by measuring actual street dirt loadings on many street segments immediately before and after typical street cleaning. These large-scale tests are of most interest and were used to develop the street cleaning performance curves used in SLAMM.

Storm Drainage System Inlet Structures

Storm drainage system inlet structures can be separated into three general categories. The first category is a simple inlet that is comprised of a grating at the curb and a box, with the discharge located at the bottom of the box which connects directly to the main storm drainage or combined sewerage. This inlet simply directs the runoff to the drainage system and contains no attributes that would improve water quality. However, large debris (several cm in size) may accumulate (if present in the stormwater, which is unlikely) in them. The second type of inlet is similar to the simple inlet, but it contains a sump that typically extends up to 0.5 to 1 m below the bottom of the outlet. This is termed a catchbasin in the U.S., or a gully pot in the U.K. (usually smaller than a catchbasin), and has been shown to trap appreciable portions of the course sediment (somewhat less than a mm in size and larger). The third category is also similar to the simple inlet, but contains some type of screening to trap debris. These include small cast iron perforated buckets placed under the street grating as used in Germany, large perforated stainless steel plates placed under the inlet grating as used in Austin, Texas, and a number of proprietary devices incorporating filter fabric or other types of screening placed to intercept the stormwater flow. This last category may trap large debris and litter, depending on the overflow provisions, but have not been shown to produce important water quality improvements.

Catchbasins and Gully Pots

Catchbasin performance has been investigated for some time in the U.S. Sartor and Boyd (1972) conducted controlled field tests of a catchbasin in San Francisco, using simulated sediment in fire hydrant flow. They sampled water flowing into and out of a catchbasin for sediment and basic pollutant analyses, for varying conditions and times since flow began. Lager, *et al.* (1977) was the first EPA funded research effort that included a theoretical laboratory investigation to evaluate sedimentation in catchbasins and to develop effective designs. They also conducted extensive laboratory tests using simulated runoff.

The mobility of catchbasin sediments was investigated by Pitt (1979) during a research project sponsored by the U.S. EPA's Storm and Combined Sewer Section. Long-duration tests were conducted using an “idealized” catchbasin (based on Lager, *et al*.’s 1977 design), retro-fitted in San Jose, CA. The research focused on re-suspension of sediment from a full catchbasin over an extended time period. This project used particulate fluorescent tracers mixed with catchbasin sediment. It was concluded that the amount of catchbasin and sewerage sediment was very large in comparison with storm runoff yields, but was not very mobile. Cleaning catchbasins would enable catchbasins to continue to trap sediment instead of reaching a steady-state loading and allowing flows to remain untreated.

The removal of overlying water above sediment in catchbasins readily occurs and has been noted by Sartor and Boyd (1972) as their largest water quality problem. However, Pitt (1985) statistically compared catchbasin supernatant with outfall water quality and could not detect any significant differences. EDP (1980) examined “first flushes” from catchbasins and found the quality of the water leaving the catchbasins to be much less than the high concentrations of pollutants in the gutter flows during early parts of rains. However, Butler, *et al.* (1995) have recently investigated gully pot supernatant water and have found that it may contribute to the more greatly polluted first flush of stormwater reported for some locations. Specific problems have been associated with the anaerobic conditions that rapidly form in the supernatant water during dry weather, causing the release of oxygen demanding material, ammonium, and possible sulfides. These anaerobic conditions also affect the bio-availability of the heavy metals in the flushed water.

Aronson, *et al*. (1983) reported a field evaluation of three catchbasins in West Roxbury, MA, for four events. An inlet strainer was also tested for three events at each site. They monitored suspended solids and conventional pollutants.

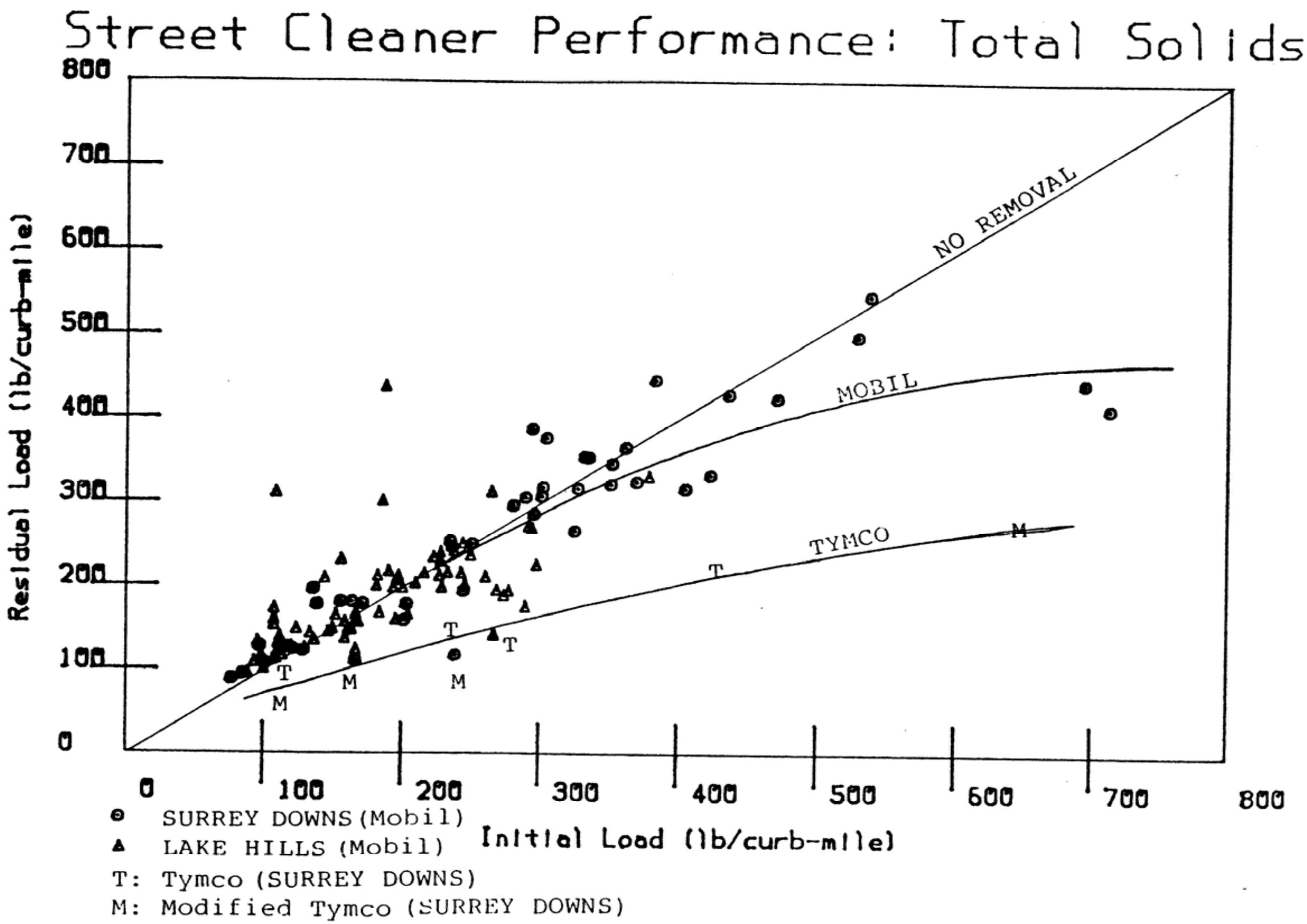


Figure D-1. Measured performance of street cleaners in Bellevue, WA, for different total solids loadings on the street before cleaning (Pitt 1984).

Catchbasins, simple inlets, man-holes, and sewerage sediment accumulations were monitored at more than 200 locations in Bellevue, Washington at two mixed residential and commercial study areas (Pitt 1985). These locations were studied over three years to monitor accumulation of sediment and sediment quality. The sediment in the catchbasins and the sewerage was found to be the largest particles that were washed from the streets. A few unusual locations were dominated by erosion sediment from steep hillsides adjacent to the storm sewer inlets. The sewerage and catchbasin sediments had a much smaller median particle size than the street dirt and were therefore more potentially polluting than the particulates that can be removed by street cleaning, but the particulates were much larger than those generally found in stormwater. Basically, catchbasins remove the largest particulates that are washed from the watershed during rains, preventing them from being deposited in downstream sewerage and in the receiving water. If the catchbasins are full, they also cannot remove any additional particulates from the runoff. Catchbasin sump particulates can be conveniently removed to restore the trapping of these particulates, and some of the runoff pollutants. Cleaning catchbasins twice a year was found to allow the catchbasins to capture particulates for most rains. This cleaning schedule was found to reduce the annual discharges of total solids and lead by between 10 and 25 percent, and COD, total Kjeldahl nitrogen, total phosphorus, and zinc by between 5 and 10 percent (Pitt and Shawley 1982).

The median particle size of the sump particles is shown to be between about 300 and 3000 μm, with less than 10% of the particles smaller than 100 μm, the typical upper limit of particles found in stormwater (Butler, *et al.* 1995). Catchbasin sumps trap the largest particles that are flowing in the water, and allow the finer particles to flow through the inlet structure. Relatively few pollutants are associated with these coarser solids found in the sumps, compared to the finer particles.

Butler, *et al*. (1995) and Butler and Karunaratne (1995) present equations for sediment accumulation in gully pots, based on detailed laboratory tests. The sediment trapping performance was found to be dependent on the flow rate passing through the gully pot, and to the particle sizes of the sediment. The depth of sediment in the gully pot had a lesser effect on the capture performance. In all cases, decreased flows substantially increased the trapping efficiency and larger particles had substantially greater trapping efficiency than smaller particles, as expected.

Butler, *et al*. (1993) examined the build-up rate of sediment in roadside gully pots. They found that for most gullies, the build-up rate is fairly constant, at about 18 mm per month, while the average rates ranged from 14 to 24 mm per month. The average drainage area for each of the gully pots examined was 228 m^2. They also evaluated the costs of sediment removal by gully pots, comparing them to street cleaning costs, sewerage cleaning costs, and costs to remove the sediment at the treatment facility. They concluded that it was more cost-effective to remove the sediment at the treatment facility. However, they also concluded that the transport of all sediments to the treatment facility is not practicable for most systems, and the role of gully pots in limiting sediment entry to the sewerage system was deemed vital.

Storm Drain Inlets with Filters

Little information is available in the literature concerning the performance of filter fabrics in removing stormwater pollutants. They have been used for years in controlling construction site runoff, but in filter fence arrangements, where they act as small impoundments and not as true filters. Research at the University of Alabama at Birmingham (Clark, *et al*. 1995) is analyzing many filter fabrics, including fabrics being used in the inlet devices. The biggest disadvantage of using filter fabrics in catchbasins is their likelihood of quickly clogging. During controlled laboratory tests, they were found to provide important reductions (about 50%) in suspended solids and COD. However, the filter fabrics can only withstand very thin accumulations of sediment before they clog. The maximum sediment thickness on the fabrics before absolute clogging was between 1 and 2 mm, and the sediment loading was about 3.8 kg sediment per m^2 of fabric. The median particle size was 43 μm, 90% of the particles were smaller than 96 μm, and the largest particle observed was 130 μm in the runoff sample used in these clogging tests.

If the stormwater had a typical suspended solids concentration of 100 mg/L, then about 40 meters of stormwater could be loaded on the filter fabric before absolute failure due to clogging. If the suspended solids concentration was a high 500 mg/L, then only about 7.5 meters of stormwater could be loaded. These are small loading rates and would require extremely large filter surfaces or very frequent fabric exchanges. As an example, if a 1 ha paved area drained to an inlet having a 1 m^2 filter fabric, and the runoff had a suspended solids concentration of 100 mg/L, a rainfall of only about 5 mm would cause absolute clogging. This would basically require exchanging the filter after almost every rain, plus having the filter clog even before the end of many common rains. If the water was pre-treated (such as in the multi-chambered treatment train (MCTT) which uses the Gunderboom fabric, as described later under combination devices), then much more rain can be tolerated before clogging. In the Minocqua, WI, MCTT, for example, a Gunderboom filter fabric 24 m^2 in area is used for a paved drainage area about 1 ha in size (Pitt 1996). Because of the pre-treatment provided in the MCTT before the filter fabric (suspended solids are about 5 mg/L, and less than about 10 μm in size) and the large area of fabric, this filter should tolerate at least 2.5 meters of rain over the drainage area before clogging and needing replacement (at least 3 to 4 years of operation).

Three storm drain inlets were evaluated in Stafford Township, New Jersey as part of an EPA sponsored research project (Clark, *et al*. 1995; Pitt, *et al.* 1997). A conventional catchbasin, with a sump, and two representative designs that used filter material were tested. The inlet devices were located in a residential area. The filter fabrics were also evaluated in the laboratory using stormwater runoff from a large parking area on the campus of UAB. The monitoring program began in January 1994 and included 12 inlet and effluent samples from each device over several different storms, ending in late summer of 1994. Complete organic and metallic toxicant analyses, in addition to conventional pollutants, were included in the analytical program. An optimally designed catchbasin with a sump was constructed by installing a sump in the bottom of an existing storm drain inlet by digging out the bottom and placing a section of 36 inch concrete pipe on end. The outlet pipe was reduced to 8 inches and the sump depth was 36 inches. Inlet water was sampled before entering the catchbasin, while outlet water was sampled after passing through the unit. Twelve storms were evaluated for each of the three inlet units by making composite influent and effluent samples using a dipper grab sampler over the storm duration. The samples were analyzed for a broad range of conventional pollutants, metals, and organic toxicants, both in total and filtered forms. The catchbasin with the sump was the only device that showed important and significant removals for several pollutants:

total solids (0 to 50%, average 22%).
suspended solids (0 to 55%, average 32%).
turbidity (0 to 65%, average 38%).
color (0 to 50%, average 24%).

Design Suggestions to Enhance Pollution Control with Storm Drain Inlet Structures

The goal is a storm drainage inlet device that:

- prevents entry of unwanted material and is safe for small children and pets,
- does not cause flooding when it clogs with debris,
- does not force stormwater through the captured material,
- does not have adverse hydraulic head loss properties,
- maximizes pollutant reductions, and
- requires inexpensive and infrequent maintenance.

The following suggestions and design guidelines should meet these criteria (Pitt, *et al*. 1997). These options are all suitable for retro-fitting into existing simple storm drainage inlets. However, the materials used should be concrete, plastic, aluminum or stainless steel; especially do not use galvanized metal or treated woods. Catchbasins in newly developing areas could be more optimally designed than the suggestions below, especially by enlarging the sumps and by providing large and separate offset litter traps.

1) The basic catchbasin (having an appropriately sized sump) and an inverted outlet should be used in most areas. This is the most robust configuration. In almost all full-scale field investigations, this design has been shown to withstand extreme flows with little scouring losses, no significant differences between supernatant water quality and runoff quality, and minimal insect problems. It will trap the bed-load from the stormwater (especially important in areas using sand for traction control) and will trap a low to moderate amount of suspended solids (about 30 to 45% of the annual loadings). The largest fraction of the sediment in the flowing stormwater will be trapped, in preference

to the finer material that has greater amounts of associated pollutants. Their hydraulic capacities are designed using conventional procedures (grating and outlet dimensions), while the sump is designed based on the desired cleaning frequency. Figure D-2 is this basic recommended configuration (from Lager, *et al.* 1977).

The size of the catchbasin sump is controlled by three factors: the runoff flow rate, the suspended solids concentration in the runoff, and the desired frequency at which the catchbasin will be cleaned without sacrificing efficiency. Table D-2 shows the calculated volume of sediment captured in a catchbasin sump for a one acre paved drainage area and for runoff having 50 to 500 mg/L suspended solids concentrations. The 1976 Birmingham, AL, rain year was used to obtain typical rain depths and flow rates for each rain. The Rv (volumetric runoff coefficient) was obtained from the small storm hydrology tests conducted by Pitt (1987).

An estimate of the required catchbasin sump volume and cleanout frequency can be calculated using this table and site conditions. For example, assume the following conditions:

- paved drainage area: 1.3 ha (3.3 acres),
- 250 mg/L suspended solids concentration, and
- 640 mm (25 in) of rain per year.

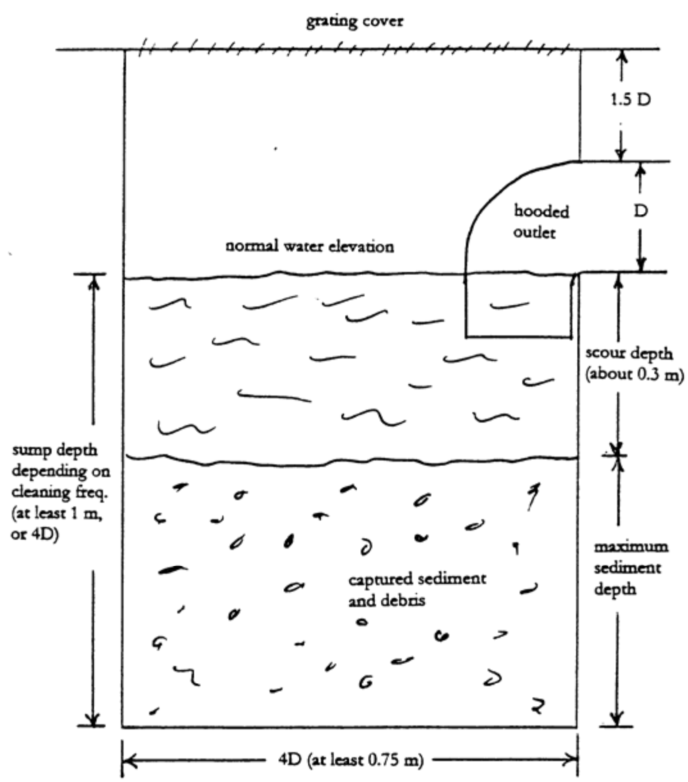


Figure D-2 conventional catchbasin with inverted sump (after Lager, *et al*. 1977).

Table D-2. Approximate Suspended Solids Accumulations in Catchbasin Sump for Different Accumulative Rain Depths and Suspended Solids Concentrations, for Birmingham, AL, Rain Pattern (m^3/ha and ft^3/acre of pavement)

Total Rainfall (mm)	Total Rainfall (inches)	50 mg/L SS conc.		100 mg/L SS conc.		250 mg/L SS conc.		500 mg/L SS conc.	
130	5	0.0092	0.13	0.019	0.27	0.047	0.67	0.092	1.3
250	10	0.019	0.27	0.038	0.54	0.092	1.3	0.19	2.7
380	15	0.028	0.40	0.057	0.81	0.14	2.0	0.28	4.0
640	25	0.047	0.67	0.092	1.3	0.24	3.4	0.47	6.7
1,300	50	0.092	1.3	0.19	2.7	0.47	6.7	0.92	13
2,500	100	0.19	2.7	0.38	5.4	0.92	13	1.9	27
5,100	200	0.38	5.4	0.78	11	1.9	27	3.8	54

The sediment accumulation rate in the catchbasin sump would be about 0.24 m^3/ha (3.4 ft^3/acre) of pavement per year. For a 1.3 ha (3.3 acre) paved drainage area, the annual accumulation would therefore be about 0.3 m^3 (10 ft^3). The catchbasin sump diameter should be at least four times the diameter of the outlet pipe. Therefore, if the outlet from the catchbasin is a 250 mm (10 in) diameter pipe, the sump should be at least 1 m (40 in) in diameter (having a surface area of 0.8 m^3, or 9 ft^2). The annual accumulation of sediment in the sump for this situation would therefore be about 0.4 m (1.3 ft). If the sump was to be cleaned about every two years, the total accumulation between cleanings would therefore be about 0.8 m (2.6 ft). An extra 0.3 m (1 ft) of sump depth should be provided as a safety factor because of potential scour during unusual rains. Therefore, a total sump depth of about 1.1 m (3.6 ft) should be used. In no case should the total sump depth be less than about 1 m (3 ft) and the sump diameter less than about 0.75 m (2.5 ft). This would provide an effective sump volume of about 0.8 m^3 (9 ft^3) assuming a safety factor of about 1.6.

2) A relatively safe add-on to the basic recommended configuration is an adversely sloped inclined screen covering the outlet side of the catchbasin, as shown in Figure D-3. The inclined screen would be a relatively coarse screening (such as the SoilSave™, which is a 6 mm thick plastic foam and has 1 mm apertures) that should trap practically all trash of concern. The bottom edge of the inclined screen would be solidly attached to the inside wall of the catchbasin below the inverted outlet. The screen would tilt outwards so it covers the inverted outlet. The sides of the screen need to be sealed against the sides of the catchbasin. The top edge of the screen would extend slightly above the normal water surface. A solid top plate would extend out from the catchbasin wall on the outlet side covering the top opening of the inclined screen. This plate would overhang the top of the screen, but provide a slot opening above the screen for a large overflow in case the screen was clogged. The slot opening should be several inches high and extend the width of the catchbasin. This design will also capture grit and the largest suspended solids, plus much of the trash. This design would allow the trapped material to fall into the sump instead of being forced against the screen by out-flowing water.

Summary of Sewerage Inlet Devices as Stormwater Control Practices

The best catchbasin configuration for a specific location would be dependent on site conditions and would probably incorporate a combination of features from several different inlet designs. The primary design should incorporate a catchbasin with a sump, as described by Lager, *et al.* (1977), and an inverted (hooded) outlet. If large enough, catchbasins with sumps have been shown to provide a moderate level of suspended solids reductions in stormwater under a wide range of conditions in many studies in the U.S. and Europe. The use of filter fabrics in catchbasins is not likely to be beneficial because of their rapid clogging from retained sediment and trash. The use of coarser screens in catchbasin inlets is also not likely to result in water quality improvements, based on conventional water pollutant analyses. However, well designed and maintained screens can result in substantial trash and litter reductions. It is important that the screen not trap organic material in the flow path of the stormwater. Tests during recent research found that stormwater flowing through decomposing leaves degraded the stormwater quality (Pitt, *et al.* 1997). Prior research (Pitt 1979 and 1985) has shown that if most of the trapped material is contained in the catchbasin sump, it is out of the direct flow path and unlikely to be scoured during high flows, or to degrade

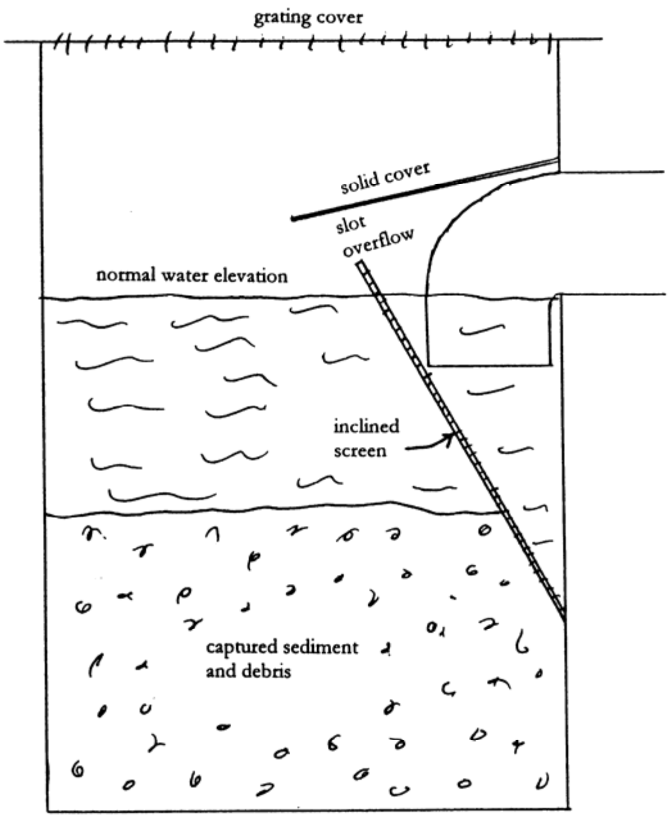


Figure D-3. Catchbasin with sump and inclined screen (Pitt, et al. 1997).

overlying supernatant water. Storm drainage inlet devices also should not be considered as leaf control options, or used in areas having very heavy trash loadings, unless they can be cleaned after practically every storm.

Catchbasin Cleaning Performance Calculations used in SLAMM

SLAMM calculates catchbasin cleaning water quality benefits by keeping track of the accumulation of sediment in the catchbasins from rains and the amount of material removed during catchbasin cleaning operations. Research (Lager, *et al.* 1977a, Pitt 1979, and Pitt 1984) has found that the amount of material accumulated in catchbasins is related to the inflow rate. The following nonlinear equation describes this accumulation of sediment in catchbasins (with a calculated R^2value of 0.97):

Percent removal from inflow = 44.04 (0.51^{x}) (1.061^{x2}), for values of x less than 5 ft^3/sec, and

Percent removal from inflow = 6.5 percent for values of x greater than 5 ft^3/sec.

where x is the inlet flow rate (in ft^3/sec). These equations have been found to be applicable for catchbasin sumps ranging from 2 to 100 ft^3 in volume.

After the catchbasins are 60 percent full, the sediment accumulation is zero. Therefore, cleaning operations need to be scheduled to maintain the catchbasin accumulation of sediment below 60 percent of capacity. When the catchbasin is fuller than this amount, no sediment removal occurs. The following list summarizes some sediment removal values for different flow rates:

Flow rate (ft^3/sec)	Percent removal
0.01	44 %
0.25	37
0.50	32
1.25	21
3.2	9.5
4.7	6.9
>5.0	6.5

Several studies (Sartor and Boyd 1972, Lager, *et al.* 1977a, Pitt 1979, and Pitt 1984) have found very small sediment loading changes due to flushing during rains. Pitt (1984) even monitored about 200 catchbasins during a period of time that included a rain of greater than 4 inches, with no appreciable change in sediment loadings in the catchbasins. It was possible that flushed material was immediately replaced during the same rain, but the net change was zero.

The removal of overlying water above sediment in catchbasins readily occurs and has been noted by Sartor and Boyd (1972) as their largest water quality problem. However, Pitt (1984) statistically compared catchbasin supernatant with outfall water quality and could not detect any significant differences. EDP (1980) examined "first flushes" from catchbasins and found the quality of the water leaving the catchbasins to be much less than the high concentrations of pollutants in the gutter flows during early parts of rains. It is possible that bacteria and soluble heavy metal concentrations could be increased by the residence times between rains due to "favorable" chemical and temperature conditions in catchbasins.

Sedimentation

Detention ponds are probably the most common management practice for the control of stormwater sediment. If properly designed, constructed, and maintained, they can be very effective in controlling a wide range of pollutants and peak runoff flow rates. In an early 1980 survey of cities in the U.S. and Canada, the American Public Works Association found more than 2,000 wet ponds, more than 6,000 dry ponds, more than 3,000 parking lot multi-use detention areas, and more than 500 rooftop storage facilities (Smith 1982). About half of the wet detention ponds were publicly owned. In some areas of the U.S., detention ponds have been required for some time and are therefore much more numerous than elsewhere. In Montgomery County, Maryland, as an example, detention ponds were first required in 1971, with more than 100 facilities planned during that first year, and about 50 actually constructed. By 1978, more than 500 detention facilities had been constructed in Montgomery County alone (Williams 1982). In DuPage County, Illinois, near Chicago, more than 900 stormwater detention facilities (some natural) receive urban runoff (McComas and Sefton 1985).

There is probably more information concerning the design and performance of detention ponds in the literature than for any other stormwater control device. Wet detention ponds are also a very robust method for reducing stormwater pollutants. They typically show significant pollutant reductions as long as a few design-related attributes are met (most important being size). Many details are available to enhance performance, and safety, that should be followed. Many processes are responsible for the pollutant removals observed in wet detention ponds. Physical sedimentation is the most significant removal mechanism. However, biological and chemical processes can also contribute important pollutant reductions. The extensive use of aquatic plants, in a controlled manner, can provide additional pollutant removals. Magmedov, *et al.* (1996), for example, report on the use of wetlands for treatment of stormwater runoff in the UK and in the Ukraine, including design guidelines. Wet detention ponds also are suitable for enhancement with chemical and advanced physical processes. Lamella separators, air floatation, filtration, and UV disinfection are examples of treatment enhancements being investigated in France (Bernard, *et al.* 1996; Delporte 1996).

Wet Detention Pond Performance Reported in the Literature

The use of detention ponds for both water quality and quantity benefits is relatively new. Wet pond stormwater quality benefits have been commonly reported in the literature since the 1970s, while the water quality benefits of dry detention ponds have only recently been adequately described (Hall 1990).

The Nationwide Urban Runoff Program included full-scale monitoring of nine wet detention ponds (EPA 1983). The Lansing project included two up-sized pipes, plus a larger detention pond. The NURP project located in Glen Ellyn (west of Chicago) monitored a small lake, the largest pond monitored during the NURP program. Ann Arbor, Michigan, monitoring included three detention ponds, Long Island, New York, studied one pond, while the Washington D.C. project included one pond. About 150 storms were completely monitored at these ponds, and the performances ranged from negative removals for the smallest up-sized pipe installation, to more than 90 percent removal of suspended solids at the largest wet ponds. The best wet detention ponds also reported BOD_5 and COD removals of about 70 percent, nutrient removals of about 60 to 70 percent, and heavy metal removals of about 60 to 95 percent.

The Lansing NURP project monitored a wet detention pond (Luzkow, *et al.* 1981). The monitored pond was located on a golf course (receiving urban runoff from an adjacent residential and commercial area). Suspended solids removals were about 70 percent for moderate rains (10 to 25 mm rains) while phosphorus removals were usually greater than 50 percent. Total Kjeldahl nitrogen removals ranged from about 30 to 50 percent.

Two wet detention ponds near Toronto, Ontario, were monitored from 1977 through 1979 (Brydges and Robinson 1980). Lake Aquitaine is 1.9 ha in size and receives runoff from a 43 ha urban watershed. Observed pollutant reductions were about 70 to 90 percent for suspended solids, 25 to 60 percent for nitrogen, and about 80 percent for phosphorus. The much smaller Lake Wabukayne (0.8 ha) received runoff from a much larger urban area (186 ha). The smaller Lake Wabukayne experienced much smaller pollutant reductions: about 30 percent for suspended solids, less than 25 percent for nitrogen, and 10 to 30 percent for phosphorus.

Oliver, *et al.* (1981), monitored a small lake detention facility in Rolla, Missouri. Suspended solids yield reductions averaged about 88 percent, with 54 and 60 percent yield reductions for COD and total phosphorus. Organic nitrogen yields were reduced by about 22 percent.

Gietz (1983) studied a 1.3 ha wet detention pond serving a 60 ha urban watershed near Ottawa, Ontario. Batch operation of the pond resulted in substantial pollutant control improvements for particulate residue, bacteria, phosphorus, and nitrate nitrogen. Continuous operation gave slightly better performance for BOD_5 and organic nitrogen. Suspended solids reductions were about 80 to 95 percent, BOD_5 reductions were about 35 to 45 percent, bacteria was reduced by about 50 to 95 percent, phosphorus by about 70 to 85 percent, and organic nitrogen by about 45 to 50 percent.

Yousef (1986) reported long-term nutrient removal information for a detention pond in Florida having very long residence times and substantial algal and rooted aquatic plant growths. He found 80 to 90 percent removals of soluble nutrients due to plant uptake. Particulate nutrient removals, however, were quite poor (about ten percent).

Hvitved-Jacobsen, *et al.* (1987) along with Martin and Miller (1987) described pollutant removal benefits of wet detention ponds. Niemczynowicz (1990) described stormwater detention pond practices in Sweden. Van Buren, *et al.* (1996) also recently reported on the performance of a on-stream pond located in Kingston, Ontario. They describe their monitoring activities and measures taken to enhance performance.

Hvitved-Jacobsen, *et al.* (1994) examined the most effective treatment systems for treating urban and highway runoff in Denmark. They concluded that wet detention ponds were the most efficient and suitable solution for the removal of most pollutants of concern from both highway and urban runoff. Denmark does not have any effluent standards and the acceptable pollutant discharges are therefore determined based on specific receiving water requirements. They concluded that CSO problems were causing acute receiving water effects (hydraulic problems, oxygen depletion, high bacterial pollution, etc.), requiring treatment designs based on design storm concepts. However, both urban and highway runoff were mostly causing accumulative (chronic) effects (associated with suspended solids, toxicants, and nutrient discharges) and treatment designs therefore need to be based on long-term pollutant mass discharge reductions. It was evident that relatively low concentrations of pollutants must be reduced, and that large volumes of water must be treated in a short time period. For these reasons, and for the specific pollutants of concern, they concluded that wet detention ponds were the most effective option, even though the first wet detention pond was only constructed in Denmark in 1989. Their recommended design was based on: detention pond volume (about 250 m^3 per effective hectare of drainage area), water depth, pond shape, use of plants (covering at least 30% of the water surface), and the use of a grit removal forebay. This pond design was evaluated using the computer program MOUSE/SAMBA for long-term simulations using Aalborg, Denmark, rains. The resulting mass removals using this design were excellent for suspended solids (80 to 90%) phosphorus (60 to 70%) and heavy metals (40 to 90%).

Mayer, *et al*. (1996) examined sediment and water quality conditions in four wet detention ponds in Toronto. They found that poor water circulation in the summer months between rains decreased the pond water quality, especially for dissolved oxygen and nutrients. Anaerobic conditions near the pond water-sediment interface in two of the ponds caused elevated ammonia concentrations. They felt that decomposition of nitrogenous organic matter (from terrestrial and aquatic plant debris) was the likely source of the ammonia. They also found prolific algal growths in the same two ponds in the summer, with chlorophyll *a* concentrations of about 30 μg/L. The chlorophyll *a* concentrations in the other two ponds were much lower, between about 3 and 10 μg/L.

Maxted and Shaver (1996) examined the biological and habitat characteristics downstream from several headwater wet detention ponds in Delaware to measure beneficial effects. They found that the ponds did not improve the habitat conditions or several benthic indices, compared to similar sites without ponds, when the watershed impervious cover exceeded about 20%. They stress that more research is needed examining other stream indicators, especially in less developed watersheds and in other parts of the country. They concluded that riparian zone protection, which is commonly overlooked in extensively developed watersheds, needs much more attention. The use of stormwater management practices apparently only is able to overcome part of the detrimental effects of development.

Stanley (1996) examined the pollution removal performance at a dry detention pond in Greenville, NC, during eight storms. The pond was 0.7 ha in size and the watershed was 81 ha of mostly medium density single family residential homes, with some multifamily units, and a short commercial strip. The observed reductions were low to moderate for suspended solids (42 to 83%), phosphate (-5 to 36%), nitrate nitrogen (-52 to 21%), ammonia nitrogen (-66 to 43%), copper (11 to 54%), lead (2 to 79%), and zinc (6 to 38%). Stanley also summarized the median concentration reductions at dry detention ponds studied by others, shown in Table D-3. In all cases, the removals of the stormwater pollutants is substantially less than would occur at well designed and operated wet detention ponds. The resuspension of previously deposited sediment during subsequent rains was typically noted as the likely cause of these low removals. The conditions at the Greenville pond were observed three years after its construction. The most notable changes was that the pond bottom and interior banks of the perimeter dike were covered with weeds and many sapling trees (mostly willows), indicating that the interior areas have been too wet to permit mowing. The perforated riser was also partially clogged and some pooling was occurring near the pond outlet. It seemed that the dry pond was evolving into a wetlands. The monitoring activity was conducted a few months after the pond was constructed and was not affected by these changes. Stanley felt that the wetlands environment, with the woody vegetation, if allowed to spread, could actually increase the pollutant trapping performance of the facility. With continued no maintenance, the dry pond will eventually turn into a wet pond, with a significant permanent pool. The pollutant retention capability would increase, at the expense of decreased hydraulic benefits and less flood protection than originally planned. Maintenance problems in dry ponds had also been commonly noted in earlier Maryland surveys.

The benefits of off-line stormwater detention ponds were examined by Nix and Durrans (1996). Off-line ponds (side-stream ponds) are designed so that only the peak portion of a stream flow is diverted to the pond (by an in-stream diversion structure). They are designed to reduce the peak flows from developed areas, with no direct water quality benefits, and are typically dry ponds. Off-line ponds are smaller (by as much as 20 to 50%) than on-line ponds (where the complete storm flow passes through the pond) for the same peak flow reductions. However, the outflow hydrographs from the two types of ponds are substantially different. The off-line ponds produce peak outflows earlier and the peak flows no not occur for as long a period of time. If located in the upper portion of a watershed, off-line ponds may worsen flooding problems further downstream, whereas downstream on-line ponds tend to worsen basin outlet area flooding. Off-line dry ponds can be used in conjunction with on-line wet ponds to advantage to provide both water quality and flood prevention benefits. Off-line ponds have an advantage in that they do not interfere with the passage of fish and other wildlife and they do not have to dramatically affect the physical character of the by-passed stream itself. On-line dry ponds would substantially degrade the steam habitat by removing cover and radically changing the channel dimensions. The peak flow rate reductions can also have significant bank erosion benefits in the vicinity of the pond, although these benefits would be decreased further downstream.

Problems with Wet Detention Ponds

Wet detention ponds may experience various operating and nuisance problems. The following discussion attempts to describe these negative aspects of wet ponds, as reported in the literature, and to describe how they have been overcome through specific designs.

Safety of Wet Detention Ponds

The most important wet detention pond design guidelines are to maintain public safety. The following discussion briefly summarizes common suggestions to maintain and improve safety at wet detention facilities. Marcy and Flack (1981) state that drownings in general most often occur because of slips and falls into water, unexpected depths, cold water temperatures, and fast currents. Four methods to minimize these problems include: eliminate or minimize the hazard, keep people away, make the onset of the hazard gradual, and provide escape routes. Many of the design suggestions and specifications contained in this section are intended to accomplish these methods.

Jones and Jones (1982) consider safety and landscaping together because landscaping can be an effective safety element. They feel that appropriate slope grading and landscaping can provide a more desirable approach than wide-spread fencing around a wet detention pond. Fences are expensive to install and maintain and usually produce unsightly pond edges. They collect trash and litter, challenge some individuals who like to defy barriers, and impede emergency access if needed. Marcy and Flack (1981) state that limited fencing may be appropriate in special areas. When the pond side slopes cannot be made gradual (such as when against a railroad right-of-way or close to a roadway), steep sides having submerged retaining walls may be needed. A chain link fence located directly on the top of the retaining wall very close to the water's edge would be needed (to prevent human occupancy of the narrow ledge on the water side of the fence). Another area where fencing may be needed is at the inlet and outlet structures. However, fencing usually gives a false sense of security, as most can be easily crossed (Eccher 1991).

Pond side slopes need to be gradual near the water edge, with a submerged shallow ledge close to shore. Aquatic plants on the ledge would decrease the chance of continued movement to deeper water and thick vegetation on shore near the water edge would discourage access to the water edge and decrease the possibility of falling into the water accidentally. Pathways should not be located close to the water's edge, or turn abruptly near the water.

Marcy and Flack (1981) also encourage the placement of escape routes in the water whenever possible. These could be floats on cables, ladders, hand-holds, safety nets, or ramps. However, they should not be placed to encourage entrance into the water.

Table D-3. Summary of Dry Detention Pond Pollutant Removal (Stanley 1996)

	Detention pond name and location						
	Lakeridge northern Virgina[a]	London northern Virgina[b]	Stedwick Montgomery Co., Md.[c]	Maple Run Austin, Tex.[d]	Oakhampton Baltimore, Md.[e]	Lawrence Kans.[f]	Greenville, N.C.[g]
Watershed, acres	88	11	34	28	17	12	200
Imperviousness, %						49	
Hours to drain after filling	1–2	<10	6–12	–9		6–16	75
Storms monitored	28	27	25	17		19	8
Removal efficiencies, %							
TSS	14	29	70	30	87	3	71
TP	20	40	13	18	26	19	14
PO_4-P	–6				–12	0	26
TN	10	25	24	35			26
NO_3-N	9			52	–10	20	–2
NH_4-N				55	54	69	9
TOC				30		–3	10
POC							45
DOC							–6
Cu				31			26
Pb		39	62	29		66	55
Zn	–10	24	57	–38		65	26

Each study differs with respect to pond design, number of storms monitored, pollutant removal calculation techniques, and monitoring techniques. Therefore, exact comparisons cannot be made.

[a] MWCOG (1983); [b] OWML (1987); [c] Schueler and Helfrich (1988); [d] City of Austin, 1991 personal communication, cited in Schueler *et al.* (1992); [e] Baltimore Department of Public Works (1989); [f] Pope and Hess (1988); [g] this study.

The use of inlet and outlet trash racks and antivortex baffles is also needed to prevent access to locations having dangerous water velocities. Racks need to be placed where water velocities are less than three feet per second through the racks to allow people to escape and the openings should be less than 6 inches across (Marcy and Flack 1981). Besides maintaining safe conditions, racks also help keep trash from interfering with the operation of outlet structures.

Eccher (1991) lists the following pond attributes to ensure maximum safety, while having good ecological control:

1) There should be no major abrupt changes in water depth in areas of uncontrolled access,
2) slopes should be controlled to insure good footing,
3) all slope areas should be designed and constructed to prevent or restrict weed and insect growth (generally requiring some form of hardened surface on the slopes), and
4) shoreline erosion needs to be controlled.

Nuisance Conditions in Wet Detention Ponds and Degraded Water Quality
Most new detention ponds require from three to six years before an ecological balance is obtained (Ontario 1984). Excessive algal growths, fish kills, and associated nuisance odors may occur during this period, creating management problems for municipal officials and developers. Water quality is also generally poor in wet detention ponds, but unauthorized swimming can be common if alternative swimming facilities are not conveniently available. The poorest water and sediment quality in wet detention ponds usually occurs near the inlets and in depressions (Free and Mulamoottil 1983 and Wigington, *et al.* 1983). Some urban lakes have also been subjected to duck plagued disease which is a deadly virus that thrives in lakes having excessive algae growths (Ontario 1984). Schueler and Galli (1992) reported that water discharged from wet detention ponds may be warmed by as much as 10 to 15°F in the summer months, unless shaded or subsurface discharges are used.

The haphazard installation of detention ponds can increase downstream flooding and erosion problems if a regional analysis and careful plan is not developed and followed (Duru 1981 and 1983, Jones and Jones 1982, and Hawley, *et al*. 1981). This can occur by increasing the duration of erosive flow velocities and by adding the delayed high discharge flows from a pond to the natural high flows from upstream areas. These problems can be substantially reduced with careful design and maintenance, as described in the following paragraphs.

Attitudes of Nearby Residents and Property Values
Wet detention ponds may create potential nuisance conditions if they are not properly designed or maintained. However, many people living near wet detention ponds do so because of the close presence of the wetlands, and their property values are typically greater than lots further from the ponds (Marsalek 1982). Marsalak (1982) also reported that small (well maintained) wet detention ponds are less subject to controversy that larger ponds (that are more commonly neglected). Debo and Ruby (1982) summarized a survey conducted in Atlanta of residents living near and downstream of 15 small detention ponds and found that almost half of the people surveyed who lived in the immediate areas of the ponds did not even know that they existed. Wiegand, *et al*. (1986) also stated that wet detention ponds, when properly maintained, are more preferred by residents than any other urban runoff control practice.

Emmerling-DiNovo (1995) reported on a survey of homeowners in the Champaign-Urbana area living in seven subdivisions having either dry or wet detention ponds. She reported that past studies have recognized that developers are well aware that proximity to water increases the appeal of a development. Detention ponds can create a sense of identity, distinguishing one development from another, and can be prominent design elements. Increased value is important because the added cost of the detention facility, including loss of developable land, must be recovered by increasing the housing costs. Others have also found that the higher costs of developments having stormwater detention facilities can also be offset by being able to sell the housing faster. In a prior survey in Columbia, MD, 73% of the respondents would be willing to pay more for property located in an area having a wet detention pond if designed to enhance fish and wildlife use. Although the residents were concerned about nuisances and hazards, they felt that these concerns were out-weighed by the benefits. In her survey, Emmerling-DiNovo (1995) received 143 completed surveys. Overall attractiveness of the neighborhood was the most important factor in purchasing their home. Resale value was the second most important factor, while proximity to water was slightly important. More than 74% of the respondents believed that wet detention ponds contributed positively to the image of the neighborhood and they were a positive factor in choosing that subdivision. In contrast, the respondents living in the subdivisions with the dry ponds felt that the dry ponds were not a positive factor in locating in their subdivision. Respondents living adjacent to the wet ponds felt that the presence of the pond was very positive in the selection of their specific lot. The lots adjacent to the wet ponds were reported to be worth about 22% more than lots that were not adjacent to the wet ponds. Lots adjacent to the dry ponds were actually worth less (by about 10%) than other lots. Dry detention ponds actually decreased the assessed values of adjacent lots in two of the three dry basin subdivisions studied. The respondents favored living adjacent to wet ponds even more than next to golf courses. Living adjacent to dry ponds were the least preferred location.

Another example of increased land value occurred in Fairfax, VA (*Land and Water* 1996). A 1.6 acre wet detention pond was constructed using a modular concrete block retaining wall system. Total construction time was about six weeks and resulted in an attractive pond that added substantial value to the new housing development.

The Hennepin (MN) park district (John Barten, personal communication) reports that the park district is frequently asked by developers to be allowed to "improve" the parks by putting their wet detention ponds on park land that is adjacent to new developments. Needless to say, the park district cannot afford to convert their dry land to lakes which would dramatically decrease the utilization of the park by the park users. The park district is also frequently asked by residents of subdivisions to improve the water quality in the wet detention ponds located in their subdivisions, especially to allow fishing and swimming. The residents do not understand that their "lake" is actually a water treatment system and is not a natural lake or park and is not intended for water contact recreation or fishing. However, because many of these subdivisions are marketed by stressing the benefits of "lakeside" living, some of the residents expect the city to improve the wet detention ponds for recreational use. The park department, under a lot of citizen and political pressure, has actually had to construct new wet detention ponds upstream of some of these wet detention ponds.

Maintenance Requirements of Wet Detention Ponds

In order for detention ponds to perform as anticipated, they must be regularly maintained. Poor operation and maintenance not only reduces the pollutant and flow rate reduction effectiveness of detention ponds, but can cause detention facilities to become eyesores, nuisances, and health hazards (Poertner 1974). If a pond does not "need" maintenance (such as sediment removal), then it is not providing significant water quality benefits. Ponds can be designed to minimize maintenance, however, a maintenance free detention facility (that is working properly) does not exist (SEMCOG 1981).

Institutional arrangements must be made to insure continued detention pond maintenance after construction. SEMCOG (1981) recommends that appropriate maintenance programs specifically identify the organization or person who will perform the maintenance and how the maintenance operations will be financed. They also found that major detention pond maintenance (dredging) is usually needed within about ten years after pond construction. More frequent (routine) maintenance may include: structural repairs (bank stabilization), removal of debris and litter from the water and surrounding land, grass cutting, fence repairing, algal control, mosquito control, and possible fish stocking. Wet detention ponds require a lot of attention.

Routine Maintenance Requirements

The following summary of routine maintenance requirements is based on a discussion by Schueler (1987).

Mowing. The most costly routine maintenance required of a detention facility is mowing the surrounding area. In residential areas, frequent mowing (up to 12 times a year) may be necessary to maintain a lawn surrounding the pond. Some native plants (such as in the small prairie surrounding the Monroe Street detention pond in Madison at the University of Wisconsin Arboretum) require much less maintenance. In all cases, the emergency spillway, side slopes, and pond embankments need to be mowed at least twice a year to control undesirable plants that may interfere with pond operation. Attractive landscaping and adequate landscaping maintenance are always needed. Careful plant selection (water and salt tolerant, disease and winter hardy, and slow growing) should be made in conjunction with a landscape architect or the Soil Conservation Service.

Debris and litter removal. During the routine mowing operations and after each major storm, debris and litter should also be removed from the site, especially from the inlet and outlet grates and the water surface.

Inspections. Wet detention ponds need to be inspected at least once a year, and after each major storm. The inspection should include checking the pond embankments for subsidence, erosion, and tree growth. The conditions of the emergency spillway and inlets and outlets also need to be determined during the inspection. The adequacy of any channel erosion protection measures near the pond should also be investigated. Sediment accumulation in the pond (especially near, and in, the inlets and outlets) also needs to be examined.

Sediment Removal from Wet Detention Ponds

Large sediment accumulations in detention ponds can have significantly adverse affects on pond performance. Bedner and Fluke (1980) reported on the long term effects of detention ponds that received little maintenance. Lack of dredging actually caused the silted-in ponds to become a major sediment source to downstream areas. Poorly maintained ponds only delayed the eventual delivery of the sediment downstream, they did not prevent it.

Based on the NURP detention pond monitoring results (EPA 1983), a pond having a surface area of about 0.6 percent of the contributing area should remove about 90 percent of the settleable solids (particulate residue) from the runoff. The Milwaukee NURP project (Bannerman, *et al.* 1983) estimated an annual sediment delivery of about 500 pounds per acre for medium density residential land uses and about 2500 pounds per acre for commercial areas. Other land uses contribute sediment generally between these values. Assuming a density of about 120 pounds per cubic feet, about 3.6 and 18 cubic feet of sediment would be deposited in a well designed detention pond for each medium density residential or commercial acre per year. With a pond 0.6 percent of the contributing area in size, this would only result in the deposition of between 0.2 and 0.9 inches per year. McComas and Sefton (1985) report two measured sediment accumulation rates in Chicago area wet detention ponds (about two and three percent of the drainage pond in size) of 0.24 and 1.3 inches per year. Kamedulski and McCuen (1979) report a much greater sedimentation rate of about three inches per year in another pond. When uncontrolled construction site erosion is allowed to enter a detention pond, the pond can literally fill up over night.

Most of the sedimentation would occur near the inlet and the resulting sediment accumulation would be very uneven throughout the pond. Sediment removal in a wet pond may therefore be needed about every five to ten years, depending on the variation in sediment deposition over the pond and the sacrificial storage volume designed.

It is necessary to plan for required maintenance during the design and construction of detention ponds. Ease of access of heavy equipment and the possible paving of a sediment trap near the inlet would ease maintenance problems. Deposited sediment can be heavily polluted and may require special disposal practices. Sediment concentrations of up to 100,000 mg organic carbon, several thousand mg lead, several hundred mg zinc, and more than ten mg arsenic per kg dry sediment are not uncommon for lakes receiving urban runoff (Pitt and Bozeman 1979). Dredged sediment is usually placed directly onto trucks, or is placed on the pond banks for dewatering before hauling to the disposal location. One common practice is to keep an area adjacent to the detention pond available for on-site sediment disposal. Small mounds can be created of the dried sediment and covered with top soil and planted.

Poertner (1974) reviewed various sediment removal procedures. An underwater scoop can be pulled across the pond bottom and returned to the opposite side with guiding cables. If drains and underwater roads were built during the initial pond construction, the pond can be drained and front-end-loaders, draglines, and trucks can directly enter the pond area. Small hydraulic dredges can also be towed on trailers to ponds. The dredge pumps sediment to the shore through a floating line where the sediment is then dewatered and loaded into trucks or piled. A sediment trap can also be constructed near the inlet of the pond. The entrances into the pond are widened and submerged dams are used to retain the heavier materials in a restricted area near the inlets. This smaller area can then be cleaned much easier and with less expense than the complete pond. Hey and Schaefer (1983) report the successful use of a submerged dam across the pond inlet in Lake Ellyn.

The estimated cost of removing sediment from a detention pond varies widely, depending on the amount to be removed and the disposal requirements. Costs as low as one dollar per cubic yard have been reported, but this low cost does not include any possible special disposal practices. Sediment removal costs are estimated to generally range from about $5 to $25 per cubic yard of sediment removed.

Problems with Contaminated Sediments in Wet Detention Ponds. Frequently, concern arises about the safety of disposing sediments from wet detention ponds. There have recently been several studies that have addressed this issue, as summarized in the following paragraphs. Dewberry and Davis (1990) analyzed sediments from 21 ponds in northern Virginia. They found trace metals in many of the sediments, but the available forms of the metals were significantly less than applicable toxic thresholds. They concluded that the dredged materials could be safely disposed either on-site or at sanitary landfills without danger of health problems. However, they recommend that sediment samples from specific ponds be analyzed before dredging.

Yousef and Lin (1990) conducted extensive pond water quality and sediment quality analyses in six wet detention ponds in Florida as part of a Florida Dept. of Transportation study to develop pond maintenance procedures. The ponds had all been constructed from 4 to 13 years prior to analyses and received runoff from various urban watersheds that all contained different amounts of highway runoff. The dissolved oxygen levels in the ponds all dropped significantly with depth, in many cases being lower than 1 mg/L at the water-sediment interface. The pH of the pond water was also generally acidic in all of the ponds, being from 5.5 to 7.2 throughout the water columns. The temperature differences between the water surface and the bottom of the ponds was generally less than 1^{o}C. The sediment accumulation rates were found to be between 0.25 and 0.72 cm per year and correlated with pond age, size of drainage basin and size of pond. The bottom material was found to be poorly graded sand. Appreciable amounts of heavy metals (Cu: 7 to 73 μg/g, Ni: 12 to 82 μg/g, Pb: 84 to 1025 μg/g, and Zn: 13 to 538 μg/g), and nutrients (N: 1.1 to 5.2 mg/g, and P: 0.1 to 1.2 mg/g) were found in the surface layers of the sediments. However, the concentrations of the pollutants decreased rapidly with depth, generally being less than 10% of the surface sediment concentrations below 20 cm beneath the water-sediment interface. The bottom sediments were also analyzed to determine the TCLP extractable portions of the metals. These were found to be significantly less than the whole sediment metal concentrations (Cu: 0.13, Ni: 0.31, Pb: 0.27, and Zn: 0.33). They determined that the TCLP extractable fraction was lowest for sediments having higher clay and organic material. They concluded that the sediments could be removed during normal maintenance operations and disposed of on non-agricultural land.

Jones (1995) and Jones, *et al.* (1996) discuss the implications that the Resource Conservation and Recovery Act (RCRA) may have on sediments that need to be removed from stormwater management facilities, as summarized in the following discussion. The "mixture" (40 CFR Section 261.3(a)(2)(iv)) and "derived from" (40 CFR Sections 261.3(c)(2)(1) and 261.3(d)(2)) rules can cause sediments having very low concentrations of pollutants to be classified as "hazardous." These regulations are likely to be changed in the near future, with clearer definitions for non-hazardous operations and facilities. Sediments are evaluated as being hazardous when the wet detention pond is being dredged, not while they remain in-place. Many of the materials that are listed as hazardous under RCRA may enter stormwater, especially at vehicle service facilities, industrial facilities, and even golf courses and parks. These include solvents, degreasers, hydraulic fluids, herbicides, fungicides, and pesticides. For the sediments to be considered hazardous under the current RCRA mixture rule, the source of the specific material containing the listed hazardous material must contain more than 10% of the hazardous material. This is irrespective of how much of the material actually enters the stormwater. Therefore, site inventories become important tools in determining if a sediment would be classified as hazardous. If a listed material is used on the site, but it would not come in contact with rain (either through normal use or spills), the sediment would not likely be classified as hazardous. It is difficult to conduct detailed site surveys for a large drainage area having many separate owners, but it is feasible for small wet ponds serving single facilities. Jones (1995) and Jones, *et al.* (1996) also discuss other options to minimize the chance that wet pond sediment would be classified as hazardous under RCRA:

- Reduce the likelihood that listed substances would come in contact with precipitation or runoff.
- Inventory and track hazardous materials and encourage the use of replacement compounds.
- Install stormwater pre-treatment facilities to localize the problem.
- Reduce the accumulation rate, and increase the storage area for sediment in the pond.

Vegetation Removal from Wet Detention Ponds
In shallow detention ponds, excessive rooted aquatic plant (macrophyte) growths may occur over the entire pond surface. In deeper ponds, rooted aquatic plant growths are usually restricted close to the shoreline (Ontario 1984). Floating algae may create problems anywhere in a lake, irrespective of pond depth. As noted earlier, a narrow band of natural rooted aquatic plants along the narrow "safety" shelf is desirable as a barrier and to add habitat for pond wildlife.

Excessive algal growths create nuisance problems with strong odors, but more serious problems may also occur. Schimmenti (1980) reports that decaying vegetation, if not removed, promotes the breeding of mosquitoes. Certain types of algae (*Anabaena*, *Aphanizomenon*, and *Anacystis*) naturally produce toxins that can kill animals (including fish) which drink the water and can cause skin irritation and nausea in humans (Ontario 1984). Algae is usually mechanically controlled in detention ponds by using algae harvestors or by dewatering the pond. Certain fish also consume large amounts of algae, but the most common type of algae control is by using aquatic herbicides. Many rooted aquatic plant growth problems can be significantly reduced by using a deep pond which restricts light penetration.

Small weed harvestors can be delivered to a detention pond by trailer. The use of chemicals for algae control is popular, but must be carefully done to prevent contamination of the receiving water. Dead algae and rooted plants must also be removed to prevent odor and dissolved oxygen problems. Mechanical barriers can also be placed on the pond bottom to reduce rooted aquatic plant growth. AquaScreen is a fairly fine, dark mesh that is laid on the pond bottom that restricts sunlight from reaching the rooted aquatic plants. In tests conducted on Lake Washington, Perkins (1980) concluded that a two or three month use of the material resulted in about an 80 percent reduction of rooted aquatic plants where the material had been placed. Again, increased pond depth, possibly at less cost, can do the same thing.

Guidelines to Enhance Pond Performance
The Natural Resources Conservation Service (NRCS, renamed from SCS, undated) has prepared a design manual that addresses specific requirements for such things as anti-seep collars around outlet pipes, embankment widths, type of fill required, foundations, emergency spillways, etc., for a variety of wet detention pond sizes and locations. That manual must be followed for detailed engineering requirements.

The rest of this discussion presents some of the many design suggestions that have been made by researchers having many years of design and monitoring experience with detention ponds. Akeley (1980) listed several modifications that can be made to existing ponds to improve their performance. Gravel, or cement, should be added along unstable banks and near the inlet and control structures. A baffle should be placed at the inlet to reduce turbulence, and barriers can be used to separate the pond into compartments to reduce short-circuiting. On-going maintenance is also needed to remove deposited sediment. Hawley, *et al.* (1983) also recommended similar design considerations. Hey and Schaefer (1983) found that a submerged dam near the pond inlets significantly reduced the area requiring maintenance dredging.

Insect Control, Fish Stocking and Planting Desirable Aquatic Plants
Mosquito problems at wet detention ponds are increased when large water level fluctuations occur, especially when vast amounts of aquatic plants are wetted and available for egg laying. If ponds drain to normal water levels within several hours after a rain has ended, if aquatic vegetation is kept to a minimum (such as only along a narrow ledge close to shore), and if the pond shape allows adequate water movement and wind disturbance, then mosquito problems should be minimal.

Schimmenti (1980) made several recommendations to reduce the possibility of mosquito problems in detention ponds. Wet ponds should have adequate water quality to support surface feeding fish, such as sunfish, and various minnows, that feed on mosquitoes. Carp or crayfish also make adequate biological controls for midges, reducing the need for chemical controls (Ontario 1984).

Some developers have tried to stock trout, yellow perch, and northern pike in detention ponds, but no reproduction and poor wintering soon eliminates these less tolerant fish. Detention ponds receiving urban runoff are likely to contaminate fish, making them unsuitable for consumption. Brydges and Robinson (1980) have conducted extensive heavy metal and pesticide analyses in fish in two wet detention ponds near Toronto, Ontario and have found little problem accumulations of these substances. However, other studies have reported problem toxic pollutant concentrations in fish from waters receiving urban runoff, so allowing fish consumption in wet detention facilities should only be allowed after careful study. Therefore, game fish should not generally be used in ponds, and consumptive fishing should be discouraged. Fathead minnows, stocked for mosquito control, have survived in detention ponds in Ontario.

Rooted aquatic plants should be planted along much of the shallow perimeter shelf to deter small children, for aesthetics and to provide wildlife habitat. The use of native aquatic plants is to be encouraged to lessen maintenance costs and to prevent nuisance plants from becoming established in a waterway (such as purple loosestrife). Plants that could be established in wet detention ponds include arrowhead and cattails. Cattails sometimes interfere with the operation of a surface outlet because of large floating pieces clogging the weir. Subsurface weirs and trash racks (both recommended) would decrease this problem. Other rooted aquatic plants may also be used in wet detention ponds, but their selection and planting should be done in consultation with a landscape architect and a wildlife biologist. Fuhr (1996) warns against planting trees and brush on an impoundment because seepage problems may result by root action.

An interesting use of aquatic plants to enhance wet detention pond performance was described in the February 1991 *Lake Line*. Nutri-Pods, developed by the Limnion Corporation of Concord, CA, are two m diameter mesh balls, initially filled about 25% full with coontail (*Ceratophyllum demersum*). One to five Nutri-Pods are used per acre of pond surface, for ponds at least one acre in size. These reduce nutrient concentrations in the water and successfully compete with other aquatic plants, including planktonic algae. They were tested on a 27 acre lake near Sacramento, CA, which underwent periodic major increases in nutrients (phosphates as high as 50 mg/L) from fertilizing surrounding land. It took about two to four weeks for the Nutri-Pods to stabilize the lake after each major increase. Adding *Elodea* to the Nutri-Pods helped to keep nutrient concentrations very low (phosphorus at about 0.01 mg/L and nitrates less than 0.1 mg/L). The Nutri-Pods are inspected every few weeks and when they approach 100% capacity with the internal aquatic plants, they are removed from the water, and plants are removed, except for about 25% which are used as a starter. The Nutri-Pods therefore use aquatic plants to improve wet detention pond water quality, while enabling controlled harvesting with very little specialized equipment.

Pond Side Slopes

Reported recommended side slopes of detention ponds have ranged from 4:1 (four horizontal units to one vertical unit) to 10:1. Steeper slopes will cause problems with grass cutting and may erode. Steep slopes are not as aesthetically pleasing and are more dangerous than gentle slopes (Chambers and Tottle 1980). Sclueler (1986) also recommends a minimum slope of 20:1 for land near the pond to provide for adequate drainage.

The slope near the waterline, and for about one foot below, should be relatively steep (4:1) to reduce mosquito problems (by reducing the amount of frequently wetted land surface), and to provide relatively fast pond drawdown after common storms. However, a flat underwater shelf several feet wide and about one foot below the normal pond surface is needed as a safety measure to make it easier for anyone who happens to fall into the pond to regain their footing and climb out. This shelf should also be planted with native rooted aquatic plants (marcrophytes) to increase the aesthetics and habitat benefits of a pond and to create a barrier making unwanted access to deep water difficult.

Another method of treating pond edges is placing gravel along the pond edge to decrease erosion and to make mowing easier (Chambers and Tottle 1980). This method requires placing a layer of gravel about one foot deep and 15 feet wide along the pond edge, from about ten feet above the normal waterline edge and extending about five into the water.

Enhancing Pond Performance During Severe Winter Conditions

Oberts (1990 and 1994) monitored four urban wet detention ponds during both warm and cold weather in Minnesota. The ponds performed as expected during warm weather, providing typical removals of suspended solids

(80%), lead (68%), and TP (52%). However, he found that the ponds did a much worse job of removing suspended solids (39%), organic matter (12% for COD), nutrients (4 % for TKN to 17% for TP) and lead (20%) in the winter. He found that thick ice, which can form as much as 1 m in thickness, effectively eliminated much of the detention volume for incoming snowmelt water. In addition, the first melting water was forced under the ice, causing scour of the previously sediments. Later snowmelt water flowed across the surface of the ice, with very little sedimentation opportunities. Any sediment that was accumulated on top of the underlying ice was later discharged when the ice melted. Similar research in Minnesota wetlands also showed similar dismal performance during winter conditions, for much the same reasons.

Oberts (1990 and 1994) proposed several improvements in stormwater management during winter conditions. His initial recommendation is to utilize infiltration and grass filtering in waterways before any detention facilities. He found that substantial infiltration can occur, even in clayey soils, underlying the snow. The ground under snowpacks is rarely frozen and infiltration can be significant until the soil becomes saturated. If the snowmelt is originating from areas having automobile activity (streets and parking areas) or sidewalks, care must be taken because the snowmelt likely would have high concentrations of salts which would adversely affect the local groundwater (Pitt 1996). The design of the detention pond should be modified for winter operations (Oberts 1994). A low flow channel leading to and through the pond will discourage the formation of ice. The pond can also be aerated to prevent ice formation, however, if it gets extremely cold, ice formation could then be very thick and rapid. The most important suggestion by Oberts is to use a special riser for the outlet of the pond that can be used to draw down the water elevation during the winter. Ice would then form near the bottom of the pond and seal off the sediments. As the snowmelt occurs, the bottom outlets on the riser should be closed, forming a deeper pond for better sedimentation.

Droste and Johnston (1993) examined snowmelt quality from snow disposal areas in Ottawa and conducted treatability tests to examine the benefits of different settlement times in 1 L test columns. They found that 2 to 6 hour settling times in these columns produced suspended solids and metal removals approaching 90%. These tests were conducted in controlled laboratory conditions and were not subjected to the actual site problems identified by Oberts. These tests do indicate that sedimentation treatment of snowmelt is likely beneficial, especially if the unique problems of scour and ice formation can be overcome.

Mayer, *et al*. (1996) examined the performance of four wet detention ponds in Toronto during different seasons and during non-storm conditions. The thick ice cover on the ponds during the winter severely affected the pond water quality. In addition, snowmelt and runoff from rainfall occurring on an existing snowpack, were poorly treated by the ponds. Few of the biochemical processes that normally enhance pollutant removal in wet detention ponds during warm weather are available during the winter, plus the ice pack decreases the efficiency of the physical processes, as noted by Oberts. Water beneath the winter ice was typically devoid of oxygen, causing the release of ammonia from sediments and increasing the water column concentrations to about 0.5 mg/L. High grit concentrations in snowmelt, associated with winter sanding of streets, were effectively removed in the detention ponds. However, the high chloride concentrations, from salting of the streets, were not affected by the ponds, as expected.

Particle Settling Characteristics in Stormwater

Knowing the settling velocity characteristics associated with stormwater particulates is necessary when designing wet detention ponds. Particle size is directly related to settling velocity (using Stokes law, for example, and using appropriate shape factors, specific gravity and viscosity values) and is usually used in the design of detention facilities. Particle size can also be much more rapidly measured in the laboratory than settling velocities. Settling tests for stormwater particulates need to be conducted for about three days in order to quantify the smallest particles that are of interest in the design of wet detention ponds. If designing rapid treatment systems (such as grit chambers or vortex separators) for CSO treatment, then much more rapid settling tests can be conducted. Probably the earliest description of conventional particle settling tests for stormwater samples was made by Whipple and Hunter (1981).

The particle size distributions of stormwater at different locations in an urban area greatly affect the ability of different source area and inlet controls in reducing the discharge of stormwater pollutants. A series of recent U.S. Environmental Protection Agency (USEPA) funded research projects has examined the sources and treatability of urban stormwater pollutants (Pitt, *et al.* 1995). This research has included particle size analyses of 121 stormwater inlet samples from three states (southern New Jersey; Birmingham, Alabama; and at several cities in Wisconsin) in the U.S. that were not affected by stormwater controls. Particle sizes were measured using a Coulter Counter Multi-Sizer IIe and verified with microscopic, sieve, and settling column tests. Figures D-4 and D-5 are grouped box and whisker plots showing the particle sizes (in μm) corresponding to the 10th, 50th (median) and 90th percentiles of the cumulative distributions. If 90 percent control of suspended solids (by mass) was desired, then the particles larger than the 90th percentile would have to be removed, for example. In all cases, the New Jersey samples had the smallest particle sizes (even though they were collected using manual "dipper" samplers and not automatic samplers that may miss the largest particles), followed by Wisconsin, and then Birmingham, Alabama, which had the largest particles (which were collected using automatic samplers). The New Jersey samples were obtained from gutter flows in a residential neighborhood that was xeroscaped, the Wisconsin samples were obtained from several source areas, including parking areas and gutter flows mostly from residential, but from some commercial areas, and the Birmingham samples were collected from a long-term parking area on the UAB campus. In contrast, Figure D-6 is a plot of stormwater particle sizes from the outfall at the Monroe St. site in Madison, WI (collected using both an automated sampler and bed-load samplers). These data were also not affected by stormwater controls, but do show the significant shift in particle sizes in stormwater at the outfall compared to source area sheetflow. The median particle size at the outfall was only about 8 μm, and the 90th percentile value was less than 1 μm. At the source areas, the median particle size was about twice as large, at about 15 μm, while the 90th percentile size was about 3 μm. The bed load sampler also enabled larger particles moving in the stormwater to be effectively sampled. The bed load sampler material represented about 10% (by weight) of the annual sediment load (mostly in sizes larger than about 300 μm), while the automatic sampler captured about 90% of the annual load (mostly in sizes from <1 μm to about 300 μm).

The median particle sizes ranged from 0.6 to 38μm and averaged 14μm. The 90th percentile sizes ranged from 0.5 to 11μm and averaged 3μm. These particles were all substantially smaller than have been typically assumed for stormwater. The suspended solids concentrations ranged from 4 to 1080 mg/L (averaging 130 mg/L), while the turbidity ranged from 1 to 290 NTU (averaging 41 NTU). Notably lacking was a better relationship between suspended solids and turbidity, or between suspended solids and any of the particle sizes. Additional data obtained by Pitt and Barron (1989) for the USEPA described particle sizes from many different source flows in the Birmingham, Alabama, area. These data did not indicate any significant differences in particle size distributions for different source areas or land uses, except that the roof runoff had substantially smaller particle sizes.

Pisano and Brombach (1996) recently summarized numerous solids settling curves for stormwater and CSO samples. They are concerned that many of the samples analyzed for particle size are not representative of the true particle size distribution in the sample. As an example, it is well known that automatic samplers do not sample the largest particles that are found in the bedload portion of the flows. Particles having settling velocities in the 1 to 15 cm/sec range are found in grit chambers and catchbasins, but are not seen in stormwater samples obtained by automatic samplers, for example. It is recommended that bedload samplers be used to supplement automatic water samplers in order to obtain more accurate particle size distributions (Burton and Pitt 1997). Selected US and Canadian settling velocity data are shown in Table D-4. The CSO particulates have much greater settling velocities than the other samples, while the stormwater has the smallest settling velocities.
More than 13,000 CSO control tanks have been built in Germany using the ATV 128 rule (Pisano and Bromback 1996). This rule states that clarifier tanks (about 1/3 of these CSO tanks) are to retain all particles having settling velocities greater than 10 m/hr (0.7 cm/sec), with a goal of capturing 80% of the settleable solids. Their recent

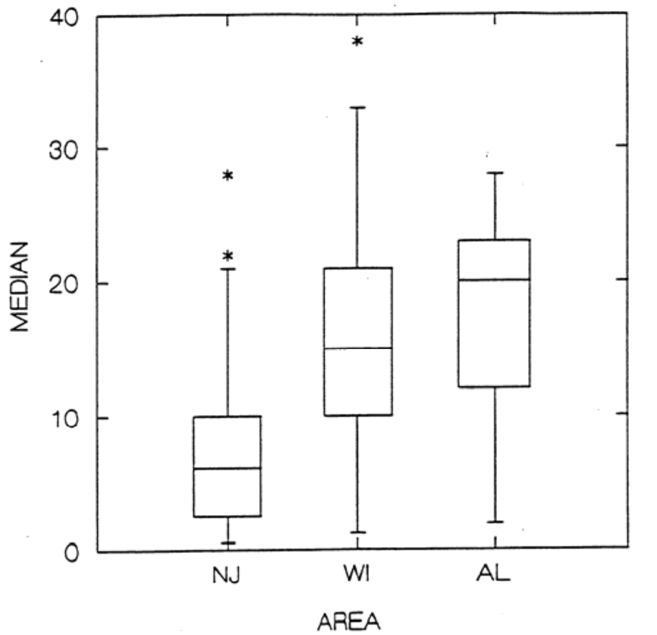


Figure D-4. Median particle sizes for stormwater sheetflow samples (Pitt, *et al.* 1995).

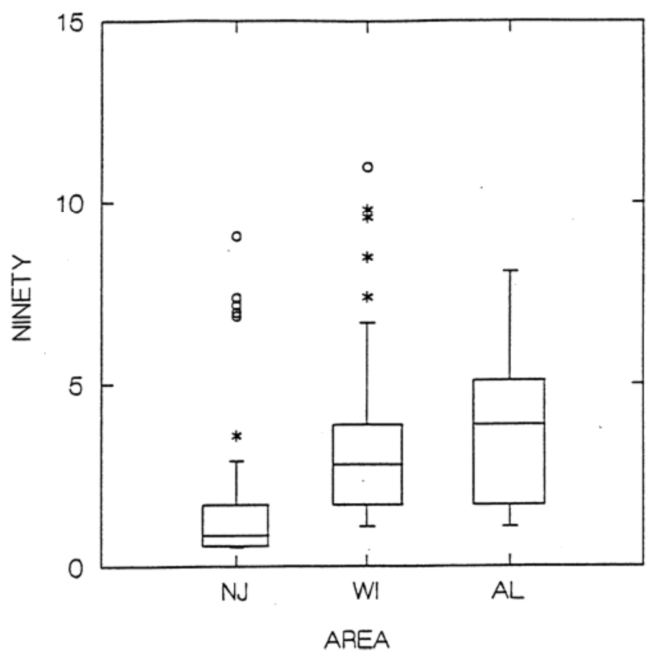


Figure D-5. Ninetieth percentile particle sizes for stormwater sheetflow samples (Pitt, *et al.* 1995).

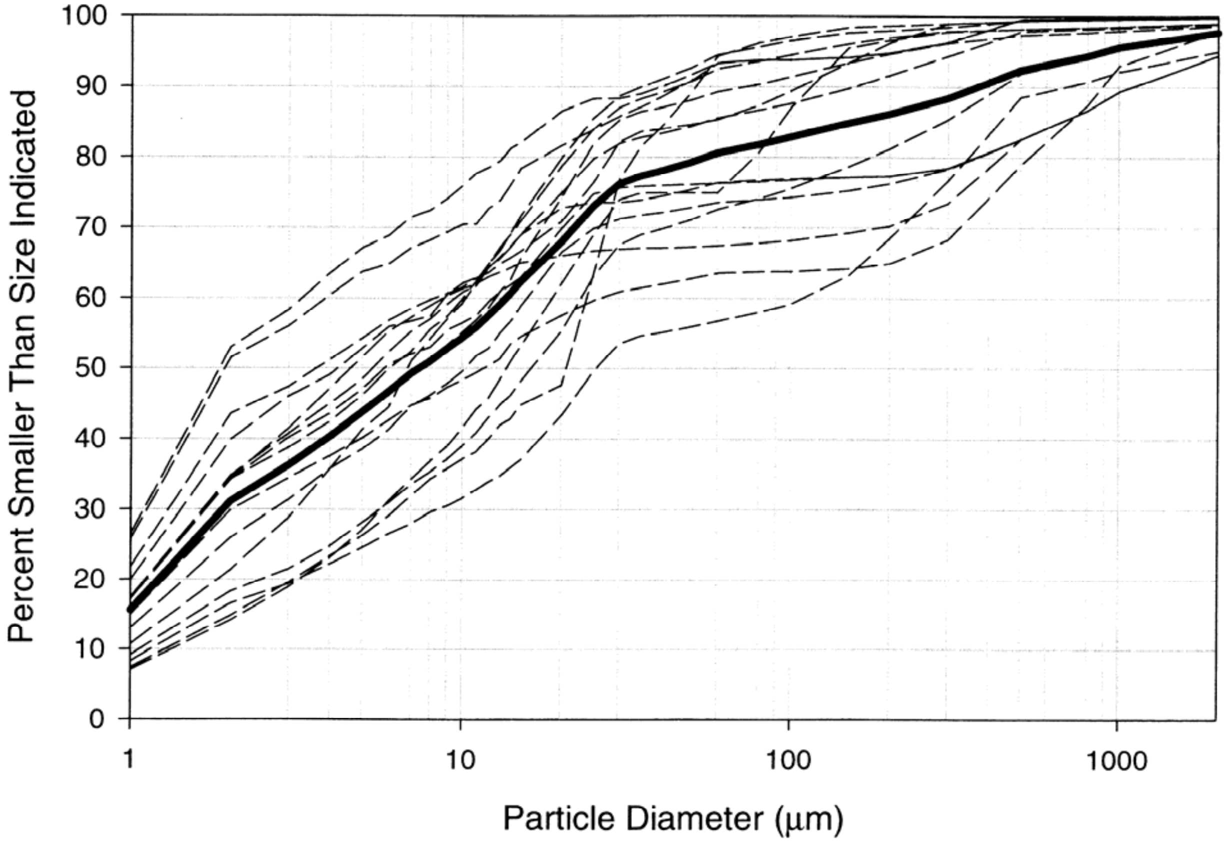


Figure D-6. Stormwater outfall particle size distribution, Monroe St., Madison, WI (WI DNR unpublished data).

measurements of overflows from some of these tanks indicate that the 80% capture was average for these tanks and that the ATV 128 rule appears to be reasonable.

The relationship between solids retention and pollution retention is important for wet detention ponds. Becker, *et al*. (1995) used settling column tests to measure the settling characteristics of different pollutants in sanitary sewage. They found that the majority of the particulate fractions of COD, copper, TKN, and total phosphorus was associated with particles having settling velocities of 0.04 to 0.9 cm/sec.

Vignoles and Herremans (1995) also examined the heavy metal associations with different particles sizes in stormwater samples from Toulouse, France. They found that the vast majority of the heavy metal loadings in stormwater were associated with particles less than 10 µm in size, as shown on Table D-5. They concluded that stormwater control practices must be able to capture the very small particles.

Wet Detention Pond Design Procedures

The basic design approaches for wet detention ponds consider either slug flow or completely mixed flow. Martin (1989) reviews these flow regimes and conducted five tracer studies in a wet detention pond/wetland in Orlando, FL, to determine the actual flow patterns under several storm conditions. Completely mixed flow conditions assumes that the influent is completely and instantaneously mixed with the contents of the pond. The concentrations are therefore uniform throughout the pond. Under plug flow conditions, the flow proceeds through the pond in an orderly manner, following streamlines and with equal velocity. The concentrations vary in the direction of flow and

Table D-4. Settling Velocities for Wastewater, Stormwater, and CSO

Samples	Geometric Means of Settling Velocities Observed (cm/sec)	Range of Medians of Settling Velocities Observed (cm/sec)
dry weather wastewater (sanitary sewage)	0.045	0.030 to 0.066
stormwater	0.011	0.0015 to 0.15
CSO	0.22	0.01 to 5.5

Source: Pisano and Bromback (1996)

Table D-5. Percentages of Suspended Solids and Distribution of Heavy Metal Loadings Associated with Various Stormwater Particulate Sizes (Toulouse, France) (Percentage associated with size class, concentration in mg/kg)

	>100 μm	50 to 100 μm	40 to 50 μm	32 to 40 μm	20 to 32 μm	10 to 20 μm	<10 μm
Suspended solids	15%	11%	6%	9%	10%	14%	35%
Cadmium	18 (13)	11 (11)	6 (11)	5 (6)	5 (5)	9 (6)	46 (14)
Cobalt	9 (18)	5 (16)	4 (25)	6 (20)	6 (18)	10 (22)	60 (53)
Chromium	5 (21)	4 (25)	2 (26)	6 (50)	3 (23)	9 (39)	71 (134)
Copper	7 (42)	8 (62)	3 (57)	4 (46)	4 (42)	11 (81)	63 (171)
Manganese	8 (86)	4 (59)	3 (70)	3 (53)	4 (54)	7 (85)	71 (320)
Nickel	8 (31)	5 (27)	4 (31)	5 (31)	5 (27)	10 (39)	63 (99)
Lead	4 (104)	4 (129)	2 (181)	4 (163)	5 (158)	8 (247)	73 (822)
Zinc	5 (272)	6 (419)	3 (469)	5 (398)	5 (331)	16 (801)	60 (1,232)

Source: Vignoles and Herremans (1995)

are uniform in cross section. The steady state resident time for both flow conditions is the same for both flow patterns, namely the pond volume divided by the discharge rate. Historically, wet detention ponds have been designed using the plug flow concept, probably because it had been used in conventional clarifier designs for water and wastewater treatment. In reality, detention ponds exhibit a combination flow pattern that Martin terms moderately mixed flow. He found that the type of mixing that actually occurs is dependent on the ratio of the storm volume to the pond storage volume. If the ratio is less than one, plug flow likely predominates. If the ratio is greater than one, the flow type is not as obvious. With faster flows in the pond, short-circuiting effectively reduces the available pond storage volume (and therefore the resident time), with less effective treatment.

The stormwater management system that Martin (1989) monitored was comprised of a 0.2 acre wet detention pond followed by a 0.7 acre wetland. The drainage area was 41.6 acres, with 33% roadway, 28% forest, 27% high density residential, and 13% low density residential land uses. The system was therefore about 2% of the drainage area, with the wet detention pond portion about 0.5% of the drainage area. The pond's maximum available live storage volume was 18,500 ft^3. The system produces moderate to high pollutant reductions of solids, lead, and zinc (between 50 and 80%) and smaller reductions for nitrogen and phosphorus (between 30 and 40%). At low discharges and with large storage volumes, the pond was found to be moderately well mixed with residence times not much less than the maximum expected if operating under ideal mixing conditions, with little short-circuiting apparent. At higher discharges and with less storage volume, significant short-circuiting occurred.

Driscoll (1989; and EPA 1986) presented a basic methodology for the design and analysis of wet detention ponds. A pond operates under dynamic conditions when the storage of the pond is increasing with runoff entering the pond and with the stage rising, and when the storage is decreasing when the pond stage is lowering. Quiescent settling occurs during the dry period between storms when storage is constant and when the previous flows are trapped in the pond, before they will be partially or completely displaced by the next storm. The relative importance of the two settling periods depends on the size of the pond, the volume of each runoff event, and the inter-event time between the rains.

Driscoll (1989) produced a summary curve, shown as Figure D-7, that relates wet pond performance to the ratio of the surface area of the pond to the drainage area, based on the numerous NURP wet detention pond observations. The NURP ponds were in predominately residential areas and were drained with conventional curb and gutters. This figure indicates that wet ponds from about 0.3 to 0.8 percent of the drainage area should produce about 90% reductions in suspended solids. Southeastern ponds need to be larger than ponds in the Rocky Mountain region because of the much greater amounts of rain and the increased size of the individual events in the southeast. Also, wet ponds intending to remove 90% of the suspended solids need to be about twice as large as ponds with only a 75% suspended solids removal objective.

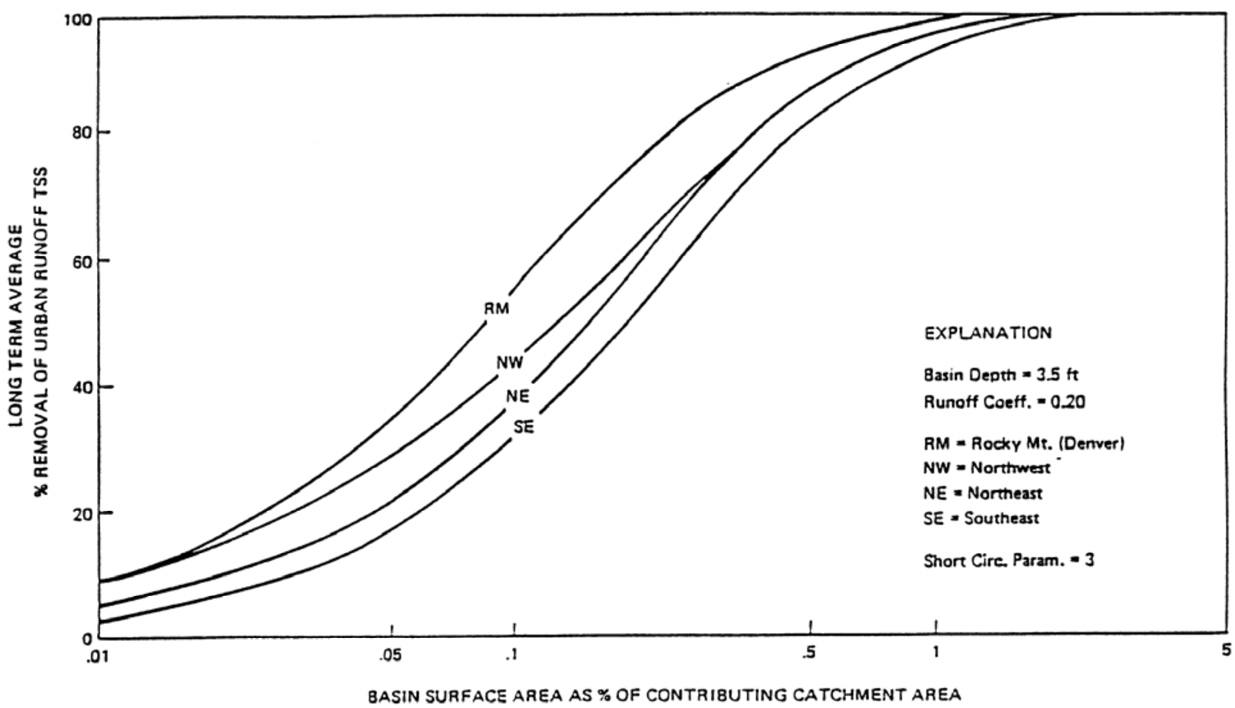


Figure D-7. Regional variations in wet detention pond performance, US EPA NURP data (Driscoll 1989).

Under dynamic conditions, particle trapping can be predicted using the basic Fair and Geyer (1954) equation that considers short-circuiting effects:

$$R = 1 - [1 + (1/n) \times (v_s /(Q/A))]^{-n}$$

where R = fraction of initial solids removed
v_s = settling velocity of particles of concern
Q = wet pond discharge
A = wet pond surface area
n = short-circuiting factor

The short-circuiting factor is typically given a value of 1 for very poor conditions, 3 for good conditions, and 5 for very good conditions. When n is extremely large, the equation reduces to the theoretical removal rate for the particle size of concern. Short-circuiting allows some large particles to be discharged that theoretically would be completely trapped in the pond. However, the following typical example shows that this has a very small detrimental effect on the suspended solids (and pollutant) removal rate of a pond.

The effect of short circuiting has little effect on suspended solids removal, especially in a well designed wet detention pond (one that is large, compared to the drainage area). For example, consider a pond that is designed to theoretically trap all particles greater than 5 μm (or having a theoretical suspended solids capture rate of about 90%, assuming that particles greater than 5 μm make up 90% of the mass of the suspended solids). The following capture of different particles would occur, for a very poor short-circuiting condition (n = 1):

Particle size:	Percent of mass of all particles smaller than size:	Removal of particle size with very poor short-circuiting conditions:
5 μm	10%	50%
20 μm	35%	94%
100 μm	95%	98%

The total effect would likely be less than 10% degraded performance for suspended solids: instead of 90% suspended solids reduction, it may be about 80% for this condition. The largest degraded performance is for particles close to the “design” size of the pond (where $Q/A = v_s$).

Very little degraded performance was observed at a pond monitored during NURP (EPA 1983) in Lansing, MI. A golf course pond located across the street from a commercial strip was converted into a stormwater pond, but the inlets and outlets were adjacent to each other in order to reduce construction costs. It was assumed that severe short circuiting would occur because of the close proximity of the inlet and outlet, but the pond produced suspended solids removals close to what was theoretically predicted, and similar to other ponds having much similar pond area to watershed area ratios. Actually, the close inlet and outlet may have resulted in less short-circuiting because the momentum of the inflowing waters may have forced the water to travel in a general circular pattern around the pond, instead of directly flowing across the pond (and “missing” some edge area) if the outlet was located at the opposite side of the pond. In another example, the USGS and the Wisconsin Department of Natural Resources have been monitoring the Monroe St. wet detention pond in Madison for a number of years. Particle size distributions of influent (including bedload) and effluent have been monitored for about 50 storms. The actual particle size distributions and suspended solids removals have been compared to calculated pond performance, using the DETPOND computer program (Pitt and Voorhees 1989; Pitt 1993a and 1993b), for different short-circuiting factors. The pond is producing suspended solids removals as designed, but the particle size distributions of the effluent indicate some moderate short circuiting (some large particles are escaping from the pond). The short circuiting has not significantly reduced the effectiveness of the pond. Therefore, care should be taken in locating and shaping ponds to minimize short circuiting problems, but not at the expense of other more important factors (especially size, or constructing the pond at all). Poor pond shapes probably cause greater problems by producing stagnant areas where severe aesthetic and nuisance problems originate.

A discussion of wet detention pond design procedures must include three very important publications that all stormwater managers should have. Tom Schueler’s *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban Best Management Practices* (1987) includes many alternative wet pond designs for various locations and conditions. *Watershed Protection Techniques* is a periodical published by Schueler at the Center for Watershed Protection (Silver Spring, Maryland) and includes many summaries of current stormwater management research, including new developing design procedures and performance data for detention ponds. In addition, Peter Stahre’s and Ben Urbonas’s book on *Stormwater Detention for Drainage, Water Quality and CSO Management* (1990) includes in-depth discussions on many detention pond design and operational issues.

Wet Detention Pond Design Guidelines for Suspended Solids Reductions

A wet detention pond performance specification for water quality control needs to result in a consistent level of protection for a variety of conditions, and to allow a developer a large range of options to best fit the needs of the site. It must also be easily evaluated by the reviewing agency and be capable of being integrated into the complete stormwater management program for the watershed. It should have minimal effects on the hydraulic routing of stormwater flows, unless a watershed-wide hydraulic analyses is available that specifies the specific hydraulic effects needed at the specific location. The following specifications should meet these objectives under most conditions. However, the specific pond sizes should be confirmed through continuous long-term simulations using many years of actual rainfall records for the area of interest. These guidelines should therefore be considered as a starting point and modified for specific local conditions. As an example, it may be desirable to provide less treatment than suggested by the following guidelines (Vignoles and Herremans 1996). The following guidelines were developed by Pitt (1993a and 1993b), based on literature information and on his personal experience.

1) The wet pond should have a minimum water surface area corresponding to land use, and desired pollutant control. The following values were extrapolated from extensive wet detention pond monitoring, mainly the EPA's NURP (EPA 1983) studies:

Percent of drainage area required as pond surface for control of suspended solids:

Land Use	5 μm (90 percent)	20 μm (65 percent)
Freeways	2.8 percent	1.0 percent
Industrial areas	2.0	0.8
Commercial areas	1.7	0.6
Institutional areas	1.7	0.6
Residential areas	0.8	0.3
Open space areas	0.6	0.2

These values are based on expected runoff volumes for typical development conditions and would therefore vary considerably for different development practices, especially if using infiltration practices. These surface area criteria have been shown to result in consistent pond performance, when used with the following criteria and good design practice.

2) The freeboard storage (the storage volume above the normal wet pond surface and below the invert of the emergency spillway) should be adequate to provide for 13 mm of runoff from the watershed, for a medium density residential area. For a typical medium density residential area, a rain of about 32 mm would produce this runoff depth. For a shopping center, a much smaller rain of about 15 mm would produce 13 mm of runoff. Pond performance is very closely related to flow rates and runoff volumes. Therefore, in order to provide a constant level of protection, freeboard storage needs to be provided for the runoff volume that would result from a constant rain depth (such as for 32 mm of rain). A pond for a highly impervious watershed would therefore be much larger than for a similar sized watershed characterized with less impervious areas. Areas having relatively clayey soils (such as SCS hydrologic type D soils) would also require larger ponds than similar areas having sandy soils. However, this rain depth specification will also be sensitive to the use of on-site infiltration controls that would be needed for most developments.

3) Require a specific surface area for each stage elevation, depending on the outlet structure selected and the desired level of pollutant control. This specification regulates the detention time periods and the draining period to produce consistent removals for all rains. The ratio of outlet flow rate to pond surface area for each stage value needs to be at the most 0.04 mm/sec for 5 μm (about 90 percent) control, 0.15 mm/sec for 10 μm (about 80 percent) control, and 0.61 mm/sec for 20 μm (about 65 percent) control. In practice, the desired pond surface area to stage relationship (simply the shape of the hole) is compared to the minimum surface areas needed at each stage for

various candidate outlet structures. As an example, the following list summarizes the minimum surface areas needed to control all particles greater than 10-micrometer particles. Also shown are the freeboard storage values below each elevation:

	45^o V-notch		90^o V-notch	
stage (feet)	storage (acre-ft)	surface (acres)	storage (acre-ft)	surface (acres)
0.5	<0.01	0.01	0.01	0.02
1.0	0.01	0.05	0.04	0.12
1.5	0.06	0.14	0.15	0.32
2.0	0.16	0.27	0.41	0.68
3.0	0.43	0.76	1.7	1.8
4.0	1.6	1.6	4.6	3.8
5.0	3.8	2.7	9.7	6.8
6.0	7.3	4.3	18	11

The large stage values are only needed for ponds having hydraulic benefits and the water quality objectives may not apply. Many alternative outlet devices could be selected, depending on the pond geometry, and still obtain relatively consistent pond performance.

4) The ponds must be constructed according to specific design guidelines to insure the expected performance and adequate safety. The guidelines need to specify such things as pond depth, side slopes, vegetation, and shape.

Summary of Detention Ponds as a Stormwater Control

Detention ponds are probably the most commonly used stormwater quality devices and have substantial literature documenting their performance and problems. Wet detention ponds have been shown to be very effective, if their surface area is large enough in comparison to the drainage area and expected runoff volume. Small wet ponds and dry ponds have been shown to be much less effective. Detention ponds can be easily integrated into a comprehensive stormwater management program, but only if land is available and if installed at the time of development. They are very difficult and expensive to retro-fit into existing areas. Care must also be taken to minimize safety and environmental hazards associated with ponds in urban areas. In addition to safety concerns, contaminated sediment management and poor water quality are major issues.

SLAMM Calculation Procedures for Wet Detention Ponds

SLAMM calculates particulate deposition in wet detention ponds using the upflow velocity method (Linsley and Franzini 1964). Hydrograph routing through the pond is first calculated using the storage-indication procedure summarized by McCuen (1982) and as used by the RESVOR reservoir routing subroutine of the Natural Resources Conservation Service in Tech. Releases 20 and 55 (SCS 1986).

Detention pond hydraulic performance is dependent on the basin inflow hydrograph, the stage-area curve of the pond, and the outfall structure. The inflow hydrograph is based on the rain being considered and the source areas. Small storm hydrology principles are used by SLAMM to calculate runoff volume. Related research on urban hydrograph shapes (Pitt 1987) was used to statistically describe the peak and duration of the inflowing runoff hydrograph. The model user must describe the stage-surface area relationship for each pond and select the outlet structures. SLAMM allows a variety of outlet structures to be used in many combinations (including rectangular weirs, various V-notch weirs, orfices, drop structures, etc.). Weir ratings are built into SLAMM from standard weir formulas. In addition, the user can describe any stage-outfall velocity desired, reflecting laboratory tests, or open channels.

SLAMM expands on the storage-indication procedure by calculating incremental upflow velocities for each calculation interval. SLAMM automatically determines the most efficient calculation interval. The upflow velocity is defined as the pond outfall rate divided by the pond surface area. Any particle that has a settling velocity greater than this upflow velocity will be retained in the pond. The user describes a particle size distribution for the inflowing water, which SLAMM uses to calculate the particle settling rates from Stoke and Newton settling equations. SLAMM calculates the critical particle sizes retained in each calculation interval and sums the retained particles for the complete event. Hydraulic performance of an outfall pond is also summarized by giving the peak flow rate reduction factor (PRF) and the pond flushing ratio (ratio of incoming runoff volume to normal pond volume for each event. The stand-alone detention pond program (DETPOND) results in much more performance information, if desired, along with allowing the user to specify any runoff inflow hydrograph.

Infiltration

Benefits and Problems Associated with Stormwater Infiltration

In most urban areas, stormwater is directed to subsurface drainage systems. In areas having combined sewer systems, such as in most of Europe, in the large cities of Asia, and in many older cities of the U.S., this additional water causes overflows of raw or poorly treated domestic sewage during periods of moderate to heavy rainfalls. Even in areas having separate sewerage systems, the use of conventional subsurface sewerage radically alters the receiving waters. The frequent and high flows in receiving waters causes detrimental biological conditions, causes increased erosion of channels, causes flood damage, and dramatically reduces the amount of rainfall that recharges the local groundwaters. This recharge reduction causes severe low flow problems in many areas during prolonged dry periods, further worsening the biological habitat, decreasing recreation benefits, and reducing the assimilative capacity for downstream wastewater discharges.

Infiltration techniques have been used for many years to control stormwater quality and flooding. They offer many advantages when integrated into conventional drainage systems (Azzout, *et al.* 1994, Novatech 1992, Novatech 1995):

- lower the costs of the sewerage systems;
- limited required maintenance;
- good integration in urban environment;
- preservation of the hydrological balance in the environment.

The following infiltration techniques are most often used :

- reservoir structure and porous pavements;
- drainage trenches;
- infiltration wells;
- dry basins.

Upland infiltration devices are located at urban source areas and can significantly reduce both stormwater runoff volume and contaminant contributions from the treated areas to the receiving waters. All infiltration devices redirect runoff waters from the surface to the sub-surface environments. Therefore, they must be carefully designed using sufficient site specific information to protect the groundwater resources and to achieve the desired water quality management goals.

With development, natural groundwater recharge is reduced, with increased surface water flows during wet weather and significantly reduced surface water flows (that rely on groundwater discharge) during dry weather. The use of infiltration can help maintain the natural groundwater recharge in an urbanizing area and maintain adequate receiving water base flows during critical dry weather periods.

The Lake Tahoe (California/Nevada) Regional Planning Agency has developed a preliminary set of design guidelines for infiltration devices (Lake Tahoe 1978). They recommend the use of infiltration trenches to collect and infiltrate runoff from impervious surfaces, such as driveways, roofs, and parking lots. A secondary objective of infiltration devices in the Lake Tahoe area is to reduce soil erosion caused by high runoff flow rates. The Ontario Ministry of the Environment (1984) also included infiltration devices in its general stormwater management plan.

Beale (1992) described numerous methods to reduce problems in storm drainage. The traditional approach had been for the rapid removal of stormwater from a development to the nearest watercourse or sewer system. This approach cannot continue due to the high economic and social cost associated with upgrading existing sewerage and/or increased flooding in urban areas. Three main options are: 1) reduce flows entering the drainage system, 2) increase the capacity of the drainage system (the traditional approach), or 3) attenuate flows within the drainage system. The methods available include, indicating the role that infiltration has, especially in conjunction with storage:

to reduce incoming flows:

- Diversion
- Infiltration (plane infiltration, basin infiltration, soakaways, infiltration trenches, or infiltration boreholes)
- Control flows entering drainage (rooftop detention, control in down pipes, control in gully outlets, control by gully spacing

to attenuate flows in drainage:

- Attenuation in drainage (surface flooding, oversize sewer, on-line tank, off-line tank, storage ponds, or tank design)
- Attenuation in watercourse (on-line storage ponds, or off-line storage ponds)

Numerous recent papers describe the successful use of stormwater infiltration throughout the world. Musiake, *et al.* (1990) described the use of shallow infiltration facilities is Tokyo, and Stenmark (1990) described the use of infiltration facilities in cold climates. Other stormwater infiltration experience has been described by Wada and Miura (1990), Harada and Ichikawa (1993),Yamada (1993), and Duchene, *et al.* (1993). The Technical University of Denmark has recently conducted numerous research projects concerning the benefits of infiltration as a source area control to reduce combined sewer overflows (Geldof, *et al.* 1994; Mikkelsen, *et al.* 1994; Rosted Petersen, *et al*. 1994; and Jacobsen and Mikkelsen 1996). Rosted Petersen, *et al.* (1994), for example, found that the optimal solution for reducing CSO volumes by 40% required infiltrating 65% of the paved areas using infiltration trenches having total storage volumes of 3.6 mm. This corresponds to a return period of 0.04 years (about 2 weeks), in contrast to the commonly applied design return periods of 2 to 10 years.

Geldof, *et al.* (1993) describe many stormwater problems that can be reduced by using infiltration. The Experimental Sewer System (ESS) in Tokyo includes many infiltration components (infiltration inlets, infiltration trenches, infiltration curbs, and permeable pavements) and has significantly reduced the amount and frequency of urban flooding (Fujita 1993). The ESS has reduced the stormwater peak flows by 60% and runoff volume by 50%, compared to conventional storm sewerage systems. Furthermore, the cost of the ESS is about 1/3 of the cost of conventional detention facilities, and only about 1/10 of the cost of underground detention facilities. The infiltration trenches used as part of the ESS have been easily installed in parks and alongside roads, with little interference to the intensive use of the land. Figure D-8 is a schematic showing the major components of the ESS.

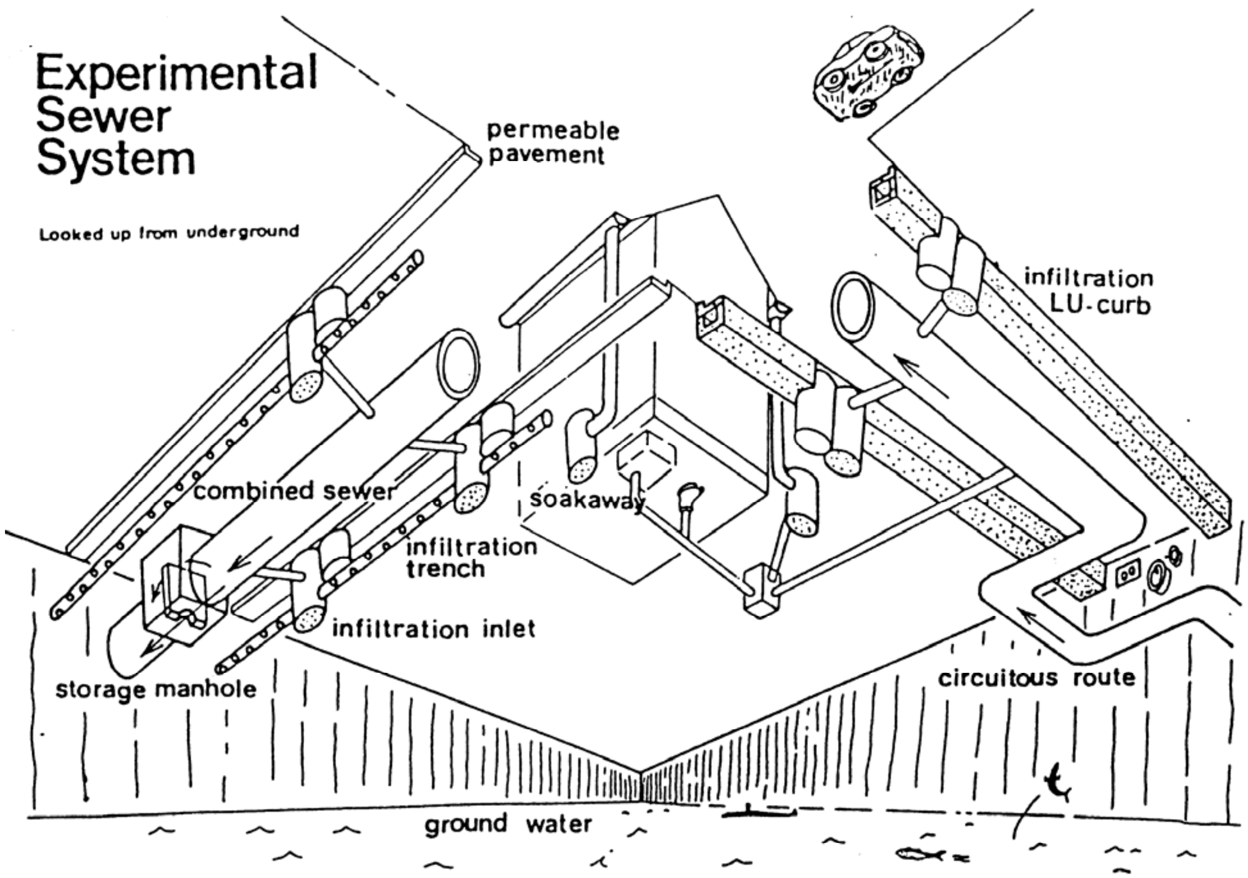


Figure D-8. Major components of the Experimental Sewer System (ESS) in Tokyo, Japan (Fujita 1990).

The main purpose of stormwater infiltration in Tokyo has shifted away from improving the conveyance of stormwater (flood prevention, soil erosion prevention, and reduction of pollution discharges) to restoring groundwater (maintenance of river base flows, prevention of heat island effects, and prevention of ground subsidence) (Fujita 1993).

The ESS is likely the largest stormwater infiltration enterprise in the world today. It is made possible by the large infiltration capacity of Tokyo area soils and the knowledge of the limitations of alternatives (Fujita 1993). Detention basins had been used in newly developing housing complexes to reduce the stormwater flow rates to sewerage, but they were much more expensive than the use of infiltration. Infiltration also has the great benefit of re-directing stormwater away from the sewerage for groundwater recharge, instead of just delaying the discharge of the runoff into the sewerage. Japanese sewerage authorities made a landmark change in policy, with a new emphasis on “reducing stormwater runoff” volume, instead of the traditional goal of “draining stormwater quickly through sewer pipes” (Fujita 1993).

The ESS includes the following components in Tokyo (from 1981 to 1992):

length of sewers	337 km
area served by ESS	1,329 ha
population served by ESS	166,000
number of infiltration inlets	30,994
length of infiltration trenches	201 km

length of infiltration curbs	70 km
permeable pavement area	450,000 m^2
cost of construction	\$US 493 million

The ESS concept has been now employed in many other Japanese cities, in addition to other areas in Tokyo. The total area of permeable pavement in Tokyo is about 3,740,000 m^2 as of 1990 (about 2.5% of the total road area in the city). Parking lots in public areas are commonly covered with permeable pavement, in addition to private parking lots. Efforts are also being made to encourage stormwater infiltration in public areas (such as at schools, athletic stadiums, tennis courts, etc.). The total estimated infiltration effort in Tokyo (in addition to the ESS) is summarized below (1981 to 1989):

permeable pavement area	3.74 km^2
length of infiltration trenches	571 km
number of infiltration inlets	86,000
length of infiltration curbs	145 km

Fujita (1994) further describes the Tokyo ESS. All footpaths are now made using porous pavements in Tokyo and some of the paver blocks are being made using ash from incinerated sewage sludge. Residents like the porous pavement walkways because no puddles form and they are not slippery. About 15,000 of these soakaways have been built in the City of Koganei (about 15 km west of central Tokyo) in the 10 years preceding 1993. As a result, many of the natural springs, which had previously dried up with conventional storm drainage use, have been revived. The extensive use of soakaways also decreases the amount of stormwater entering sewerage, enabling reductions in pipe sizes, but that has not been implemented as yet.

The infiltrating inlet is made using two adjacent small tanks. The first tank contains the inlet to the street and has a perforated plastic bucket to capture large debris, plus a grit chamber ("mudpit"). The overflow goes into the second small tank that has a perforated bottom for infiltrating stormwater. The bottom of the tank is open, but filled with gravel atop which is placed two semi-circular plates made of porous concrete to act as a filter to minimize clogging. If the runoff entering the infiltration inlet exceeds the infiltration capacity of the inlet, the excess water flows to infiltration trenches connected to the tank, up from the bottom. The ends of the infiltration trenches are covered with stainless steel screening to further minimize the entry of clogging particles into the trenches. If the runoff flow exceeds the total infiltration capacity of the whole inlet system, then the overflow enters the sewerage pipe. They have found that cleaning the perforated basket and the mudpit twice a year is sufficient to prevent clogging. They have not needed to clean any infiltration trench, as none have clogged in the ten years of operation.

Infiltration curbs are placed along both sides of streets to allow additional stormwater infiltration. The L-shaped curb is made using porous pavement if possible, although the porous concrete curb cannot withstand the weight of large vehicles. In areas where heavy vehicles are likely, normal concrete curb pieces are used. Any stormwater infiltrated through the curb is carried in the U-shaped trough which is porous or perforated.

Infiltration also improves the receiving water quality in areas served by either combined or separate sewers (Geldof, *et al*. 1993). Decreased amounts, frequencies, and durations of overflows from combined systems have dramatically lowered the discharges of many pollutants. The number of overflows in combined sewers in Tokyo have decreased from about 36 per year to about 7 in areas served by the ESS. The resulting BOD discharges have also been reduced by about 45%. Phosphorus and heavy metals in separate sewer discharges can be substantially reduced with the widespread use of infiltration (Hvitved-Jacobsen, *et al.* 1992).

Wada and Miura (1993) constructed a field test site to measure the effects of the different infiltration devices being used in Tokyo. The test site included four permeable pavement lengths, two lengths of infiltration trench, an infiltration roadside gutter, and seven infiltration street inlets. Detailed runoff and subsurface flow measurements were made during artificial rains for a variety of conditions. They produced a model that accurately simulated observed runoff values. An interesting conclusion was that groundwater had significant influence on the infiltration rates of the devices if it was within 1.5 m from the bottom of the infiltration devices.

Herath and Musiake (1994) developed and tested a stormwater model in Tokyo that successfully simulated complex arrangements of infiltration systems on a watershed scale. A lumped model was produced that accurately reproduced both flow volumes and hydrographs in areas having infiltration facilities.

The most difficult problems related to the Tokyo infiltration facilities have been clogging and groundwater contamination (Fujita 1993). A high-pressure water jet has been successfully used to restore clogged permeable pavements, along with other measures to protect the devices. Groundwater monitoring has been conducted for ten years in the ESS area, with no indication of groundwater contamination. However, efforts to improve service life and to protect groundwater quality are continuing.

Groundwater recharge is also an important benefit of infiltration (Geldof, *et al*. 1993). The Netherlands experiences sinking groundwater tables, with the deterioration of nature reserves and the drying out of moorlands during periods of drought. Infiltration of stormwater has been shown to be a viable alternative in recharging the groundwaters, compared to restrictions in domestic water pumping and prohibiting irrigation in urban areas.

Other benefits of infiltration, according to Geldof, *et al*. (1993) include preventing salt water intrusion in coastal areas, preventing consolidation of soils near buildings, and reducing damage from frost penetration.

This radical alteration of the local hydrologic cycle has prompted the use of infiltration of stormwater to mitigate these affects. As an example, Krijci, *et al.* (1993) described the mandatory use of stormwater infiltration in Switzerland to decrease the burden on combined and separate sewerage systems. The 1992 Swiss Water Pollution Control Law requires that unpolluted wastewater must be infiltrated. If local conditions prevent infiltration, then special authorization is required and detention is used. A simple system is used to determine the suitability of stormwater for infiltration, depending on the area drained and the use of the groundwater. As an example, runoff from roofs, bike lanes, and walking paths must be infiltrated in all areas, even if the groundwater has high importance as a drinking water source. Surface infiltration is required (and subsurface infiltration is prohibited) for this runoff in most drinking water protection zones. The infiltration of roadway and parking area runoff is more restricted, where only surface infiltration is allowed for all areas. Any infiltration of highway and freeway runoff is only allowed in exceptional situations. In all cases, “clean” water (runoff from yard drainage, spring water, groundwater, and cooling water) is forbidden in combined sewers.

Conradin (1995) describes how Zurich is complying with the Swiss Water Pollution Control Law. The city has 50 to 100 year old sewerage, about 80% being combined sewerage and 20% being separate sewerage. Clean flows (fountain water, spring water, yard drainage, cooling system water, and possibly roof runoff) are required to be diverted from the sewerage. All other stormwater will be directed to the combined sewerage and newly renovated treatment plants. The city is converting its system to a partially separate system that collects the clean water and directly diverts it to the Limmat River. Zurich is building open brooks along streets and walkways to collect these waters. The open brooks provide natural water channels and aesthetically revitalizes the urban area. About 12 km of brooks have been built as of 1995, and as much as 30 km total are planned. The current brooks divert about 150 L/sec from the sewerage. The brooks are designed to carry about two to five times the dry weather flows, with excess diverted to the sewerage and the treatment plants.

Payne and Davies (1993) describe the *Manual on Infiltration Methods for Stormwater Source Control* recently developed by the National Rivers Authority in the UK. This manual takes a careful approach to protect groundwater quality. Infiltration policies of about 20% of the local governments surveyed in the UK prohibit, or strongly discourage, the use of stormwater infiltration, while about 45% encourage its use, with reservations. Soakaways are the most common method of stormwater infiltration in the UK. The perceived benefits of soakaways are reduced burden on the sewer system, followed by lowered cost and ease of construction. Perceived disadvantages include the dependence on local soil conditions for their success, the lack of precise design methodologies, and uncertain maintenance responsibilities. The protection of groundwater is a high priority in the *Manual*, even though “environmental friendliness” was not a highly ranked issue when surveying the local governments. Roof runoff is acceptable for infiltration for all groundwater protection zones, while infiltration of runoff from paved areas is restricted generally directly related to the amount of automobile activity. Infiltration of runoff from industrial areas and from vehicle service areas is most restricted and requires pretreatment, at least, even in the least protected groundwater zone. They found that biofiltration controls offer a viable option for pretreatment of runoff before infiltration, but their success greatly relies on long-term maintenance.

Pratt and Powell (1993) describe a new approach for infiltration trench designs for the UK, developed by the Building Research Establishment. This is a reasonable storage/treatment approach, and relies on site investigations of soil properties. Soil infiltration rate measurements are made in relatively large test excavations of 0.3 to 1 m in width and 1 to 3 m in length, and of similar depth as the final infiltration device. Infiltration through the trench bottom is assumed to be insignificant due to clogging (as also assumed by many other trench designers), with all infiltration occurring through the upper half of the trench sides. This provides a conservative infiltration area that attempts to estimate long-term infiltration trench performance. Rains with 10-year return frequencies are used in this design in order to provide significant relief to storm sewerage for critical flooding events. BRESOAK software was developed to enable the investigation of alternative trench geometries. In most cases, the most effective trench design is determined to be long, narrow, and relatively deep, similar in geometry as many of the trenches in the successful Tokyo ESS. In some areas, these trench shapes are not allowed. Wisconsin, for example, requires all trenches to be wider than they are deep to maximize the amount of infiltration occurring through surface soils to increase soil aquifer treatment (SAT) of the infiltrating stormwater in order to minimize groundwater contamination.

Candaras, *et al.* (1995) describe an exfiltration and filtration demonstration project in Etobicoke, Ontario, near Toronto. The exfiltration system was developed to eliminate the discharge of stormwater for frequent rains, while improving the function of traditional drainage systems. The City of Etobicoke adopted a new stormwater management concept that promotes three levels of control:

1) Major drainage system (overland flow) designed to transport runoff from large and infrequent rains (such as the 100 year storm),
2) Minor drainage system (typical stormwater conveyance system) designed to transport the runoff from smaller and more frequent rains (such as the 2 and 5 year storms), and
3) Micro drainage system designed to eliminate runoff form the very frequent rains (such as rains of about 10 to 15 mm in depth).

The city developed two basic devices, currently being tested to accomplish these goals. The exfiltration system is a pair of small diameter, perforated PVC pipe that is installed below conventional storm drainage pipe. All three pipes run from manhole to manhole, but the perforated pipes are plugged at the downstream end to eliminate short-circuiting. The pipe trench is wrapped in a geotextile and back filled with 15 mm clear stone. If the storm exceeds the capacity of the stone, the excess water flows through the conventional pipe. The filtration system uses a perforated PVC pipe located above the conventional pipe, with both ends plugged. The catchbasin inlet has a lower outlet that directs runoff to the perforated pipe. The clear stone trench lining acts as a filter for the percolating water, which is picked up by another series of two perforated pipes located under the conventional pipe and connected to the lower manhole. If the filter capacity is exceeded, water flows out of the upper outlet from the catchbasin directly into the conventional pipe. Preliminary monitoring has shown that the test devices have performed better than expected.

A recurrent theme in the literature is concern for lack of appropriate design guidelines for infiltration practices (Petersen, *et al.* 1993). Very little design guidance for specific stormwater infiltration practices existed for Europe before 1991. Somewhat more guidance had been available in the U.S. However, much of the U.S. guidance had been transferred from other areas of the country having greatly different rainfall, topographic, soil, and frost conditions, with little modification. In addition, long-term performance information on infiltration practices is also limited. This makes predictions of useful life very difficult. The high failure rate of many types of infiltration practices, mostly associated with lack of any maintenance, is also of great concern, along with concerns of groundwater contamination. However, the extensive and successful use of stormwater infiltration in Tokyo, and elsewhere, plus the absence of groundwater contamination problems from stormwater infiltration for most areas, indicates that stormwater infiltration is feasible in many situations. Newer guidelines (such as described by Pratt and Powell 1993) also offer a uniform and reasonably conservative approach for the design of infiltration devices. The goal is to identify those conditions where stormwater infiltration is most likely to be successful, stress the use of robust infiltration practices (such as grass swales), be conservative in useful life estimates, provide appropriate pretreatment, and ensure adequate maintenance. It is important to use alternative stormwater controls (such as detention and biofiltration) in areas and situations that are marginal for infiltration.

General Infiltration Practices

Infiltration Device Performance Reported in the Literature

The Long Island and metropolitan Washington D.C. NURP projects (EPA 1983) examined the performance of several types of infiltration devices. The Long Island project studied a series of interconnected percolating catchbasins which were found to reduce stormwater discharges by more than 99 percent. The Washington D.C. study found that porous pavement reduced the pavement pollutant runoff loadings by 85 to 95 percent, while an infiltration trench reduced urban runoff flows by about 50 percent. The EPA concluded that, with a reasonable degree of site specific design considerations to compensate for soil characteristics, infiltration devices can be very effective in controlling urban runoff. Local conditions that can make recharge inappropriate include steep slopes, slowly percolating soils, shallow groundwater, and close-by important uses of the groundwater.

Modernizing the combined sewerage system in Tündern a suburb of Hameln, Germany, is necessitated by extensive growth during the 25 years since the current system was constructed (Adams 1993). Conventional methods would require replacement of about 40% of the sewer, plus construction of detention basins. However, the depth to groundwater (at least 2.5 m below the ground surface), plus the sandy soil, encouraged the investigation of de-centralized infiltration as an alternative. Design calculations indicate that the flooding frequency would decrease by about half, and that the COD discharges would be decreased by about 45% by using stormwater infiltration. The infiltration option would help restore the natural hydrologic cycle and reduce current problems at a much reduced cost.

An extensive report was prepared by Kuo, *et al.* (1989) on infiltration trenches. This report included an examination of the theoretical behavior of infiltrating water, and it presented the results of laboratory model studies.

Summary of Infiltration Devices as Stormwater Controls

Infiltration devices are unique in that they reduce stormwater volumes, in addition to peak flow rates and pollutant discharges. They discharge the stormwater to the groundwater and care must be taken to prevent groundwater contamination. Significant reductions in most pollutants occur in the vadose zone above the saturated layer. However, some stormwaters should not be considered for infiltration, including snowmelt water (especially in areas of de-icing salt use), industrial runoff (due to likelihood of high concentrations of filterable toxicants), and construction site runoff (due to clogging by sediment). The majority of stormwater flows can likely be safely infiltrated with significant reductions in surface water discharges and important equalizations of the hydrological cycle in urban areas. Pratt (1996) describes the current widespread installations of “soakaways” in the UK (tens of thousands per year), despite the extensive storm drainage systems available. Most are used for infiltrating runoff from small paved areas and roofs. Unfortunately, little systematic research has been conducted on their benefits and problems. Schmitt (1966) also describes current German regulations favoring the use of infiltration controls for stormwater located at source areas to reduce combined sewer problems.

SLAMM Calculation Procedures for Infiltration Devices

Infiltration devices are assumed to affect water volume, but not pollutant concentrations. As the water volume is reduced, the pollutant yield is obviously decreased. SLAMM calculates the runoff volume reductions for each source area (served by an infiltration device) for each individual rain in the study period. Runoff volume reduction is assumed to be equal to:

volume reduction = (Pr/Rr) (As/At)

where Pr is the percolation volume rate,
Rr is the runoff rate to the device,
As is the area served by the device, and

At is the total study area.

The ratio Pr/Rr used in this equation can never be greater than 1.0. The percolation volume rate is the capacity of the infiltration device to infiltrate runoff, expressed as:

Pr = (1 + 0.67/width to depth ratio) (percolation rate)(percolation area)

The side walls of an infiltration trench have 0.33 of the infiltration capacity as the trench bottom, reflected in the 0.67 factor in the equation (assuming two side walls). The runoff rate is the flow rate of water entering the infiltration device:

Rr = runoff volume / runoff duration

The runoff volume for the source area is calculated using the procedures described in Section 3, or basically the event volumetric runoff coefficient times the area served times the rain depth. The runoff duration is the base of the inflow hydrograph and is calculated using the regression equation derived by Pitt (1987):

Runoff duration = 0.90 + 0.98 (rain duration), expressed in hours

An example of use of this procedure follows:

Percolation rate = 3 in/hr
Total rain = 1.7 in
Rain duration = 6 hours
Volumetric runoff coefficient = 0.35
Area served by infiltration trench = 1.3 acres
Total area in study = 5.6 acres
Trench bottom area (percolation area) = 5500 ft^2
Trench width/depth ratio = 2

Therefore:

runoff volume = 0.35 (1.7 in)(1.3 acres) = 0.774 ac-in
runoff duration = 0.90 + 0.98(6 hours) = 6.78 hours

and Rr = 0.774/6.78 = 0.114 ac-in/hr = 0.115 ft^3/sec.

Pr = [1 + 0.67/2] (3 in/hr) (5500 ft^2) (ft/12 in) (hr/3600 sec) = 0.510 ft^3/sec.

Therefore Pr/Rr = 0.51/0.114 = 4.434 which is greater than 1.0, so 1.0 must be used in the equation. (The infiltration trench is oversized for this event: all of the runoff from the service area is infiltrated.) The study area volume reduction performance is therefore: 1.3 acres/5.6 acres = 0.23. (23 percent of the runoff and pollutant yield are infiltrated).

Grass Swales and Grass Filter Strips

Grass swale drainages can be used in place of concrete curb and gutter drainages in most land uses, except strip commercial, manufacturing industrial, and high density residential areas. Grass swales reduce urban runoff problems by a combination of mechanisms. Infiltration of the runoff and associated pollutants is probably the most important process. Filtering of particulate pollutants in grass waterways may also occur, but the flows are usually too large (and deep) to permit effective filtering by the grass. Groundwater contamination concerns are frequently raised whenever stormwater infiltration is proposed. Pitt (1996) reported that groundwater contamination is not a major concern for most stormwaters, if using surface spreading (such as occurs in grass swales). Lind and Karro (1995) also recently reported on the accumulation of stormwater pollutants in the surface soils of swales, minimizing groundwater contamination problems.

Performance of Grass Swales and Filters as Reported in the Literature

Several large-scale urban runoff monitoring programs have included test sites that were drained by grass swales. Bannerman, *et al*. (1979), as part of the International Joint Commission (IJC) monitoring program to characterize urban runoff inputs to the Great Lakes, monitored a residential area served by swales and a similar residential area served by concrete curb and gutters in the Menomonee River watershed in the Milwaukee area. This monitoring program included extensive flow and pollutant concentration measurements during a variety of rains. They found that the swale drained area, even though it had soils characterized as poorly drained, had significantly less flows and pollutant yields (up to 95 percent less) as compared to the curb and gutter area.

The ability of grass swales to reduce source area sheetflow pollutant concentrations was also monitored by the Durham, New Hampshire NURP project (EPA 1983). A special grass swale was constructed to treat runoff from a commercial parking lot. Flow measurements were not available to measure pollutant yield reductions, but pollutant concentration reductions were found. Soluble and particulate heavy metal (copper, lead, zinc, and cadmium) concentrations were reduced by about 50 percent. COD, nitrate nitrogen, and ammonia nitrogen concentrations were reduced by about 25 percent, while no significant concentration reductions were found for organic nitrogen, phosphorus, and bacteria.

Wang, *et al*. (1980) monitored the effectiveness of grass swales at several freeway sites in Washington. They found that 55 to 75 m of grass swale removed most of the heavy metals in the runoff. Lead was more consistently and effectively removed than the other metals, possibly because of its greater association with particulates in the runoff. Lead concentration reductions, with 55 m grass swales, were typically 80 percent, or more, while copper was reduced by about 60 percent, and zinc was reduced by about 70 percent. They concluded that it may be necessary to remove the contaminated sediments and replant the grass periodically to prevent the dislodgment of the deposited polluted sediment. Part of the swales monitored by Wang, *et al*. (1980) were bare earth lined. Pollutant concentrations were not found to be effectively reduced in these sections, and the earth lining was not contaminated. Again, infiltration effects on flow volumes and pollutant yields were not monitored, and the concentration observations were only affected by grass filtration.

A project to specifically study the effects of grass swale drainages was also conducted in Brevard County, Florida by Kercher, *et al*.(1983). Two adjacent low density residential areas, about 5.6 ha in area and having about 50 homes, were selected for study. One area had conventional concrete curbs and gutters, while the other had grass swales for roadside drainage. The two areas had very similar characteristics (soils, percentage imperviousness, slopes, vegetation, etc.). Thirteen rains were monitored in the areas for flow and several selected pollutants. The curb and gutter area produced runoff flows during all 13 events, while the grass swale area only produced runoff during three events. Estimated annual pollutant yields from the curb and gutter area were much greater than for the grass swale area. BOD_5 annual discharges from the guttered area were estimated to be about 130 times the discharges from the swale area. Yield increases from the guttered area as compared to the swale area for some other pollutants were reported as follows: 160 times for total nitrogen, 450 times for total phosphorus, and 90 times for suspended solids. The grass swale system also cost about one-half the cost of the curb and gutter system.

In another large scale urban runoff monitoring project, Pitt and McLean (1986) monitored a residential area in Toronto served about evenly by both swales and concrete curbs and gutters. The pollutant concentrations in both types of drainage systems were similar, but the area had annual flows (and therefore pollutant yields) about 25 percent less than if the area was served solely by curbs and gutters. For small but frequent rains (less than about 13 mm), very little runoff was observed in the grass swales. If the area had all grass swales, the flow and pollutant yields would have been even less.

Schueler (1996) summarized grass swale performance literature and related pollutant reductions to drainage swales or water quality swales. The water quality swales had appreciable concentration and mass reductions, mainly by enhancing infiltration through the swale bottom, widening the bottom width of the swale, providing a subsurface infiltration trench under the swale, or even by planting wetland plants in a swale that was in an area that has a high groundwater table. The drainage channels provided little concentration reductions, but some had significant mass reductions due to infiltration. In all cases, more care can be taken in designing swales to enhance their water quality performance, while still providing necessary drainage benefits. Claytor and Schueler (1996) have published a manual for designing water quality swales (along with other stormwater filtering systems).

Yu, *et al*. (1993) constructed and monitored a grass filter in Charlottesville, VA. A 4 ha paved commercial area drained to the 3,800 m^2 grass filter. Stormwater was directed to the grass filter via an infiltration trench and a level spreader. The level spreader system cost about $15,000 (1986). The filter had moderate removals for suspended solids (54 to 84%), total phosphorus (25 to 40%), and zinc (47 to 55%), but only poor removals for nitrate nitrogen (-27 to 20%) and lead (-16 to 55%).

Summary of Grass Swales for Stormwater Control

Grass swales (and grass filters in general) may be an effective stormwater control practice to reduce pollutants before the stormwater is discharges. Grass swales are inexpensive compared to conventional curb and gutter systems, but their use is restricted to areas that have relatively low density developments. In addition, current design and construction practices for grass swales are very poor, leading to many problems with maintenance. Much greater care needs to be used in the utilization of grass swales.

Grass Swale Performance Calculations in SLAMM

SLAMM calculates the performance of grass swales in a similar manner as other infiltration devices, by assuming (Pr/Rr) (As/At) as indicative of swale infiltration. SLAMM calculates runoff volume entering the swale as the addition of all upland source area flows. The water percolation rate in the swale is calculated by:

Pr = (dynamic percolation rate) (percolation area)

where the percolation area is simply the swale length times the swale width. The percolation rate in the swale is for dynamic flow conditions and is generally about ½ of the typically measured static infiltration rate (Wanielista, *et al.* 1983).

This procedure is generally independent of swale routing: it assumes that the water is in the swale long enough to be infiltrated. “Long” swales serving “small” service areas encourage infiltration. Grass filters include infiltration as a function of flow distance for different slopes and infiltration rates and can therefore be used to estimate needed flow length in swales (Pitt 1985 and 1987). Obviously, swale design (like all other controls) must be carefully done to encourage performance. As an example, these procedures would not be appropriate for steep swale gradients. The ratio of area served by swales to total area therefore needs to be reduced if steep swales are present, or if the swales are “short.”

The swale length is calculated from the swale density times the area served by swales. Typical swale density values for different land uses are as follows (Pitt and McLean 1986):

Land Use	Swale Density (ft/acre)
Low density residential	160
Medium density residential	350
High density residential	375
Strip commercial	630
Shopping centers	280
Industrial	125

Of course, not all of these land uses, especially high density residential or strip commercial areas, are suitable for grass swales. Again, the selection and design of any control practice must be carefully done.

An example of the calculations for swale performance follows:

Total contributing area flows = 1140 ft^3
Rain duration = 5.5 hours
Dynamic percolation rate in swale = 3.5 in/hr (1/2 of measured static infiltration rate)
Swale density = 350 ft/acre
Wetted swale width = 5 ft
Area served by swales = 1.5 acres
Study area = 3.3 acres

Therefore the runoff duration = 0.90 + 0.98 (5.5 hours) = 6.29 hours, and:

Rr = 1140 ft^3/6.29 hrs = 181 ft^3/hr = 0.05 ft^3/sec

Pr = (3.5 in/hr)(350 ft/acre)(1.5 acre)(5 ft)(hr/3600 sec)(ft/12 in) = 0.21 ft^3/sec

Therefore Pr/Rr = 0.213/0.05 = 4.26, which is greater than 1.0 and the swale is larger than necessary for this rain (total infiltration). The study area runoff reduction is therefore 1.5 acres/3.3 acres = 0.46 (46 percent reduction in flows and pollutant yields due to the swales).

Porous Pavements

Porous pavement is a “hard” surface that can support a certain amount of activity, while still allowing water to pass through. Porous pavement is generally used in areas of low traffic, such as service roads, storage areas, and parking lots. Several different types of porous pavement exist. Open mixes of asphalt appear to be similar to regular asphalt, but only use a specific size range of rocks in the hot mix. The porosity of the finished asphalt is much higher than regular asphalt, if properly designed and constructed. Concrete grids have open holes up to several cm wide, possibly containing sand or gravel. It is possible to plant grass in the holes, if traffic is very light and if light and moisture conditions are adequate. Recent tests have found few problems with porous pavement in areas having severe winters. They can be designed to eliminate all of the runoff from paved areas.

Performance of Porous Pavements as Reported in the Literature

Porous pavements can be effectively used in areas having soils with adequate percolation characteristics. The percolation requirements for porous pavements are not as critical as they are for other infiltration devices, unless runoff from other areas is directed towards the paved area. The percolation of the soils underlying the porous pavement installation only need to exceed the rain intensity directly. In most cases, several cm of storage is available in the asphalt base to absorb short periods of very high rain intensities. Diniz (1980) states that the entire area contributing to the porous pavement can be removed from the surface hydrologic regime.

Gburek and Urban (1983) studied a porous pavement parking lot in Pennsylvania. They found that percolation below the pavement occurred soon after the start of rain. For small rains (less than 6 mm), no percolation under the pavement was observed, with all of the rain being contained in the pavement base. Percolation during large rains was equal to about 70 to 90 percent of the rainfall, resulting in similar runoff flow and pollutant reductions of 70 to 90 percent. The differences between the rain amounts and the observed percolation quantities were caused by flash evaporation (not estimated) and storage in the asphalt base material.

Goforth, *et al*. (1983 and 1984) evaluated a porous pavement parking lot in Austin, Texas over several years under heavy traffic conditions. Infiltration rates through the pavement averaged about 45 m per hour, while the 50 mm pavement base had an infiltration rate of about 1,800 mm per hour.

Day (1980) conducted a series of laboratory tests using several different types of concrete grid pavements. The geometry of the grid was more important than the percentage of open space in determining the ability of the grid to absorb and detain rainwater. The volumetric runoff coefficients from the grids ranged from 0.06 to 0.26 (resulting in runoff volume and pollutant reductions from about 75 to 95 percent) depending on the rain intensity, ground slope, and subsoil type.

Numerous recent papers have described successful applications of porous pavements throughout the world. Niemczynowicz and Hogland (1987) describe tests of porous pavements in Sweden. Hogland (1990) gave an overview of porous pavement use in the U.S. and in Sweden. Pratt (1990) described design and maintenance issues, Nawang and Saad (1993) and Sztruhar and Wheater (1993) presented results of experimental field tests of porous pavements, and Fujita (1993) described the extensive use of porous pavements as part of the Experimental Sewer System in Tokyo.

Recent work at the University of Guelph in Ontario (Thompson and James 1995) has found that porous pavement systems can also be effective filters to remove particulate pollutants from the runoff, even with an underdrain that captures the runoff after pavement percolation. Runoff from typical pavement also had greater masses of pollutants than runoff from the porous pavements. Porous pavement research at the University of Essen in Germany (personal communication, Wolfgang Geiger 1995) also found significant water quality benefits from using porous pavement systems. However, Diniz (1993) measured the water quality of underdrain water from different porous pavement systems, gravel trenches located on the edge of an asphalt area, and conventional asphalt and concrete pavement during controlled sprinkler tests. Lead concentrations were about the same for all surfaces (12 to 25 μg/L, flow-weighted averages), while zinc (20 to 90 μg/L for porous pavements, vs. 7 to 12 μg/L for conventional pavements) and TKN (1.4 to 2.2 mg/L for porous pavements, vs. 0.5 to 1.3 mg/L for conventional pavements) were all higher for the porous pavement drain waters, compared to the conventional pavement runoff. Some, but not all, of the suspended solids and COD porous pavement drainage water concentrations were greater than for the conventional pavement runoff. The few data presented make conclusions uncertain, but it is likely that porous pavement may contribute some pollutants to the water, while removing others. In all cases, the amount of runoff diverted from the surface flows can be very large.

Recent French experiments in Nantes, Bordeaux and Paris have shown that porous pavements (with substantial subsurface reservoir capacity) were very efficient in reducing the pollutant loads discharged into the receiving water (Baladès, *et al.* 1995a and 1995b). These French studies have shown that the pollutant removal efficiencies of suspended solids can be between 50 and 70%, between 54 and 89% for COD, and between 78 and 93% for lead. These reductions were associated with the high amount of infiltration of water, and associated pollutants, through the pavements, away from the surface drainage. These experiments confirm results from previous studies in other countries (Hogland, *et al.* 1987, Pratt, *et al.* 1989, Pratt, *et al.* 1995).

Analyses of samples taken at the outlet of porous pavement structures by Baladès, *et al.* (1995a and 1995b) have shown that the discharged water met the French national standards for raw waters to be used for drinking water supplies, and that there were no problems that would restrict this water from being infiltrated directly into the ground.

The use of porous pavements in cold climates was investigated by Stenmark (1995) in northern Sweden. A 3.3 ha drainage area was modified because of existing problems associated with frost heaves and ice blocking the conventional drainage system. A porous pavement was installed over a thick subbase having a drainage pipe to remove excessive water. The width of the streets were also reduced to accommodate wider roadside grass swales, and the street surface was re-shaped to eliminate backwater problems. During preliminary observations, much less snowmelt water (about 30 to 40% of the accumulated water content of the snow, instead of close to 100%) originated from the area than from conventionally paved areas. Infiltration measurements in frozen soils indicated infiltration rates of about 0.004 mm/min (0.01 in/hr) to 5 mm/min (12 in/hr) for silts and sands. Increased water content in the frozen soil decreased the infiltration rates. Frost heaving was also reduced because the road materials were more homogeneous (no manholes, gutters, or shallow pipes were used), with less differences in heat properties. Frost heaving was more pronounced in a special test area having a thinner subbase. They concluded that the subbase should be at least 0.6 m thick.

The primary objective of using porous pavements is to mimic natural flow and infiltration conditions as closely as possible. It is therefore very important to pay attention to the following aspects to reduce groundwater contamination potential (Pitt 1996):

- depth to groundwater;
- groundwater uses;
- risks due to industrial activities in the catchment;
- use and traffic levels on the porous pavement;
- use of de-icing salts on the street.

Maintenance of Porous Pavements

Clogging of porous pavements is only a superficial phenomenon (typically extending to a depth of about 1 to 2 cm). Progressive clogging with time is caused by an increase of accumulated solids in the first few centimetres of the pavement and not to the moving of the clogging front within the pavement structure. The decrease in permeability in porous pavement may cause a drop by about 50% over three years. The mean diameter of the particles which are responsible for this clogging is about 300 µm. For sites where there is only a thin porous pavement layer above an impervious structure layer, it has been observed that the mean diameter of the clogging particles is finer, with about 30% of the particles responsible for the clogging being finer than 100 µm. Typical street dirt mean particle sizes are in the range of 200 µm, indicating that the particles responsible for the clogging are very common. Particles in these sizes are also suitable for effective removal by most conventional street cleaning operations. The masses of particles extracted from porous pavements depend on the use of the street, on the traffic intensity, on the cleaning equipment used and on the cleaning frequency. However, the amount of extracted particles is always very high: 0.2 to 1.5 kg/m^2. The highest value has been measured several times in residential streets which have not been cleaned during the last 2 or 3 years (Artières1987).

The masses of particles extracted from impervious streets range between 0.5 and 2 kg/m^2, depending on the site, on the cleaning frequency, and on the cleaning machine. As shown by several authors (Sartor, *et al*. 1974, Novotny, *et al*. 1985, Artières 1987), 50 to 80% of the mass of particles accumulated on streets are located near the curb for light parking conditions. The curb-side loading decreases as the parking density increases (Pitt 1979). It is very important to be able to efficiently clean the part of the street where the street dirt is located. Cleaning in the driving lanes may also be needed in areas where parking conditions are intense. The street surface texture, the street dirt loading, the parking conditions, and the street cleaning equipment operating conditions all have a significant effect on the cleaning efficiency. Severe porous pavement clogging will require very powerful cleaning techniques, whereas regular cleaning with usual techniques should be satisfactory to keep the porous pavement surface in a relatively good state.

Summary of Porous Pavement Control Benefits

For porous pavements subjected to traffic below 100 vehicles/day, and especially for parking lots, monthly cleaning by vacuuming is sufficient to keep an almost constant infiltration capacity. If clogging is already evident, a stronger cleaning technique using high pressure water jetting and vacuuming is necessary. Techniques which recycle the cleaning water are obviously preferred in order to avoid flushing of the pollutants to the receiving water. In all sites where measurements have been carried out, the extraction was very efficient and the porous pavement infiltration capacity was usually well restored. Bertrand-Krajewski, *et al.* (1994), in a comparative study of available street cleaning techniques, showed that they have the following ability to improve infiltration through partially clogged porous pavements (cm/s enhanced infiltration capacity after cleaning):

- simple wetting and sweeping (<0.01 cm/s);
- sweeping and vacuuming (0.13 cm/s);
- vacuuming (0.28 cm/s); and

- high pressure jetting and vacuuming (0.80 cm/s).

SLAMM Calculation Procedures for Porous Pavements

SLAMM uses a calculation procedure similar to the general infiltration device procedure for porous pavement performance. However, porous pavements are only assumed to treat the paved area, with no additional flows from upland areas discharging to the pavement. The volume reduction is therefore:

(Pr/Ir) (Ap/At)

where Pr is the percolation rate of the porous pavement, the pavement base, or the soil, whichever is less,
Ir is the rain intensity: total rain/rain duration,
Ap is the paved area, and
At is the total study area.

Again, the ratio Pr/Ir must be less than, or equal to, 1.0. An example follows:

Percolation rate = 3 in/hr
Total rain = 1.7 in
Rain duration = 6 hrs
Porous pavement area = 0.7 acres
Total study area = 5.3 acres

Therefore Ir = 1.7 in/6 hrs = 0.283 in/hr

The ratio of Pr/Ir therefore is 3/0.283 = 10.6 which indicates an over-design for this rain, requiring the use of 1.0 in the performance equation. The volume reduction is therefore 0.7 acres/5.3 acres = 0.13 (13 percent reduction in flow and pollutant yield).

Filtration of Stormwater

Treatment of Stormwater Using Filtration Media

Small source area stormwater runoff treatment devices using various forms of filtration have been developed and are currently being marketed. The control of small critical area contributions to urban runoff may be the most cost-effective approach for treatment/reduction of stormwater toxicants. The general features of the critical source areas appear to be large paved areas, heavy vehicular traffic (especially frequent and large numbers of vehicle starts, such as at convenience stores) and outdoor use or storage of problem pollutants. The following paragraphs describe the different filtering media that have been evaluated for stormwater control:

Sand

The use of sand filtration is common throughout the U.S. Water supply treatment plants have successfully used sand filtration for many years. Wastewater treatment plants often use sand filtration to polish their effluent before release, especially as the regulatory requirements become more stringent. Sand filtration of stormwater began in earnest in Austin, Texas. The Austin sand filters are used both for single sites and for drainage areas less than 20 ha. The filters are designed to hold and treat the first 13 mm of runoff and the pollutant removal ability of the sand filters has been found to be very good.

According to the City of Austin design guidelines, the minimum depth of sand should be 0.5 m. If the City's design guidelines are followed, the assumed pollutant removal efficiencies, which are based upon the preliminary results of the City of Austin’s stormwater monitoring program, are as follows:

Pollutant	Removal Efficiency (%)
Fecal Coliform Bacteria	76

Total Suspended Solids (TSS)	70
Total Nitrogen	21
Total Kjeldahl Nitrogen	46
Nitrate - Nitrogen	0
Total Phosphorus	33
BOD	70
Total Organic Carbon	48
Iron	45
Lead	45
Zinc	45

Ref: City of Austin 1988.

In Washington, D.C., sand filters are used both to improve water quality and to delay the entrance of large slug inputs of runoff into the combined sewer system. Water quality filters are designed to retain and treat 8 to 13 mm of runoff with the final design based upon the amount of imperviousness in the watershed.

The State of Delaware considers the sand filter to be an acceptable method for achieving the eighty percent reduction requirement of suspended solids. Sand filters in Delaware are intended for sites which have impervious areas that will drain directly to the filter. The purpose of the sand filter in many areas is to help prevent or postpone clogging of an infiltration device. According to the State of Delaware guidelines, sand filtration is "intended for use on small sites where overall site imperviousness is maximized. Examples of these sites would be fast food restaurants, gas stations or industrial sites where space for retrofitting with other infiltration devices, such as detention ponds, is not available" (Shaver undated).

According to Delaware's recommendations, the sand filter will adequately remove particulates (TSS removal efficiency 75 - 85 %) but will not remove soluble compounds. Studies of a sand filter in Maryland show that it is now just becoming clogged after six years of use in a heavily used parking lot. Inspection of the sand below the surface of the filter has shown that oil, grease and finer sediments have migrated into the filter, but only to a depth of approximately 50 to 75 mm (Shaver undated).

It has been generally expected that sand would retain any particles that it trapped. However, preliminary tests (Clark, *et al*. 1995) showed that fresh sand (without aging and associated biological growths) by itself did not retain stormwater toxicants (which are mostly associated with very fine particles). This lack of ability to retain stormwater toxicants prompted the investigation of other filtration media during this research. Combinations of filtration media, especially those using organic materials (activated carbon, peat moss, composted leaves and ion exchange resins) along with sand, are currently being investigated for their ability to more permanently retain stormwater pollutants.

Activated Carbon

Activated carbon filtration/separation has long been used in the chemical process industry and in hazardous waste cleanup as an effective method for removing trace organics from liquids. Activated carbon is made first by charring materials such as almond, coconut and walnut hulls, other woods, or coal. The char particles are activated by exposing them to an oxidizing gas at high temperatures. The activation process makes the particles porous which creates a large internal surface area available for pollutant adsorption (Metcalf and Eddy 1991).

The ability of the activated carbon to adsorb organics is based upon the molecular structure, solubility and the substitute groups on the organic molecule. Examples of compounds adsorbed by activated carbon include *n*-butyl phthalate, chlorobenzene, carbon tetrachloride, phenol, chloroform and nitrobenzene. Compounds that activated carbon does not adsorb include butylamine, cyclohexylamine, ethylenediamine and hexamethylenediamine. In the adsorption process, molecules attach themselves to the solid surface through attractive forces between them and the adsorbent carbon (Bennett, *et al*. 1982). Activated carbon filtration is limited by the number of adsorption sites in the media.

Activated carbon has a very small net surface charge and is ineffective at removing free hydrated metal ions, unless they are complexed with easily-adsorbed organics prior to contact with the activated carbon filter. However, once they are complexed with these usually insoluble organics, the complexed metals are readily adsorbed onto the carbon which results in high removal rates (Rubin and Mercer 1981).

Composted Leaves

Composts made from yard waste, primarily leaves, have been found to have a very high capacity for adsorbing heavy metals, oils, greases, nutrients and organic toxins due to the humic content of the compost. These humic compounds are stable, insoluble and have a high molecular weight. The humics act like polyelectrolytes and adsorb the toxicants.

The composted leaf filter was developed by W&H Pacific (now Stormwater Management) for Washington County (Washington), the Unified Sewer Agency and the Metropolitan Service District of Washington County (W&H Pacific 1992). The exact content of the composts and aging process for the composts used by W&H Pacific are not public knowledge with the result that the filter installation/maintenance company supplies the compost to the stormwater treatment device owner. The initial filter design consists of a bottom impermeable membrane with a drainage layer above. Above the drainage layer is a geotextile fabric above which is the compost material. A new design, the CSF II includes a concrete vault, having a flow spreader and a main tank area. The tank includes modular units containing the compost, and the stormwater flows horizontally through the compost. These modular units can be easily removed for maintenance. The actual pollutant removal occurs in the compost material. The removal processes that occur in the compost are filtration, adsorption, ion exchange and biodegradation of organics. Testing of a prototype of the initial design has shown the following pollutant removal rates:

Pollutant	Removal Rate (%)
Turbidity	84
Suspended Solids	95
Total Volatile Suspended Solids	89
COD	67
Settleable Solids	96
Total Phosphorus	40
Total Kjeldahl Nitrogen	56
Cooper	67
Zinc	88
Aluminum	87
Iron	89
Petroleum Hydrocarbons	87 .

Ref: W&H Pacific 1992.

Peat Moss

Peat is partially decomposed organic material, excluding coal, that is formed from dead plant remains in water in the absence of air. The physical structure and chemical composition of peat is determined by the types of plants (mosses, sedges and other wetland plants) from which it is formed. Peat is physically and chemically complex and is highly organic. Peat's main components are humic and fulvic acids and cellulose.

Peat's permeability varies greatly and is determined by its degree of decomposition and the plants from which it came. Generally, the more decomposed the peat is, the lower its hydraulic conductivity. Peats are generally light-weight when dry and are highly adsorptive of water. Because of the lignins, cellulosic compounds and humic and fulvic acids in peat, peat is highly colloidal and has a high cation-exchange capacity. Peat also is polar and has a high specific adsorption for dissolved solids such as transition metals and polar organic compounds. Peat has an excellent natural capacity for ion exchange with copper, zinc, lead and mercury, especially at pH levels between 3.0 and 8.5. This adsorption, complexing and exchange of various metal cations occur principally through the carboxyl, phenolic and hydroxyl groups in the humic and fulvic acids. This capacity to bind and retain cations, though, is finite and reversible and is determined mostly by the pH of the solution.

Peat is an excellent substrate for microbial growth and assimilation of nutrients and organic waste materials because of its high C:N:P ratio, which often approaches 100:10:1. Nitrifying and denitrifying bacteria are typically present in large numbers in natural peat. Peat's ability to retain phosphorus in the long-term is related to its calcium, aluminum, iron and ash content with the higher the content of each of the above constituents, the higher the retention capability.

Peat moss (sphagnum moss) is a fibric peat. It has easily identifiable undecomposed fibrous organic materials and its bulk density is generally less than 0.1 g/cc. Because of its highly porous structure, peat moss can have a high hydraulic conductivity, up to 140 cm/hr. It is typically brown and/or yellow in color and has a high water holding capacity.

For filtration devices, peat generally has been combined with sand to create a peat-sand filter (PSF). The PSF is a “man-made” filtration system, unlike the sand or peat filtration systems that were first used as wastewater treatment systems in areas where these soils naturally occur. The PSF removes most of the phosphorus, BOD and pathogens and with a good grass cover, additional nutrient removal occurs.

The Peat-Sand Filter System designed by the Metropolitan Washington Council of Governments (Washington, D.C.) has a good grass cover on top underlain by 300 to 500 mm of peat. The peat layer is supported by a 100 mm mixture of sand and peat which is supported by a 500 to 600 mm layer of fine to medium grain sand. Under the sand is gravel and the drainage pipe. The mixture layer is required because it provides the necessary continuous contact between the peat and the sand layers, ensuring a uniform water flow. Because this is a biological filtration system, it works best during the growing season when the grass cover can provide the additional nutrient removal that will not occur in the peat-sand regimes of the system (Galli 1990).

The PSF is usually an aerobic system. However, modifications to the original design by the Metropolitan Washington Council have been made to account for atypical site conditions or removal requirements. The estimated pollutant removal efficiency for the PSF system for stormwater runoff is given below:

Pollutant	Removal Efficiency (%)
Suspended Solids	90
Total Phosphorus	70
Total Nitrogen	50
BOD	90
Trace Metals	80
Bacteria	90

Ref. Galli 1990.

Recent Filtration Tests

The Department of Civil and Environmental Engineering at the University of Alabama at Birmingham is engaged in a multi-year cooperative agreement with the Storm and Combined Sewer Program of the U.S. EPA. Additional funding was provided by the U.S. Army Corps of Engineers Construction Engineering Research Laboratory in Champaign, IL. As part of this cooperative agreement, potential filtration and sorption media for stormwater runoff treatment from critical source areas were examined (Clark 1996).

Stormwater filters currently in operation typically use sand, leaf compost, or peat. This research tested the capabilities of these media, plus others with expected pollutant removal capability (activated carbon, Zeolite, a cotton milling waste, and a waste agrofiber), in both controlled laboratory and field tests. Influent and effluent samples from each test column were analyzed for toxicity (using Microtox™ screening test), turbidity, conductivity, pH, major anions and cations, semi-volatile organics, pesticides, particle size distribution, and heavy metals. This research also tested the influence that atypical influent pH and ionic strengths have on a medium's pollutant removal capability, since a potential exists that stormwater filters will be retrofit or designed for places that either receive snowmelt runoff with its high salt concentrations or runoff from an area, such as an industry or commercial establishment, where the pH is unusual. The pollutant removal abilities of two geotextiles were also investigated and their removal capacities compared with that of the traditional media.

The main objective of this research was to monitor a variety of media used to treat stormwater runoff to determine their overall pollutant removal capabilities. Generally, a variety of mechanisms, including straining, sorption, and ion-exchange, are responsible for removing pollutants during "filtration". No attempt was made to determine which mechanisms were responsible for removing a particular pollutant. In these tests, it soon became apparent that the media were limited by clogging caused by suspended solids in the stormwater runoff. Clogging occurred long before reductions in the pollutant removal capabilities could be determined when using typical pavement runoff. It is suggested that in order to lengthen the run time and better use the pollutant retention capacity of the media, the influent suspended solids concentration should be no more than about 10 mg/L.

Table D-6 provides a ranking of the media based only on suspended solids removal during 12 filter tests using stormwater collected from a large parking area on the UAB campus. Another series of 12 tests were also conducted using stormwater collected from the same location, but pretreated by settling for 1 to 3 days in a 1 m deep tank.

Table D-7 shows the levels of removal of stormwater pollutants that had significantly different influent and effluent concentrations after passing through the media (for normal stormwater that was not pretreated). Pollutant removal efficiency increased for all the media after they had aged because they typically develop a biofilm that aids in pollutant removal, and they have fewer small particles available in the medium to be washed out. Because many of the pollutants in stormwater runoff are associated with the particulate matter, more significant reductions in pollutant concentrations were noted when the runoff was not pretreated prior to filtering and when the media itself removed significant quantities of suspended solids.

Table D-6. Removal Efficiency for Suspended Solids

Ranked Media	Percent TSS Reduction (Pretreated) (Avg. Influent TSS = 10 mg/L)	Percent TSS Reduction (Avg. Influent TSS = 30 to 60 mg/L)
Sand	>50%	>90%
Carbon-Sand		>90%
Zeolite-Sand	20 - 50%	>90%
Filter Fabrics		10%
Peat-Sand	<10 %	80-90%
Enretech-Sand		>90%
Compost-Sand		80%

Table D-7. Pollutant Removal for Stormwater Treatment Media (not pretreated, TSS = 30 to 50 mg/L)

Media	Additional Comments
Carbon-Sand	Reduced toxicity (>95%), color (60%), alkalinity (30 to 50%), nitrate (95%), potassium (45%), suspended and volatile solids (50 to 80%), COD (50%), while increasing sulfate concentration in effluent.
Peat-Sand	Reduced toxicity (60%), fluoride (<10%), hardness and alkalinity (60%), while increasing turbidity, color, COD, and small particle concentrations in effluent. Lowered pH 1 unit.
Zeolite-Sand	Reduced toxicity (50 to 80%), potassium (35%), solids (15 to 50%), with minimal deterioration of effluent.
Sand	Reduced solids (10 to 70%), with minimal degradation of effluent.
Enretech-Sand	Reduced toxicity (< 10%), with minimal degradation of effluent.
Compost-Sand	Reduced toxicity (70 to >95%), large particle sizes (<30%), while increasing color and potassium concentration in effluent.
Filter Fabrics	Reduced solids (<30%), with minimal degradation of effluent.

Pretreatment of the stormwater was conducted to reduce the solids loadings on the media in order to increase the run times before clogging. This was done to better take advantage of the chemical retention capabilities of the filters. The settling reduced the stormwater suspended solids concentrations to about 10 mg/L, with about 90% of the particles being less than 10 μm in size (similar to the suspended solids conditions that is obtained using a well designed and operated wet detention pond). The pretreatment also reduced the other stormwater pollutant concentrations (for example, color and turbidity were reduced by about 50%, and COD by about 90%). This pretreatment had a significant effect on the media's pollutant removal performance, as shown in Table D-8. The suspended solids concentrations were generally not further reduced by the media, and its removal by itself would no longer be a suitable criterion for selecting a treatment medium, if the stormwater was pretreated.

Table D-8. Pollutant Removal for Stormwater Treatment Media (pretreated stormwater, TSS = 10 mg/L)

Media	Additional Comments
Carbon-Sand	Reduced toxicity (80%), color (25%), alkalinity (>95%), zinc (50 to 75%), COD (85 to 95%), 2,4-dinitrophenol (40%), bis(2-ethylhexyl) phthalate (90%), with minimal effluent degradation.
Peat-Sand	Reduced toxicity (60%), alkalinity and hardness (50 to 100%), chloride (<20%), large solids (<50%), zinc (60 to 70%), 2,4-dinitrophenol (35%), di-n-butyl phthalate (65%), bis(2-ethylhexyl) phthalate (20%), dieldrin (70%), while adding color, turbidity, and reducing pH (1-2 units).
Zeolite-Sand	Reduced toxicity (>90%), chloride (<10%), potassium (40%), calcium (15%), zinc (60 to 75%), bis(2-ethylhexyl) phthalate (80%), pentachlorophenol (90%), with minimal effluent degradation.
Enretech-Sand	Reduced volatile solids (20%), zinc (65 to 75%), 2,4-dinitrophenol (30%), pentachlorophenol (85%), with minimal effluent degradation.
Forest-Sand	Reduced zinc (75 to 80%), pentachlorophenol (90%), with minimal effluent degradation.
Sand	Reduced volatile solids (<10%), zinc (75 to 80%), bis(2-ethylhexyl) phthalate (100%), with minimal effluent degradation.
Compost-Sand	Reduced zinc (75 to 80%), while adding color to effluent.
Filter Fabrics	Reduced COD (20 to 50%), with minimal effluent degradation. Gunderboom reduced 2,4-dinitrophenol (75 to 80%) and di-n-butyl phthalate (75 to 80%).

As shown during these results, the characteristics of the influent water greatly influence the performance of the treatment medium. Generally, most stormwater filters are designed based upon the influent suspended solids concentration and desired suspended solids removal. For most applications, this likely will remain the primary design factor. However, the selection of the media may likely be different when the influent suspended solids concentration is low, or when the pH is not near neutral and/or the ionic strength is high. Stormwater filter designers also need to consider that most of these media are also ion exchange materials: when ions are removed from solution by the treatment material, other ions are released into the effluent. In most instances, these ions are not a problem in receiving waters, but the designer should know what is added to the water. For the activated carbon examined during these tests, the exchangeable ion was found to be mostly sulfate; while for the compost, the exchangeable ion was found to be mostly potassium. The Zeolite tested appeared to exchange sodium and some divalent cations (measured as increasing hardness) for the ions it removed.

The stormwater control objectives may dictate a combination of filter media. The peat-sand and compost-sand mixtures provided excellent removal for most pollutants, but they added some potentially undesirable constituents to the water. A three-media filter (peat, sand, and activated carbon) has been tested to deal with the addition of some of the undesirables. This design currently is in operation as the polishing chamber of a Multi-Chamber Treatment Train (MCTT) in Milwaukee, WI (Pitt 1996). Based upon the results from a year of monitoring, the addition of activated carbon to the peat-sand media has enhanced the removal ability of the material without adding the undesirable elements like color and turbidity to the effluent. For many stormwater treatment applications, this multi-media approach may be the best solution for treating runoff before it reaches any sensitive receiving waters.

Roberts (1996) described the use of underground detention storage using pipes, in combination with an underground stormwater filtration system as an emerging technology. The city of Alexandria has recently published a regional stormwater management manual that includes several designs for sand filters. In addition, the Center for Watershed Protection (1996) has also recently published a design manual for stormwater filtration. Tenney, *et al*. (1995), at the University of Texas, also recently published a detailed report on highway runoff filtration systems.

Design of Stormwater Filters

The information obtained during this EPA sponsored research can be used to develop design guidelines for stormwater filtration, especially in conjunction with reported information in the literature. The design of a stormwater filter needs to be divided into two phases. The first phase is the selection of the media to achieve the desired pollutant removal goals. The second phase is the sizing of the filter to achieve the desired run time before replacement of the media. The main objective of this research was to monitor a variety of filtration media to determine their pollutant removal capabilities, as noted previously. However, it soon became apparent that the filters were more limited by clogging caused by suspended solids in the stormwater, long before reductions in their pollutant removal capabilities could be identified. Therefore, measurements in filter run times, including flow rates and clogging parameters, were added to the research activities. However, the small-scale filter set-ups used for the pollutant removal measurements (using 1 L test columns) probably under-predicted the actual run times that could be achieved under full-scale applications. Even with the increased filter depth utilization and better drying between storms that may be achieved with full-scale applications, pretreatment of the stormwater so the suspended solids content is about 10 mg/L, or less, is probably necessary in order to take greater advantage of the pollutant retention capabilities of most of the media. This level of pretreatment, however, may make further stormwater control unnecessary, except for unusual conditions. Of course, it may be more cost-effective to consider shortened filter run times, without pretreatment, and not utilize all of the pollutant retention capabilities of the media.

Selection of Filtration Media for Pollutant Removal Capabilities. The selection of the filter media needs to be based on the desired pollutant removal performance and the associated conditions. If based on suspended solids alone for untreated stormwater (a likely common and useful criteria), then the filtration media would be ranked according to the following:

1) >90% control of suspended solids: compost/sand, act. carbon/sand, Zeolite/sand, Enretech/sand
2) 80 - 90% control of suspended solids: sand, peat/sand

3) very little control of suspended solids: filter fabrics

If based on a wider range of pollutants for untreated stormwater, then the ranking would be as follows:

1) sand, act. carbon/sand, Enretech/sand (no pollutant degradation, but sand by itself may not offer "permanent" pollutant retention until aged and has biological growths and/or deposition of silts and oils - that is the reason supplements were added to the sand during this research)
2) Zeolite/sand (no degradation)
3) compost/sand (color degradation)
4) peat moss/sand (turbidity and pH degradation)
5) filter fabrics alone (very little pollutant removal benefit)

Pre-settling of the stormwater was conducted to reduce the solids loadings on the filters to increase the run times before clogging in order to take better advantage of the pollutant retention capabilities of the filters. Settling reduced the stormwater suspended solids to about 10 mg/L, with about 90% of the particles (by volume) less than 10 μm in size. The untreated stormwater had a suspended solids concentration of about 30 to 50 mg/L, but many of the particles were larger, with about 90% of the particles being less than 50 μm. The pre-settling also reduced the other stormwater pollutants (color and turbidity by about 50%, and COD by about 90%, for example). This pre-settling was similar to what would occur with a well designed and operated wet detention pond. This pre-settling had a significant effect on the filter performance, as noted, and the rankings would be as follows, considering a wide range of stormwater pollutants (suspended solids removal by itself would not be a suitable criteria, as it is not likely to be reduced any further by the filters after the pre-settling):

1) peat moss/sand (with degradation in color, turbidity, and pH)
2) activated carbon/sand (no degradation, but fewer benefits)
3) Enretech/sand, forest/sand, sand (few changes, either good or bad)
4) compost/sand (many negative changes)

Obviously, knowing the stormwater control objectives and options will significantly affect the selection of the treatment media. This is most evident with the compost material. If suspended solids removal is the sole criterion, with minimal stormwater pre-treatment, then it is the recommended choice (if one can live with a slight color increase in the stormwater, which is probably not too serious). However, if a filter is to be used after significant pre-treatment in order to have a longer filter life, a compost filter would be the last choice (not considering economics).

The following list summarizes the likely significant reductions in concentrations observed for the filters:

- Sand: Medium to high levels of control for most pollutants, if the stormwater is not pre-treated. These levels of control are associated with retention of suspended solids and the associated particulate fractions of the pollutants. Can relatively easily flush previously captured pollutants. With pretreatment, has little additional benefit. Likely minimum effluent concentrations: 10 mg/L for suspended solids, 50 HACH color units, 10 NTU for turbidity.

- Peat moss/sand: Medium to high levels of control for most pollutants, for both untreated and pre-settled stormwater. Largest range and number of pollutants benefited under pre-settled conditions. Caused increases in color and turbidity, and reductions in pH (by about one pH unit). Likely minimum effluent concentrations: 5 mg/L for suspended solids, 85 HACH color units, 10 - 25 NTU for turbidity.

- Activated carbon/sand: Very good control for most pollutants, especially if the stormwater is not pre-treated. Also large number of benefited pollutants under pre-settled conditions. Caused no adverse changes for any pollutant. Likely minimum effluent concentrations: 5 mg/L for suspended solids, 25 HACH color units, 5 NTU for turbidity.

• Zeolite/sand: Medium to high levels of control for many pollutants for untreated stormwater, but no likely benefits for pre-settled stormwater. Caused increased color and turbidity on pre-settled stormwater. Likely minimum effluent concentrations: 10 mg/L for suspended solids, 75 HACH color units, 15 NTU for turbidity.

• Compost/sand: Medium to very high levels of control for many pollutants for untreated stormwater, but worsened water quality for many pollutants if pre-settled. Increased color under all conditions and had increased phosphate and potassium in effluent. Likely minimum effluent concentrations: 10 mg/L for suspended solids, 100 HACH color units, 10 NTU for turbidity.

• Enretech/sand: Medium to high levels of control for many pollutants for untreated stormwater, but had little effect on pre-settled stormwater. Likely minimum effluent concentrations: 10 mg/L for suspended solids, 80 HACH color units, 10 NTU for turbidity.

• Filter fabrics: No significant and/or important reductions for any pollutants using either untreated or pre-settled stormwater.

Design of Filters for Specified Filtration Durations. The filtration durations measured during these tests can be used to develop preliminary filter designs. It is recommended that allowable suspended solids loadings be used as the primary controlling factor in filtration design. Clogging is assumed to occur when the filtration rate becomes less than about 1 m/day. Obviously, the filter would still function at smaller filtration flow rates, especially for the smallest rains in arid areas, but an excessive amount of filter by-passing would likely occur for moderate rains in humid areas. Tables D-9 and D-10 summarize the observed filtration capacities of the different media tested. The wide ranges in filter run times as a function of water are mostly dependent on the suspended solids content of the water, especially when the water is pre-treated. Therefore, the suspended solids loading capacities are recommended for design purposes.

Table D-9. Filtration Capacity as a Function of Suspended Solids Loadings

Filtration Media	Capacity to 20 m/day	Capacity to 10 m/day	Capacity to <1 m/day
Sand	150-450 gSS/m^2	400->2000 gSS/m^2	1200-4000 gSS/m^2
Peat/sand	100-300	150-1000	200-1700
Peat	?	?	200
Leaves	?	?	2100
Activated carbon/sand	150-900	200-1100	500->2000
Zeolite/sand	200-700	800-1500	1200->2000
Compost/sand	100-700	200-750	350-800
Enretech/sand	75-300	125-350	400-1500

Table D-10. Filtration Capacity as a Function of Pre-Treated Water (generally <10 mg SS /L) Loading

Filtration Media	Capacity to 20 m/day	Capacity to 10 m/day	Capacity to <1 m/day
Sand	6-20 m	8->25 m	13->40 m
Peat/sand	3-17	4-22	7-30
Activated carbon/sand	5-25	6->25	15->40
Zeolite/sand	7-25	8->25	14->40
Compost/sand	3-20	4-30	6->30
Enretech/sand	3-11	4-25	15->30

The most restrictive materials (the Enretech and Forest Products media) are very fibrous and still show compaction, even when mixed with sand. The most granular media (activated carbon and the Zeolite) are relatively uniform in shape and size, but have sand interspersed to fill the voids to slow the water to increase the contact time for better pollutant removal. The sand has the highest filtration rates because it has the most uniform shape and size.

The test observations indicated that only about 2.5 cm of the filter columns (about 10%) were actually used for solids retention during these tests. A full-scale filter could utilize about 5 times these depths for solids retention, if care was taken to allow selective piping to deeper depths, while not providing short-circuiting through the complete filter column. This could be most easily accomplished by placing a turf grass layer on top of the media (as in the peat-sand filter designs of the Metropolitan Washington (D.C.) Council of Governments). It is recommended that the roots of the grass used in the cover layer do not extend below about one-half of the filtration depth (the root depth should therefore be up to about 12 cm). Mechanical removal of the clogged layer to recover filter flow rates was not found to be very satisfactory during this research, but has been used successfully during full-scale operations. Great care must be taken when removing this layer, as loosening the media, besides increasing the flow capacity of the filter, will also enable trapped pollutants (associated with the suspended solids) to be easily flushed from the media.

The flow rates through filters that have thoroughly dried between filter runs significantly increases. Our small-scale tests restricted complete drying during normal inter-event periods which may occur more commonly with full-scale filters. Wetting and drying of filters (especially peat) has been known to produce solution channels through the media that significantly increases the flow. If these solution channels extend too far through the filter, they would cause short-circuiting and would therefore reduce pollutant retention. Adequate filter depths will minimize this problem. Table D-11 shows the observed increases in filter flow rates for saturated (and partially clogged filters) and the associated flow capacity recovery for filters that have been thoroughly dried and then re-wetted. The filter fabrics did not indicate any flow rate improvements with wetting and drying, while the peat moss/sand filter had the greatest improvement in flow capacity (by about ten times), as expected. The other media showed much more modest improvements (but still about two to three times).

Table D-11. Filter Flow Rates (m/day) for Saturated (and Partially Clogged) Filters and Recovered Filtration Capacity after Through Drying

Filter Condition	sand	peat moss/ sand	act. carbon/ sand	Zeolite/ sand	compost/ sand	Enretech/ sand	forest/ sand	Emcon™ fabric	Gunder-boom™ fabric
Saturated/ partially clogged	13	4.0	17	17	13	8.4	8.4	850	200
Recovered flow capacity after drying	40	42	33	39	32	24	17	850	200
Increase in flow (multiple)	3.1X	11X	1.9X	2.3X	2.5X	2.9X	2.0X	1.0X	1.0X

The above filter capacity ranges are associated with varying test conditions and may be further grouped into the following approximate categories, as shown on Table D-12, which are multiplied by 5 to account for an anticipated greater filter flow capacity associated with full-scale applications.

Table D-12. Expected Full-Scale Media Flow Capacities

Capacity to <1 m/day	Capacity to 10 m/day	Filtration Media Category
5,000 gSS/m^2	1,250 gSS/m^2	Enretech/sand; Forest/sand
5,000	2,500	Compost/sand; Peat/sand
10,000	5,000	Zeolite/sand; Act. Carbon/sand
15,000	7,500	Sand

Filter designs can be made based on the predicted annual discharge of suspended solids to the filtration device and the desired filter replacement interval. As an example, Table D-13 shows the volumetric runoff coefficients (Rv) that can be used to approximate the fraction of the annual rainfall that would occur as runoff for various land uses and surface conditions, based on small-storm hydrology concepts (Pitt 1987). In addition, Table D-14 summarizes likely suspended solids concentrations associated with different urban areas and waters.

Table D-13. Volumetric Runoff Coefficients (Rv) for Different Urban Areas

Area	Volumetric Runoff Coefficient (Rv)
Low density residential land use	0.15
Medium density residential land use	0.3
High density residential land use	0.5
Commercial land use	0.8
Industrial land use	0.6
Paved areas	0.85
Sandy soils	0.1
Clayey soils	0.3

Table D-14. Typical Suspended Solids Concentrations in Runoff from Various Urban Surfaces

Source Area	Suspended Solids Concentration (mg/L)
Roof runoff	10
Paved parking, storage, driveway, streets, and walk areas	50
Unpaved parking and storage areas	250
Landscaped areas	<500
Construction site runoff	10,000
Detention pond effluent water	20
Mixed stormwater	150
Effluent after high level of pre-treatment of stormwater	5

Using the information in the above two tables and the local annual rain depth, it is possible to estimate the annual suspended solids loading from an area. The following three examples illustrate these simple calculations.

1) A 1.0 ha paved parking area, in an area receiving 1.0 m of rain per year:

(50 mg SS/L) (0.85) (1 m/yr) (1 ha) (10,000 m^2/ha) (1,000 L/m^3) (g/1,000 mg) = 425,000 g SS/yr

Therefore, if a peat/sand filter is to be used having an expected suspended solids capacity of 5,000 g/m^2 before clogging, then 85 m^2 of this filter will be needed for each year of desired operation for this 1.0 ha site. This is about 0.9% of the paved area per year of operation. If this water is pre-treated so the effluent has about 5 mg/L suspended solids, then only about 0.2% of the contributing paved area would be needed for the filter. A sand filter would only be about 1/3 of this size.

2) A 100 ha medium density residential area having 1.0 m of rain per year:

(150 mg SS/L) (0.3) (1 m/yr) (100ha) (10,000 m^2/ha) (1,000 L/m^3) (g/1,000 mg) = 45,000,000 g SS/yr

The unit area loading of suspended solids for this residential area (450 kg SS/ha-yr) is about the same as in the previous example (425 kg SS/ha-yr), requiring about the same area dedicated for the filter. The reduced amount of runoff is balanced by the increased suspended solids concentration.

3) A 1.0 ha rooftop in an area having 1.0 m of rain per year:

(10 mg SS/L) (0.85) (1 m/yr) (1 ha) (10,000 m^2/ha) (1,000 L/m^3) (g/1,000 mg) = 85,000 g SS/yr

The unit area loading of suspended solids from this area (85 kg SS/ha-yr) is much less than for the other areas and would only require a filter about 0.2% of the roofed drainage area per year of operation.

It is recommended that the filter media be about 50 cm in depth and that a surface grass cover be used, with roots not extending beyond half of the filter depth. This should enable a filtration life of about five times the basic life observed during these tests. In addition, it is highly recommended that significant pre-treatment of the water be used to reduce the suspended solids concentrations to about 10 mg/L before filtration for pollutant removal. This pre-treatment can be accomplished using grass filters, wet detention ponds, or other specialized treatment (such as the sedimentation chamber in the multi-chambered treatment train, MCTT). The selection of the specific filtration media should be based on the desired pollutant reductions, but should in all cases include amendments to plain sand if immediate and permanent pollutant reductions are desired.

Summary of Filtration as a Stormwater Control

In all cases, comprehensive chemical analyses are showing limited changes in the pollutant reductions with time. The media is apparently clogging before the media is experiencing chemical break-though. It is not yet clear if depth filtering media will be a cost-effective stormwater control, considering the pre-treatment needed to prevent clogging. The pretreatment alone may provide adequate control alone, with the additional filtration cost. Large-scale filtration installations (especially sand) have been shown to perform well for extended periods of time with minimal problems. The use of supplemental materials (such as organic compounds) should increase their performance for soluble compounds.

SLAMM Calculation Procedures for Media Filters

SLAMM is currently being modified to incorporate media filters using the on-going UAB research. The specific procedures have not yet been finalized, although they will be similar to the design procedures described above (clogging as a critical issue, with pollutant removal relatively constant until clogging).

Combination Devices (Example use of the Multi-Chambered Treatment Train, MCTT)

Earlier bench-scale treatability studies, sponsored by the U. S. Environmental Protection Agency (EPA), found that the most beneficial treatment for the removal of stormwater toxicants (as measured using the Microtox™ test) included quiescent settling for at least 24 hours in a 1 meter settling column (generally 40% to 90% reductions), screening through at least 40 µm screens (20% to 70% reductions), and aeration and/or photo-degradation for at least 24 hours (up to 80% reductions) (Pitt, *et al.* 1995). The MCTT contains aeration, sedimentation, sorption, and sand/peat filtration and was developed by Pitt at the University of Alabama at Birmingham (Robertson, *et al*. 1995).

The MCTT is most suitable for use at relatively small and isolated paved critical source areas, from about 0.1 to 1 ha (0.25 to 2.5 acre) in area, where surface land is not available for stormwater controls. Typical locations include gas stations, junk yards, bus barns, public works yards, car washes, fast food restaurants, convenience stores, etc., and other areas where the stormwater has a high probability of containing high concentrations of oils and filterable toxic pollutants that are difficult to treat by other means. A typical MCTT requires between 0.5 and 1.5 percent of the paved drainage area, which is about 1/3 of the area required for a well-designed wet detention pond, and is generally installed below ground. A pilot-scale MCTT was constructed in Birmingham, AL, at a large parking area at the University of Alabama at Birmingham campus, and tested over a six month monitoring period. Two additional full-scale MCTT units have also been constructed and are being monitored as part of Wisconsin's 319 grant from the U.S. EPA. Complete organic and metallic toxicant analyses, in addition to conventional pollutants, are included in the evaluation of these units.

Figure D-9 shows a general cross-sectional view of a MCTT. It includes a special catchbasin followed by a two chambered tank that is intended to reduce a broad range of toxicants (volatile, particulate, and dissolved). The MCTT includes a special catchbasin (based on Lager, *et al*.'s 1977 design) followed by two tank chambers that is intended to reduce a broad range of suspended solids and stormwater toxicants (volatile, particulate, and dissolved). The runoff enters the catchbasin chamber by passing over a flash aerator (small column packing balls with counter-current air flow) to remove any highly volatile components present in the runoff (unlikely). This catchbasin also serves as a grit chamber to remove the largest (fastest settling) particles. The second chamber serves as an enhanced settling chamber to remove smaller particles and has inclined tube settlers to enhance sedimentation. The settling time in this main settling chamber usually ranges from 20 to 70 hours. This chamber also contains fine bubble diffusers and sorbent pads to further enhance the removal of floatable hydrocarbons and additional volatile compounds. The water is then pumped to the final chamber at a slow rate to maximize pollutant reductions. The

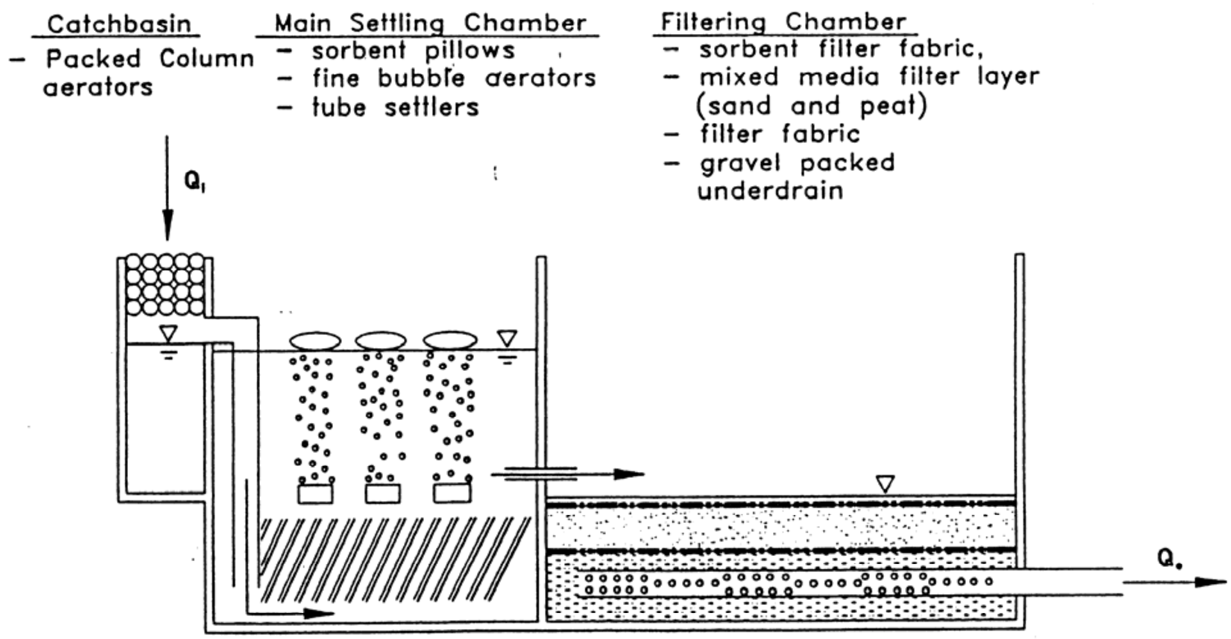


Figure D-9. General schematic of MCTT (Pitt 1995).

final chamber contains a mixed media (sand and peat) slow filter, with a filter fabric layer. The MCTT is typically sized to totally contain all of the runoff from a 6 to 20 mm (0.25 to 0.8 in) rain, depending on treatment objectives, inter-event time, typical rain size, and rain intensity for an area.

Table D-15 shows the median toxicity reductions for various holding times for a 2.1m deep main settling chamber, based on laboratory bench-scale treatability tests. Table D-16 shows how this device would operate for Birmingham, Alabama, rains. Short holding times result in much of the annual rainfall being treated (the unit is empty before most of the rains begin, because it rains about every 3 to 5 days), but each rain is not treated very well, because of the short settling periods. Therefore, the annual treatment level approaches a constant level with long holding periods. In this example, a relatively large main settling chamber is needed in order to contain large fractions of most of the rains. Long-term continuous analyses have been conducted to identify the most cost-effective MCTT sizes (and holding times) for different treatment objectives for many U.S. locations (Pitt 1996).

Table D-15. Median Toxicity Reductions for Different Treatment Holding Times

Holding Period for 2.1 m depth (h)	Median Toxicity Reduction (%) per Individual Rain
6	46
12	60
24	75
36	84
48	92
72	100

Table D-16. Effects of Storage Volume and Holding Periods on Annual Runoff Treated and on Total Annual Toxicity Reduction (Birmingham, AL rains)

Holding Period (h)	% Annual Runoff Treated	% Annual Toxicity Reduction	% Annual Runoff Treated	% Annual Toxicity Reduction
	Storage volume corresponding to: 12.7 mm rain with 10.2 mm runoff (0.50 in. rain with 0.40 in. runoff)		Storage volume corresponding to: 38.1 mm rain with 33.5 mm runoff (1.50 in. rain with 1.32 in. runoff)	
6	84	39	100	46
12	62	37	100	60
24	52	39	98	73
36	48	41	91	77
48	46	42	88	81
72	44	44	84	84

During monitoring of 13 storms at the Birmingham pilot-scale MCTT facility (designed for 90% toxicity reductions), the following overall median removal rates were observed: 96% for total toxicity (as measured using the Microtox™ screening test), 98% for filtered toxicity, 83% for suspended solids, 60% for COD, 40% for turbidity, 100% for lead, 91% for zinc, 100% for n-Nitro-di-n-proplamine, 100% for pyrene, and 99% for bis (2-ethyl hexyl) phthalate. The color was increased by about 50% due to staining from the peat and the pH decreased by about one-half pH unit, also from the peat media. Ammonia nitrogen was increased by several times, and nitrate nitrogen had low removals (about 14%). The MCTT performed better than intended because of the additional treatment provided by the final ion exchange/filtration chamber. It had very effective removal rates for both filtered and particulate stormwater toxicants and suspended solids. Increased filterable toxicant removals were obtained in the peat/sand mixed media filter/ion exchange chamber, at the expense of increased color, lowered pH, and depressed COD and nitrate removal rates.

Preliminary results from the full-scale Wisconsin tests collaborate the high levels of treatment observed during the Birmingham pilot-scale tests. Table D-17 shows the treatment levels that have been observed to date, based on seven tests in Minocqua (during one year of operation) and three tests in Milwaukee (during the first several months of operation). This initial data indicates very high removals (generally >90%) for suspended solids, COD, turbidity, phosphorus, lead, zinc, and many organic toxicants. None of the organic toxicants were ever observed in effluent water from either full-scale MCTT, even considering the excellent detection limits available in the Wisconsin laboratories. The MCTT effluent concentrations were also very low for all of the other constituents monitored: <10 mg/L for suspended solids, <0.1 mg/L for phosphorus, <5 μg/L for cadmium and lead, and <20 μg/L for copper and zinc. The pH changes in the Milwaukee MCTT were much less than observed during the Birmingham pilot-scale tests, possibly because of the added activated carbon in the final chamber in Milwaukee. Color was also much better controlled in the full-scale Milwaukee MCTT.

The Milwaukee installation is at a public works garage and serves about 0.1 ha (0.25 acre) of pavement. This MCTT was designed to withstand very heavy vehicles driving over the unit and was a custom-built concrete tank. The estimated cost was $54,000 (including a $16,000 engineering cost), but the actual cost was $72,000. The high cost was likely due to uncertainties associated with construction of an unknown device by the contractors and because it was a retrofitted installation. It therefore had to fit within very tight site layout constraints. As an example, installation problems occurred due to sanitary sewerage not being accurately located as mapped.

Table D-17. Preliminary Performance Information for Full-Scale MCTT Tests (median removals and median effluent quality)

	Milwaukee MCTT (3 initial tests)	**Minocqua MCTT (7 initial tests)**
suspended solids	>95 (<5 mg/L)	85 (10 mg/L)
COD	90 (10 mg/L)	na

turbidity	90 (5 NTU)	na
pH	-7 (8 pH)	na
ammonia	50 (<0.03 mg/L)	na
nitrates	0 (0.3 mg/L)	na
phosphorus	90 (0.03 mg/L)	80 (0.1 mg/L)
cadmium	90 (0.1 μg/L)	na
copper	90 (3 μg/L)	65 (15 μg/L)
lead	95 (2 μg/L)	nd (<3 μg/L)
zinc	>85 (<20 μg/L)	90 (15 μg/L)
benzo(a)anthracene	>45 (<0.05 μg/L)	>65 (<0.2 μg/L)
benzo(b)fluoranthene	>95 (<0.1 μg/L)	>75 (<0.1 μg/L)
dibenzo(a,h)anthracene	>80 (<0.02 μg/L)	>90 (<0.1 μg/L)
fluoranthene	>95 (<0.1 μg/L)	>90 (<0.1 μg/L)
indeno(l,2,3-cd)pyrene	>90 (<0.1 μg/L)	>95 (<0.1 μg/L)
phenanthrene	>70 (<0.05 μg/L)	>65 (<0.2 μg/L)
pyrene	>80 (<0.05 μg/L)	>75 (<0.2 μg/L)

na: not analyzed
nd: not detected

The Minocqua site was a 1 ha (2.5 acre) newly paved parking area serving a state park and commercial area. This MCTT was constructed using standard 10' x 15' concrete culvert sections. It was located underneath a grassed area, with the runoff piped to the MCTT. It was also a retro-fitted installation, designed to fit within an existing storm drainage system. The installed cost of this MCTT was about $95,000. It is anticipated that MCTT costs could be substantially reduced if designed to better integrate with a new drainage system and not installed as a retro-fitted stormwater control practice. Plastic tank manufactures have also expressed an interest in preparing pre-fabricated MCTT units that could be sized in a few standard sizes for small critical source areas. It is expected that these pre-fabricated units would be much less expensive and easier to install than the custom-built units tested to date.

The development and testing of the MCTT showed that the treatment unit provided substantial reductions in stormwater toxicants (both in particulate and filtered phases), and suspended solids. Increases in color and a slight decrease in pH also occurred during the filtration step at the pilot-scale unit. The main settling chamber resulted in substantial reductions in total and dissolved toxicity, lead, zinc, certain organic toxicants, suspended solids, COD, turbidity, and color. The filter/ion exchange unit is also responsible for additional filterable toxicant reductions. However, the catchbasin/grit chamber did not indicate any significant improvements in water quality, although it is an important element in reducing maintenance problems by trapping bulk material.

SLAMM Calculation Procedures for Combination Devices (specifically the MCTT)
SLAMM is currently being modified to incorporate combination devices. The MCTT will be modeled using the catchbasin procedures, plus the detention pond procedures for the main settling chamber, and finally the media filter procedures for the last chamber (if used).

References and Bibliography

Adams, R. "Stormwater infiltration as a part of an environmentally compatible drainage concept." Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 975 - 980. 1993.

Aires, N, and J.P. Tabuchi. "Hydrocarbons separators and stormwater treatment." (in French) *TSM, Special Issue «Stormwater»*, no 11, pp 862-864. 1995.

Akeley, R.P. "Retention basins for control of urban stormwater quality." In Proceedings: *National Conference on Urban Erosion and Sediment Control: Institutions and Technology*, EPA-905/9-80-002, Chicago, January 1980.

Alhajjar, B.J., Harkin, J.M., and Chesters, G. "Detergent formula and characteristics of wastewater in septic tanks." *J. Water Poll. Control Fed.*, 61(5). 1989.

Allard, L.A., E. Graham, W. Platz, R. Carr, and J. Wheeler. "The StormTreat™ system used as a storm water best management practice." Proceedings of: *Watershed'96, A National Conference on Watershed Management*. June 8 -12, 1996. Baltimore, MA. Tetra Tech, Inc. ISBN: 1-57278-028-2. pp. 463 - 465. 1996.

Aronson, G., D. Watson, and W. Pisano. *Evaluation of Catchbasin Performance for Urban Stormwater Pollution Control*. U.S. EPA. Grant No. R-804578. EPA-600/2-83-043. 78 pages. Cincinnati, June 1983.

Artières, O. *Deposits in Sewer Systems : Origins, Characteristics, Pollution, Transport*. (in French) PhD thesis of the Louis Pasteur University of Strasbourg, 214 p. September 1987.

Austin, Texas (City of). *Design Guidelines for Water Quality Control Basins* . Environmental DCM. City of Austin Transportation and Public Services Department. 1988.

Austin, G., A. Iatrou, and A. Rheams. "Art and fun help save Lake Pontchartrain." Proceedings: *Urban Wet Weather Pollution: Controlling Sewer Overflows and Stormwater Runoff*. June 16 - 19, 1996. Quebec City, Quebec. Water Environment Federation, Alexandria, VA. pp. 9-33 - 9-36. 1996.

Ayyoubi, A.H. *Physical Treatment of Urban Storm Water Runoff Toxicants*. MSCE Thesis. Department of Civil Engineering. University of Alabama at Birmingham. Birmingham, Alabama. 118 pages. 1993.

Azzout, Y., S. Barraud, F.N. Crès, and E. Alfakih. "Alternative techniques for urban storm drainage." (in French) *Tech et Doc, ed. Lavoisier*, Paris, 372 p. 1994.

Baladès, J.D., P. Bourgogne, and H. Madiec. "Assessment of pollutant removal through a compensating technique structure." (in French) *International Conference NOVATECH 92*, Lyon, pp. 66-75. 1992.

Baladès, J.D., P. Bourgogne, and Gourioux. "A reservoir structure pavement for the urban storm drainage of a supermarket area of 120.000 m2 in Bordeaux." (in French) *International Conference NOVATECH 95*, Lyon, pp. 329-336. 1995a.

Baladès, J.D., M. Legret, and H. Madiec. "Porous pavements as tools to control the pollutant loads on urban streets." (in French) *International Conference NOVATECH 95*, Lyon, pp. 345-352. 1995b.

Bannerman, R., J.G. Konrad, and D. Becker. *The IJC Menomonee River Watershed Study*. EPA-905/4-79-029. US Environmental Protection Agency. Chicago Illinois. 1979.

Bannerman, R., K. Baun, M. Bohn, P.E. Hughes, and D.A. Graczyk. *Evaluation of Urban Nonpoint Source Pollution Management in Milwaukee County, Wisconsin*, Vol. I. Grant No. P005432-01-5, PB 84-114164. US Environmental Protection Agency, Water Planning Division, November 1983.

Barron. P.F. *Characterization of Polynuclear Aromatic Hydrocarbons in Urban Runoff*. MSCE Thesis. Department of Civil Engineering. The University of Alabama at Birmingham, Birmingham. Alabama. 90 pages. 1990.

Barten, J.M. "Lawn fertilizer as a source of phosphorus runoff." North American Lake Management Society (NALMS) Conference presentation. Minneapolis/St. Paul. October 1996.

Beale, D.C. "Recent developments in the control of urban runoff." *Water and Environmental Management*. Vol. 6, no. 2, pp. 141 - 150. April 1992.

Beech, R.M. and A.F. Dake. *Designing an Effective Communication Program: A Blueprint for Success*. University of Michigan, School of Natural Resources and Environment. For the U.S. Environmental Protection Agency, Region 5. 1992.

Becker, F.A., P.D. Hedges, and R.P.M. Smisson. "The relationship between pollutants and specific sewage settling velocity fractions." *NOVATECH 95, 2nd International Conference on Innovative Technologies in Urban Storm Drainage*. May 30 - June 1, 1995. Lyon, France. pp. 607-610. Organized by Eurydice 92 and Graie. 1995.

Bedner, R.E. and D.J. Fluke. *Demonstration of Debris Basin Effectiveness in Sediment Control*. Environmental Protection Agency, Industrial Environmental Research Laboratory - Cincinnati, EPA-600/7-80-154. Cincinnati, Ohio, 1980.

Bennett, Gary F., Frank S. Feates and Ira Wilder. *Hazardous Materials Spills Handbook*. McGraw-Hill Book Company, New York, 1982. pp. 9-9 - 9-57.

Bernard, C., P. Herviou, T. Poujol, and C. Zobrist. "Procedures for treatment of stormwater and quality objectives: two practical representative examples." Proceedings: *Urban Wet Weather Pollution: Controlling Sewer Overflows and Stormwater Runoff*. Quebec City, Quebec. June 16 - 19, 1996. Water Environment Federation, Alexandria, VA. Pp. 15-59 - 15-68. 1996.

Bertrand-Krajewski, J.-L. "Modeling of flows and of solid transport in sewer systems: literature review." (in French) *Lyonnaise des Eaux/ENGEES report*, Strasbourg, 207 p April 1991.

Bertrand-Krajewski, J.-L., B. Breuil, L. Herremans, and D. Renard. "How to reduce stormwater discharges and their impact on receiving water?" (in French) *La Houille Blanche*, no1/2, pp 155-169. 1994.

Brydges, T. and G. Robinson. “Two examples of urban stormwater impoundment for aesthetics and for protection of receiving waters.” In: *Restoration of Lakes and Inland Waters: International Symposium on Inland Waters and Lake Restoration*. Portland, Main, September 1980. Proceedings published by the U.S. Environmental Protection Agency, Washington, D.C. 1986.

Butler, D., P. Clark, and J. Payne. “Management of sediment in drainage catchments.” Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 736 - 741. 1993.

Butler, D. and S.H.P.G. Karunaratne. “The suspended solids trap efficiency of the roadside gully pot.” *Wat. Res*. Vol. 29, No. 2. pp. 719-729. 1995.

Butler, D., Y. Xiao, S.H.P.G. Karunaratne, and S. Thedchanamoorthy. “The gully pot as a physical and biological reactor.” *Water Science & Technology*. Vol. 31, No. 7, pp. 219-228. 1995.

Cairncross and R.G. Feacham. *Environmental Health Engineering in the Tropics*. John Wiley & Son. NY. 1993.

Candaras, A.M., L.M.J. Carvalho, and M-K. Koo. “City of Etobicoke exfiltration and filtration systems pilot/demonstration project.” *Modern Methods for Modeling the Management of Stormwater Impacts*. Edited by W. James. Computational Hydraulics International, Guelph, Ontario. pp. 399 - 419. 1995.

Chambers, G.M. and C.H. Tottle. *Evaluation of Stormwater Impoundments in Winnipeg*. Report SCAT-1, Environment Canada, Ottawa, April 1980.

Clark, D.E.,Jr., and W.C. Cobbin. *Removal Effectiveness of Simulated Dry Fallout from Paved Areas by Motorized and Vacuumized Street Sweepers*. USNRDL-TR-746, U.S. Naval Radiological Defense Laboratory, Alexandria, Virginia, 1963.

Clark, S., R. Pitt, and R. Field. “Stormwater treatment: inlet devices and filtration.” Presented at the *Stormwater NPDES Related Monitoring Needs* ASCE conference, Mt. Crested Butte, CO. Proceedings edited by H. Torno. Published by ASCE, New York. pp. 641-650. 1995.

Clark, S. *Evaluation of Filtration Media for Stormwater Runoff Treatment*. MSCE thesis. Department of Civil and Environmental Engineering, University of Alabama at Birmingham. 442 pgs. 1996

Claytor, R. and T. Schueler. *Design of Stormwater Filtering Systems*. Center for Watershed Protection. Silver Spring, MD. 200 pgs. September 1996.

Conradin, F. “Zurich modifies collection system by building open brooks.” *Water Environment & Technology*. pp. 26 - 27. November 1995.

Day, G.E. “Investigation of concrete grid pavements.” In Proceedings - *National Conference on Urban Erosion and Sediment Control: Institutions and Technology*, EPA-905/9-80-002, U.S. Environmental Protection Agency, Chicago, Ill., January 1980.

Debo, T.N. and Ruby. “Detention ordinances -- Solving or causing problems?,” Proceedings: *Conference on Stormwater Detention Facilities, Planning, Design, Operation, and Maintenance*. Henniker, New Hampshire, Edited by W. DeGroot, published by the American Society of Civil Engineers, New York, August 1982.

Delporte, C. “Treating rainfall - enhancing discharges from urban areas using lamellar decantation.” Proceedings: *Urban Wet Weather Pollution: Controlling Sewer Overflows and Stormwater Runoff*. Quebec City, Quebec. June 16 - 19, 1996. Water Environment Federation, Alexandria, VA. Pp. 15-1 - 15-9. 1996.

Dewberry and Davis, Inc. *Investigation of Potential Sediment Toxicity from BMP Ponds*. Prepared for the Northern Virginia Planning District Commission, the Occoquan Policy Board, and the Virginia State Water Control Board. May 1990.

Diniz, E.V. *Porous Pavement; Phase I, Design and Operational Criteria*. EPA-600/2-80-135. U.S. Environmental Protection Agency, Cincinnati, Ohio, August 1980.

Diniz, E.V. “Hydrologic and water quality comparisons of runoff from porous and conventional pavements.” In: *Integrated Stormwater Management*. Edited by R. Field, M.L. O’Shea, and K.K. Chin. Lewis Publishers. Boca Raton. pp. 149 - 162. 1993.

Driscoll, E. D. “Detention and retention controls for urban stormwater.” Engineering Foundation Conference: *Urban Runoff Quality - Impact and Quality Enhancement Technology*. Henniker, New Hampshire, edited by B. Urbonas and L. A. Roesner. Pp. 145 - 163. Published by the American Society of Civil Engineers, New York, June 1986.

Driscoll, E. D. “Long term performance of water quality ponds.” Engineering Foundation Conference: *Design of Urban Runoff Quality Controls*. Potosi, Missouri. July 10 - 15, 1988. Edited by L. A. Roesner, B. Urbonas and

M.B. Sommen. Published by the American Society of Civil Engineers, New York, June 1989.
Driscoll, E.D. and E.W. Strecker "Assessment of BMP's being used in the U.S. and Canada." Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 945 - 950. 1993.
Droste, R.L. and J.C. Johnston. "Urban snow dump quality and pollutant reduction in snowmelt by sedimentation." *Canadian Journal of Civil Engineering*. Vol. 20, pp. 9-21. February 1993.
Duchene, M., E. McBean, and N. Thomson. "Infiltration characteristics associated with the use of trenches in stormwater management." Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 1115 - 1120. 1993.
Duru, J. O. "On-site detention: A stormwater management or mismanagement technique." *Second International Conference on Urban Storm Drainage*, Urbana, Illinois, June 1981.
Eccher. C.J. "Thoughtful design is prime factor in water safety." *Lake Line*. pp. 4-8. May 1991.
EDP (Environmental Design and Planning, Inc.). *Evaluation of Catchbasin Monitoring*. Contract No. R804578010, U.S. Environmental Protection Agency, Cincinnati, Ohio, March 1980.
Ellis, J.B. "Pollutional aspects of urban runoff." *Urban Runoff Pollution*, NATO ASI series, vol. G10, Springer Verlag, Berlin, pp. 1-38. 1986.
Ellis, J.B. "Wetland BMP design for urban runoff pollution control in Europe and Australia." Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 957 - 962. 1993.
Emmerling-DiNovo, C. "Stormwater detention basins and residential locational decisions." *Water Resources Bulletin*. Vol. 31, no. 3, pp. 515-521. June 1995.
EPA (U.S. Environmental Protection Agency). *Final Report for the Nationwide Urban Runoff Program*. Water Planning Division, Washington, D.C., December 1983.
EPA (U.S. Environmental Protection Agency). *Methodology for Analysis of Detention Basins for Control of Urban Runoff Quality*. Office of Water, NonPoint Source Division. Washington, D.C., September 1986.
EPA. *Urban Runoff Management Information/Education Products*. Developed for US EPA Region 5, Water Division, Wetlands and Watershed Section Watershed Management Unit and USEPA Office of Wastewater Enforcement and Compliance Permits Division, NPDES Program Branch, Stormwater Section, Version 1. 1993.
EPA. *Nonpoint Source News Notes*. Issue #46. Also available through http://www.epa.gov. August/September 1996.
Fair, G.M. and J.C. Geyer. *Water Supply and Waste Water Disposal*. John Wiley and Sons. New York. 1954.
Federal Register. 55 (No. 222; November 16), 48062. 1990.
Field, R. and R. Pitt. "Combined sewer overflow control through in-receiving water storage: an efficiency evaluation." *Water Environment Federation Specialty Conference on A Global Perspective for Reducing CSOs: Balancing Technologies, Costs, and Water Quality*. Louisville, KT. July 1994a.
Field, R. and R. Pitt. "Optimization of CSO storage and treatment systems." *Water Environment Federation Specialty Conference on A Global Perspective for Reducing CSOs: Balancing Technologies, Costs, and Water Quality*. Louisville, KT. July 1994b.
Field, R., R. Pitt, D. Jaeger, and M. Brown. "Combined sewer overflow control through in-receiving water storage: an efficiency evaluation." *Water Resources Bulletin*, the Journal of the American Water Resources Association. Vol. 30, No. 5. pp. 921-928. October 1994.
Field, R. M.P. Brown, W.V. Vilkelis. *Stormwater Pollution Abatement Technologies*. U.S. Environmental Protection Agency, Office of Research and Development. Cincinnati. OH. EPA/600/R-94/129. 1994.
Field, R., R. Pitt, M. Lalor, M. Brown, W. Vilkelis, and E. Thackston. "Investigation of dry-weather pollutant entries into storm-drainage systems." *J. Envir. Eng*. Vol. 120, No. 5, pp. 1044-1066. Sept./Oct. 1994.
Field, R., R. Pitt, M. Brown, and T. O'Conner. "Combined sewer overflow control using storage in seawater." *Water Research.* Elsevier Science. Vol. 29, No. 6, pp. 1505-1514. 1995.
Forndran, A., R. Field, K. Dunkers, and D. Moran. "Balancing flow for CSO abatement." *Water Environment & Technology*. pp. 54-58. May 1991.

Fourage, M. “Assessment of the efficiency of a prefabricated separator for stormwater treatment. Thoughts to and tests of materials to trap hydrocarbons.” (in French) *Unpublished DESS student report, Universities of Nancy and Metz*, September 1992.

Free, B. M. and G. G. Mulamoottil. “The limnology of Lake Wabukayne, A storm-water impoundment.”, *Water Resources Bulletin*, Vol. 19, no. 5, pg. 821, October 1983.

Fuhr, M. “Will your pond hold water?” *Land and Water*, Vol. 40, no. 6, pg. 38. Nov./Dec. 1996.

Fujita, S. “Infiltration in congested urban areas of Tokyo.” Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 993 - 998. 1993.

Fujita, S. “Infiltration structures in Tokyo.” *Water Science and Technology*. Vol. 30, no. 1, pp. 33 - 41. 1994.

Galli, John. *Peat-Sand Filters: A Proposed Stormwater Management Practice for Urbanized Areas.* Prepared for the Coordinated Anacostia Retrofit Program and Office Of Policy and Planning, D.C. Department of Public Works. December 1990.

Gburek, W.J. and J.B. Urban. “Storm water detention and groundwater recharge using porous asphalt - initial results.” *1983 International Symposium on Urban Hydrology, Hydraulics and Sediment Control*, University of Kentucky, Lexington, Kentucky, July 1983.

Geldof, G., P. Jacobsen, and S. Fujita. “Urban stormwater infiltration perspectives.” Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 963 - 968. 1993.

Geldof, G., P. Jacobsen, and S. Fujita. “Urban stormwater infiltration perspectives.” *Water Science and Technology*. Vol. 29, no. 1 - 2, pp. 245-254. 1994.

Gietz, R.J. *Urban Runoff Treatment in the Kennedy-Burnett Settling Pond*. For the Rideau River Stormwater Management Study, Pollution Control Division, Works Department, Regional Municipality of Ottawa-Carleton, Ottawa, Ontario, March 1983.

Goforth, G.F., E.V. Diniz, and J.B. Rauhut. *Stormwater Hydrological Characteristics of Porous and Conventional Paving Systems*. EPA-600/2-83-106, U.S. Environmental Protection Agency, Cincinnati, Ohio, February 1984 (also dated October 1983).

Green, M.B. and J.R. Martin. “Constructed reed beds clean up storm overflows on small wastewater treatment works.” *Water Environment Research*. Vol. 68, no. 6, pp. 1054 - 1060. Sept./Oct. 1996.

Grottker, M. “Pollutant removal by gully pots in different catchment areas.” *The Science of the Total Environment*. Vol. 93. pp. 515-522. 1990.

Hall, M.J. “The design of flood storage ponds: catering for both quality and quantity of runoff.” *Developments in Storm Drainage - A Symposium on Infiltration and Storage of Stormwater in New Developments*. Sheffield City. Jan. 1990. Pp. 21 - 33. 1990.

Harada, S. and A. Ichikawa. “A study on the performance of the drainage infiltration strata.” Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 1104 - 1109. 1993.

Harper, H.H. and J.L. Herr. “Alum treatment of stormwater - The first ten years: What have we learned and where do we go from here?” North American Lake Management Society (NALMS) Conference presentation. Minneapolis/St. Paul. October 1996.

Hawley, M. E., T. R. Bondelid, and R. H. McCuen. “A planning method for evaluating downstream effects of detention basins.” *Water Resources Bulletin*, Vol. 17. no. 5, pg. 806, October 1981.

Heinzmann, B. “Coagulation and flocculation of stormwater from a separated storm sewer - A new possibility for enhanced treatment.” *2nd International Conference on: Upgrading of Wastewater Treatment Plants*. Berlin. September 21 - 24, 1993. Sponsored by IAWQ and EWPCA. Pp. 304 - 313. 1993.

Herr, J.L. and H.H. Harper. “The evaluation and design of an alum stormwater treatment system to improve water quality in Lake Maggiore, St. Petersburg, Florida” North American Lake Management Society (NALMS) Conference presentation. Minneapolis/St. Paul. October 1996.

Herath, S. and K. Musiake. “Simulation of basin scale runoff reduction by infiltration systems.” *Water Science and Technology*. Vol. 29, no. 1 - 2, pp. 267 - 275. 1994.

Hey, D.L. and G.C. Schaefer. *An Evaluation of the Water Quality Effects of Detention Storage and Source Control*.

U.S. Environmental Protection Agency and the Northeastern Illinois Planning Commission, Chicago, August 1983.
Hvitved-Jacobsen, T., K. Keiding, and Y.A. Yousef. “Urban runoff pollution removal in wet detention ponds.” Proceedings of the 4th *International Conference on Urban Storm Drainage*. Lausanne, Switzerland. August 1987. Water Resources Publications. pp. 137 - 142. 1987.
Hvitved-Jacobsen, T., N.B. Johansen, and Y.A. Yousef. “Treatment systems for urban and highway runoff in Denmark.” In: the 4th International Symposium on Highway Pollution, Madrid, Spain. May 18-22, 1992. *The Science of the Total Environment*, 1992.
Hvitved-Jacobsen, T., N.B. Johansen, and Y.A. Yousef. “Treatment systems for urban and highway runoff in Denmark.” *The Science of the Total Environment*. No. 146/147, pp. 499-506. 1994.
Herricks, E.E., editor. *Stormwater Runoff and Receiving Systems: Impact, Monitoring, and Assessment*. Engineering Foundation and ASCE. CRC/Lewis. Boca Raton, FL. 1995.
Hogland, W., J. Niemczynowicz , and T. Wahlman. “The unit superstructure during the construction period.” *The Science of the Total Environment*, 1987, vol. 59, pp. 411-424. 1987.
Hogland, W. “Pervious asphalt construction - an overview of the situation in Sweden and the U.S.A.” *Developments in Storm Drainage - A Symposium on Infiltration and Storage of Stormwater in New Developments*. Sheffield City. Jan. 1990. Pp. 122 - 135. 1990.
Jackson, H.B. “Global needs and developments in urban sanitation.” *Proc. Int. Conf. On Low Cost Sewerage*. Univ.Leeds, UK, July 1995.
Jacobsen, P. and P.S. Mikkelsen. “Reduction of urban runoff pollutant loads using detention ponds and stormwater infiltration techniques.” *Proceedings of the 7th Conference of Urban Storm Drainage*. Hanover, Germany. Sept. 9-13, 1996.
Jones, J. E. and D. E. Jones. “Interfacing considerations in urban detention ponding.” Proceedings of the Conference: *Stormwater Detention Facilities, Planning, Design, Operation, and Maintenance*. Henniker, New Hampshire, Edited by W. DeGroot, published by the American Society of Civil Engineers, New York, August 1982.
Jones, J. “Beware the sediment scare.” *Civil Engineering*. pp. 56-57. July 1995.
Jones, J., S. Anderson, J. Fognani. F.R. McGregor, and T. Axley. “Stormwater best management practices: When is sediment considered hazardous?” *Water Environment & Technology*. Vol. 8, no. 10, pp. 51-57. October 1996.
Kamedulski, G. E. and R. H. McCuen. "The effect of maintenance on storm water detention basin efficiency.” *Water Resources Bulletin*, Vol. 15, no. 4, pg. 1146, August 1979.
Karunaratne, S.H.P.G. *The Influence of Gully Pot Performance on the Entry of Sediment into Sewers*. Ph.D. dissertation. South Bank University. London. 1992.
Kercher, W.C., J.C. Landon and R. Massarelli. “Grassy swales prove cost-effective for water pollution control”. *Public Works*, April 1983.
Kloiber, S.M. and P.L. Brewonik. “Effectiveness of continuous alum treatment for phosphorus removal from stormwater.” North American Lake Management Society (NALMS) Conference presentation. Minneapolis/St. Paul. October 1996.
Krejci, V., P. Haldimann, and M. Grottker. “Administrative aspects of stormwater infiltration in Switzerland.” Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 999 - 1004. 1993.
Kuo, C.Y., J.L. Zhu, and L.A. Dollard. *A Study of Infiltration Trenches*. VPI-VWRRC-BULL 163. 3.5C. Virginia Water Resources Research Center, Virginia Polytechnic Institute and State University. Blacksburg, VA. 87 pgs. 1989.
Lager, J.A., W.G. Smith, and G. Tchobanoglous. *Catchbasin Technology Overview and Assessment*. U.S. EPA. Contract No. 68-03-0274. EPA-600/2-77-051. 129 pages Cincinnati, May 1977.
Lager, J.A., W.G. Smith, W.G. Lynard, R.M. Finn, and E.J. Finnemore. *Urban Stormwater Management and Technology: Update and Users' Guide*. U.S. Environ. Protection Agency, EPA-600/8-77-014, 313 p. Cincinnati, Ohio, September 1977.
Lake Line “The Nutri-Pod: A new way.” pp. 2-19. February 1991.
Lake Tahoe Regional Planning Agency. *Lake Tahoe Basin Water Quality Management Plan, Volume II, Handbook of Best Management Practices*. Lake Tahoe, California, January 1978.

Lalor, M. M. *Assessment of Non-Stormwater Discharges to Storm Drainage Systems in Residential and Commercial Land-Use Areas*, Ph.D. thesis, Vanderbilt University, Nashville, Tennessee. 1993.

Land and Water "Storm pond turned into selling feature" Vol. 40, no. 6, pg. 35. Nov./Dec. 1996.

Laplace, D., A. Bachoc, Y. Sanchez, and D. Dartus. "Truck sewer clogging development - description and solutions." *Water Science and Technology*. Vol. 25, No. 8, pp. 91-100. 1992.

Legrand, J., H. Maillot, F. Nougarède, and S. Defontaine. "A device for stormwater treatment in the urban development zone of Annœullin." (in French) *TSM*, no 11, pp 639-643. 1994.

Legret, M., D. Demare, V. Colandini, J-D. Balades, and H. Madiec. "Behaviour of metallic pollutants in a pervious road construction." Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 1201 - 1206. 1993.

Lind, B.B. and E. Karro. "Stormwater infiltration and accumulation of heavy metals in roadside green areas in Goteborg, Sweden." *Ecological Engineering*. Vol. 5, no. 4, pp. 533-529. Dec. 1995.

Luzkow, S.M., D.A. Scherger, and J.A. Davis. "Effectiveness of two in-line urban stormwater best management practices (BMP's)." *1981 International Symposium on Urban Hydrology, Hydraulics, and Sediment Control,* University of Kentucky, Lexington, Kentucky, July 1981.

Magmedov, V.G., M.A. Zakharchenko, L.I. Yakovleva, and M.E. Ince. "Use of constructed wetlands for the treatment of runoff and drainage waters: the UK and Ukraine experience." *Water Science and Technology*. Vol. 33, no. 4 - 5, pp. 315-323. 1996.

Marcy, S. J. and J. E. Flack. "Safety considerations in urban storm drainage design." *Second International Conference on Urban Storm Drainage*. Urbana, Illinois, June 1981.

Marsalek, J., D. Weatherbe, and G. Zukovs. "Institutional aspects of stormwater detention." Proceedings of the Conference: *Stormwater Detention Facilities, Planning, Design, Operation, and Maintenance*. Henniker, New Hampshire, Edited by W. DeGroot, published by the American Society of Civil Engineers, New York, August 1982.

Martin, E. and R.A. Miller. "Efficiency of an urban stormwater detention system." Proceedings of the 4th *International Conference on Urban Storm Drainage*. Lausanne, Switzerland. August 1987. Water Resources Publications. pp. 143 - 148. 1987.

Martin, E.H. "Mixing and residence times of stormwater runoff in a detention system." Engineering Foundation Conference: *Design of Urban Runoff Quality Controls*. Potosi, Missouri. July 10 - 15, 1988. Edited by L. A. Roesner, B. Urbonas and M.B. Sommen. pp. 164 - 179. Published by the American Society of Civil Engineers, New York, June 1989.

Maxted, J. and E. Shaver. "The use of retention basins to mitigate stormwater impacts on aquatic life." Engineering Foundation Conference: *Effects of Watershed Development & Management on Aquatic Ecosystems*. Snowbird, Utah. August 4-9, 1996. To be published by the Engineering Foundation, New York, 1997.

Mayer, T., J. Marsalek, and E. Delos Reyes. "Nutrients and metal contaminants status of urban stormwater ponds." *Journal of Lake and Reservoir Management*. Vol. 12, no. 3, pp. 348-363. 1996.

McComas, S.R. and D.F. Sefton. "Comparison of stormwater runoff impacts on sedimentation and sediment trace metals for two urban impoundments." In: *Lake and Reservoir Management: Practical Applications*, proceedings of the Fourth Annual Conference and International Symposium, October, 1984, North American Lake Management Society, McAfee, New Jersey, 1985.

Metcalf & Eddy, Inc. *Wastewater Engineering: Treatment, Disposal, and Reuse*. McGraw-Hill Publishing Company, New York, New York. 1991.

Metcalf & Eddy Inc. *Handbook: Urban Runoff Pollution Prevention and Control Planning*. U.S. Environmental Protection Agency, Office of Research and Development. Cincinnati. OH. EPA/625/R-93/004. 1993.

Metropolitan Washington Council of Governments. *Analysis of Urban BMP Performance and Longevity*. Prince George's County, Department of Environmental Resources. 1992.

Mikkelsen, P.S., G. Weyer, C. Berry, Y. Walden, V. Colandini, S. Paulsen, D. Grotehusmann, and R. Rohlfing. "Pollution from urban stormwater infiltration." *Water Science and Technology*. Vol. 29, no. 1 - 2, pp. 293-302. 1994.

Montoya, B.l. *Urban Runoff Discharges From Sacramento, California*. CVRWQCB Report Number 87-1SPSS, prepared for the California Regional Water Quality Control Board, Central Valley Region. 1987.

Mugass, R.J. “Home lawn care practices to help protect surface water quality.” North American Lake Management Society (NALMS) Conference presentation. Minneapolis/St. Paul. October 1996.

Musiake, K., J. Okamura, and J. Matsushita. “The urban hydrological system with shallow infiltration facilities - a case study of an area in Tokyo Metropolis.” Proceedings of the 5th *International Conference on Urban Storm Drainage*. Osaka, Japan. July 1990. pp. 113 - 118. 1990.

Nawang, W.M. and S. Saad “Stormwater infiltration investigation using porous pavement” Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 1092 - 1097. 1993.

Newman, T.L., W.M. Leo, J.A. Muekker, and R. Gaffoglio. “Effectiveness of street cleaning for floatables control.” Proceedings: *Urban Wet Weather Pollution: Controlling Sewer Overflows and Stormwater Pollution*. June 16 - 19, 1996. Quebec City, Quebec. Water Environment Federation. Alexandria, VA. 1996.

Niemczynowicz, J. and W. Hogland. “Tests of porous pavement in Lund, Sweden.” Proceedings of the 4th *International Conference on Urban Storm Drainage*. Lausanne, Switzerland. August 1987. Water Resources Publications. pp. 79 - 80. 1987.

Niemczynowicz, J. “Swedish stormwater detention practices.” Proceedings of the 5th *International Conference on Urban Storm Drainage*. Osaka, Japan. July 1990. pp. 197 - 202. 1990.

Niemczynowicz, J. “New aspects of urban drainage and pollution reduction towards sustainability.” *Wat.Sci.Tech*. Vol.30, No.5, pp269-277. 1994.

Nix, S.J. and S.R. Durrans. “Off-line stormwater detention systems.” *Water Resources Bulletin*. Vol. 32, no. 6, pp. 1329 - 1340. December 1996.

NOVATECH. “International conference on new technologies for urban storm drainage.” (in French and English) *GRAIE/Eurydice 92 editors*, Lyon, 568 p. 1992.

NOVATECH. “2nd International conference on new technologies for urban storm drainage.” (in French and English) *GRAIE/Eurydice 92*, Lyon, 670 p. 1995.

Novotny, V., H.M. Sung, R. Bannerman, and K. Baum. “Estimating non-point pollution from small urban watersheds.” *Journal of Water Pollution Control Federation*, vol. 57, no 4, pp 339-348. 1985.

Oberts, G. “Design considerations for management of urban runoff in wintry conditions.” Proceedings: *International Conference on Urban Hydrology under Wintry Conditions*. March 19 - 21, 1990. Narvik, Norway. 1990.

Oberts, G. Performance of stormwater ponds and wetlands in winter.” Technical note 16. *Watershed Protection Techniques*. Vol. 1, no. 2, pp. 64-68. Summer 1994.

Oliver, L.J. and S.G. Grigoropoulis. “Control of storm-generated pollution using a small urban lake.” *Journal Water Pollution Control Federation*, Vol 53, No. 5, May 1981.

Ontario (Province of). *Urban Drainage Design Guidelines (Draft)*. Urban Drainage Policy Implementation Committee, Technical Sub-Committee No. 3. March 1984.

Payne, J. and A. Davies. “Manual on infiltration methods for stormwater source control.” Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 981 - 986. 1993.

Perkins, M. A. “Managing aquatic plants with fiberglass screens.” In: *Restoration of Lakes and Inland Waters.* Proceedings of the International Symposium on Inland Waters and Lake Restoration, Portland, Maine, September 1980, published by the U.S. Environmental Protection Agency, Washington. D.C., December 1980.

Petersen, C.R., T. Faarbaek, G.H. Jensen, G. Weyer, S. Fujita, K. Ishikawa, G. Geldof, C. Stenmark, and C.J. Pratt. “Urban stormwater infiltration design practice and technology: state of the art assessment.” Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 969 - 974. 1993.

Pisano, W.C. and H. Brombach. “Solids settling curves: Wastewater solids data can aid design of urban runoff controls.” *Water Environment & Technology*. Vol. 8, no. 4, pp. 27-33. April 1996.

Pitt, R., J. Ugelow, and J.D. Sartor. *Systems Analysis of Street Cleaning Techniques*. Prepared for the American Public Works Association and the National Science Foundation, RANN Program, Washington, D.C., March 1976.

Pitt, R. *Demonstration of Nonpoint Pollution Abatement Through Improved Street Cleaning Practices*. U.S. EPA. Grant No. S-804432. EPA-600/2-79-161. 270 pages. Cincinnati, August 1979.

Pitt, R. and M. Bozeman. *Lake Merritt Management Plan*. City of Oakland Department of Public Works, Oakland, California, May 1979.

Pitt, R. and G. Shawley. *A Demonstration of Non-Point Source Pollution Management on Castro Valley Creek.* Alameda County Flood Control and Water Conservation District (Hayward, CA) for the Nationwide Urban Runoff Program, U.S. Environmental Protection Agency, Water Planning Division, Washington, D.C., June 1982.

Pitt, R. and R. Sutherland. *Washoe County Urban Stormwater Management Program; Volume 2, Street Particulate Data Collection and Analyses*. Washoe Council of Governments, Reno, Nevada, August 1982.

Pitt, R. *Characterizing and Controlling Urban Runoff through Street and Sewerage Cleaning*. U.S. EPA. Contract No. R-805929012. EPA/2-85/038. PB 85-186500/AS. 467 pages. Cincinnati, June 1985.

Pitt, R. and J. McLean. *Toronto Area Watershed Management Strategy Study - Humber River Pilot Watershed Project*. Ontario Ministry of the Environment, Toronto, Ontario, June 1986.

Pitt, R. *Small Storm Urban Flow and Particulate Washoff Contributions to Outfall Discharges*. Ph.D. dissertation. Dept. of Civil and Environmental Engineering, the University of Wisconsin, Madison, Wisconsin. Listed in Dissertation Abstracts International, University Microfilms International, Vol. 49, No. 1, 1988. November 1987.

Pitt, R. and J. Voorhees. *DETPOND 4: A Water Quality Detention Pond Design Program; Model Documentation and Users Manual*. Wisconsin Department of Natural Resources, May 1989.

Pitt, R. and K. Dunkers. "Combined treatment of stormwater and lakewater in Lake Rönningesjön, Sweden." *12th Annual International Symposium, North American Lake Management Society*, Cincinnati, Ohio, November 1992.

Pitt, R. "Detention pond design for water quality improvement." *National ASCE Hydraulic Conference*. San Francisco, California. July 1993a.

Pitt, R. "The stormwater quality detention pond model (DETPOND)." *26th Annual Water Resources Conference*. University of Minnesota. October 1993b.

Pitt, R. and K. Dunkers. "Lake water quality improvements from treatment of stormwater using the Flow Balancing Method." *66th Annual Water Environment Federation Conference*. Anaheim, California. October 1993.

Pitt, R. E., Field, R. I., Lalor, M. M., Adrian, D. D., Barbe', D.. *Investigation of Inappropriate Pollutant Entries into Storm Drainage Systems: A User's Guide.* Rep. No. EPA/600/R-92/238, NTIS Rep. No. PB93-131472/AS, US EPA, Storm and Combined Sewer Pollution Control Program (Edison, New Jersey), Risk Reduction Engineering Lab., Cincinnati, Ohio. 1993

Pitt, R. "Water quality trends from stormwater controls." In: *Stormwater NPDES Related Monitoring Needs* (Edited by H.C. Torno). Engineering Foundation and ASCE. pp. 413-434. 1995a.

Pitt, R. "Preliminary investigation of EquaFlow™ system for Town Lake, Austin, TX." Unpublished report prepared for Loomis and Associates and the City of Austin, TX, October 1995b.

Pitt, R. *Groundwater Contamination from Stormwater*. ISBN 1-57504-015-8. Ann Arbor Press, Inc. Chelsea, Michigan. 219 pages. 1996.

Pitt, R., R. Field, M. Lalor, and M. Brown. "Urban stormwater toxic pollutants: assessment, sources and treatability." *Water Environment Research*. Vol. 67, No. 3, pp. 260-275. May/June 1995. Discussion and closure in Vol. 68, No. 4, pp. 953-955. July/August 1996.

Pitt, R. E. and Lalor, M. M. *Final Draft Report: Demonstration Project for the Investigation of Inappropriate Pollutant Entries into Storm Drainage Systems*. Contract No.68-C9-0033, U.S. Environmental Protection Agency, Risk Reduction Engineering Lab., Cincinnati, Ohio. To be published in 1997.

Pitt, R. "The control of toxicants at critical source areas." In: *Effects of Watershed Development and Management on Aquatic Ecosystems*. Engineering Foundation Conference: *Effects of Watershed Development & Management on Aquatic Ecosystems*. Snowbird, Utah. August 4-9, 1996. To be published in 1997.

Pitt, R., R. Field, and K. Gordon. *An Evaluation of Storm Drainage Inlet Devices for Stormwater Quality Treatment*. Cooperative agreement CR 819573. U.S. Environmental Protection Agency, Risk Reduction Engineering Lab., Cincinnati, Ohio. To be published in 1997.

Poertner, H.G. *Practices in Detention of Urban Stormwater Runoff*. American Public Works Association, OWRR Contract No. 14-31-0001-3722, Chicago, 1974.

Poertner, H.G. *Stormwater Management in the United States*. Office of Water Research and Technology. Dept. of the Interior. Project No. C-5239. September 1980.

Pratt, C.J., G.E.P. Elliott, and G.A. Fulcher. "Suspended solids discharge from highway gully pots in a residential catchment." *The Science of the Total Environment*. Vol. 59. pp. 355-364. 1987.

Pratt, C.J., J.D.G. Mantle, and P.A. Schoffield. "Urban stormwater reduction and quality improvement through the use of permeable pavements." *Urban Discharges and Receiving Water Quality Impacts*. Pergamon Press, Oxford, 1989, pp. 123-132. 1989.

Pratt, C.J. "Permeable pavements; design and maintenance" *Developments in Storm Drainage - A Symposium on Infiltration and Storage of Stormwater in New Developments*. Sheffield City. Jan. 1990. Pp. 136 - 151. 1990.

Pratt, C.J. "An assessment of effectiveness of a BMP strategy in urban drainage in the U.K." Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 951 - 956. 1993.

Pratt, C.J. and J.J.M. Powell. "A new UK approach for the design of sub-surface infiltration systems." Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 987 - 992. 1993.

Pratt, C.J., J.D.G. Mantle, and P.A. Schoffield. "UK research into the performance of permeable pavement, reservoir structures in controlling stormwater discharge quantity and quality." *International Conference NOVATECH 95*, Lyon, pp. 337-344. 1995.

Pratt, C.J. "Research and development in methods of soakaway design." *Journal of the Chartered Institution of Water and Environmental Management*. Vol. 10, no. 1, pp. 47-51. Feb. 1996.

Ranchet, J., F. Penaud, R. Le Grand, A. Constant, P. Obry, and B. Soudieu. (1993). "Comparison of an impervious pavement and a porous pavement from hydraulic and stormwater pollutant removal points of view." (in French) *Bulletin de Liaison des Laboratoires des Ponts et Chaussées*, no 188 November/December 1993.

Roberts, B. "Storm-water treatment goes underground." *Civil Engineering*. pp. 56-57. July 1996.

Robertson, B., R. Pitt, A. Ayyoubi, and R. Field. "A multi-chambered stormwater treatment train." In: *Stormwater NPDES Related Monitoring Needs* (Edited by H.C. Torno). Engineering Foundation and ASCE. pp. 631-640. 1995.

Roesner, L.A., B.R. Urbonas and M.B. Sonnen, editors. *Design of Urban Runoff Quality Controls*. Proceedings of an Engineering Foundation Conference on Current Practice and Design Criteria for Urban Quality Control, American Society of Civil Engineers, NY. 1989.

Rosted Petersen, C.O., P. Jacobsen, P.S. Mikkelsen. "Design of stormwater infiltration for reduction of combined sewer overflow (CSO)." *Water Science and Technology*, Vol. 30, no. 1, pp. 53-61. 1994.

Rubin, Alan J. and D.L. Mercer. "Adsorption of free and complexed metals from solution by activated carbon." In: *Adsorption of Inorganics at Solid-Liquid Interfaces*. Edited by Marc A. Anderson and Alan J. Rubin. Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan, 1981. pp. 295-326.

Rupperd, Y. "A lamellar separator for urban street runoff treatment." (in French) *Bulletin de Liaison des Laboratoires des Ponts et Chaussées*, no 183, pp 85-90.1993.

Salvato, J.A. *Environmental Engineering and Sanitation*. 4th Ed. John Wiley & Sons. NY. 1992.

Sartor, J. and G. Boyd. *Water Pollution Aspects of Street Surface Contaminants*. U.S. EPA. Contract No. 14-12-921. EPA-R2-72-081. 236 pages. Washington, D.C., November 1972.

Sartor, J.D., G.B. Boyd, and F.J. Agardy. "Water pollution aspects of street surface contaminants." *Journal of Water Pollution Control Federation*, vol. 46, no 3, pp 458-467. 1974.

Schmitt, T.G. "Integrated storm water management in urban areas." *European Water Pollution Control*. Vol. 6, no. 3, pp. 14 - 20. May 1996.

Schimmenti, F.G. "Stormwater detention basins must control more than runoff." *American City and County*. December 1980.

Schumacher, J.W. and R.F. Grimes. "A model public education process for stormwater management." *Public Works*. Vol. 123. pp. 55 - 58. September 1992.

Schueler. T. *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban Best Management Practices*. Metropolitan Washington Council of Governments. 280 pgs. 1987.

Schueler, T.R. and J. Galli. "The environmental impact of stormwater ponds." Engineering Foundation Conference: *Urban Runoff and Receiving Systems: An Interdisciplinary Analysis of Impact, Monitoring, and Management*. Mt. Crested Butte, Colorado. August 4-9, 1991. Published by the American Society of Civil Engineers, New York,

June 1992.
Schueler, T. (editor). “Hydrocarbon hotspots in the urban landscape: can they be controlled?” *Watershed Protection Techniques*. Vol. 1, No. 1, pp. 3 - 5. Feb. 1994.
Schueler, T. (editor). “Vegetated rock filter treats stormwater pollutants in Florida” *Watershed Protection Techniques*. Vol. 2, No. 2, pp. 372 - 374. Spring 1996.
Schueler, T. (editor). “Ditches or biological filters? Classifying the pollutant removal performance of open channels” *Watershed Protection Techniques*. Vol. 2, No. 2, pp. 379 - 383. Spring 1996.
SEMCOG (Southeast Michigan Council of Governments). *Detention Basin Maintenance, Program Needs and Financing Options*. Technical Bulletin No. 3, Detroit, Michigan, May 1981.
Shaver, Earl. *Use of Sand Filters as an Urban Stormwater Management Practice*. State of Delaware Department of Natural Resources and Environmental Control.
Smith, W.G. “Water quality enhancement through stormwater detention.” *Proceedings of the Conference on Stormwater Detention Facilities, Planning, Design, Operation, and Maintenance*, Henniker, New Hampshire, Edited by W. DeGroot, published by the American Society of Civil Engineers, New York, August 1982.
Stahre, P. “Assessment of BMP’s being used in Scandinavia.” Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 939 - 944. 1993.
Stahre, P. and B. Urbonas. *Stormwater Detention for Drainage, Water Quality and CSO Management*. Prenticd Hall. Englewood Cliffs. 340 pgs. 1990.
Stanley, D.W. “Pollutant removal by a stormwater dry detention pond.” *Water Environment Research*. Vol. 68, no. 6, pp. 1076 - 1083. Sept./Oct. 1996.
Stenmark, C. “Local infiltration of urban storm water in cold climate.” Proceedings of the 5*th International Conference on Urban Storm Drainage*. Osaka, Japan. July 1990. pp. 809 - 814. 1990.
Stenmark, C. “An alternative road construction for stormwater management in cold climates.” *Water Science & Technology*. Vol. 32, no. 1, pp. 79 - 84. 1995.
Sutherland, R.C. and S.L. Jelen. “Sophisticated stormwater quality modeling is worth the effort.” In: *Advances in Modeling the Management of Stormwater Impacts*. Edited by W. James. Computational Hydraulics International. Guelph, Ontario. 1996.
Sutherland, R.C. “Studies show sweeping has beneficial impact on stormwater quality.” *APWA Reporter*. pp. 8 - 23. 1996.
Swaffield, J.A. and L.S. Gallowin. *The Engineered Design of Building Drainage Systems*. Ashgate publishing, Aldershot. 1992.
Sztruhar, D. and H.S. Wheater. “Experimental and numerical study of stormwater infiltration through pervious parking lots.” Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 1098 - 1103. 1993.
Tenney, S., M.E. Barrett, J.F. Malina, R.J. Charbeneau, and G.H. Ward. *An Evaluation of Highway Runoff Filtration Systems*. Center for Research in Water Resources. Technical Report CRWR 265. The University of Texas at Austin. 133 pgs. September 1995.
Terstriep, M.L., G.M. Bender, and D.C. Noel. *Final Report - NURP Project, Champaign, Illinois: Evaluation of the Effectiveness of Municipal Street Sweeping in the Control of Urban Storm Runoff Pollution*. State Water Survey Division, Illinois Dept. of Energy and Natural Resources, Champaign-Urbana, Illinois, December 1982.
Thompson, M.K. and W. James. “Provision of parking lot pavements for surface water pollution control studies.” *Modern Methods for Modeling the Management of Stormwater Impacts*. Edited by W. James. Computational Hydraulics International, Guelph, Ontario. pp. 381 - 398. 1995.
Tyson, J.M. “Quo Vadis - sustainability?” *Water Science and Technology* Vol.32, No. 5-6, pp1-5. 1995.
Urbonas, B. and P. Stahre. *Stormwater: Best Management Practices and Detention*. Prentice Hall, Englewood Cliffs, NJ. 1993.
Valiron, F. “Usual techniques for stormwater pollutant removal in urban areas.” (in French) *Provisory report for the Seine-Normandie Water Agency*, February 1992, 61 p. 1992.
Van Buren, M.A., W.E. Watt, and J. Marsalek. “Enhancing the removal of pollutants by an on-stream pond.” *Water Science and Technology*. Vol. 33, no. 4 - 5, pp. 325-332. 1996.

Vignoles M., and L. Herremans. "Street cleaning: an alternative to stormwater treatment?" (in French). *NOVATECH International Conference*, Lyon, 1992, pp 272-283. 1992.

Vignoles M., and L. Herremans. "Metal pollution of sediments contained in runoff water in the Toulouse city." (in French). *NOVATECH 95, 2nd International Conference on Innovative Technologies in Urban Storm Drainage*. May 30 - June 1, 1995. Lyon, France. pp. 611-614. Organized by Eurydice 92 and Graie. 1995.

Vignoles, M. and L. Herremans. "Motorway pollution: total suspended solids in runoff water and settling tank design approach." *69th Annual Water Environment Federation Technical Exposition and Conference (WEFTEC)*. Dallas, TX. Water Environment Federation, Alexandria, VA. Vol. 4, parts I and II. Pp. 167-176. 1996.

Virginia Soil and Water Conservation Commission. *Virginia Erosion and Sediment Control Handbook*. 1980.

W&H Pacific (now Stormwater Management). *Compost Storm Water Filter (CSF): Answers to Typical Questions*. Stormwater Management, Portland, Oregon. 1992.

W&H Pacific (now Stormwater Management). *Compost Storm Water Treatment System: Executive Summary*. Stormwater Management, Portland, Oregon. 1992.

W&H Pacific (now Stormwater Management). *Methods and Results Summary: Compost Storm Water Filter System*. Stormwater Management, Portland, Oregon. 1992.

Wada, Y. and H. Miura "Effect and evaluation of storm runoff control by permeable combined infiltration facilities for controlling storm runoff." Proceedings of the 5th *International Conference on Urban Storm Drainage*. Osaka, Japan. July 1990. pp. 789 - 794. 1990.

Wada, Y. and H. Miura "Prediction and estimation of stormwater runoff control by the combined stormwater infiltration facilities with simulation model." In: *Integrated Stormwater Management*. Edited by R. Field, M.L. O'Shea, and K.K. Chin. Lewis Publishers. Boca Raton. pp. 337 - 353. 1993.

Wang, T.S., D.E. Spyridakis, B.W. Mar, and R.R. Horner. *Transport Deposition and Control of Heavy Metals in Highway Runoff*. WA-RD-39.10, U.S. Dept. of Transportation and Washington State Department of Transportation, Seattle, January 1980.

Water Environment & Technology. "Illinois turns to communities for grassroots watershed work." pg. 19. March 1996.

Whipple, W., Jr. And J.V. Hunter. "Settleability of urban runoff pollution." *Water Pollution Control Federation Journal*. Vol. 53, no. 12. pp. 1726-1731. Dec. 1981.

Wiegand, C., T. Schueler, W. Chittenden, and D. Jellick. "Comparative costs and cost effectiveness of urban best management practices." Engineering Foundation Conference: *Urban Runoff Quality - Impact and Quality Enhancement Technology*. Henniker, New Hampshire, edited by B. Urbonas and L. A. Roesner, published by the American Society of Civil Engineers, New York, June 1986.

Wigington, P. J., C. W. Randall, and T. J. Grizzard. "Accumulation of selected trace metals in soils of urban runoff detention basins." *Water Resources Bulletin*, Vol. 19, no. 5, pg. 709, October 1983.

Willett, Gerald. Urban Erosion, in *National Conference on Urban Erosion and Sediment Control; Institutions and Technology*. EPA 905/9-80-002. U.S. Environmental Protection Agency, 1980.

Williams, L.H. "Effectiveness of stormwater detention." *Proceedings of the Conference on Stormwater Detention Facilities, Planning, Design, Operation, and Maintenance*, Henniker, New Hampshire, Edited by W. DeGroot, published by the American Society of Civil Engineers, New York, August 1982.

Wind, S. "Three years after - failure or success." *Land and Water*, Vol. 40, no. 6, pg. 37. Nov./Dec. 1996.

Yamada, K. "Infiltration pitch for individual houses to mitigate storm water impact." Proceedings of the *6th International Conference on Urban Storm Drainage*. Edited by J. Marsalek and H.C. Torno. Niagara Falls, Ontario. September 12 - 17, 1993. IAWQ, London. Published by Seapoint Publishers, Victoria, B.C. pp. 1110 - 1114. 1993.

Yousef, Y.A., M.P. Wanielista, and H.H. Harper. "Design and effectiveness of urban retention basins." *Engineering Foundation Conference: Urban Runoff Quality - Impact and Quality Enhancement Technology*, Henniker, New Hampshire, edited by B. Urbonas and L. A. Roesner, published by the American Society of Civil Engineers, New York, June 1986.

Yousef, Y.A. and L.Y. Lin. "Toxicity of bottom sediments in detention ponds." *Environmental Engineering: Proceedings of the 1990 Specialty Conference*. pp. 809 - 816. American Society of Civil Engineering, New York. 1990.

Yu, S.L., S-L. Liao, G.M. Fitch, and S. Long. "Constructed wetlands for stormwater management." *69th Annual Water Environment Federation Technical Exposition and Conference (WEFTEC)*. Dallas, TX. Water Environment Federation, Alexandria, VA. Vol. 7, parts I, II, and III. pp. 167-178. 1996.

Yu, S.L., M.A. Kasnick, and M.R. Byearne. "A level spreader/vegetative buffer strip system for urban stormwater management." In: *Integrated Stormwater Management*. Edited by R. Field, M.L. O'Shea, and K.K. Chin. Lewis Publishers. Boca Raton. pp. 93 - 103. 1993.

Appendix E
SLAMM Source Code

Attribute VB_Name = "CalcMainModule"

```
Option Explicit

Private mDumm$
Private fDum As Long
Private fDummy As Variant
Private fBlank$
Private fDrainType As Variant
Private Oth$
Private A As Integer
Private fColumn As Integer
Private DTStart As Integer
Private WashPartFrac As Single

Private MyDate$
Private gTimeStep$

Private ColNum As Integer
Private fDATFOPT As Integer
Private pStreetRound As Integer   'used when recalculating street dirt stored due in delivery system
  '  Round 1 == initial street dirt loadings
  '  Round 2 == recalculate street dirt loadings using variable StDirtStored
  '  DOS == STROUND
Private pLUCurbRatio(15) As Single


Private mRv(9, 17) As Single   '  R sub v value from Runoff Coefficient Parameter File, DOS == Rv()
Private mRainAr(17) As Single   '  Rainfall Array values from Runoff Coef. parameter file, DOS ==
RainAr()
Private mDEC(12, 17) As Single  ' Drainage Efficiency Coefficient, DOS == DEC()
Private mRSubVRow() As Single  ' Runoff Coefficent Row from Run. Coeff Parameter file, DOS ==
RVROW
Private mDrainEffRow() As Single  ' Drainage Effic. Coefficent Row from Run. Coeff Parameter file, DOS
== DECROW
Private mPartSolRow() As Single   ' Particulate solids Row from PSC parameter file, DOS ==

Private mTSC(66, 14) As Single ' Total Solids Concentration values from Particulate Solids Conc.
Parameter file, DOS == TSC()
Private mPRRFrac(5, 14) As Single ' Particulate Residue Reduction due to delivery value, from PRR
Parameter file, DOS == PRRFrac()

Dim FROMCALC As String     'Type of calc module being processed - land uses or outfall    DOS ==
FROMCALC$

Dim mInfilVolRed As Single
Dim mOtherVolRed As Single
Dim mOtherTSSRed As Single


Public Function funWordWrap(OldString) As String
   ' JM7/20/97-A
   ' Substitute vbCrLf characters for the blank spaces within the string argument.  This
   ' will allow the string to wrap to multiple lines within a Spread cell, provided the
```

```
    ' cell .TypeEditMultiLine = True.        vbCrLf = Chr$(13) & Chr$(10)
    Dim i As Integer

    funWordWrap = Trim$(OldString)

    For i = 1 To Len(funWordWrap)
       If Mid$(funWordWrap, i, 1) = " " Then
          Mid$(funWordWrap, i, 1) = vbCrLf
       End If
    Next i

End Function


Private Sub proOtherTSSRed(s As Integer, mOtherTSSRed As Single)

    Dim AOth As Single
    Dim BOth As Single

    AOth = gOtherConcRed(gSAArNum(s))
    BOth = gOtherAServed(gSAArNum(s)) / gTSArea(gSAArNum(s))
    mOtherTSSRed = AOth * BOth

End Sub

Public Sub proRunoffCalc()

'    Dim StreetE As Integer     'defines consecutive street source area number, DOS == EE
    Dim s As Integer  ' defines consecutive source area number, DOS == S
    Dim A As Integer  ' defines rain number, DOS == A
    Dim InitRunVol As Single   '  defines Initial Runoff Volume, DOS == RUNVOLI
    Dim TtlPCVolRed As Single  ' Total Percent Volume Reduction, DOS == TOTPCVRED
    Dim RSubv As Single
    Dim PPVolRed As Single

'  Runoff Volume Calculation proceedure
    E = 0
    gPondLUNum(gNumAreas - 1) = 10
    gPondLUNum(gNumAreas) = 11
    For s = 1 To gNumAreas - 2
       If gTSArea(gSAArNum(s)) > 0 Then 'GoTo 6120
          ''For A = 1 To gNumRains
          For A = gFirstRainNum To gLastRainNum     ' JM7/22/97
             If gRainDur(A) > 0 Then '  GoTo 6060
                   Call proCalcRSubv(A, s, RSubv)    'GoSub 7140: Rem    calc Rsubv
                   If RSubv > 0 Then    'GoTo 6060
                      InitRunVol = RSubv * gRain(A) * gTSArea(gSAArNum(s)) * 43560! / 12
                      PPVolRed = 0
                      mInfilVolRed = 0
                      mOtherVolRed = 0
                      If gP$(gSAArNum(s)) = "P" Then Call proPorPavVolRed(s, A, PPVolRed)     '  gosub
7700
                      If gI$(gSAArNum(s)) = "I" Then Call proInfilVolRed(s, A, RSubv, mInfilVolRed)   'GoSub
7840
```

```
                  If gOth$(gSAArNum(s)) = "O" Then Call proOtherVolRed(s, mOtherVolRed)   'GoSub
7980
                  TtlPCVolRed = 1 - ((1 - PPVolRed) * (1 - mInfilVolRed) * (1 - mOtherVolRed))
                  gRunoffVol(A, s) = InitRunVol * (1 - TtlPCVolRed)
                  Rem WRITE #10, A, S, gPondLUNum(S), gRain(A)
                End If
            End If
          Next A   '6060
'       DPE = 0
        End If
    Next s   '6120

End Sub

Private Sub proPorPavVolRed(s As Integer, A As Integer, PPVolRed As Single)

    Dim APav As Single
    Dim BPav As Single
    'Dim PPVolRed As Single   ' Porous Pavement Volume Reduction, DOS == PVOLRED

    APav = gPorPavPercRate(gSAArNum(s)) * gRainDur(A) * 24 / gRain(A)
    '   APav == [in/hr] * [days] * 24 hrs/day * [1/in] == [unitless fraction]
    If APav > 1 Then APav = 1
    BPav = gPorPavArea(gSAArNum(s)) / gTSArea(gSAArNum(s))
    '   BPav == [ac] / [ac] == [unitless fraction]
    PPVolRed = APav * BPav

End Sub

Private Sub proOtherVolRed(s As Integer, mOtherVolRed As Single)

    Dim AOth As Single
    Dim BOth As Single

    AOth = gOtherVolRed(gSAArNum(s))
    BOth = gOtherAServed(gSAArNum(s)) / gTSArea(gSAArNum(s))
    mOtherVolRed = AOth * BOth

End Sub

Private Sub proInfilVolRed(s As Integer, A As Integer, RSubv As Single, mInfilVolRed As Single)

    Dim AInf As Single
    Dim BInf As Single
    'Dim InfilVolRed As Single  'Infiltration volume reduction, DOS == IVOLRED

    AInf = (1 + 0.67 / gIDWToD(gSAArNum(s))) * gIDPRate(gSAArNum(s)) * gIDArea(gSAArNum(s)) *
(0.00002296) * _
              (0.9 + 0.98 * 24 * gRainDur(A)) / (RSubv * gRain(A) * gIDAServ(gSAArNum(s)))
    If AInf > 1 Then AInf = 1
    BInf = gIDAServ(gSAArNum(s)) / gTSArea(gSAArNum(s))
    mInfilVolRed = AInf * BInf

End Sub
```

```
Private Sub proDimensionMainVariables()

'    ReDim gEventTtlPartSolConc(gFirstRainNum To gLastRainNum)
   'ReDim gRunoffVol(gNumRains, gNumAreas)
   ReDim gRunoffVol(gFirstRainNum To gLastRainNum, gNumAreas)  ' JM7/20/97-B
   ReDim gPercentCBVolFull(gFirstRainNum To gLastRainNum)
   ReDim gPartSolConc(gFirstRainNum To gLastRainNum, gNumAreas)
   ReDim gPartSolYield(gFirstRainNum To gLastRainNum, gNumAreas)
   ReDim gTtlSolAccum(gFirstRainNum To gLastRainNum)
   ReDim mRSubVRow(gNumAreas)
   ReDim mDrainEffRow(gNumAreas)
   ReDim mPartSolRow(gNumAreas)
   ReDim gWeightedTtlSolRed162(gFirstRainNum To gLastRainNum)
   ReDim gDPVolRed162(gFirstRainNum To gLastRainNum)
   ReDim gStDirtStored(gFirstRainNum - 1 To gLastRainNum, gNumAreas)
   ReDim gEventTtlPartLoad(gFirstRainNum To gLastRainNum)
   ReDim gEventTtlPartConc(gFirstRainNum To gLastRainNum)
   ReDim gModelRunTotal(2)

End Sub

Private Sub proInitSARSubVRows()
   Dim s As Integer   ' Consecutive source area numbers.

   For s = 1 To gNumAreas - 2
      gPondLUNumber = gPondLUNum(s)
      If gTSArea(gSAArNum(s)) = 0 Then GoTo 3560
      If gSAName(gSAArNum(s)) >= 1 And gSAName(gSAArNum(s)) <= 5 And gSAArNum(s) < 151 Then
         GoSub 3620     ' A
      End If
      If (gSAName(gSAArNum(s)) >= 6 And gSAName(gSAArNum(s)) <= 8) Or _
        (gSAName(gSAArNum(s)) >= 11 And gSAName(gSAArNum(s)) <= 17) Then
         GoSub 3920     ' B
      End If
      If gSAName(gSAArNum(s)) = 9 Or gSAName(gSAArNum(s)) = 10 Then
         GoSub 4140     ' C
      End If
      If (gSAName(gSAArNum(s)) >= 21 And gSAName(gSAArNum(s)) <= 26) Or
gSAName(gSAArNum(s)) = 28 Or _
        (gSAArNum(s) >= 156 And gSAArNum(s) <= 158) Then
         GoSub 4360      ' D
      End If
      If gSAName(gSAArNum(s)) = 29 Or gSAArNum(s) = 159 Then
         mRSubVRow(s) = 3
      End If
      If gSAName(gSAArNum(s)) = 30 Or gSAArNum(s) = 160 Then
         GoSub 4440      ' E
      End If
      If gSAArNum(s) >= 151 And gSAArNum(s) <= 155 Then
         GoSub 4640      ' F
      End If
      If gSAName(gSAArNum(s)) >= 18 And gSAName(gSAArNum(s)) <= 20 Then
```

```
      GoSub 4780 '      ' gPondLUNumber
    End If
3560   Rem LPRINT
gsaarnum(s)(S),gPondLUNumber,gSAName(gsaarnum(s)),gRoof(gsaarnum(s)),gTypeSA(gsaarnum(s)),
DIRT(S),gDensity(gsaarnum(s)),gAlley(gsaarnum(s)),mRSubVRow(S),mDrainEffRow(S)
  Next s

  Exit Sub

3620 Rem   A
  If gRoof(gSAArNum(s)) = 1 And gTypeSA(gSAArNum(s)) = 1 Then
    mRSubVRow(s) = 1
  ElseIf gRoof(gSAArNum(s)) = 2 And gTypeSA(gSAArNum(s)) = 1 Then
    mRSubVRow(s) = 2
  ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 1 Then
    mRSubVRow(s) = 5
  ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 And _
   (gPondLUNumber = 1 Or gPondLUNumber = 2 Or gPondLUNumber = 4 Or gPondLUNumber = 6)
And _
   gDensity(gSAArNum(s)) = 1 Then
    mRSubVRow(s) = 6
  ElseIf gRoof(gSAArNum(s)) = 1 And gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 _
   And (gPondLUNumber = 1 Or gPondLUNumber = 2 Or gPondLUNumber = 4 Or gPondLUNumber =
6) _
   And gDensity(gSAArNum(s)) = 2 And gAlley(gSAArNum(s)) = 1 Then
    mRSubVRow(s) = 1: mDrainEffRow(s) = 11
  ElseIf gRoof(gSAArNum(s)) = 2 And gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 _
   And (gPondLUNumber = 1 Or gPondLUNumber = 2 Or gPondLUNumber = 4 Or gPondLUNumber =
6) _
   And gDensity(gSAArNum(s)) = 2 And gAlley(gSAArNum(s)) = 1 Then
    mRSubVRow(s) = 2: mDrainEffRow(s) = 11
  ElseIf gRoof(gSAArNum(s)) = 1 And gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 _
   And (gPondLUNumber = 1 Or gPondLUNumber = 2 Or gPondLUNumber = 4 Or gPondLUNumber =
6) _
  And gDensity(gSAArNum(s)) = 2 And gAlley(gSAArNum(s)) = 2 Then
    mRSubVRow(s) = 1: mDrainEffRow(s) = 10
  ElseIf gRoof(gSAArNum(s)) = 2 And gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 _
   And (gPondLUNumber = 1 Or gPondLUNumber = 2 Or gPondLUNumber = 4 Or gPondLUNumber =
6) _
   And gDensity(gSAArNum(s)) = 2 And gAlley(gSAArNum(s)) = 2 Then
    mRSubVRow(s) = 2: mDrainEffRow(s) = 10
  ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 And gPondLUNumber = 5 Then
    mRSubVRow(s) = 6
  ElseIf gRoof(gSAArNum(s)) = 1 And gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 _
   And gPondLUNumber = 3 Then
    mRSubVRow(s) = 1
    mDrainEffRow(s) = 12
  ElseIf gRoof(gSAArNum(s)) = 2 And gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 _
   And gPondLUNumber = 3 Then
    mRSubVRow(s) = 2
    mDrainEffRow(s) = 12
  End If
  Return
```

```
3920 Rem    B
    If gTypeSA(gSAArNum(s)) = 1 Then
      mRSubVRow(s) = 3
    ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 1 Then
       mRSubVRow(s) = 5
    ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 And _
      (gPondLUNumber = 1 Or gPondLUNumber = 2 Or gPondLUNumber = 4 Or gPondLUNumber = 6) _
      And gDensity(gSAArNum(s)) = 1 Then
       mRSubVRow(s) = 6
    ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 And _
      (gPondLUNumber = 1 Or gPondLUNumber = 2 Or gPondLUNumber = 4 Or gPondLUNumber = 6) _
      And gDensity(gSAArNum(s)) = 2 And gAlley(gSAArNum(s)) = 1 Then
       mRSubVRow(s) = 3
       mDrainEffRow(s) = 11
    ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 And _
      (gPondLUNumber = 1 Or gPondLUNumber = 2 Or gPondLUNumber = 4 Or gPondLUNumber = 6) _
      And gDensity(gSAArNum(s)) = 2 And gAlley(gSAArNum(s)) = 2 Then
       mRSubVRow(s) = 3
       mDrainEffRow(s) = 10
    ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 And gPondLUNumber = 5 Then
       mRSubVRow(s) = 6
    ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 And gPondLUNumber = 3 Then
       mRSubVRow(s) = 3
       mDrainEffRow(s) = 12
    End If
    Return

4140 Rem    C
    If gTypeSA(gSAArNum(s)) = 1 Then
      mRSubVRow(s) = 4
    ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 1 Then
      mRSubVRow(s) = 5
    ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 And _
      (gPondLUNumber = 1 Or gPondLUNumber = 2 Or gPondLUNumber = 4 Or gPondLUNumber = 6) _
      And gDensity(gSAArNum(s)) = 1 Then
      mRSubVRow(s) = 6
    ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 And _
      (gPondLUNumber = 1 Or gPondLUNumber = 2 Or gPondLUNumber = 4 Or gPondLUNumber = 6) _
      And gDensity(gSAArNum(s)) = 2 And gAlley(gSAArNum(s)) = 1 Then
      mRSubVRow(s) = 4
      mDrainEffRow(s) = 11
    ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 And _
      (gPondLUNumber = 1 Or gPondLUNumber = 2 Or gPondLUNumber = 4 Or gPondLUNumber = 6) _
      And gDensity(gSAArNum(s)) = 2 And gAlley(gSAArNum(s)) = 2 Then
       mRSubVRow(s) = 4
       mDrainEffRow(s) = 10
    ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 And gPondLUNumber = 5 Then
       mRSubVRow(s) = 6
    ElseIf gTypeSA(gSAArNum(s)) = 2 And gDirt(gSAArNum(s)) = 2 And gPondLUNumber = 3 Then
       mRSubVRow(s) = 4
       mDrainEffRow(s) = 12
    End If
    Return
```

```
4360 Rem     D
   If gDirt(gSAArNum(s)) = 1 Then
      mRSubVRow(s) = 5
   End If
   If gDirt(gSAArNum(s)) = 2 Then
      mRSubVRow(s) = 6
   End If
   Return

4440 Rem      E
   If gDirt(gSAArNum(s)) = 1 Then
      mRSubVRow(s) = 5
   ElseIf gDirt(gSAArNum(s)) = 2 And (gPondLUNumber = 1 Or gPondLUNumber = 2 Or
gPondLUNumber = 4 Or gPondLUNumber = 6) _
     And gDensity(gSAArNum(s)) = 1 Then
      mRSubVRow(s) = 6
   ElseIf gDirt(gSAArNum(s)) = 2 And (gPondLUNumber = 1 Or gPondLUNumber = 2 Or
gPondLUNumber = 4 Or gPondLUNumber = 6) _
     And gDensity(gSAArNum(s)) = 2 And gAlley(gSAArNum(s)) = 1 Then
      mRSubVRow(s) = 3
      mDrainEffRow(s) = 11
   ElseIf gDirt(gSAArNum(s)) = 2 And (gPondLUNumber = 1 Or gPondLUNumber = 2 Or
gPondLUNumber = 4 Or gPondLUNumber = 6) _
     And gDensity(gSAArNum(s)) = 2 And gAlley(gSAArNum(s)) = 2 Then
      mRSubVRow(s) = 3
      mDrainEffRow(s) = 10
   ElseIf gDirt(gSAArNum(s)) = 2 And gPondLUNumber = 5 Then
      mRSubVRow(s) = 6
   ElseIf gDirt(gSAArNum(s)) = 2 And gPondLUNumber = 3 Then
      mRSubVRow(s) = 3
      mDrainEffRow(s) = 12
   End If
   Return

4640 Rem       F
   If gFreewayText(gSAArNum(s) - 150) = 1 Then
      mRSubVRow(s) = 7
   ElseIf gFreewayText(gSAArNum(s) - 150) = 2 Then
      mRSubVRow(s) = 8
   ElseIf gFreewayText(gSAArNum(s) - 150) >= 3 Then
      mRSubVRow(s) = 9
   End If
   Return

4780 Rem       gPondLUNumber
   Dim EE As Long
   EE = gSAArNum(s) + 10 - 27 * gPondLUNumber
   If gStTexture(EE) = 1 Then
      mRSubVRow(s) = 7
   ElseIf gStTexture(EE) = 2 Then
      mRSubVRow(s) = 8
   ElseIf gStTexture(EE) >= 3 Then
      mRSubVRow(s) = 9
   End If
```

```
    Return

End Sub

Private Sub proJCatchCleanDate()
    ' Calculate catchbasin cleaning dates.
    Dim CCT As Integer
    Dim JDate As Double

    For CCT = 1 To gNumCBClngs
        Call proJulianDateAndTime(gCBCleanDate$(CCT), "00:00", JDate)
        Rem GOSUB 6980
        gJCatchCleanDate(CCT) = JDate
    Next CCT

    gJCatchCleanDate(gNumCBClngs + 1) = 1000000!
    CCT = 1

End Sub

Private Sub proJulianDateAndTime(gDate As String, gTime As String, JDate As Double)

    Dim JOne As Double
    Dim JTwo As Double
    Dim JThree As Double
    Dim Year As Integer
    Dim Month As Integer
    Dim Day As Integer
    Dim Hour As Integer
    Dim Min As Integer

    Year = Val(Mid$(gDate, 7, 2))
    Month = Val(Mid$(gDate, 1, 2))
    Day = Val(Mid$(gDate, 4, 2))
    Hour = Val(Mid$(gTime, 1, 2))
    Min = Val(Mid$(gTime, 4, 2))

    Year = Year - 52
    JOne = (Year) * 365 + Int((Year - 1) / 4) + (Month - 1) * 28
    JTwo = Val(Mid$("000303060811131619212426", (Month - 1) * 2 + 1, 2))
    JThree = Day + ((Hour + Min / 60) / 24) - ((Month > 2) And (((Year) And Not -4) = 0))
    ' I removed  + 1 from the end of JThree to correct date calcs.  This may affect
    ' street date calcs.
    JDate = JOne + JTwo + JThree

End Sub

Public Sub proCalcMain()

    Dim s As Integer
    'On Error GoTo ErrorTrap

    If funValidateFiles = False Then
        Exit Sub
```

```
    End If

    Call proPondLUNumValues
    Call proLoadRSubVFile
    Call proLoadPSCFile
    Call proLoadPartRedRatioFile
    Call proInitRainArrayValues
    Call proLoadRainFile
    Call proJCatchCleanDate
    Call proDimensionMainVariables
    Call proInitSARSubVRows
    Call proInitTSCRows
    Call proRunoffCalc
    Call proTSSCalcs
    Call proRecalcStDirtLoadings

    FROMCALC$ = ""
    For s = 1 To gNumAreas - 2
       If gW$(gSAArNum(s)) = "W" Then
          FROMCALC$ = "landuses"
          Call proMainWetDet(FROMCALC$)
          Exit For
       End If
    Next s
    Call proReCalcWithDetention(FROMCALC$)
    Call proCalcEventSATotals

    Call proOutfall

    Call proMainPolCalc

    Select Case gOutOption
       Case 1 To 4
          proShowCentered frmCalcTabs, vbModal, frmMainMenu
          Set frmCalcTabs = Nothing
       Case 5
          proOutput5RunoffFlowSum
       Case 6 To 8
          gPrnHeadings = False
          If gW$(gSAArNum(gNumAreas)) = "W" Then
                Call proConvertHydroToEvenTimeSteps
                Kill ("ModelHydrograph.TMP")
             Else
                Call proTriHydrograph
          End If
    End Select

    Exit Sub

ErrorTrap:

    Screen.MousePointer = vbDefault
    MsgBox "Error " & Format(Err.Number) & ":  " & Err.Description, _
       vbInformation, "proCalcMain"
```

```
    Exit Sub

End Sub

Private Sub proInitTSCRows()
    ' Initialize totals solids rows.
    Dim s As Integer   ' Consecutive source area numbers.

    'E = 0
    For s = 1 To gNumAreas - 2
        gPondLUNumber = gPondLUNum(s)
        If (gSAName(gSAArNum(s)) >= 1 And gSAName(gSAArNum(s)) <= 5) And gPondLUNumber <= 5
Then
            mPartSolRow(s) = (gPondLUNumber - 1) * 12 + 1
        ElseIf (gSAName(gSAArNum(s)) >= 6 And gSAName(gSAArNum(s)) <= 8) And gPondLUNumber
<= 5 Then
            mPartSolRow(s) = (gPondLUNumber - 1) * 12 + 2
        ElseIf (gSAName(gSAArNum(s)) >= 9 And gSAName(gSAArNum(s)) <= 10) And gPondLUNumber
<= 5 Then
            mPartSolRow(s) = (gPondLUNumber - 1) * 12 + 3
        ElseIf (gSAName(gSAArNum(s)) >= 11 And gSAName(gSAArNum(s)) <= 12) And gPondLUNumber
<= 5 Then
            mPartSolRow(s) = (gPondLUNumber - 1) * 12 + 4
        ElseIf (gSAName(gSAArNum(s)) >= 13 And gSAName(gSAArNum(s)) <= 15) And gPondLUNumber
<= 5 Then
            mPartSolRow(s) = (gPondLUNumber - 1) * 12 + 5
        ElseIf (gSAName(gSAArNum(s)) >= 16 And gSAName(gSAArNum(s)) <= 17) And gPondLUNumber
<= 5 Then
            mPartSolRow(s) = (gPondLUNumber - 1) * 12 + 6
        ElseIf (gSAName(gSAArNum(s)) >= 21 And gSAName(gSAArNum(s)) <= 22) And gPondLUNumber
<= 5 Then
            mPartSolRow(s) = (gPondLUNumber - 1) * 12 + 7
        ElseIf (gSAName(gSAArNum(s)) >= 24 And gSAName(gSAArNum(s)) <= 26) And gPondLUNumber
<= 5 Then
            mPartSolRow(s) = (gPondLUNumber - 1) * 12 + 8
        ElseIf gSAName(gSAArNum(s)) = 23 And gPondLUNumber <= 5 Then
            mPartSolRow(s) = (gPondLUNumber - 1) * 12 + 9
        ElseIf gSAName(gSAArNum(s)) = 28 And gPondLUNumber <= 5 Then
            mPartSolRow(s) = (gPondLUNumber - 1) * 12 + 10
        ElseIf gSAName(gSAArNum(s)) = 29 And gPondLUNumber <= 5 Then
            mPartSolRow(s) = (gPondLUNumber - 1) * 12 + 11
        ElseIf gSAName(gSAArNum(s)) = 30 And gPondLUNumber <= 5 Then
            mPartSolRow(s) = (gPondLUNumber - 1) * 12 + 12
        ElseIf (gSAArNum(s) >= 151 And gSAArNum(s) <= 155) And gPondLUNumber = 6 Then
            mPartSolRow(s) = 61
        ElseIf gSAArNum(s) >= 156 And gPondLUNumber = 6 Then
            mPartSolRow(s) = gSAArNum(s) - 94
        End If
    Next s

End Sub
```

```
Private Sub proInitRainArrayValues()
' Initialize rain array values for Rv coefficient and mTSC value.

    mRainAr(0) = 0
    mRainAr(1) = 1
    mRainAr(2) = 2
    mRainAr(3) = 3
    mRainAr(4) = 5
    mRainAr(5) = 10
    mRainAr(6) = 15
    mRainAr(7) = 20
    mRainAr(8) = 25
    mRainAr(9) = 30
    mRainAr(10) = 40
    mRainAr(11) = 50
    mRainAr(12) = 60
    mRainAr(13) = 70
    mRainAr(14) = 80
    mRainAr(15) = 90
    mRainAr(16) = 100
    mRainAr(17) = 125

End Sub


Private Sub proLoadPartRedRatioFile()
' Load the particulate reduction ratio file.
    Dim FileNum As Integer
    Dim MissingFile As String
    Dim ErrorMsg As String

    On Error GoTo ErrorTrap

    FileNum = FreeFile

  '  If gPartResDelF$ = "" Then
  '      gPartResDelF$ = "ZERORED.PRR"
  '      TYPEDRAIN = 1
  '  End If
    MissingFile$ = gPartResDelF$
    Open gPartResDelF$ For Input As #FileNum
        Input #FileNum, mDumm$, mDumm$
        For fColumn = 1 To 14
            Input #FileNum, mPRRFrac(1, fColumn), mPRRFrac(2, fColumn), mPRRFrac(3, fColumn),
mPRRFrac(4, fColumn), mPRRFrac(5, fColumn)
        Next fColumn
    Close #FileNum

    MissingFile$ = ""

    Exit Sub


ErrorTrap:
```

```
   Select Case Err.Number
     Case 53       ' Object doesn't support this property or method
         ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
           & Chr(10) & Chr(10) & "Procedure proLoadPartRedRatioFile in CalcMainModule" _
             & Chr(10) & Chr(10) & "File " & MissingFile$ & " was not found."
         MsgBox ErrorMsg, vbCritical, "File Not Found Error"
         Close   'Close all files
         Exit Sub  ' e.g., the text box was disabled just as the focus shifted there.
     Case Else
         ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
           & Chr(10) & Chr(10) & "Procedure proLoadPartRedRatioFile in CalcMainModule"
         MsgBox ErrorMsg, vbCritical, "Error Trap"
         Exit Sub
   End Select

End Sub


Private Sub proLoadPSCFile()
' Load the PSC (particulate solids) file.
   Dim Row As Integer
   Dim FileNum As Integer
   Dim MissingFile As String
   Dim ErrorMsg As String

   On Error GoTo ErrorTrap

   FileNum = FreeFile
   MissingFile$ = gPSCncF$

   Open gPSCncF$ For Input As #FileNum

   Input #FileNum, mDumm$, mDumm$

   For Row = 1 To 66
      Input #FileNum, Row, mTSC(Row, 1), mTSC(Row, 2), mTSC(Row, 3), mTSC(Row, 4), mTSC(Row,
5), mTSC(Row, 6), mTSC(Row, 7), mTSC(Row, 8), mTSC(Row, 9), mTSC(Row, 10)
      Input #FileNum, mTSC(Row, 11), mTSC(Row, 12), mTSC(Row, 13), mTSC(Row, 14)
   Next Row

   Close #FileNum
   MissingFile$ = ""

   Exit Sub

ErrorTrap:
   Select Case Err.Number
     Case 53      ' File not found
         ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
           & Chr(10) & Chr(10) & "Procedure proLoadPSCFile in CalcMainModule" _
             & Chr(10) & Chr(10) & "File " & MissingFile$ & " was not found."
         MsgBox ErrorMsg, vbCritical, "File Not Found Error"
         Close   'Close all files
         Exit Sub  ' e.g., the text box was disabled just as the focus shifted there.
```

```
      Case Else
          ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
            & Chr(10) & Chr(10) & "Procedure proLoadPSCFile in CalcMainModule"
          MsgBox ErrorMsg, vbCritical, "Error Trap"
          Exit Sub
    End Select

End Sub

Private Sub proLoadRainFile()
' Load the rain file. Calculate catchbasin cleaning dates.
    Dim FileNum As Integer
    Dim A As Integer
    Dim N As Integer
    Dim JDate As Double
    Dim JulianEndDate As Double         ' Formerly JulianEndDate
    Dim StartTime As String             ' Formerly STRTTM$
    Dim EndDate As String               ' Formerly ENDDT$
    Dim EndTime As String               ' Formerly ENDTM$
    Dim Year As Integer
    Dim Month As Integer
    Dim Day As Integer
    Dim Hour As Integer
    Dim Min As Integer
    Dim MissingFile As String
    Dim ErrorMsg As String

    On Error GoTo ErrorTrap

    FileNum = FreeFile
    MissingFile$ = gRainFile$

    gFirstRainNum = 1

    'Open "raindata.txt" For Output As #50

    Open gRainFile$ For Input As #FileNum
    Input #FileNum, N
    ReDim gRainEventStartDate(N) As String
    ReDim gStartTime(N) As String
    ReDim gRain(N) As Single
    ReDim gJulianEventStartTime(N) As Single
    ReDim gJulStartDate(N) As Single
    ReDim gRainDur(N) As Single
    ReDim gJulDPStartDate(N) As Double
    ReDim gJulInterEventPer(N) As Double

    For A = 1 To N
        Input #FileNum, gRainEventStartDate(A), gStartTime(A), EndDate, EndTime, gRainVal
        gRain(A) = Val(gRainVal)
        Call proJulianDateAndTime(gRainEventStartDate(A), gStartTime(A), JDate)

        If JDate < Val(gJulianStartDate$) Then
            gFirstRainNum = gFirstRainNum + 1
```

```
        End If

        If Int(JDate) > Val(gJulianEndDate$) Then
            gLastRainNum = A - 1
            A = N
          Else
            gLastRainNum = A
        End If

        If JDate >= Val(gJulianStartDate$) Or JDate <= Val(gJulianEndDate$) Then
          gJulStartDate(A) = JDate
          Call proJulianDateAndTime(EndDate, EndTime, JDate)
          JulianEndDate = JDate
          gRainDur(A) = JulianEndDate - gJulStartDate(A)
          gJulianEventStartTime(A) = gJulStartDate(A)
                    'Write #50, A, gRain(A), gRainEventStartDate(A), gJulStartDate(A), gRainDur(A)
          gJulDPStartDate(A) = gJulStartDate(A)
          gJulStartDate(A) = Int(gJulStartDate(A))
        End If
      Next A

      Close #FileNum

      MissingFile$ = ""

      For A = gFirstRainNum To gLastRainNum - 1
        gJulInterEventPer(A) = gJulDPStartDate(A + 1) - gJulDPStartDate(A)
      Next A

      gNumRains = gLastRainNum - gFirstRainNum + 1

'    For A = 1 To gNumRains
'      gRainEventStartDate(A) = gRainEventStartDate(A + gFirstRainNum - 1)
'      gRain(A) = gRain(A + gFirstRainNum - 1)
'      gJulianEventStartTime(A) = gJulianEventStartTime(A + gFirstRainNum - 1)
'      gJulStartDate(A) = gJulStartDate(A + gFirstRainNum - 1)
'      gRainDur(A) = gRainDur(A + gFirstRainNum - 1)
'    Next A

      Exit Sub

ErrorTrap:
      Select Case Err.Number
        Case 53      ' File not found
          ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
            & Chr(10) & Chr(10) & "Procedure proLoadRainFile in CalcMainModule" _
              & Chr(10) & Chr(10) & "File " & MissingFile$ & " was not found."
          MsgBox ErrorMsg, vbCritical, "File Not Found Error"
          Close   'Close all files
          Exit Sub  ' e.g., the text box was disabled just as the focus shifted there.
        Case Else
          ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
            & Chr(10) & Chr(10) & "Procedure proLoadRainFile in CalcMainModule"
          MsgBox ErrorMsg, vbCritical, "Error Trap"
```

```
        Exit Sub
    End Select

End Sub



Private Sub proLoadRSubVFile()
' Load the RSubV file.  RSubV is the coefficient for runoff.  Range: 0 to 1.
    Dim FileNum As Integer
    Dim Row As Integer
    Dim MissingFile As String
    Dim ErrorMsg As String

    On Error GoTo ErrorTrap

    FileNum = FreeFile
    MissingFile$ = gRSubVF$

    Open gRSubVF$ For Input As #FileNum

    Input #FileNum, mDumm$, mDumm$

    For Row = 1 To 9
        Input #FileNum, Row, mRv(Row, 1), mRv(Row, 2), mRv(Row, 3), mRv(Row, 4), mRv(Row, 5),
mRv(Row, 6), mRv(Row, 7), mRv(Row, 8), mRv(Row, 9), mRv(Row, 10)
        Input #FileNum, mRv(Row, 11), mRv(Row, 12), mRv(Row, 13), mRv(Row, 14), mRv(Row, 15),
mRv(Row, 16), mRv(Row, 17)
    Next Row
    For Row = 10 To 12
        Input #FileNum, Row, mDEC(Row, 1), mDEC(Row, 2), mDEC(Row, 3), mDEC(Row, 4),
mDEC(Row, 5), mDEC(Row, 6), mDEC(Row, 7), mDEC(Row, 8), mDEC(Row, 9), mDEC(Row, 10)
        Input #FileNum, mDEC(Row, 11), mDEC(Row, 12), mDEC(Row, 13), mDEC(Row, 14), mDEC(Row,
15), mDEC(Row, 16), mDEC(Row, 17)
    Next Row

    Close #FileNum

    MissingFile$ = ""

    Exit Sub

ErrorTrap:
    Select Case Err.Number
      Case 53      ' File not found
        ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
          & Chr(10) & Chr(10) & "Procedure proLoadRSubVFile in CalcMainModule" _
            & Chr(10) & Chr(10) & "File " & MissingFile$ & " was not found."
        MsgBox ErrorMsg, vbCritical, "File Not Found Error"
        Close   'Close all files
        Exit Sub  ' e.g., the text box was disabled just as the focus shifted there.
      Case Else
        ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
          & Chr(10) & Chr(10) & "Procedure proLoadRSubVFile in CalcMainModule"
```

```
            MsgBox ErrorMsg, vbCritical, "Error Trap"
            Exit Sub
    End Select

End Sub

Private Sub proPondLUNumValues()
    ' Determine the gPondLUNumValues.
    Dim s As Integer            ' Consecutive source area numbers.
    ReDim gPondLUNum(gNumAreas)

    For s = 1 To gNumAreas - 2  'JV 8/4/97
        If gSAArNum(s) <= 30 Then
            gPondLUNum(s) = 1
        ElseIf gSAArNum(s) > 30 And gSAArNum(s) <= 60 Then
            gPondLUNum(s) = 2
        ElseIf gSAArNum(s) > 60 And gSAArNum(s) <= 90 Then
            gPondLUNum(s) = 3
        ElseIf gSAArNum(s) > 90 And gSAArNum(s) <= 120 Then
            gPondLUNum(s) = 4
        ElseIf gSAArNum(s) > 120 And gSAArNum(s) <= 150 Then
            gPondLUNum(s) = 5
        ElseIf gSAArNum(s) > 150 And gSAArNum(s) <= 160 Then
            gPondLUNum(s) = 6
        End If
    Next s

End Sub



Private Sub proCalcRSubv(A As Integer, s As Integer, RSubv As Single)

    ' this procedure determines the value of RSubv

    Dim Col As Integer   ' Column number, DOS == COL
    Dim DrainEffCoef As Single  ' Drainage Efficiency Coefficient, DOS == DREFFCOEF
    Dim RainRatio As Single  ' Rainfall ratio for interpolation, DOS == RAINRATIO

    RSubv = 0
    gRain(A) = gRain(A) * 25.4
    For Col = 1 To 17
        If mRainAr(Col) >= gRain(A) Then
            RainRatio = (gRain(A) - mRainAr(Col - 1)) / (mRainAr(Col) - mRainAr(Col - 1))
            RSubv = mRv(mRSubVRow(s), Col - 1) + (mRv(mRSubVRow(s), Col) - mRv(mRSubVRow(s),
Col - 1)) * RainRatio
            Col = 17
        End If
    Next Col
    If gRain(A) > 125 Then RSubv = mRv(mRSubVRow(s), 17)
    For Col = 1 To 17
        If mRainAr(Col) >= gRain(A) And mDrainEffRow(s) <> 0 Then
            RainRatio = (gRain(A) - mRainAr(Col - 1)) / (mRainAr(Col) - mRainAr(Col - 1))
```

```
            DrainEffCoef = mDEC(mDrainEffRow(s), Col - 1) + (mDEC(mDrainEffRow(s), Col) -
mDEC(mDrainEffRow(s), Col - 1)) * RainRatio
            RSubv = RSubv * DrainEffCoef
            Col = 17
        End If
    Next Col
    If gRain(A) > 125 And mDrainEffRow(s) <> 0 Then
        DrainEffCoef = mDEC(mDrainEffRow(s), 17)
        RSubv = RSubv * DrainEffCoef
    End If
     Rem
'     For Col = 1 To 14
 '      If mRainAr(Col) >= gRain(A) Then GoSub 7620: Col = 14
 '    Next Col
'     If gRain(A) > 80 Then TSCNC = mTSC(mPartSolRow(S), 14)
 '    If (CO >= 18 And CO <= 20) Then TSCNC = 0
    gRain(A) = gRain(A) / 25.4

'7620 RAINRATIO = (gRain(A) - mRainAr(Col - 1)) / (mRainAr(Col) - mRainAr(Col - 1))
 '   TSCNC = mTSC(mPartSolRow(S), Col - 1) + (mTSC(mPartSolRow(S), Col) - mTSC(mPartSolRow(S),
Col - 1)) * RAINRATIO
 '    Return

End Sub

Public Sub proLoadPolFile()

    Dim ErrorMsg As String            ' JM8
    Dim Dum As Integer
    Dim Dumm As String
    Dim FileNum As Integer
    Dim DirPolF As String
    Dim Pol As Integer
    Dim Other As Integer
    Dim Row As Integer
    Dim MissingFile As String
    Dim PPDFileVersion As String
    Dim PPDMsg As String

    FileNum = FreeFile
    MissingFile$ = gPolProbDistF$

    On Error GoTo LoadPolFileError:   ' JM8

  Rem      loading previously entered file
        ReDim gPolMean(32, 16, 6) As Single
        ReDim gPolCOV(32, 16, 6) As Single
        ReDim gPolCntr(32) As Integer
        DirPolF$ = gPolProbDistF$

        Open DirPolF$ For Input As #FileNum
        Input #FileNum, Dumm$, Dumm$, PPDFileVersion$
        Close #FileNum
        If PPDFileVersion$ = "V6.6" Then
```

```
            Open DirPolF$ For Input As #FileNum
               Input #FileNum, Dumm$, Dumm$, Dumm$
               For Pol = 1 To 32
                  'Input #FileNum, pol, gPolCntr(pol)
                  Input #FileNum, Dum, gPolCntr(Pol)
                  If gPolCntr(Pol) = 0 Then GoTo 7480
                  For Row = 1 To 16
                     Input #FileNum, Dum, gPolMean(Pol, Row, 1), gPolMean(Pol, Row, 2), gPolMean(Pol,
Row, 3), gPolMean(Pol, Row, 4), gPolMean(Pol, Row, 5), gPolMean(Pol, Row, 6)
                     Input #FileNum, Dum, gPolCOV(Pol, Row, 1), gPolCOV(Pol, Row, 2), gPolCOV(Pol,
Row, 3), gPolCOV(Pol, Row, 4), gPolCOV(Pol, Row, 5), gPolCOV(Pol, Row, 6)
                  Next Row
7480           Next Pol
               If gSeed < 0 Then ReDim gPolCOV(32, 16, 6)
               For Other = 1 To 6
                  Input #FileNum, Dum, gUDPartPolUnit(31 + (Other - 1) * 3), gUDPartPolName$(31 +
(Other - 1) * 3), gUDFiltPolName$(32 + (Other - 1) * 3), gUDFiltPolUnit(32 + (Other - 1) * 3)
               Next Other
            Close #FileNum
      Else
            PPDMsg$ = "Phosphate, Nitrate, Chromium, and Aluminum Data in this file are not correct. " &
_
                        "Do not use this file if you are evaluating any of these pollutants."
            MsgBox PPDMsg$, vbCritical, "Old .PPD File Format Warning"

             Open DirPolF$ For Input As #FileNum
               Input #FileNum, Dumm$, Dumm$
               For Pol = 1 To 32
                  'Input #FileNum, pol, gPolCntr(pol)
                  Input #FileNum, Dum, gPolCntr(Pol)
                  If gPolCntr(Pol) = 0 Then GoTo 7481
                  For Row = 1 To 16
                     Input #FileNum, Dum, gPolMean(Pol, Row, 1), gPolMean(Pol, Row, 2), gPolMean(Pol,
Row, 3), gPolMean(Pol, Row, 4), gPolMean(Pol, Row, 5), gPolMean(Pol, Row, 6)
                     Input #FileNum, Dum, gPolCOV(Pol, Row, 1), gPolCOV(Pol, Row, 2), gPolCOV(Pol,
Row, 3), gPolCOV(Pol, Row, 4), gPolCOV(Pol, Row, 5), gPolCOV(Pol, Row, 6)
                  Next Row
7481           Next Pol
               If gSeed < 0 Then ReDim gPolCOV(32, 16, 6)
               For Other = 1 To 6
                  Input #FileNum, Dum, gUDPartPolUnit(31 + (Other - 1) * 3), gUDPartPolName$(31 +
(Other - 1) * 3), gUDFiltPolName$(32 + (Other - 1) * 3), gUDFiltPolUnit(32 + (Other - 1) * 3)
               Next Other
            Close #FileNum
      End If

      MissingFile$ = ""

   Exit Sub                     ' JM8

LoadPolFileError:                  ' JM8

   Select Case Err.Number
     Case 53      ' File not found
```

```
        ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
          & Chr(10) & Chr(10) & "Procedure proLoadPolFile in CalcMainModule" _
            & Chr(10) & Chr(10) & "File " & MissingFile$ & " was not found."
        MsgBox ErrorMsg, vbCritical, "File Not Found Error"
        Close   'Close all files
        Exit Sub  ' e.g., the text box was disabled just as the focus shifted there.
     Case Else
        ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
          & Chr(10) & Chr(10) & "Procedure proLoadPolFile in CalcMainModule"
        MsgBox ErrorMsg, vbCritical, "Error Trap"
        Exit Sub
   End Select

 End Sub



Private Function funValidateFiles() As Boolean

   On Error GoTo ErrorTrap

   funValidateFiles = True

   If gRSubVF$ = "" Then
      MsgBox "The R Sub V file was not selected.", vbInformation, "File Not Selected"
      funValidateFiles = False
   ElseIf gPSCncF$ = "" Then
      MsgBox "The Particulate Solids file was not selected.", vbInformation, "File Not Selected"
      funValidateFiles = False
   ElseIf gPartResDelF$ = "" Then
      MsgBox "The Particulate Reduction Ratio file was not selected.", vbInformation, "File Not Selected"
      funValidateFiles = False
   ElseIf gRainFile$ = "" Then
      MsgBox "The Rain file was not selected.", vbInformation, "File Not Selected"
      funValidateFiles = False
   End If
   If funValidateFiles = False Then Exit Function

   If Dir(gRSubVF$) = "" Then
      MsgBox "The file " & UCase(gRSubVF$) & " was not found.", vbInformation, "File Not Found"
      funValidateFiles = False
   ElseIf Dir(gPSCncF$) = "" Then
      MsgBox "The file " & UCase(gPSCncF$) & " was not found.", vbInformation, "File Not Found"
      funValidateFiles = False
   ElseIf Dir(gPartResDelF$) = "" Then
'     If Dir("ZERORED.PRR") = "" Then
         MsgBox "The file " & UCase(gPartResDelF$) & " was not found.", vbInformation, "File Not Found"
         funValidateFiles = False
'     End If
   ElseIf Dir(gRainFile$) = "" Then
      MsgBox "The file " & UCase(gRainFile$) & " was not found.", vbInformation, "File Not Found"
      funValidateFiles = False
   End If
```

```
   Exit Function

ErrorTrap:

   ' When using the Dir() function, trap for the error 76, ' "Path not found" - the path must exist in
    ' Dir(path), or else an error occurs.
   If Err.Number = 76 Then
      Resume Next
   Else
      MsgBox "Error " & Format(Err.Number) & ":  " & Err.Description, _
      vbInformation, "funValidateFiles"
      Exit Function
   End If

End Function

Public Sub proCatchbasin()

   Dim CCTimeNum As Integer    'Catchbasin Cleaning Time Number, DOS == CCTimeNum
   Dim ScourDepth As Single    '  Catchbasin scour depth.
   Dim ScourVolume As Single   '  Catchbasin scour volume, DOS == MARK
   Dim SumpVolAvail As Single   '   Sump volume available, DOS == SMPVAVAIL
   Dim CBFull As Boolean     '   Catchbasin full?
   Dim Flow As Single    '
   Dim TtlSolidAccumLbs As Single      'Total Solids Accumulated in Catchbasin [lbs], DOS ==
TSACCUMLBS
   Dim s As Integer
   Dim DCNum As Integer  '  Drainage Control Number, ie SA Number 161,  DOS == S
   Dim RSubv As Single
   Dim PCVolRed161 As Single      'DOS == PCVolRed161
   Dim PCTSSRed161 As Single      'DOS == PCTSRED161
   Dim UnavailSumpVol As Single      'DOS == MARK
   Dim TtlBsnAreaTtlSolidsYield As Single   ' DOS == TBSNATSYLD
   Dim PcTtlSolidsConcRedForCB As Single  '  DOS = TSCNCREDCBPC  Percent Total Solids
Concentration Reduction For Catch Basins


   'ScourDepth = 1   'value selected by Bob P.
   UnavailSumpVol = 0.4 * gTtlSumpVol
   'ScourVolume = gTtlSumpVol / gSumpDepth * ScourDepth
   SumpVolAvail = gTtlSumpVol * (1 - gPCSumpVolFull / 100)
   CCTimeNum = 1
   While gJulStartDate(1) > gJCatchCleanDate(CCTimeNum)
     CCTimeNum = CCTimeNum + 1
   Wend
   DCNum = gNumAreas - 1
   For A = gFirstRainNum To gLastRainNum
      If gRunoffVol(A, DCNum) > 0 Then    'GoTo 15800
         If gTtlSumpVol > 0 Then      'GoTo 15750
            If gJulStartDate(A) > gJCatchCleanDate(CCTimeNum) Then
               SumpVolAvail = gTtlSumpVol
               CBFull = False
               CCTimeNum = CCTimeNum + 1
            End If
```

```
            If CBFull = False Then    'GoTo 15700
                TtlBsnAreaTtlSolidsYield = gPartSolYield(A, DCNum)
                Flow = gRunoffVol(A, DCNum) * 0.0002788 / (0.9 + 0.98 * gRainDur(A) * 24)
                If Flow > 5 Then
                    PcTtlSolidsConcRedForCB = 0.065
                  Else
                    PcTtlSolidsConcRedForCB = 0.4404 * (0.51 ^ Flow) * 1.061 ^ (Flow ^ 2) *
gCBAreaServ / gTtlBasinArea
                End If
                gTtlSolAccum(A) = PcTtlSolidsConcRedForCB * gPartSolYield(A, DCNum) * 0.010685
'cubic feet
                SumpVolAvail = SumpVolAvail - gTtlSolAccum(A)
                'If SumpVolAvail < ScourVolume Then
                If SumpVolAvail < UnavailSumpVol Then
                  CBFull = True
                  'gTtlSolAccum(A) = SumpVolAvail + gTtlSolAccum(A) - ScourVolume
                  gTtlSolAccum(A) = SumpVolAvail + gTtlSolAccum(A) - UnavailSumpVol
                End If
                TtlSolidAccumLbs = gTtlSolAccum(A) / 0.010685: Rem  in pounds
                gPartSolYield(A, DCNum) = gPartSolYield(A, DCNum) - TtlSolidAccumLbs: Rem   in
pounds
                gPartSolConc(A, DCNum) = gPartSolYield(A, DCNum) / (gRunoffVol(A, DCNum) * (28.32
/ 454000!))
                '  [mg/L] == [lbs]/[cf]*[10E-3m^3/L]*[1cf/0.0283m^3]*[10E6mg/kg]*[0.4536kg/lb]
              ElseIf CBFull = True Then
                'SumpVolAvail = ScourVolume      '15700
                SumpVolAvail = UnavailSumpVol
            End If
            gPercentCBVolFull(A) = ((gTtlSumpVol - SumpVolAvail) / gTtlSumpVol + _
                  0.4 / 0.6 * ((gTtlSumpVol - SumpVolAvail) / gTtlSumpVol)) * 100
            If gPercentCBVolFull(A) > 100 Then gPercentCBVolFull(A) = 100   'JV 12/6/98 added to
prevent value >100%
          End If
        End If
          If gI$(161) = "I" Then         '15750
            mInfilVolRed = 0
            mOtherVolRed = 0
            mOtherTSSRed = 0
              RSubv = gRunoffVol(A, DCNum) / (gRain(A) * gTtlBasinArea * 43560! / 12): Rem   units - cu
ft/(in*acres)
              Call proInfilVolRed(DCNum, A, RSubv, mInfilVolRed)      '   GoSub 7840
          End If
          If gOth$(161) = "O" Then
            Call proOtherVolRed(DCNum, mOtherVolRed)
            Call proOtherTSSRed(DCNum, mOtherTSSRed)
          End If
          PCVolRed161 = 1 - (1 - mInfilVolRed) * (1 - mOtherVolRed)
          PCTSSRed161 = 1 - (1 - mOtherTSSRed)
          gRunoffVol(A, DCNum) = gRunoffVol(A, DCNum) * (1 - PCVolRed161)
          If gRunoffVol(A, DCNum) = 0 Then
              gPartSolConc(A, DCNum) = 0
            Else       ': GoTo 15800
              gPartSolYield(A, DCNum) = gPartSolConc(A, DCNum) * gRunoffVol(A, DCNum) * (28.32 /
454000!) * (1 - PCTSSRed161)
```

```
            gPartSolConc(A, DCNum) = gPartSolYield(A, DCNum) / (gRunoffVol(A, DCNum) * (28.32 /
454000!))
        End If
    Next A     '15800

End Sub

Public Function funGetLUNum(SANum As Integer) As Integer
' Return a Land Use number based upon the source area number passed as an argument.
    Select Case SANum
        Case 1 To 30
            funGetLUNum = 1
        Case 31 To 60
            funGetLUNum = 2
        Case 61 To 90
            funGetLUNum = 3
        Case 91 To 120
            funGetLUNum = 4
        Case 121 To 150
            funGetLUNum = 5
        Case 151 To 160
            funGetLUNum = 6
        Case Else

            MsgBox "An incorrect Source Area number (" & Format(SANum) & ") was passed to the function
funGetLUNum.", _
                vbInformation
            funGetLUNum = 0
    End Select

End Function
Public Sub proGrassSwales()

    'ReDim gEventTtlRunVol(gFirstRainNum To gLastRainNum) As Single
    Dim AGDS As Single
    Dim BGDS As Single
    Dim GrSwlVolRed As Single  '  DOS == GDSVOLRED
    Dim DCNum As Integer  '  Drainage Control Number, ie SA Number 161,  DOS == S
    Dim SANum As Integer

    '15100 Rem    grass swale calcs
    DCNum = gNumAreas - 1
    For A = gFirstRainNum To gLastRainNum    '1 to gnumrains
        'For SANum = 1 To gNumAreas - 2
        '    gEventTtlRunVol(A) = gEventTtlRunVol(A) + gRunoffVol(A, dcnumANum)
        'Next SANum
        If gEventTtlRunVol(A) > 0 Then 'GoTo 15300, Next A
            AGDS = gSwlInfilRate * gSwlDensity * gSwlWidth * gTtlBasinArea * (0.9 + 0.98 * gRainDur(A) *
24) * 0.0833 / gEventTtlRunVol(A)
            BGDS = gSwlAreaServedBy / gTtlBasinArea
            If AGDS > 1! Then AGDS = 1!
            GrSwlVolRed = AGDS * BGDS
            gRunoffVol(A, DCNum) = gEventTtlRunVol(A) * (1 - GrSwlVolRed)
            If gRunoffVol(A, DCNum) > 0 Then ': GoTo 15300 (next A)
```

```
            DTStart = 1
            Call proPartResReduction(DTStart, WashPartFrac, A)          'GoSub 7900:   Rem  calc part
residue reduction
            gPartSolYield(A, DCNum) = gEventTtlPartConc(A) * gRunoffVol(A, DCNum) * (28.32 /
454000!) * WashPartFrac
            Rem WRITE #10, A, dcnum, gPartSolYield(A, dcnum), gEventTtlPartConc(A), gRunoffVol(A,
dcnum), (28.32 / 454000!), WASHPARTFrac, gRain(A)
            gPartSolConc(A, DCNum) = gPartSolYield(A, DCNum) / gRunoffVol(A, DCNum) / (28.32 /
454000)
          Else
            'gPartSolConc(A, dcnum) = 0
        End If
      End If
   Next A    '15300

End Sub

Public Sub proOutfall()

   '15000 Rem        calculations for source areas 161 and 162  (outfall source areas)
   Dim OFNum As Integer  '  OutFall Number, DOS == S
   'Dim IVolRed As Single
   'Dim OVolRed As Single
   Dim TtlPCVolRed As Single  '  Total Percent Volume Reduction, DOS == TOTPCVRED
   Dim TtlPCConcRed As Single    'Total Percent Concentration Reduction, DOS == TOTPCCNCRED
   Dim RSubv As Single

   gTtlBasinArea = funTtlBasinArea

   proGrassSwales
   proCatchbasin

   'GoSub 15500: Rem  catchbasin cleaning calcs
   'GoSub 15920: Rem  to detention pond subprogram if necessary
   If gW$(gSAArNum(gNumAreas)) = "W" Then
        FROMCALC$ = "outfall"
        Call proMainWetDet(FROMCALC$)
   End If


   '15850 Rem    outfall calcs
   OFNum = gNumAreas
   For A = gFirstRainNum To gLastRainNum     '1 To gNumRains
      If gRunoffVol(A, OFNum - 1) > 0 Then     'GoTo 15900, Next A
        mInfilVolRed = 0
        mOtherVolRed = 0
        mOtherTSSRed = 0
        If gI$(162) = "I" Then
          RSubv = gRunoffVol(A, OFNum - 1) / (gRain(A) * gTtlBasinArea * 43560! / 12)     '[cu ft / (in
*acres * 43560 sf / acre / 12 in / ft)]
          Call proInfilVolRed(OFNum, A, RSubv, mInfilVolRed)
        End If
        If gOth$(162) = "O" Then
          Call proOtherVolRed(OFNum, mOtherVolRed)      'GoSub 7980
```

```
            Call proOtherTSSRed(OFNum, mOtherTSSRed)
        End If
        TtlPCVolRed = 1 - (1 - mInfilVolRed) * (1 - mOtherVolRed) * (1 - gDPVolRed162(A) *
(gPondAreaServ(gSANum) / gTtlBasinArea))
        gRunoffVol(A, OFNum) = gRunoffVol(A, OFNum - 1) * (1 - TtlPCVolRed)
        gModelRunTotal(1) = gModelRunTotal(1) + gRunoffVol(A, OFNum)

        If gRunoffVol(A, OFNum) > 0 Then   'GoTo 15900
            TtlPCConcRed = 1 - ((1 - (gWeightedTtlSolRed162(A) * gPondAreaServ(gSANum) /
gTtlBasinArea)) * (1 - mOtherTSSRed))
            gPartSolConc(A, OFNum) = gPartSolConc(A, OFNum - 1) * (1 - TtlPCConcRed)
            gPartSolYield(A, OFNum) = gPartSolConc(A, OFNum) * gRunoffVol(A, OFNum) * (28.32 /
454000!)
            gModelRunTotal(2) = gModelRunTotal(2) + gPartSolYield(A, OFNum)
        End If
      End If
   Next A   ' 15900

End Sub

Public Function funCN(RunoffVol As Single, Rain As Single, Area As Single) As Single

   Dim Q As Single

   ''Q = RunoffVol / (gTtlBasinArea * 43560!) * 12
   Q = RunoffVol / (Area * 43560!) * 12
   funCN = 1000 / (10 + 5 * Rain + 10 * Q - 10 * (Q ^ 2 + 1.25 * Q * Rain) ^ (1 / 2))

End Function

Public Function funRvCalculated(RunoffVol As Single, Rain As Single, Area As Single) As Single

   ''funRvCalculated = RunoffVol * 12 / (Rain * gTtlBasinArea * 43560!)
   funRvCalculated = RunoffVol * 12 / (Rain * Area * 43560!)

End Function

Public Function funTtlLosses(RunoffVolume As Single, Rain As Single, Area As Single) As Single

   Dim Q As Single

   ''Q = RunoffVolume / (gTtlBasinArea * 43560!) * 12  '[ft^3/(ac * 43560 ft^2/ac) * 12 in/ft]
   Q = RunoffVolume / (Area * 43560!) * 12  '[ft^3/(ac * 43560 ft^2/ac) * 12 in/ft]
   funTtlLosses = Rain - Q

End Function

Public Sub proTSSCalcs()

   Dim TtlPCConcRed As Single     '  Total Percent Concentration Reduction, DOS == TOTPCCNCRED
   Dim EE As Integer      '  Street source gstreetlen number, DOS == EE
   Dim s As Integer
   Dim RSubv As Single
   Dim TSConc As Single
```

```
    Dim AT As Single  ' total street length in land use, DOS == AT
    Dim DTStart As Integer    '  Start calc cycle at drain type number ___  DOS == DTSTART
    Dim WashPartFrac As Single          '  DOS == WASHPARTFrac

    For s = 1 To gNumAreas - 2
       EE = gSAArNum(s) + 10 - 27 * gPondLUNum(s)
'       If gS$(S) = "S" Then Call JSCSCHED(EE, gJulStClDate())

       If gTSArea(gSAArNum(s)) > 0 Then 'GoTo 6120
          ''For A = 1 To gNumRains
          For A = gFirstRainNum To gLastRainNum     ' JM7/22/97
             If gRainDur(A) > 0 Then '  GoTo 6060
                   Call proCalcRSubv(A, s, RSubv)    'GoSub 7140: Rem    calc Rsubv
                   If RSubv > 0 Then    'GoTo 6060
                      Call proCalcTSConc(A, s, TSConc)
                      mOtherTSSRed = 0
                      If gOth$(gSAArNum(s)) = "O" Then Call proOtherTSSRed(s, mOtherTSSRed)   'GoSub
7980
                      TtlPCConcRed = 1 - ((1 - mOtherTSSRed))
                      If (gSAArNum(s) >= 151 And gSAArNum(s) <= 155) Then
                            Call proTSSFreeways(s, A, TtlPCConcRed)       'GoSub 11920     'calc pave lane
and shoulder gPartSolYield
          '                  GoTo 6060    ' goto next rain
                         ElseIf (gSAName(gSAArNum(s)) >= 18 And gSAName(gSAArNum(s)) <= 20) Then
'street calcs, gosub 6500
                            If pLUCurbRatio(EE) = 0 Then
                               If gPondLUNum(s) = gPondLUNum(s + 1) Then
                                     If gPondLUNum(s) = gPondLUNum(s + 2) Then
                                           AT = gStreetLen(EE) + gStreetLen(EE + 1) + gStreetLen(EE + 2)
                                           pLUCurbRatio(EE) = gStreetLen(EE) / AT
                                           pLUCurbRatio(EE + 1) = gStreetLen(EE + 1) / AT
                                           pLUCurbRatio(EE + 2) = gStreetLen(EE + 2) / AT
                                        Else
                                           AT = gStreetLen(EE) + gStreetLen(EE + 1)
                                           pLUCurbRatio(EE) = gStreetLen(EE) / AT
                                           pLUCurbRatio(EE + 1) = gStreetLen(EE + 1) / AT
                                     End If
                                  Else
                                     pLUCurbRatio(EE) = 1
                               End If
                            End If
                            Rem    calculate street gPartSolYield
                            Call proTSSStreets(A, s, EE, pStreetRound)
                         Else
                            gPartSolConc(A, s) = TSConc * (1 - TtlPCConcRed)
                            gPartSolYield(A, s) = gPartSolConc(A, s) * gRunoffVol(A, s) * (28.32 / 454000!)
                   End If
                   DTStart = 3
                   Call proPartResReduction(DTStart, WashPartFrac, A)               '             GoSub 7900
                   If (gSAName(gSAArNum(s)) >= 18 And gSAName(gSAArNum(s)) <= 20) Then
                      gStDirtStored(A, gPondLUNum(s)) = gStDirtStored(A, gPondLUNum(s)) +
gPartSolYield(A, s) * (1 - WashPartFrac)
                   End If
                End If
```

```
            End If
          Next A   '6060
'        DPE = 0
        End If
    Next s   '6120

End Sub

Public Sub proCalcTSConc(A As Integer, s As Integer, TSConc As Single)

    ' this procedure determines the value of TSC == Total Solids Concentration

    Dim Col As Integer   ' Column number, DOS == COL
    Dim RainRatio As Single  ' Rainfall ratio for interpolation, DOS == RAINRATIO

    TSConc = 0
    gRain(A) = gRain(A) * 25.4

    For Col = 1 To 14
        If mRainAr(Col) >= gRain(A) Then   ' GoSub 7620 (calc RainRatio)
            RainRatio = (gRain(A) - mRainAr(Col - 1)) / (mRainAr(Col) - mRainAr(Col - 1))
            TSConc = mTSC(mPartSolRow(s), Col - 1) + (mTSC(mPartSolRow(s), Col) -
mTSC(mPartSolRow(s), Col - 1)) * RainRatio
            Col = 14
        End If
    Next Col
    If gRain(A) > 80 Then TSConc = mTSC(mPartSolRow(s), 14)
'    If (CO >= 18 And CO <= 20) Then TSConc = 0

    gRain(A) = gRain(A) / 25.4

End Sub

Public Static Sub proTSSFreeways(s As Integer, A As Integer, TtlPCConcRed As Single)

    Dim CurrentLoad As Single     '  DOS ==> CURLOAD
    Dim CurrentTime As Single       '  DOS == CURTIME#
    Dim NStar As Single   'DOS == NSTAR
    Dim TimeOfAccumDur   'Time of accumulation duration [days]    DOS == TACCDUR#
    Dim AvailTtlRes As Single     'Available total residue     DOS == AVAILTOTRES
    Dim NSubo As Single     'DOS == NSUBO
    Dim k As Single    '  DOS == k
    Dim Washoff As Single    '  DOS == WASHOFF

    If A = gFirstRainNum Then
    'If gFreewayInitLoad(gSAArNum(S) - 150) > 0 Then      'GoTo 12040
        CurrentLoad = gFreewayInitLoad(gSAArNum(s) - 150)
        'gFreewayInitLoad(gSAArNum(S) - 150) = 0
        CurrentTime = Val(gJulianStartDate$)
        TimeOfAccumDur = gJulianEventStartTime(A) - CurrentTime
    End If
    '12040 Rem  paved ln and shldr calc loop
    If TimeOfAccumDur > 20 Then TimeOfAccumDur = 20
```

```
   AvailTtlRes = 0.007 * (gAvgDailyTraf(gSAArNum(s) - 150) ^ 0.89) * gFreewayLen(gSAArNum(s) - 150)
_
         * TimeOfAccumDur + CurrentLoad
   NSubo = 0.53 * AvailTtlRes: Rem  avail part residue
   k = 0.26
   NStar = NSubo * Exp(-k * gRain(A) * 25.4)
   Rem UNAVAILAFTRAIN=AVAILTOTRES-NSUBO
   Rem TOTAFTRAINLOAD=UNAVAILAFTRAIN+NSTAR
   Washoff = AvailTtlRes - NStar
   If Washoff < 0 Then Washoff = 0
   gPartSolYield(A, s) = Washoff * (1 - TtlPCConcRed)
   gPartSolConc(A, s) = gPartSolYield(A, s) / gRunoffVol(A, s) * (454000! / 28.32)
   If A = gLastRainNum Then
       Exit Sub
     Else
       TimeOfAccumDur = gJulianEventStartTime(A + 1) - (gJulianEventStartTime(A) + gRainDur(A))
   End If
   CurrentLoad = NStar

End Sub

Public Static Sub proTSSStreets(A As Integer, s As Integer, EE As Integer, pStreetRound As Integer)
'Public Sub proTSSStreets(gPartSolYield(), gPartSolConc(), gPondLUNum(), A, S, EE, gStDirtStored(),
pLUCurbRatio(), gJulStClDate(), pStreetround)

   Dim RainInt As Single   ' Rainfall Intensity [mm/hr]   DOS == RAININT
   Dim Value As Single   'DOS == VALUE
   Dim Rain As Single  ' Rain depth in [mm]
   Dim MaxLoad As Single  ' Maximum street dirt load  DOS == MAXLOAD
   Dim InitGTMax As String   'Initial street load is greater than the maximum street load    DOS ==
INITGTMAX$
   Dim CurrentLoad As Single   'Current street dirt load  DOS == CURLOAD
   Dim MaxAccumTime As Single   ' Maximum time allowed to accumulate street dirt  DOS ==
MAXACCTIME
   Dim PreviousTime As Single   '  DOS == PREVTIME

   Dim P00 As Single, P10 As Single, P01 As Single, P11 As Single
   Dim SCNum As Integer   'Street Cleaning number   DOS == SCNUM
   Dim TypeEvent As Integer    'Type of event:  1==> Street cleaning   2 ==> Washoff      DOS ==
TYPEVENT
   Dim AccumDur As Single   'Accumulation duration time [days]   DOS == TACCDUR
   Dim CurTime As Single   'Current time [julian date]  DOS == CURTIME
   Dim BeforeEventLoad As Single   '  DOS == BEFOREVENTLOAD
   Dim AfterEventLoad As Single    '  DOS == AFTEVENTLOAD
   Dim NSub0 As Single     '  DOS == NSUBO
   Dim NStar As Single      '  DOS == NSTAR
   Dim AvailFactor As Single     '   DOS == AVAILFACTOR
   Dim Washoff As Single     'DOS == WASHOFF
   Dim LinInt1 As Single, LinInt2 As Single, LinInt3 As Single    '  DOS == LININT1,LININT2,LININT3
   Dim CorFactor As Single    ' Correction factor   DOS == CORFACTOR
   Dim UnavailAftRain As Single    '  Particulates unavailable for washoff after rain    DOS ==
UNAVAILAFTRAIN
   Dim k As Single     '  DOS == k
```

```
Rem $STATIC
'   Static Sub STREETS(gPartSolYield(), gPartSolConc(), gPondLUNum(), A, S, EE, gStDirtStored(),
pLUCurbRatio(), gJulStClDate(), pStreetround)

   Rem OPEN "STRTV62.CSV" FOR APPEND AS #9

9020  Rem  street loading subroutine
   Rem  calc first street cleaning number SCNUM
   If A = gFirstRainNum Then  ' initialize values at the beginning of the run
      ReDim gJulStClDate(365)
      If gS$(gSAArNum(s)) = "S" Then
         Call proJulianStCleanDates(EE, gJulStClDate()) '   GOSUB 12440: REM   calc street cleaning
julian dates
         SCNum = 1
         While gJulStClDate(SCNum) < Val(gJulianStartDate$)
            SCNum = SCNum + 1
         Wend
      End If
      If gCStAcc(EE) = 0 Then
            MaxLoad = gAStAcc(EE) + gBStAcc(EE) * 50
         Else
            MaxLoad = gAStAcc(EE) + gBStAcc(EE) ^ 2 / (4 * gCStAcc(EE))
      End If
      If gInitStLoad(EE) > MaxLoad Then InitGTMax$ = "Y" Else InitGTMax$ = "N"
      CurrentLoad = gInitStLoad(EE): Rem  [lbs/curb-mi]
      Rem A = 1
      PreviousTime = Val(gJulianStartDate$)
      Rem   loading based on derivitive of accumulation equation
      If gCStAcc(EE) = 0 Then
            MaxAccumTime = 50
         Else
            MaxAccumTime = -1 * (gBStAcc(EE) / (2 * gCStAcc(EE)))
      End If
      Rem WRITE #10, ""
      Rem WRITE #10, "BEGIN STREET CLEANING/WASHOFF LOOP FOR STREET", EE
   End If

9220  Rem beginning of street cleaning/washoff loop
   Do Until A = gFirstRainNum + gNumRains
      If gS$(gSAArNum(s)) <> "S" Then
         CurTime = gJulianEventStartTime(A)
         TypeEvent = 2
         GoTo 9380
      End If
      If gJulStClDate(SCNum) < gJulianEventStartTime(A) Then
            CurTime = gJulStClDate(SCNum)
            TypeEvent = 1   ' Street cleaning event
         ElseIf gJulStClDate(SCNum) >= gJulianEventStartTime(A) Then
            CurTime = gJulianEventStartTime(A)
            TypeEvent = 2    '  Washoff event
      End If
      If gJulStClDate(SCNum) >= gJulianEventStartTime(A) And gJulStClDate(SCNum) <= _
                (gJulianEventStartTime(A) + gRainDur(A)) Then
```

```
        SCNum = SCNum + 1
      End If
      If gJulStClDate(SCNum) = 0 Then
        CurTime = gJulianEventStartTime(A)
        TypeEvent = 2
      End If
9380 AccumDur = CurTime - PreviousTime
      PreviousTime = CurTime
      GoSub CalcAccumulation
'         GoSub 9540      ' Calculate accumulation
      On TypeEvent GoSub 9680, 9760
      If pStreetRound <> 2 Then
            CurrentLoad = AfterEventLoad
            Exit Sub
         Else
            Select Case TypeEvent
              Case 1: Rem    street cleaning
                  CurrentLoad = AfterEventLoad
                  Rem WRITE #11, typeevent, A - 1, S, EE, gPondLUNum(S), gPartSolYield(A - 1, S),
Currentload, Aftereventload, gStDirtStored(A - 1, gPondLUNum(S)), pLUCurbRatio(EE)
              Case 2: Rem    washoff from rain event
                  Rem IF A = gNumRains + 1 THEN EXIT SUB
                  Rem IF A = gNumRains + 1 THEN : CLOSE #9: EXIT SUB
                  CurrentLoad = AfterEventLoad + (gStDirtStored(A - 1, gPondLUNum(s)) / gStreetLen(EE))
* pLUCurbRatio(EE): Rem  [lbs/curb-mi]
                  Rem WRITE #11, typeevent, A - 1, S, EE, gPondLUNum(S), gPartSolYield(A - 1, S),
Currentload, Aftereventload, gStDirtStored(A - 1, gPondLUNum(S)), pLUCurbRatio(EE), gStreetLen(EE)
                  Exit Sub
            End Select
      End If
      Rem WRITE #10, typeevent, A - 1, S, EE, gPondLUNum(S), gPartSolYield(A - 1, S), Currentload,
Aftereventload, gStDirtStored(A - 1, gPondLUNum(S)), pLUCurbRatio(EE)
      Rem IF A = gNumRains + 1 THEN WRITE #10, ""
   Loop
   Exit Sub
   'If A = gNumRains + 1 Then Exit Sub Else GoTo 9220: Rem  end of street cleaning/washoff loop
         Rem IF A = gNumRains + 1 THEN CLOSE #9: EXIT SUB ELSE GOTO 9220: REM  end of street
cleaning/washoff loop

CalcAccumulation:
9540 Rem   calculate accumulation [lbs/curb-mi] to get before event loading
    If AccumDur > MaxAccumTime Then AccumDur = MaxAccumTime
    BeforeEventLoad = gBStAcc(EE) * AccumDur + gCStAcc(EE) * AccumDur ^ 2 + CurrentLoad: Rem
lbs/(curb mi - day)
    If InitGTMax$ = "Y" And BeforeEventLoad < MaxLoad Then InitGTMax$ = "N"
    If InitGTMax$ = "N" And BeforeEventLoad > MaxLoad Then BeforeEventLoad = MaxLoad
    Return

9680 Rem   calculate street dirt removal from street cleaning
    If BeforeEventLoad < gB(EE) / (1 - gM(EE)) Then
        AfterEventLoad = BeforeEventLoad
      Else
        AfterEventLoad = gM(EE) * BeforeEventLoad + gB(EE)
    End If
```

```
    Rem WRITE #9, gJulStClDate(SCNUM), typeevent, "S", beforeeventload, "BEFORE EVENT LOAD",
SCNUM, S
    Rem WRITE #9, gJulStClDate(SCNUM), typeevent, "S", Aftereventload, "AFTER EVENT LOAD",
SCNUM, S
    SCNum = SCNum + 1
    Return

9760 Rem    calc washoff from rain event  TypeEvent = 2
      GoSub 10140:     Rem   calc availability factor
      NSub0 = BeforeEventLoad * AvailFactor
      GoSub 10500:     Rem   calc K
      GoSub 10680:     Rem   calc correction factor
      NStar = NSub0 * Exp(-k * gRain(A) * 25.4) * CorFactor: Rem  K -  [1/mm] , gRain - [in] , after storm
avail load
      UnavailAftRain = BeforeEventLoad - NSub0
      AfterEventLoad = UnavailAftRain + NStar
      Washoff = BeforeEventLoad - AfterEventLoad: Rem   [lbs/curb-mile]
      If Washoff < 0 Then
          Washoff = 0
          AfterEventLoad = BeforeEventLoad
      End If
      gPartSolYield(A, s) = Washoff * gStreetLen(EE): Rem  [lbs]
      gPartSolConc(A, s) = gPartSolYield(A, s) / gRunoffVol(A, s) * (454000! / 28.32)
      PreviousTime = gJulianEventStartTime(A) + gRainDur(A)
      Rem WRITE #9, gJulianEventStartTime(A), typeevent, "W", beforeeventload, "BEFORE EVENT
LOAD", A, S, gRain(A)
      Rem WRITE #9, gJulianEventStartTime(A), typeevent, "W", Aftereventload, "AFTER EVENT LOAD",
A, S
    Rem A = A + 1
    Return

10140 Rem    calc availality factor
    Select Case gStTexture(EE)
      Case 1, 2: Rem  for smooth & intermediate streets
       P00 = 0.098: P10 = 0.13: P01 = 0.077: P11 = 0.26
      Case 3, 4: Rem  for rough & very rough streets
       P00 = 0.028: P10 = 0.032: P01 = 0.061: P11 = 0.11
    End Select
    GoSub 11480: Rem   two-way linear interpolation algorithm
    AvailFactor = Value
    Return

10500 Rem    calc K
    P00 = 0.62: P10 = 0.12: P01 = 0.33: P11 = 0.92
    GoSub 11480
    k = Value
    Return

10680 Rem    calc correction factor
    Rain = gRain(A) * 25.4: Rem   25.4mm/in
    Value = 0
    Select Case gStTexture(EE)
       Case 1, 2: Rem  smooth and int text
          If Rain >= 4 And RainInt >= 12 Then
```

```
            Value = 1
          Else
            P00 = 1
            P10 = 1
            If Rain <= 0.5 Then
                P01 = 0.7
              ElseIf Rain > 0.5 And Rain < 1 Then
                P01 = 0.7 + (1 - 0.7) / (1 - 0.5) * (Rain - 0.5)
              ElseIf Rain >= 1 Then
                P01 = 1
            End If
            P11 = 1
        End If
      Case 3, 4: Rem  rough and very rough
        If Rain >= 2 And RainInt >= 12 Then
            Value = 1
          Else
            P00 = 1
            If Rain <= 1.25 Then
                P10 = 0.15
              ElseIf Rain > 1.25 And Rain < 2 Then
                P10 = 0.15 + (1 - 0.15) / (2 - 1.25) * (Rain - 1.25)
              ElseIf Rain >= 2 Then
                P10 = 1
            End If
            If Rain <= 0.5 Then
                P01 = 0.15
              ElseIf Rain > 0.5 And Rain <= 1 Then: P01 = 0.15 + (0.6 - 0.15) / (1 - 0.5) * (Rain - 0.5)
              ElseIf Rain > 1 And Rain <= 1.5 Then: P01 = 0.6 + (0.75 - 0.6) / (1.5 - 1) * (Rain - 1)
              ElseIf Rain > 1.5 And Rain <= 2 Then: P01 = 0.75 + (1 - 0.75) / (2 - 1.5) * (Rain - 1.5)
              ElseIf Rain > 2 Then: P01 = 1
            End If
            P11 = 1
        End If
    End Select
    If Value = 1 Then
        CorFactor = 1
        Return
      Else
        GoSub 11480
        CorFactor = Value
    End If
    Return

11480 Rem   two-way linear int algorithm
    RainInt = gRain(A) * 25.4 / (gRainDur(A) * 24): Rem   Rain Intensity [mm/hr] = [in] * 25.4 mm/in /
([days] * 24 hrs/day)
    If RainInt <= 3 And BeforeEventLoad >= 135 Then
        Value = P00
      ElseIf (RainInt > 3 And RainInt < 12) And BeforeEventLoad >= 135 Then
        GoSub 11800: Value = LinInt1
      ElseIf RainInt >= 12 And BeforeEventLoad >= 135 Then
        Value = P10
      ElseIf RainInt >= 12 And (BeforeEventLoad > 25 And BeforeEventLoad < 135) Then
```

```
         LinInt1 = P10: LinInt2 = P11: GoSub 11880: Value = LinInt3
      ElseIf RainInt >= 12 And BeforeEventLoad <= 25 Then
         Value = P11
      ElseIf (RainInt > 3 And RainInt < 12) And BeforeEventLoad <= 25 Then
         GoSub 11840: Value = LinInt2
      ElseIf RainInt <= 3 And BeforeEventLoad <= 25 Then
         Value = P01
      ElseIf RainInt <= 3 And (BeforeEventLoad > 25 And BeforeEventLoad < 135) Then
         LinInt1 = P00: LinInt2 = P01: GoSub 11880: Value = LinInt3
      ElseIf (RainInt > 3 And RainInt < 12) And (BeforeEventLoad > 25 And BeforeEventLoad < 135) Then
         GoSub 11800: GoSub 11840: GoSub 11880: Value = LinInt3
   End If
   Return

   Rem   linear int. calcs
11800   LinInt1 = P00 + (P10 - P00) / (12 - 3) * (RainInt - 3)
   Return
11840   LinInt2 = P01 + (P11 - P01) / (12 - 3) * (RainInt - 3)
   Return
11880   LinInt3 = LinInt2 + (LinInt1 - LinInt2) / (135 - 25) * (BeforeEventLoad - 25)
   Return

End Sub

Public Sub proJulianStCleanDates(EE As Integer, gJulStClDate() As Single)

'   Sub JSCSCHED(EE, JSCDATE())
   '  gJulStClDate()   Julian Street Cleaning Date  DOS == JSCDATE()
   ReDim FixedJStClDate(10) As Single   '  == gStCleanDate$(10), DOS == FIXEDJSCDATE#(10)
   Dim DayName As Integer   ' DOS == DAYNAME
   Dim StCleaningNum As Integer    'Street cleaning number  DOS == SCNUM
   Dim TtlNumStCleanings As Integer  'Total number of street cleanings  DOS == TTLNUMSC
   Dim StClCyComp As Integer  'Street cleaning cycle complete, ie for one cleaning every two weeks,
   '              after two weeks StClCyComp = 1  DOS == DUM35
   Dim StClBypass As Integer  ' Used to bypass street cleaing date assignment if the schedule indicates
   '              that street cleaning does not occur on the current day, ie StClBypass = 0 ==> current day
   '              is a street cleaning day  DOS == DUM34
   Dim DaysBtwnStClDates As Integer  ' Days between street cleaning dates  DOS == DAYSBTWNSCD
   Dim Change As Integer
   Dim Day As Integer

   Rem   change schedule dates to julian dates
   For Change = 0 To gStCleanSchedChanges(EE)
'      Y = Val(Mid$(gStCleanDate$(Change, EE), 7, 2))
'      M = Val(Mid$(gStCleanDate$(Change, EE), 1, 2))
'      D = Val(Mid$(gStCleanDate$(Change, EE), 4, 2))
'      Call JULIAN(Y, M, D, H, Min, JDate#)
'      gJStCleanDate(Change) = JDate# + 0.5
      FixedJStClDate(Change) = funJulianDate(gStCleanDate$(Change, EE)) + 0.5
   Next Change
   StCleaningNum = 1
   TtlNumStCleanings = 0
   For Change = 0 To gStCleanSchedChanges(EE) - 1
      StClBypass = 0
```

```
        StClCyComp = 0
        DaysBtwnStClDates = FixedJStClDate(Change + 1) - FixedJStClDate(Change)
        If Change = gStCleanSchedChanges(EE) - 1 Then
          DaysBtwnStClDates = FixedJStClDate(Change + 1) - FixedJStClDate(Change) + 1
        End If
        DayName = (FixedJStClDate(Change) - 0.5) Mod 7 + 1
        For Day = 1 To DaysBtwnStClDates
'                Select Case gStCleanFreq(Change + 1, EE)
                Select Case gStCleanFreq(Change, EE)
                  Case 1: Rem  no street cleanings
                     StClBypass = 1
                     If DayName = 7 Then DayName = 1: StClBypass = 0: StClCyComp = 1
                  Case 2: Rem  7 passes/week
                     If DayName = 7 Then DayName = 1
                  Case 3: Rem  5 passes/week
                     If DayName = 6 Then StClBypass = 1
                     If DayName = 7 Then DayName = 1: StClBypass = 0: StClCyComp = 1
                  Case 4: Rem  4 passes/week
                     If DayName = 3 Or DayName = 6 Then StClBypass = 1
                     If DayName = 7 Then DayName = 1: StClBypass = 0: StClCyComp = 1
                  Case 5: Rem  3 passes/week
                     If DayName = 2 Or DayName = 4 Or DayName = 6 Then StClBypass = 1
                     If DayName = 7 Then DayName = 1: StClBypass = 0: StClCyComp = 1
                  Case 6: Rem  2 passes/week
                     If DayName = 1 Or DayName = 3 Or DayName = 5 Or DayName = 6 Then StClBypass = 1
                     If DayName = 7 Then DayName = 1: StClBypass = 0: StClCyComp = 1
                  Case 7: Rem  1 pass/week
                     If DayName <> 3 And DayName <> 7 Then StClBypass = 1
                     If DayName = 7 Then DayName = 1: StClBypass = 0: StClCyComp = 1
                  Case 8: Rem  1 pass/2 weeks
                     If DayName <> 10 And DayName <> 14 Then StClBypass = 1
                     If DayName = 14 Then DayName = 1: StClBypass = 0: StClCyComp = 1
                  Case 9: Rem  1 pass/4 weeks
                     If DayName <> 24 And DayName <> 28 Then StClBypass = 1
                     If DayName = 28 Then DayName = 1: StClBypass = 0: StClCyComp = 1
                  Case 10: Rem  1 pass/8 weeks
                     If DayName <> 52 And DayName <> 56 Then StClBypass = 1
                     If DayName = 56 Then DayName = 1: StClBypass = 0: StClCyComp = 1
                  Case 11: Rem  1 pass/12 weeks
                     If DayName <> 80 And DayName <> 84 Then StClBypass = 1
                     If DayName = 84 Then DayName = 1: StClBypass = 0: StClCyComp = 1
                End Select
                If StClBypass = 1 Then StClBypass = 0: GoTo 12860
                If StClCyComp = 1 Then StClCyComp = 0: GoTo 12880
                gJulStClDate(StCleaningNum) = FixedJStClDate(Change) + Day - 1
                TtlNumStCleanings = TtlNumStCleanings + 1
                StCleaningNum = StCleaningNum + 1
12860       DayName = DayName + 1
12880  Next Day
    Next Change

End Sub

Public Sub proRecalcStDirtLoadings()
```

```
   Dim EE As Integer
   Dim s As Integer
   Dim pStreetRound As Integer
   Dim A As Integer

   '6300  Rem  recalc street loadings w/ gStDirtStored
         'E = 0
         gPondLUNum(gNumAreas - 1) = 10
         gPondLUNum(gNumAreas) = 11
         pStreetRound = 2
         'ReDim gLUCurbRatio(15)
         Rem WRITE #10, "CALCULATE STREET DIRT STORED"
         For s = 1 To gNumAreas - 2
            EE = gSAArNum(s) + 10 - 27 * gPondLUNum(s)
            'If gS$(gSANum(gSAArNum(S))) = "S" Then Call proJulianStCleanDates(EE, gJulStClDate())
            If gTSArea(gSAArNum(s)) = 0 Then GoTo 6340
            For A = gFirstRainNum To gLastRainNum
               If gRainDur(A) > 0 Then 'GoTo 6320
                  If (gSAName(gSAArNum(s)) >= 18 And gSAName(gSAArNum(s)) <= 20) Then 'GoSub
6500
                     Call proTSSStreets(A, s, EE, pStreetRound)
                  End If
               End If
               Rem DTSTART = 3
               Rem GOSUB 7900
               Rem gStDirtStored(A, gPondLUNum(S)) = gStDirtStored(A, gPondLUNum(S)) +
gPartSolYield(A, S) * (1 - WASHPARTFrac)
               Rem WRITE #10, A, S, gPondLUNum(S), gStDirtStored(A, gPondLUNum(S)),
gPartSolYield(A, S), (1 - WASHPARTFrac), gRain(A)
            Next A    '  6320
6340      Next s

End Sub

Public Static Sub proPartResReduction(DTStart As Integer, WashPartFrac As Single, A As Integer)

   Dim YCol As Integer   'DOS == YCOL
   Dim DT As Integer    'DOS == DT
   Dim PRDFrac As Single   ' DOS == PRDFrac
   Dim Rain As Single
   Dim Col As Single
   Dim RainRatio As Single

   '7900    '  Particulate Residue Reduction due to Delivery calcs
   Rain = gRain(A) * 25.4
   WashPartFrac = 0
   For Col = 1 To 14
     If mRainAr(Col) >= Rain Then
        RainRatio = (Rain - mRainAr(Col - 1)) / (mRainAr(Col) - mRainAr(Col - 1))
        YCol = Col
        Exit For
     End If
   Next Col
```

```
    Rem   DT==fDrainType
    Rem  PRDFrac::Particulate Reduction in the Delivery system Fraction   -
    Rem        fraction of runoff loading from each source area that settles
    Rem        into the delivery system before the runoff reaches the outfall.
    Rem  WashPartFrac::WASHoff PARTiculate Fraction  -  particulate loading    DOS ==
WASHPARTFrac
    Rem        fraction that did not settle into the delivery system, but
    Rem        remained in the washoff
    For DT = DTStart To 5
        If Rain <= 1 Then
                PRDFrac = mPRRFrac(DT, 1)
            ElseIf Rain >= 80 Then
                PRDFrac = mPRRFrac(DT, 14)
            Else
                PRDFrac = mPRRFrac(DT, YCol - 1) + (mPRRFrac(DT, YCol) - mPRRFrac(DT, YCol - 1)) *
RainRatio
        End If
        WashPartFrac = WashPartFrac + (1 - PRDFrac) * gDrainArea(DT)
    Next DT

End Sub

Public Sub proReCalcWithDetention(FROMCALC As String)

    Dim TotPcCncRed As Single       'DOS == TOTPCCNCRED
    Dim s As Integer
    Dim X As Integer
    Dim A As Integer
    Dim DPE As Integer

'8240 Rem   recalc values using det pond results
        If FROMCALC$ = "" Then Exit Sub
        'CLS: LOCATE 13, 32: Print "Re-entered module CALC62"
        For s = 1 To gNumAreas - 2
            If gTSArea(gSAArNum(s)) > 0 Then      'GoTo 8560
                For X = 1 To gTtlNumDP
                    If gDPSANumMatch(X).SANum = gSAArNum(s) Then
                        DPE = X
                        Exit For         ': X = 10
                    End If
                Next X
                For A = gFirstRainNum To gLastRainNum
                    'LOCATE 1, 1: Print "Source Area #: "; gSANum
                    'LOCATE 2, 1: Print "Rain #: "; A
                    TotPcCncRed = gWghtdTSReduct(A, DPE) * gPondAreaServ(gSAArNum(s)) /
gTSArea(gSAArNum(s))
                    gPartSolConc(A, s) = gPartSolConc(A, s) * (1 - TotPcCncRed)
                    gRunoffVol(A, s) = gRunoffVol(A, s) * (1 - gPCDPVolReduct(A, DPE) * _
                                    gPondAreaServ(gSAArNum(s)) / gTSArea(gSAArNum(s)))
                    gPartSolYield(A, s) = gPartSolConc(A, s) * gRunoffVol(A, s) * (28.32 / 454000!)
                Next A
                DPE = 0
            End If
        Next s    '8650
```

```
End Sub

Public Sub proCalcEventSATotals()

   ReDim gEventTtlRunVol(gFirstRainNum To gLastRainNum) As Single
   Dim DCNum As Integer  '  Drainage Control Number, ie SA Number 161,  DOS == S
   Dim SANum As Integer

   '13840 Rem    calculate total, for each rain, of all source areas
   For A = gFirstRainNum To gLastRainNum    '1 to gnumrains
      For SANum = 1 To gNumAreas - 2
         gEventTtlRunVol(A) = gEventTtlRunVol(A) + gRunoffVol(A, SANum)
         gEventTtlPartLoad(A) = gEventTtlPartLoad(A) + gPartSolYield(A, SANum)
      Next SANum
      If gEventTtlRunVol(A) > 0 Then 'GoTo 15300, Next A
         gEventTtlPartConc(A) = gEventTtlPartLoad(A) / gEventTtlRunVol(A) / (28.32 / 454000)
      End If
   Next A    '15300

End Sub
```

Attribute VB_Name = "CalcPollutants"

```
Option Explicit

    Public gUnitCon(48) As Single      'UNITCON
    Public gSeqUnitCon(48) As Single      'Sequential Unit Conversion, used to put in series only those
pollutants that are being calculated in model run
    Dim mPollArrayNum(47) As Integer         'PARNUM
    Dim mFiltOthUnit(4) As Single            'FILTOTHUNIT
    Dim mPartOthUnit(3) As Single              'PARTOTHUNIT
    Dim mPolNum As Integer
    'Public gPolCalc(48) As Integer               'POLCALC  used to determine if polutant is particulate (1),
filterable (2), or total (3)
```

```
Public Function funLogNormPolVal(PolMean As Single, POLCOV As Single)

    'Log Normal Pollutant Value

    Dim MeanY As Single
    Dim VarianceY As Single
    Dim U1 As Single
    Dim U2 As Single
    Dim NormValue As Single
    Dim Y As Single

    Rem   POLMEAN = POLMEAN#(PARNUM(POL),ROW,G)
    Rem      the pollutant mean for the current value
    Rem   POLCOV = POLCOV(PARNUM(POL),ROW,G)
    Rem      the pollutant coefficient of variation for the current value
    Rem   x ==> variable value in real space
    Rem   y ==> variable value in log space; ie, y=natural log (LN(x))

    If PolMean = 0 Then
        funLogNormPolVal = 0     'POLVAL
        Exit Function
    End If
    MeanY = Log(PolMean) - (1 / 2 * Log(POLCOV ^ 2 + 1))
    VarianceY = Log(POLCOV ^ 2 + 1)
    U1 = Rnd
    U2 = Rnd
    NormValue = (-2 * Log(U1)) ^ (1 / 2) * Cos(2 * 3.14159265359 * U2)
    Y = NormValue * Sqr(VarianceY) + MeanY
    funLogNormPolVal = Exp(Y)        'POLVAL
```

```
   Rem WRITE #8, i, POLMEAN#, POLCOV, MEANy, VARIANCEy, U1, U2, NORMVALUE, y, POLVAL

End Function

Public Sub proMainPolCalc()

   Dim Pol As Integer
   Dim LUNum As Integer     'G
   Dim SANum As Integer      'E
   Dim RainNum As Integer
   Dim SourceAreaType As Integer
   Dim PolFileRow As Integer
   Dim Seed As Single
   Dim Start As Integer       'STRT
   Dim Fin As Integer          'FIN
   Dim Count As Integer      'Count
   Dim A As Integer         'j   rain number counter
   Dim s As Integer
   Dim PolValue As Single
   Dim PcPolYieldRed161 As Single
   Dim PcPolYieldRed162 As Single
   Dim EngUnitCon As Single        'English Unit Conversion value to convert lbs/cf to mg/L or ug/L

   If gSeed = 0 Then
         Seed = Timer
         Randomize Seed
      Else
         Rnd (-1)
         Randomize gSeed
   End If

   Call proInitVariables          ' initialize variables
   Call proLoadPolFile
   Call proWhichPollutants        'gosub 3000      determine other pollutants to be calculated,  gNumOfPol
   'GoSub 20280:    Rem  load 2-dim variables
   If gNumOfPol = 0 Then Exit Sub
   Call proOtherPolUnitConversion         'GoSub 3160:     Rem  determine other pollutant unit conversions
   'ReDim YLDPCRED161(NUMRNS), YLDPCRED162(NUMRNS), RUNPCRED161(NUMRNS),
RUNPCRED162(NUMRNS)
   ReDim gPolYield(gFirstRainNum To gLastRainNum, gNumAreas, gNumOfPol)
   ReDim gPolConc(gFirstRainNum To gLastRainNum, gNumAreas, gNumOfPol)
   ReDim gPolYieldAtOutfall(gFirstRainNum To gLastRainNum, gNumOfPol)
   ReDim gPolConcAtOutfall(gFirstRainNum To gLastRainNum, gNumOfPol)
   ReDim gPrintPol(1 To gNumOfPol)
   ReDim Preserve gModelRunTotal(gNumOfPol + 2)  'for totals for batch processing

   mPolNum = 0
   gNumOfPolsToPrn = 0
   For Pol = 1 To 48
      If gPolCalc(Pol) > 0 Then        'GoTo 2520
      'gPrintPol(gNumOfPolsToPrn) = Pol
         mPolNum = mPolNum + 1
         If gUsePol(Pol) = 1 Then
            gPrintPol(mPolNum) = True
```

```
            gNumOfPolsToPrn = gNumOfPolsToPrn + 1
          End If
          gSeqUnitCon(mPolNum) = Pol
          'ReDim YIELD(NUMRNS, NumAreas), CONC(NUMRNS, NumAreas), TTCNC(NUMRNS),
TTYLD(NUMRNS)
          'ReDim TTCNC161(NUMRNS), TTCNC162(NUMRNS), TTYLD161(NUMRNS),
TTYLD162(NUMRNS), TTLPSYLDF(NUMRNS)
          GoSub 3500: Rem   calc polutant values
          GoSub 4000    ' Calculate Outfall Pollutant Values
      End If
   Next Pol        '2520


   Exit Sub

3500 Rem   calc value * pollutant factor POLVAL()
   Rem    SANum == source area counter for pollutant calcs   S
   Rem    RainNum == rain counter for pollutant calcs       a
      For s = 1 To gNumAreas - 2
        If gTSArea(gSAArNum(s)) > 0 Then        'GoTo 3600
           's = s + 1
           LUNum = Int(gSAArNum(s) / 30) + 1
           For A = gFirstRainNum To gLastRainNum
              'SourceAreaType = SANum - (LUNum - 1) * 30
              Call proPolFileRow(gSAArNum(s), LUNum, PolFileRow)
              Select Case gPolCalc(Pol) 'GoSub 4200, 4440, 4500
                   Case 1        'particulate value calc       4200
                         If Pol = 1 Then
                              'PARTYLD(a, S) = PSYLDF(a, S): YIELD(a, S) = PARTYLD(a, S)
                              'CONC(a, S) = gPSCncF(a, S)
                            ElseIf Pol > 1 Then
                              PolValue = funLogNormPolVal(gPolMean(mPollArrayNum(Pol), PolFileRow,
LUNum), gPolCOV(mPollArrayNum(Pol), PolFileRow, LUNum))
                              gPolYield(A, s, mPolNum) = gPartSolYield(A, s) * PolValue * gUnitCon(Pol)
'Output Units:  lbs
                              gPolYieldAtOutfall(A, mPolNum) = gPolYieldAtOutfall(A, mPolNum) +
gPolYield(A, s, mPolNum)
                              If gRunoffVol(A, s) = 0 Then
                                    gPolYield(A, s, mPolNum) = 0
                                    gPolConc(A, s, mPolNum) = 0
                                 Else
                                    gPolConc(A, s, mPolNum) = gPolYield(A, s, mPolNum) / gRunoffVol(A, s) /
gUnitCon(Pol + 1)
                              End If
                             Rem blumfrac = (a - 3 / 8) / (NUMRNS + 1 - 3 / 4)
                             Rem blumposition = (blumfrac ^ .135 - (1 - blumfrac) ^ .135) / .1975
                             Rem WRITE #8, a, S, POL, PSYLDF(a, S), UNITCON(POL), RUNVOLF(a, S),
UNITCON(POL + 1), YIELD(a, S), a, blumposition, CONC(a, S), POLVAL
                         End If
                   Case 2        'filterable value calc     4440
                         If gRunoffVol(A, s) > 0 Then
                              gPolConc(A, s, mPolNum) =
funLogNormPolVal(gPolMean(mPollArrayNum(Pol), PolFileRow, LUNum),
gPolCOV(mPollArrayNum(Pol), PolFileRow, LUNum))
```

```
                    Else
                        gPolConc(A, s, mPolNum) = 0
                    End If
                    gPolYield(A, s, mPolNum) = gRunoffVol(A, s) * gPolConc(A, s, mPolNum) *
gUnitCon(Pol)
                    gPolYieldAtOutfall(A, mPolNum) = gPolYieldAtOutfall(A, mPolNum) + gPolYield(A, s,
mPolNum)
                   ' blumfrac = (a - 3 / 8) / (NUMRNS + 1 - 3 / 4)
                   ' blumposition = (blumfrac ^ .135 - (1 - blumfrac) ^ .135) / .1975
                   ' WRITE #8, a, S, POL, UNITCON(POL), RUNVOLF(a, S), YIELD(a, S), a,
blumposition, CONC(a, S), POLMEAN#(PARNUM(POL), ROW, G), POLCOV(PARNUM(POL), ROW, G),
POLVAL, SEED
                Case 3          'total value calc       4500
                    gPolYield(A, s, mPolNum) = gPolYield(A, s, mPolNum - 2) + gPolYield(A, s, mPolNum
- 1)
                    gPolYieldAtOutfall(A, mPolNum) = gPolYieldAtOutfall(A, mPolNum) + gPolYield(A, s,
mPolNum)
                    If gRunoffVol(A, s) = 0 Then
                        gPolConc(A, s, mPolNum) = 0
                    Else
                        gPolConc(A, s, mPolNum) = gPolYield(A, s, mPolNum) / gRunoffVol(A, s) /
gUnitCon(Pol): Rem [mg/L=lbs/cuft*4.535e5 mg/lb * 1 cuft/28.3 L]
                    End If
              End Select
          Next A
        End If
      Next s     '3600
   Return
   Exit Sub


4000  'Calculate Outfall Values

    'Calculate percent reductions for each event
    'For A = gFirstRainNum To gLastRainNum
      'gPcRunoffVolRed161(A) = 1 - (gEventTtlRunVol(A) - gRunoffVol(A, gNumAreas - 1)) /
gEventTtlRunVol(A)
      ' gPcPolYieldRed161(A) = 1 - (gEventTtlPartLoad(A) - gPartSolYield(A, gNumAreas - 1)) /
gEventTtlPartLoad(A)
      'gPcPolYieldRed162(A) = 1 - (gPcPolYieldRed161(A) - gPartSolYield(A, gNumAreas)) /
gPcPolYieldRed161(A)
    'Next A

    'Calculate outfall values
    'Pollutant Yields - calculated in proLoadPollutants as variable LUTotalPerRain(A), also as variable
gPolYieldAtOutfall(a,npolnum)
    'Pollutant Concentrations
    EngUnitCon = 0
     If Pol <= 30 Then
        If gSeqUnitCon(mPolNum) Mod 3 = 0 Then
            EngUnitCon = gUnitCon(gSeqUnitCon(mPolNum))
          Else
            EngUnitCon = (gUnitCon((gSeqUnitCon(mPolNum) \ 3 + 1) * 3))
        End If
```

```
          If Pol = 17 Then EngUnitCon = 283
        Else
          Select Case gUnitType(gSeqUnitCon(mPolNum))
'             Case 1
'                EngUnitCon = 1 / 16028000000#
            Case 1     'convert lbs/cf ==> ug/L
              EngUnitCon = 1 / 16028000
            Case 2     'convert lbs/cf ==> mg/L
              EngUnitCon = 1 / 16028
            Case 3     'convert #/100 mL ==>
              EngUnitCon = 283
          End Select
          'EngUnitCon = gUnitCon(gSeqUnitCon(mPolNum))
        End If

      For A = gFirstRainNum To gLastRainNum
        If gEventTtlRunVol(A) > 0 And EngUnitCon > 0 Then
          gPolConcAtOutfall(A, mPolNum) = gPolYieldAtOutfall(A, mPolNum) / gEventTtlRunVol(A) /
EngUnitCon         'gUnitCon(Pol)
        End If
        If gEventTtlPartLoad(A) > 0 Then
          PcPolYieldRed161 = 1 - (gEventTtlPartLoad(A) - gPartSolYield(A, gNumAreas - 1)) /
gEventTtlPartLoad(A)
        End If
        gPolYield(A, gNumAreas - 1, mPolNum) = gPolYieldAtOutfall(A, mPolNum) * PcPolYieldRed161
        If gPartSolYield(A, gNumAreas - 1) > 0 Then
          PcPolYieldRed162 = 1 - (gPartSolYield(A, gNumAreas - 1) - gPartSolYield(A, gNumAreas)) /
gPartSolYield(A, gNumAreas - 1)
        End If
        gPolYield(A, gNumAreas, mPolNum) = gPolYield(A, gNumAreas - 1, mPolNum) *
PcPolYieldRed162
        gModelRunTotal(mPolNum + 2) = gModelRunTotal(mPolNum + 2) + gPolYield(A, gNumAreas,
mPolNum)
        If gRunoffVol(A, gNumAreas - 1) > 0 And EngUnitCon > 0 Then
          gPolConc(A, gNumAreas - 1, mPolNum) = gPolYield(A, gNumAreas - 1, mPolNum) /
gRunoffVol(A, gNumAreas - 1) / EngUnitCon
        End If
        If gRunoffVol(A, gNumAreas) > 0 And EngUnitCon > 0 Then
          gPolConc(A, gNumAreas, mPolNum) = gPolYield(A, gNumAreas, mPolNum) / gRunoffVol(A,
gNumAreas) / EngUnitCon
        End If
      Next A

    Return


'4200 Rem   particulate value calc (from 3500)
'   If Pol = 1 Then
'      PARTYLD(a, s) = PSYLDF(a, s): YIELD(a, s) = PARTYLD(a, s)
'      CONC(a, s) = gPSCncF(a, s)
'   ElseIf Pol > 1 Then
'      PARTYLD(a, s) = gPartSolYield(a, s) * funLogNormPolVal * gUnitCon(Pol)
'      YIELD(a, s) = PARTYLD(a, s)
'      If gRunoffVol(a, s) = 0 Then CONC(a, s) = 0: Return
```

```
'       CONC(a, s) = PARTYLD(a, s) / gRunoffVol(a, s) / gUnitCon(Pol + 1)
'       Rem blumfrac = (a - 3 / 8) / (NUMRNS + 1 - 3 / 4)
'       Rem blumposition = (blumfrac ^ .135 - (1 - blumfrac) ^ .135) / .1975
'       Rem WRITE #8, a, S, POL, PSYLDF(a, S), UNITCON(POL), RUNVOLF(a, S), UNITCON(POL + 1),
YIELD(a, S), a, blumposition, CONC(a, S), POLVAL
'     End If
'     GTPYLD(a) = GTPYLD(a) + YIELD(a, s)
'    Return
'
'4440 Rem   filterable value calc
'    FILTYLD(a, s) = gRunoffVol(a, s) * funLogNormPolVal * gUnitCon(Pol)
'    YIELD(a, s) = FILTYLD(a, s)
'    GTFYLD(a) = GTFYLD(a) + YIELD(a, s)
'    CONC(a, s) = POLVAL
'       Rem blumfrac = (a - 3 / 8) / (NUMRNS + 1 - 3 / 4)
'       Rem blumposition = (blumfrac ^ .135 - (1 - blumfrac) ^ .135) / .1975
'       Rem WRITE #8, a, S, POL, UNITCON(POL), RUNVOLF(a, S), YIELD(a, S), a, blumposition,
CONC(a, S), POLMEAN#(PARNUM(POL), ROW, G), POLCOV(PARNUM(POL), ROW, G), POLVAL,
SEED
'    Return
'
'4500 Rem   total value calc
'     YIELD(a, s) = PARTYLD(a, s) + FILTYLD(a, s)
'     If RUNVOLF(a, s) = 0 Then
'           CONC(a, s) = 0
'        Else
'           CONC(a, s) = YIELD(a, s) / gRunoffVol(a, s) / gUnitCon(Pol): Rem [mg/L=lbs/cuft*4.535e5 mg/lb
* 1 cuft/28.3 L]
'    End If
'    Return
'
'4550 Rem   recalc percentage yield values for other polutants
'    For a = 1 To NUMRNS
'      If RUNVOLF(a, s) = 0 Then
'        PCTTLPSYLDF(a, s) = 0
'         Else: PCTTLPSYLDF(a, s) = (YIELD(a, s) / TTLPSYLDF(a)) * 100
'      End If
'    Next a
'    Return


5240 Rem    parameters and title for first heading set
'     If POL = 1 Then
'         If T = 1 Then
'          UNIT$ = "(cu. ft.)"
'         ElseIf T = 2 Then
'          UNIT$ = "(mg/L)"
'         ElseIf T = 3 Then
'          UNIT$ = "(lbs)"
'         ElseIf T > 3 Then
'          UNIT$ = ""
'         End If
'       ElseIf (POL Mod 3 = 1 And POL <> 1) Then
'         If T = 2 Then
```

```
'         If (POL > 3 And POL < 11) Or (POL > 18 And POL < 31) Then
'             UNIT$ = "(micrograms/L)"
'          ElseIf UNITCON(POL) = 0.000001 Then
'             UNIT$ = "(mg/L)"
'          ElseIf UNITCON(POL) = 0.000000001 Then
'             UNIT$ = "(micrograms/L)"
'          ElseIf UNITCON(POL) = 0.000000000001 Then
'             UNIT$ = "(nanograms/L)"
'         End If
'       ElseIf T = 3 Then
'       UNIT$ = "(lbs)"
'       End If
'     ElseIf POL Mod 3 = 2 Or POL Mod 3 = 0 Then
'       If T = 2 Then
'       If UNITCON(POL) = 0.0000624 Then
'           UNIT$ = "(mg/L)"
'         ElseIf UNITCON(POL) = 0.0000000624 Then
'           UNIT$ = "(micrograms/L)"
'         ElseIf UNITCON(POL) = 283 Then
'           UNIT$ = "(#/100 ml)"
'         ElseIf UNITCON(POL) = 0.0000000000624 Then
'           UNIT$ = "(nanograms/L)"
'       End If
'       ElseIf T = 3 Then
'       If UNITCON(POL) <> 283 Then
'          UNIT$ = "(lbs)"
'         ElseIf UNITCON(POL) = 283 Then
'          UNIT$ = "( # (count))"
'       End If
'       End If
'   End If
'   If T > 3 Then UNIT$ = ""
'   If POL >= 31 And POL Mod 3 >= 2 Then PNAME$(POL) = FILTPOLNAME$(POL)
'   If POL >= 31 And POL Mod 3 = 1 Then PNAME$(POL) = PARTPOLNAME$(POL)
'   If PNAME$(POL) = "" Then PNAME$(POL) = PNAME$(POL - 2) + " and " + PNAME$(POL - 1)
'   If POpt <= 2 Then
'     Print #w,: Print #w, LUT$(G); " - "; TBLTIT$(T);
'     If T = 1 Or T = 4 Then
'         Print #w, ""
'      Else: Print #w, PNAME$(POL); "  "; UNIT$
'     End If
'   End If

   Return

End Sub

Public Sub proInitVariables()

'15080 Rem ***********   initialize variables  ***************************
'   For V = 1 To 30
'       READ UNITCON(V)
'   Next V
'   For V = 1 To 47
```

```
'       READ PARNUM(V)
'    Next V

   Rem       UNITCON(2 - 30)
   Rem  convert mg/L to lbs pollutant for a cf volume::[28.3 L/cu.ft.*2.205e-6 lb/mg = 6.24e-5]
   Rem  [1 kg/1000000 mg = 1e-6]
   Rem  [28.3 L/cu.ft.*100 ml/.1 L = 283]
      gUnitCon(1) = 0                          'PARTICULATE SOLIDS
      gUnitCon(2) = 0.0000624              'FILTERABLE SOLIDS
      gUnitCon(3) = 0.0000624               'TOTAL SOLIDS
      gUnitCon(4) = 0.000001                'PARTICULATE PHOSPHORUS
      gUnitCon(5) = 0.0000624          'FILTERABLE PHOSPHORUS
      gUnitCon(6) = 0.0000624           'TOTAL PHOSPHORUS
      gUnitCon(7) = 0#                       'Not Applicable
'      gUnitCon(7) = 0.000001                'PARTICULATE PHOSPHATE
      gUnitCon(8) = 0.0000624             'Nitrates
'      gUnitCon(9) = 0.0000000624             'TOTAL PHOSPHATE
      gUnitCon(9) = 0.0000000624                   'Not Applicable
      gUnitCon(10) = 0.000001                 'PARTICULATE TKN
      gUnitCon(11) = 0.0000624            'FILTERABLE TKN
      gUnitCon(12) = 0.0000624            'TOTAL TKN
      gUnitCon(13) = 0.000001                    'PARTICULATE CHEMICAL OXYGEN DEMAND
      gUnitCon(14) = 0.0000624                'FILTERABLE CHEMICAL OXYGEN DEMAND
      gUnitCon(15) = 0.0000624                 'TOTAL CHEMICAL OXYGEN DEMAND
      gUnitCon(16) = 0                              '
      gUnitCon(17) = 283     'FILTERABLE FECAL COLIFORM BACTERIA  #/mL*ft^3*[0.0283
m^3/ft^3]*[1L/10e-3m^3]*[1000mL/L]
      gUnitCon(18) = 0                              'TOTAL FECAL COLIFORM BACTERIA
      gUnitCon(19) = 0.000001                 'PARTICULATE CHROMIUM
      gUnitCon(20) = 0.0000000624            'FILTERABLE CHROMIUM
      gUnitCon(21) = 0.0000000624          'TOTAL CHROMIUM
      gUnitCon(22) = 0.000001                 'PARTICULATE COPPER
      gUnitCon(23) = 0.0000000624          'FILTERABLE COPPER
      gUnitCon(24) = 0.0000000624          'TOTAL COPPER
      gUnitCon(25) = 0.000001                 'PARTICULATE LEAD
      gUnitCon(26) = 0.0000000624          'FILTERABLE LEAD
      gUnitCon(27) = 0.0000000624          'TOTAL LEAD
      gUnitCon(28) = 0.000001                 'PARTICULATE ZINC
      gUnitCon(29) = 0.0000000624          'FILTERABLE ZINC
      gUnitCon(30) = 0.0000000624          'TOTAL ZINC

      mPollArrayNum(1) = 1
      mPollArrayNum(2) = 17
      mPollArrayNum(4) = 2
      mPollArrayNum(5) = 18
      mPollArrayNum(7) = 3
      mPollArrayNum(8) = 19
      mPollArrayNum(10) = 4
      mPollArrayNum(11) = 20
      mPollArrayNum(13) = 5
      mPollArrayNum(14) = 21
      mPollArrayNum(16) = 6
      mPollArrayNum(17) = 22
      mPollArrayNum(19) = 7
```

```
    mPollArrayNum(20) = 23
    mPollArrayNum(22) = 8
    mPollArrayNum(23) = 24
    mPollArrayNum(25) = 9
    mPollArrayNum(26) = 25
    mPollArrayNum(28) = 10
    mPollArrayNum(29) = 26
    mPollArrayNum(31) = 11
    mPollArrayNum(32) = 27
    mPollArrayNum(34) = 12
    mPollArrayNum(35) = 28
    mPollArrayNum(37) = 13
    mPollArrayNum(38) = 29
    mPollArrayNum(40) = 14
    mPollArrayNum(41) = 30
    mPollArrayNum(43) = 15
    mPollArrayNum(44) = 31
    mPollArrayNum(46) = 16
    mPollArrayNum(47) = 32

    'mPartOthUnit(1) = 0.000000000001
    mPartOthUnit(1) = 0.000000001          '1 kg/10e-9 ug
    mPartOthUnit(2) = 0.000001             '1 kg/10e-6 mg
    'mFiltOthUnit(1) = 0.0000000000624
    mFiltOthUnit(1) = 0.0000000624         'lbs/cf / mFiltOthUnit(1) = ug/L
    mFiltOthUnit(2) = 0.0000624            'lbs/cf / mFiltOthUnit(2) = mg/L
    mFiltOthUnit(3) = 283

    'Rem    PARNUM(47)
    'Data 1, 17, , 2, 18, , 3, 19, , 4, 20, , 5, 21, , 6, 22, , 7, 23, , 8, 24, , 9, 25, , 10, 26
    'Data , 11, 27, , 12, 28, , 13, 29, , 14, 30, , 15, 31, , 16, 32


End Sub

Public Sub proWhichPollutants()

  Dim Pol As Integer

  'determine other pollutants to be calculated     3000
  'POLCALC(1) = 1
  'gNumOfPol == Total number of polutants whose values are to be calculated
  'gUsePol == Equals 1 for each polutant that the user has selected for analysis
  'gPolCalc == Equals 1, 2, or 3 depending upon whether a polutant whose values are to be calculated
  '                is a particulate (1), filterable (2), or total (3).

  Erase gPolCalc
  gNumOfPol = 0
  For Pol = 1 To 46 Step 3
    If Pol > 1 And gUsePol(Pol + 2) = 1 Then
        gPolCalc(Pol) = 1
        gPolCalc(Pol + 1) = 2
        gPolCalc(Pol + 2) = 3
        gUnitType(Pol) = gUDPartPolUnit(Pol)
```

```
            gUnitType(Pol + 1) = gUDPartPolUnit(Pol)
            gUnitType(Pol + 2) = gUDPartPolUnit(Pol)
            gNumOfPol = gNumOfPol + 3
         ElseIf Pol > 1 And (gUsePol(Pol) = 1 Or gUsePol(Pol + 1) = 1) Then
            If gUsePol(Pol) = 1 Then
               gPolCalc(Pol) = 1
               gUnitType(Pol) = gUDPartPolUnit(Pol)
               gNumOfPol = gNumOfPol + 1
            End If
            If gUsePol(Pol + 1) = 1 Then
               gPolCalc(Pol + 1) = 2
               gUnitType(Pol + 1) = gUDPartPolUnit(Pol)
               gNumOfPol = gNumOfPol + 1
            End If
         ElseIf Pol = 1 And gUsePol(Pol + 2) = 1 Then
            gPolCalc(Pol + 1) = 2
            gPolCalc(Pol + 2) = 3
            gNumOfPol = gNumOfPol + 2
         ElseIf Pol = 1 And gUsePol(Pol + 1) = 1 Then
            gPolCalc(Pol + 1) = 2
            gNumOfPol = gNumOfPol + 1
      End If
   Next Pol

'   'to assign sequential polutant numbers for printing
'   gNumOfPolsToPrn = 0
'   For Pol = 2 To 48
'      If gUsePol(Pol) = 1 Then
'         gNumOfPolsToPrn = gNumOfPolsToPrn + 1
'         gPrintPol(gNumOfPolsToPrn) = Pol
'      End If
'   Next Pol

End Sub

Public Sub proOtherPolUnitConversion()

   Dim Pol As Integer
   '3160 Rem    determine other pollutant unit conversions

   For Pol = 31 To 48
      If gPolCalc(Pol) > 0 Then       'GoTo 3460
         If (Pol Mod 3 = 1) Then
               gUnitCon(Pol) = mPartOthUnit(gUDPartPolUnit(Pol))
               If gUnitCon(Pol) = 0.000000001 Then
                     gUnitCon(Pol + 1) = 0.0000000624
                  ElseIf gUnitCon(Pol) = 0.000001 Then
                     gUnitCon(Pol + 1) = 0.0000624
                  ElseIf gUnitCon(Pol) = 0.000000000001 Then
                     gUnitCon(Pol + 1) = 0.0000000000624
               End If
            ElseIf (Pol Mod 3 = 2) Then
               gUnitCon(Pol) = mFiltOthUnit(gUDFiltPolUnit(Pol))
            ElseIf (Pol Mod 3 = 0) Then
```

```
            gUnitCon(Pol) = gUnitCon(Pol - 1)
        End If
      End If
    Next Pol      '3460

End Sub

Public Sub proPolFileRow(SANum As Integer, LUNum As Integer, PolFileRow As Integer)

'proPolFileRow(SANum, LUNum, PolFileRow)
    Dim SourceAreaType As Integer

    If SANum < 151 Then
        SourceAreaType = SANum - (LUNum - 1) * 30
      Else
        SourceAreaType = SANum
    End If

'3640 Rem  calc pollutants rows for g=1 to 5
    Select Case SourceAreaType
      Case 1 To 5
         PolFileRow = 1
      Case 6 To 8
        PolFileRow = 2
      Case 9 To 10
        PolFileRow = 3
      Case 11 To 12
        PolFileRow = 4
      Case 13 To 15
        PolFileRow = 5
      Case 16 To 17
        PolFileRow = 6
      Case 18 To 20
        PolFileRow = 7
      Case 21 To 22
        PolFileRow = 8
      Case 23
        PolFileRow = 9
      Case 24 To 26
        PolFileRow = 10
      Case 27
        PolFileRow = 11
      Case 28
        PolFileRow = 12
      Case 29
        PolFileRow = 13
      Case 30
        PolFileRow = 14
       Case 151 To 155
        PolFileRow = 15
      Case 156
        PolFileRow = 16
      Case 157
        PolFileRow = 9
```

```
        Case 158
            PolFileRow = 12
        Case 159
            PolFileRow = 13
        Case 160
            PolFileRow = 14
    End Select

End Sub
```

Attribute VB_Name = "Procedures"

```
Option Explicit

Dim fAreaSum, fCounter

' These constants are used with proLoadgSourceArea          ' JM8/03/97
Public Const GRID_FORMAT = 0
Public Const SPREAD_FORMAT = 1

Public gAppPath As String

Declare Function GetWindowsDirectory Lib "kernel32" Alias "GetWindowsDirectoryA" (ByVal lpBuffer As
String, ByVal nSize As Long) As Long

Public Sub DisplayErrorMessage(sTitle As String)
' This is a procedure to display the current error number and description.  This procedure
' can be called from error traps anywhere in the project.  The argument sTitle is the name
' of the calling procedure.

MsgBox "The following event occurred...  " & vbCrLf & vbCrLf & Format$(Err.Number) & _
   ":  " & Err.Description & vbCrLf & vbCrLf & "...in " & sTitle, vbInformation, _
   "For Your Information"

End Sub

Public Sub proLoadgSourceArea(WhichFormat As Integer)
' JM8/03/97
' Assign text strings to the elements of the array gSourceArea$().  If the
' argument is SPREAD_FORMAT, insert vbCrLf between words to force the text
' to wrap to multiple lines - this wrapped text will appear in heading row
' cells of a spread control.
' Argument values:  GRID_FORMAT, SPREAD_FORMAT

   If WhichFormat = GRID_FORMAT Then
      gSourceArea$(1) = "Roofs 1"
      gSourceArea$(2) = "Roofs 2"
      gSourceArea$(3) = "Roofs 3"
      gSourceArea$(4) = "Roofs 4"
      gSourceArea$(5) = "Roofs 5"
      gSourceArea$(6) = "Paved Parking/Storage 1"
      gSourceArea$(7) = "Paved Parking/Storage 2"
      gSourceArea$(8) = "Paved Parking/Storage 3"
      gSourceArea$(9) = "Unpaved Prkng/Storage 1"
      gSourceArea$(10) = "Unpaved Prkng/Storage 2"
      gSourceArea$(11) = "Playground 1"
      gSourceArea$(12) = "Playground 2"
      gSourceArea$(13) = "Driveways 1"
      gSourceArea$(14) = "Driveways 2"
      gSourceArea$(15) = "Driveways 3"
      gSourceArea$(16) = "Sidewalks/Walks 1"
      gSourceArea$(17) = "Sidewalks/Walks 2"
      gSourceArea$(18) = "Street Area 1"
      gSourceArea$(19) = "Street Area 2"
```

```
    gSourceArea$(20) = "Street Area 3"
    gSourceArea$(21) = "Large Landscaped Area 1"
    gSourceArea$(22) = "Large Landscaped Area 2"
    gSourceArea$(23) = "Undeveloped Area"
    gSourceArea$(24) = "Small Landscaped Area 1"
    gSourceArea$(25) = "Small Landscaped Area 2"
    gSourceArea$(26) = "Small Landscaped Area 3"
    gSourceArea$(27) = "Isolated Area"
    gSourceArea$(28) = "Other Pervious Area"
    gSourceArea$(29) = "Other Dir Cnctd Imp Area"
    gSourceArea$(30) = "Other Part Cnctd Imp Area"

    gSourceArea$(34) = "Entire Basin"
    gSourceArea$(35) = "Outfall"

    gSourceArea$(151) = "Pavd Lane & Shldr Area 1"   ' "Paved Lane & Shldr Area 1"
    gSourceArea$(152) = "Pavd Lane & Shldr Area 2"   ' "Paved Lane & Shldr Area 2"
    gSourceArea$(153) = "Pavd Lane & Shldr Area 3"   ' "Paved Lane & Shldr Area 3"
    gSourceArea$(154) = "Pavd Lane & Shldr Area 4"   ' "Paved Lane & Shldr Area 4"
    gSourceArea$(155) = "Pavd Lane & Shldr Area 5"   ' "Paved Lane & Shldr Area 5"
    gSourceArea$(156) = "Large Turf Areas"
    gSourceArea$(157) = "Undeveloped Areas"
    gSourceArea$(158) = "Other Pervious Areas"
    gSourceArea$(159) = "Other Directly Conctd Imp"   ' "Othr Directly Conctd Imp Area"
    gSourceArea$(160) = "Other Partially Conctd Imp"   ' "Othr Partially Conctd Imp Area"
ElseIf WhichFormat = SPREAD_FORMAT Then
    ' Insert carriage returns and line feeds for use in a Spread control.
    gSourceArea$(1) = "Roofs 1"
    gSourceArea$(2) = "Roofs 2"
    gSourceArea$(3) = "Roofs 3"
    gSourceArea$(4) = "Roofs 4"
    gSourceArea$(5) = "Roofs 5"
    gSourceArea$(6) = "Paved" & vbCrLf & "Parking/" & vbCrLf & "Storage 1"
    gSourceArea$(7) = "Paved" & vbCrLf & "Parking/" & vbCrLf & "Storage 2"
    gSourceArea$(8) = "Paved" & vbCrLf & "Parking/" & vbCrLf & "Storage 3"
    gSourceArea$(9) = "Unpaved" & vbCrLf & "Parking/" & vbCrLf & "Storage 1"
    gSourceArea$(10) = "Unpaved" & vbCrLf & "Parking/" & vbCrLf & "Storage 2"
    gSourceArea$(11) = "Playground" & vbCrLf & "1"
    gSourceArea$(12) = "Playground" & vbCrLf & "2"
    gSourceArea$(13) = "Driveways" & vbCrLf & "1"
    gSourceArea$(14) = "Driveways" & vbCrLf & "2"
    gSourceArea$(15) = "Driveways" & vbCrLf & "3"
    gSourceArea$(16) = "Sidewalks/" & vbCrLf & "Walks 1"
    gSourceArea$(17) = "Sidewalks/" & vbCrLf & "Walks 2"
    gSourceArea$(18) = "Street" & vbCrLf & "Area 1"
    gSourceArea$(19) = "Street" & vbCrLf & "Area 2"
    gSourceArea$(20) = "Street" & vbCrLf & "Area 3"
    gSourceArea$(21) = "Large" & vbCrLf & "Landscaped" & vbCrLf & "Area 1"
    gSourceArea$(22) = "Large" & vbCrLf & "Landscaped" & vbCrLf & "Area 2"
    gSourceArea$(23) = "Undeveloped" & vbCrLf & "Area"
    gSourceArea$(24) = "Small" & vbCrLf & "Landscaped" & vbCrLf & "Area 1"
    gSourceArea$(25) = "Small" & vbCrLf & "Landscaped" & vbCrLf & "Area 2"
    gSourceArea$(26) = "Small" & vbCrLf & "Landscaped" & vbCrLf & "Area 3"
    gSourceArea$(27) = "Isolated" & vbCrLf & "Area"
```

```
      gSourceArea$(28) = "Other" & vbCrLf & "Pervious Area"
      gSourceArea$(29) = "Other" & vbCrLf & "Dir Cnctd" & vbCrLf & "Imp Area"
      gSourceArea$(30) = "Other" & vbCrLf & "Part Cnctd" & vbCrLf & "Imp Area"

      gSourceArea$(34) = "Entire" & vbCrLf & "Basin"
      gSourceArea$(35) = "Outfall"

      gSourceArea$(151) = "Pavd Lane" & vbCrLf & "& Shouldr" & vbCrLf & "Area 1"
      gSourceArea$(152) = "Pavd Lane" & vbCrLf & "& Shouldr" & vbCrLf & "Area 2"
      gSourceArea$(153) = "Pavd Lane" & vbCrLf & "& Shouldr" & vbCrLf & "Area 3"
      gSourceArea$(154) = "Pavd Lane" & vbCrLf & "& Shouldr" & vbCrLf & "Area 4"
      gSourceArea$(155) = "Pavd Lane" & vbCrLf & "& Shouldr" & vbCrLf & "Area 5"
      gSourceArea$(156) = "Large" & vbCrLf & "Turf" & vbCrLf & "Areas"
      gSourceArea$(157) = "Undeveloped" & vbCrLf & "Areas"
      gSourceArea$(158) = "Other" & vbCrLf & "Pervious" & vbCrLf & "Areas"
      gSourceArea$(159) = "Other" & vbCrLf & "Directly" & vbCrLf & "Conctd Imp"
      gSourceArea$(160) = "Other" & vbCrLf & "Partially" & vbCrLf & "Conctd Imp"
   End If


End Sub






Public Function GetWindowsDir() As String
   ' JM7/01/97
   Dim Temp As String
   Dim X As Integer

   Temp = String$(145, 0)              ' Size Buffer
   X = GetWindowsDirectory(Temp, 145)  ' Make API Call
   Temp = Left$(Temp, X)               ' Trim Buffer

   If Right$(Temp, 1) <> "\" Then      ' Add \ if necessary
      GetWindowsDir = Temp & "\"
   Else
      GetWindowsDir = Temp
   End If

End Function
Public Function funDecimalFilter(KeyAscii As Integer) As Integer
' Ascii 8 = backspace key     JM5

If (KeyAscii >= Asc("0") And KeyAscii <= Asc("9")) Or (KeyAscii = 8) _
  Or (KeyAscii = Asc(".")) Then
   funDecimalFilter = KeyAscii
Else
   funDecimalFilter = 0
End If

End Function
```

```
Public Sub proShowCentered(vChild, Optional vShowMode, Optional vParent)
' JM6
Dim oParent As Object
Dim Mode As Integer, ParentLeft As Integer, ParentTop As Integer

If IsMissing(vParent) Then
   Set oParent = Screen            ' Default is screen
ElseIf TypeOf vParent Is Form Then
   Set oParent = vParent
Else
   Exit Sub
End If

If IsMissing(vShowMode) Then
   Mode = vbModal   '0 ==> can move to another form during run time
Else
   Mode = Abs(vShowMode) Mod 2      ' Forces a value of 0 or 1
End If

If TypeOf oParent Is Form Then       ' Cannot use Left and Top for screen
   ParentLeft = oParent.Left
   ParentTop = oParent.Top
End If

Load vChild

vChild.Move (ParentLeft + (oParent.Width - vChild.Width) / 2), _
  (ParentTop + (oParent.Height - vChild.Height) / 2)

vChild.Show Mode    'since not identified w/ a form, it shows current form

End Sub


Public Sub proGetScreenResolution()
Dim WidthResolution, HeightResolution

WidthResolution = Screen.Width / Screen.TwipsPerPixelX
HeightResolution = Screen.Height / Screen.TwipsPerPixelY

'gScreenResolution = Format$(WidthResolution) & "x" & Format$(HeightResolution)


End Sub



Public Function funTtlBasinArea() As Single

funTtlBasinArea = 0
For fCounter = 1 To 160
   funTtlBasinArea = funTtlBasinArea + gTSArea(fCounter)
Next  'fCounter
```

```
gTSArea(161) = funTtlBasinArea
gTSArea(162) = funTtlBasinArea
'lblArea = "Total Basin Area:  " & gTtlBasinArea & " acres"

End Function

Public Sub proSetSelected()
    Dim ErrorMsg As String          ' JM8

   'used to select all of the text in a text box

   'On Error GoTo SetSelectedError  ' JM8
   On Error Resume Next

   Screen.ActiveControl.SelStart = 0        'go flush to the left of the text box text
   Screen.ActiveControl.SelLength = Len(Screen.ActiveControl.Text)       'select all the text

   Exit Sub                        ' JM8

SetSelectedError:
   Select Case Err.Number
     Case 438       ' Object doesn't support this property or method
        Exit Sub  ' e.g., the text box was disabled just as the focus shifted there.
     Case Else
        ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
          & Chr(10) & Chr(10) & "Procedure proSetSelected in SLMPROC.BAS"
        MsgBox ErrorMsg, vbCritical, "Error Trap"
        Exit Sub
   End Select

End Sub

Public Sub Main()

   gAppPath = App.Path
   If Right$(gAppPath, 1) <> "\" Then
      gAppPath = gAppPath & "\"
   End If

   App.HelpFile = gAppPath & "wslamm80.hlp"


'   this is the procedure that centers the initial form against the screen
   proShowCentered frmTitlePage, vbModal

End Sub

Public Sub proShowTagTip(MyForm As Form, MyControl As Control)

   ' Call this procedure from the MouseMove() event procedure of the control,
   ' e.g.  proShowTagTip Me, cmdContinue
   ' Key a message into the Tag property of the control.
   ' Create a label called lblTagTip with these properties:
```

```
    '   .Alignment = Center    .AutoSize = True   BackColor = (white or yellow)
    '   .BorderStyle = FixedSingle    .Visible = False

    MyForm!lblTagTip.Caption = MyControl.Tag
    MyForm!lblTagTip.Top = MyControl.Top + MyControl.Height
    MyForm!lblTagTip.Left = MyControl.Left - _
    (MyForm!lblTagTip.Width - MyControl.Width) / 2
    MyForm!lblTagTip.Visible = True

    ' On the MouseMove() event of the form, put this code:
    '  lblTagTip.Visible = False

End Sub


Public Sub proShowDateMessage(BadDate As String)
    Dim Message As String  ' JM9

    Message = "The value you entered (" & BadDate _
           & ") is not a valid date: The date format must be (mm/dd/yy)."
    MsgBox Message, vbExclamation, "Not a Date"

End Sub



Public Function funCheckDateSequence(ScheduleNum) As Boolean   'JM9
    ' The return boolean value is only used with cmdContinue
    Dim Index As Integer

    funCheckDateSequence = True     ' Default is True

    For Index = 1 To ScheduleNum      ' Start with 1, not 0
        If CDate(gStCleanDate$(Index, gStNum)) <= _
           CDate(gStCleanDate$(Index - 1, gStNum)) Then
            MsgBox "The dates are out of sequence.", vbExclamation, "Date Sequence"
            funCheckDateSequence = False
            Exit For
        End If
    Next Index

End Function


Public Function funIntegerFilter(KeyAscii As Integer) As Integer

    '  KeyAscii =8 is the backspace key

    If (KeyAscii >= Asc("0") And KeyAscii <= Asc("9")) Or (KeyAscii = 8) Then
            funIntegerFilter = KeyAscii
        Else
            funIntegerFilter = 0
    End If
```

```
End Function

Public Sub proDatFileV80Load()

   Dim SAIndex As Integer
   Dim ErrorMsg As String
   Dim Response As String
   Dim Version As String
   Dim TSArea As Single
   Dim SAName As Single
   Dim IDPRate As Single
   Dim IDAServ As Single
   Dim IDArea As Single
   Dim IDWToD As Single
   Dim OtherConcRed As Single
   Dim PorPavPercRate As Single
   Dim PorPavArea As Single
   Dim PondAreaServ As Single
   Dim CBCleanDate As String
   Dim FreewayText As Single, AvgDailyTraf As Single, FreewayLen As Single, FreewayInitLoad As
Single
   Dim FreewayInitLoadType As Single
   Dim FileNum As Integer
   Dim Dum As String
   Dim Dumm As Single
   Dim Blank As String
   Dim DrainType As Integer

   On Error GoTo LoadDatFileError
   FileNum = FreeFile

   If gSADF$ = "Cancel" Then
      Exit Sub
   End If
  '  load file into program for editing

  Open gSADF$ For Input As #FileNum
      Input #FileNum, gRainFile$
      Input #FileNum, gPolProbDistF$
      Input #FileNum, gPartResDelF$
      Input #FileNum, gRSubVF$
      Input #FileNum, gPSCncF$, Dum$
      Input #FileNum, Version$
      If Int(Right(Version$, Len(Version$) - 1)) <> App.Major Then
         Response = MsgBox("This data file is not compatible with Version " & Format(App.Major) & "." &
Format(App.Minor) _
                  & Chr$(13) & "Do you want to continue loading the .DAT file?", vbYesNo, "Incorrect
Version")
         If Response = vbNo Then
               proClearFileVariable
               Close #FileNum
               gSADF$ = ""
               frmMainMenu.lblSADF1.Caption = ""
               frmMainMenu.Caption = "WinSLAMM"
```

```
            frmCurrentFileData.lblSADF1.Caption = ""
            Exit Sub
        End If
    End If
    Input #FileNum, gStartDate$, gEndDate$, gJulianStartDate$, gJulianEndDate$
    Input #FileNum, gOutOption, gSeed, Dumm, Dum$, gOutOpt$, Dumm, gNumAreas
    Input #FileNum, gSiteDes$
    Input #FileNum, gG$, gSwlInfilRate, gSwlDensity, gSwlWidth, gSwlAreaServedBy
    Input #FileNum, gC$, gTtlSumpVol, gCBAreaServ, gPCSumpVolFull, gNumCBClngs, gSumpDepth

    ' JM30
    SAIndex = 1   ' JM7/20/97-A
    'ReDim gSAArNum(gNumAreas - 2)  ' Do not include S.A.'s 161 and 162.  ' JM7/20/97-A
    ReDim gSAArNum(gNumAreas)  ' Added S.A.'s 161 and 162. to get outfall calcs to work ' JV5/16/98

    For A = 1 To gNumAreas   '  E ==> gSANum
        Input #FileNum, E, TSArea, SAName, IDPRate, IDAServ, IDArea, IDWToD, _
                OtherConcRed, PorPavPercRate, PorPavArea, PondAreaServ
        Input #FileNum, Blank, gOtherVolRed(E), gOtherAServed(E), gI$(E), gW$(E), gOth$(E), gP$(E),
_
                gD$(E), gS$(E), gSpreadingArea$(E)
        Input #FileNum, Blank, gRoof(E), gTypeSA(E), gDirt(E), gAlley(E), gDensity(E)
        gTSArea(E) = TSArea
        gSAName(E) = SAName
        gIDPRate(E) = IDPRate
        gIDAServ(E) = IDAServ
        gIDArea(E) = IDArea
        gIDWToD(E) = IDWToD
        gOtherConcRed(E) = OtherConcRed
        gPorPavPercRate(E) = PorPavPercRate
        gPorPavArea(E) = PorPavArea
        gPondAreaServ(E) = PondAreaServ
       ' JM7/20/97  This array is used with getting the S.A. name (text) for use in the Windows
       ' Calc module.  The text serves as column headers.
       'If E < 161 Then  ' JM30 Remove the If test.
           gSAArNum(SAIndex) = E
           SAIndex = SAIndex + 1
       ' End If
    Next A

    For A = 1 To 5
        Input #FileNum, Dumm, gCBCleanDate$(A), gFreewayText(A), gAvgDailyTraf(A),
gFreewayLen(A), gFreewayInitLoad(A), gFreewayInitLoadType(A)
        'gCBCleanDate$(A) = CBCleanDate$
        'gFreewayText(A) = FreewayText
        'gAvgDailyTraf(A) = AvgDailyTraf
        'gFreewayLen(A) = FreewayLen
        'gFreewayInitLoad(A) = FreewayInitLoad
        'gFreewayInitLoadType(A) = FreewayInitLoadType
    Next A
    For A = 0 To 15
        Input #FileNum, Dumm, gUsePol(A * 3 + 1), gUsePol(A * 3 + 2), gUsePol(A * 3 + 3)
    Next A
    For A = 1 To 15
```

```
        Input #FileNum, Dumm, gStreetLen(A), gAStAcc(A), gBStAcc(A), gCStAcc(A), gInitStLoad(A), _
                  gStDirtAccType(A)
        Input #FileNum, gPrkCon$(A), gStClProd(A), gM(A), gB(A), gPrkDen(A), gStTexture(A),
gInitStDirtType(A), _
                  gStCleanSchedChanges(A)
        'Input #filenum, gStCleanFreq(0, A), gStCleanFreq(1, A), gStCleanFreq(2, A), gStCleanFreq(3,
A), _
                  gStCleanFreq(4, A), gStCleanFreq(5, A), gStCleanFreq(6, A), gStCleanFreq(7, A), _
                  gStCleanFreq(8, A), gStCleanFreq(9, A), gStCleanFreq(10, A)
        Input #FileNum, Dumm, gStCleanFreq(0, A), gStCleanFreq(1, A), gStCleanFreq(2, A),
gStCleanFreq(3, A), _
                  gStCleanFreq(4, A), gStCleanFreq(5, A), gStCleanFreq(6, A), gStCleanFreq(7, A), _
                  gStCleanFreq(8, A), gStCleanFreq(9, A)
        Input #FileNum, gStCleanDate$(0, A), gStCleanDate$(1, A), gStCleanDate$(2, A),
gStCleanDate$(3, A), _
                  gStCleanDate$(4, A), gStCleanDate$(5, A)
        Input #FileNum, gStCleanDate$(6, A), gStCleanDate$(7, A), gStCleanDate$(8, A),
gStCleanDate$(9, A), _
                  gStCleanDate$(10, A)
      Next A
      For DrainType = 1 To 5
        Input #FileNum, gDrainArea(DrainType)
      Next DrainType
      'fDum = 99999
      For A = 6 To 14
        Input #FileNum, Dumm
      Next A
      Dumm = 0
   Close #FileNum

   proLandUseAreaSum

   Exit Sub                    ' JM8

LoadDatFileError:                    ' JM8

    Select Case Err.Number
      Case 53     ' File not found
        ErrorMsg = "The file you selected was not found."
        MsgBox ErrorMsg, vbCritical, "File Not Found"
        Exit Sub
      Case Else
        ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
          & Chr(10) & Chr(10) & "Procedure proDatFileV80Load"
        MsgBox ErrorMsg, vbCritical, "Error Trap"
        Exit Sub
    End Select

End Sub


Public Sub proDatFileV81Load()

    Dim SAIndex As Integer
```

```
    Dim ErrorMsg As String
    Dim Response As String
    Dim Version As String
    Dim TSArea As Single
    Dim SAName As Single
    Dim IDPRate As Single
    Dim IDAServ As Single
    Dim IDArea As Single
    Dim IDWToD As Single
    Dim OtherConcRed As Single
    Dim PorPavPercRate As Single
    Dim PorPavArea As Single
    Dim PondAreaServ As Single
    Dim CBCleanDate As String
    Dim FreewayText As Single, AvgDailyTraf As Single, FreewayLen As Single, FreewayInitLoad As
Single
    Dim FreewayInitLoadType As Single
    Dim FileNum As Integer
    Dim Dum As String
    Dimm As Single
    Dim Blank As String
    Dim DrainType As Integer
    Dim PN As Integer '    PN==Pond Number
    Dim ONm As Integer    '  ONm==Outlet Number
    Dim M As Integer    '  M==Month
    Dim SE As Integer   '  SE==Stage Elevation

    On Error GoTo LoadDatFileError
    FileNum = FreeFile

    If gSADF$ = "Cancel" Then
       Exit Sub
    End If
   '  load file into program for editing

   Open gSADF$ For Input As #FileNum
       Input #FileNum, gRainFile$
       Input #FileNum, gPolProbDistF$
       Input #FileNum, gPartResDelF$
       Input #FileNum, gRSubVF$
       Input #FileNum, gPSCncF$, Dum$
       Input #FileNum, Version$
       If Int(Right(Version$, Len(Version$) - 1)) <> App.Major Then
          Response = MsgBox("This data file is not compatible with Version " & Format(App.Major) & "." &
Format(App.Minor) _
                  & Chr$(13) & "Do you want to continue loading the .DAT file?", vbYesNo, "Incorrect
Version")
          If Response = vbNo Then
                proClearFileVariable
                Close #FileNum
                gSADF$ = ""
                frmMainMenu.lblSADF1.Caption = ""
                frmMainMenu.Caption = "WinSLAMM"
                frmCurrentFileData.lblSADF1.Caption = ""
```

```
            Exit Sub
        End If
    End If
    Input #FileNum, gStartDate$, gEndDate$, gJulianStartDate$, gJulianEndDate$
    Input #FileNum, gOutOption, gSeed, Dumm, Dum$, gOutOpt$, Dumm, gNumAreas
    Input #FileNum, gSiteDes$
    Input #FileNum, gG$, gSwlInfilRate, gSwlDensity, gSwlWidth, gSwlAreaServedBy
    Input #FileNum, gC$, gTtlSumpVol, gCBAreaServ, gPCSumpVolFull, gNumCBClngs, gSumpDepth

    ' JM30
    SAIndex = 1   ' JM7/20/97-A
    'ReDim gSAArNum(gNumAreas - 2)  ' Do not include S.A.'s 161 and 162.  ' JM7/20/97-A
    ReDim gSAArNum(gNumAreas)  ' Added S.A.'s 161 and 162. to get outfall calcs to work ' JV5/16/98

    For A = 1 To gNumAreas   '  E ==> gSANum
        Input #FileNum, E, TSArea, SAName, IDPRate, IDAServ, IDArea, IDWToD, _
                OtherConcRed, PorPavPercRate, PorPavArea, PondAreaServ
        Input #FileNum, Blank, gOtherVolRed(E), gOtherAServed(E), gI$(E), gW$(E), gOth$(E), gP$(E),
_
                gD$(E), gS$(E), gSpreadingArea$(E)
        Input #FileNum, Blank, gRoof(E), gTypeSA(E), gDirt(E), gAlley(E), gDensity(E)
        gTSArea(E) = TSArea
        gSAName(E) = SAName
        gIDPRate(E) = IDPRate
        gIDAServ(E) = IDAServ
        gIDArea(E) = IDArea
        gIDWToD(E) = IDWToD
        gOtherConcRed(E) = OtherConcRed
        gPorPavPercRate(E) = PorPavPercRate
        gPorPavArea(E) = PorPavArea
        gPondAreaServ(E) = PondAreaServ
       ' JM7/20/97  This array is used with getting the S.A. name (text) for use in the Windows
       ' Calc module.  The text serves as column headers.
       'If E < 161 Then  ' JM30 Remove the If test.
            gSAArNum(SAIndex) = E
            SAIndex = SAIndex + 1
       ' End If
    Next A

    For A = 1 To 5
        Input #FileNum, Dumm, gCBCleanDate$(A), gFreewayText(A), gAvgDailyTraf(A),
gFreewayLen(A), gFreewayInitLoad(A), gFreewayInitLoadType(A)
    Next A
    For A = 0 To 15
        Input #FileNum, Dumm, gUsePol(A * 3 + 1), gUsePol(A * 3 + 2), gUsePol(A * 3 + 3)
    Next A
    For A = 1 To 15
        Input #FileNum, Dumm, gStreetLen(A), gAStAcc(A), gBStAcc(A), gCStAcc(A), gInitStLoad(A), _
                gStDirtAccType(A)
        Input #FileNum, gPrkCon$(A), gStClProd(A), gM(A), gB(A), gPrkDen(A), gStTexture(A),
gInitStDirtType(A), _
                gStCleanSchedChanges(A)
        Input #FileNum, Dumm, gStCleanFreq(0, A), gStCleanFreq(1, A), gStCleanFreq(2, A),
gStCleanFreq(3, A), _
```

```
                        gStCleanFreq(4, A), gStCleanFreq(5, A), gStCleanFreq(6, A), gStCleanFreq(7, A), _
                        gStCleanFreq(8, A), gStCleanFreq(9, A)
         Input #FileNum, gStCleanDate$(0, A), gStCleanDate$(1, A), gStCleanDate$(2, A),
gStCleanDate$(3, A), _
                        gStCleanDate$(4, A), gStCleanDate$(5, A)
         Input #FileNum, gStCleanDate$(6, A), gStCleanDate$(7, A), gStCleanDate$(8, A),
gStCleanDate$(9, A), _
                        gStCleanDate$(10, A)
      Next A
      For DrainType = 1 To 5
         Input #FileNum, gDrainArea(DrainType)
      Next DrainType
      'fDum = 99999
      For A = 6 To 14
         Input #FileNum, Dumm
      Next A
      Dumm = 0

      proLandUseAreaSum

      'Detention Pond Data
      Input #FileNum, gTtlNumDP '      , gVersion$
      For PN = 1 To gTtlNumDP
         Input #FileNum, gDPSANumMatch(PN).PndIndex, gDPSANumMatch(PN).SANum,
gPndLUNum(PN), gSACO(PN), gInitStage(PN), gStageIncVarOrConst(PN)
         Input #FileNum, gNumIncAr(PN), gStageIncr(PN), gPondDepth(PN), gPartSizeF$(PN)
         For SE = 0 To gNumIncAr(PN)
            Input #FileNum, PN, SE, gStageAr(PN, SE), gPndAreaAr(PN, SE)
         Next 'SE
         Input #FileNum, PN, gNumOutlets(PN)
         For ONm = 1 To gNumOutlets(PN)
            Input #FileNum, PN, ONm, gOutletType(PN, ONm)
            Input #FileNum, gWeirHeight(PN, ONm), gInvertElev(PN, ONm)
            Input #FileNum, gWeirLength(PN, ONm), gVWeirAngle(PN, ONm), gOrificeDia(PN, ONm)
            Input #FileNum, gInfilRate(PN, ONm), gSeepWidth(PN, ONm), gSeepLen(PN, ONm)
            If gOutletType(PN, ONm) = 5 Then
               For SE = 0 To gNumIncAr(PN)
                  Input #FileNum, SE, ONm, gNaturalSeep(SE, PN, ONm)
               Next  'SE
            End If
            If gOutletType(PN, ONm) = 6 Then
               For M = 1 To 12
                  Input #FileNum, M, ONm, gEvap(M, PN, ONm)
               Next 'M
            End If
            If gOutletType(PN, ONm) = 7 Then
               For SE = 0 To gNumIncAr(PN)
                  Input #FileNum, SE, PN, ONm, gStageAr(PN, SE), gQOutOther(SE, PN, ONm)
               Next 'SE
            End If
         Next 'ONm
      Next ' PN
   Close #FileNum
```

```
  Exit Sub                              ' JM8

LoadDatFileError:                        ' JM8

    Select Case Err.Number
      Case 53      ' File not found
          ErrorMsg = "The file you selected was not found."
          MsgBox ErrorMsg, vbCritical, "File Not Found"
          Exit Sub
      Case Else
          ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
            & Chr(10) & Chr(10) & "Procedure proDatFileV81Load"
          MsgBox ErrorMsg, vbCritical, "Error Trap"
          Exit Sub
    End Select

End Sub

Public Sub proDatFileV62Load()

    Dim SAIndex As Integer
    Dim ErrorMsg As String
    Dim Response As String
    Dim Version As String
    Dim TSArea As Single
    Dim SAName As Single
    Dim IDPRate As Single
    Dim IDAServ As Single
    Dim IDArea As Single
    Dim IDWToD As Single
    Dim OtherConcRed As Single
    Dim PorPavPercRate As Single
    Dim PorPavArea As Single
    Dim PondAreaServ As Single
    Dim CBCleanDate As String
    Dim FreewayText As Single, AvgDailyTraf As Single, FreewayLen As Single, FreewayInitLoad As
Single
    Dim FreewayInitLoadType As Single
    Dim FileNum As Integer
    Dim Dum As String
    Dim Dumm As Single
    Dim Blank As String
    Dim DrainType As Integer

    On Error GoTo LoadDatFileError
    FileNum = FreeFile

    If gSADF$ = "Cancel" Then
        Exit Sub
    End If
  '  load file into program for editing

  Open gSADF$ For Input As #FileNum
      Input #FileNum, gRainFile$
```

```
        Input #FileNum, gPolProbDistF$
        Input #FileNum, gPartResDelF$
        Input #FileNum, gRSubVF$
        Input #FileNum, gPSCncF$, Dum$
        Input #FileNum, Version$
        If Int(Right(Version$, Len(Version$) - 1)) <> App.Major Then
           Response = MsgBox("This data file is not a Version " & Format(App.Major) & "." &
Format(App.Minor) & " data file." _
                    & Chr$(13) & "All data needed for this version of SLAMM may not be in the file." & _
                    Chr$(13) & "Do you want to continue loading the .DAT file?", vbYesNo, "Incorrect
Version")
           If Response = vbNo Then
                 proClearFileVariable
                 Close #FileNum
                 gSADF$ = ""
                 frmMainMenu.lblSADF1.Caption = ""
                 frmMainMenu.Caption = "WinSLAMM"
                 frmCurrentFileData.lblSADF1.Caption = ""
                 Exit Sub
           End If
        End If
        Input #FileNum, gStartDate$, gEndDate$, gJulianStartDate$, gJulianEndDate$
        Input #FileNum, gOutOption, gSeed, Dumm, Dum$, gOutOpt$, Dumm, gNumAreas
        Input #FileNum, gSiteDes$
        Input #FileNum, gG$, gSwlInfilRate, gSwlDensity, gSwlWidth, gSwlAreaServedBy
        Input #FileNum, gC$, gTtlSumpVol, gCBAreaServ, gPCSumpVolFull, gNumCBClngs  ',
gSumpDepth

        ' JM30
        SAIndex = 1   ' JM7/20/97-A
        'ReDim gSAArNum(gNumAreas - 2)  ' Do not include S.A.'s 161 and 162.  ' JM7/20/97-A
        ReDim gSAArNum(gNumAreas)  ' Added S.A.'s 161 and 162. to get outfall calcs to work ' JV5/16/98

        For A = 1 To gNumAreas   '  E ==> gSANum
           Input #FileNum, E, TSArea, SAName, IDPRate, IDAServ, IDArea, IDWToD, _
                    OtherConcRed, PorPavPercRate, PorPavArea, PondAreaServ
           Input #FileNum, Blank, gOtherVolRed(E), gOtherAServed(E), gI$(E), gW$(E), gOth$(E), gP$(E),
_
                    gD$(E), gS$(E), gSpreadingArea$(E)
           Input #FileNum, Blank, gRoof(E), gTypeSA(E), gDirt(E), gAlley(E), gDensity(E)

           gTSArea(E) = TSArea
           gSAName(E) = SAName
           gIDPRate(E) = IDPRate
           gIDAServ(E) = IDAServ
           gIDArea(E) = IDArea
           gIDWToD(E) = IDWToD
           gOtherConcRed(E) = OtherConcRed
           gPorPavPercRate(E) = PorPavPercRate
           gPorPavArea(E) = PorPavArea
           gPondAreaServ(E) = PondAreaServ
          ' JM7/20/97  This array is used with getting the S.A. name (text) for use in the Windows
          ' Calc module.  The text serves as column headers.
          'If E < 161 Then  ' JM30 Remove the If test.
```

```
          gSAArNum(SAIndex) = E
          SAIndex = SAIndex + 1
        ' End If

      Next A
      For A = 1 To 5
         Input #FileNum, Dumm, gCBCleanDate$(A), gFreewayText(A), gAvgDailyTraf(A),
gFreewayLen(A), gFreewayInitLoad(A), gFreewayInitLoadType(A)
         'gCBCleanDate$(A) = CBCleanDate$
         'gFreewayText(A) = FreewayText
         'gAvgDailyTraf(A) = AvgDailyTraf
         'gFreewayLen(A) = FreewayLen
         'gFreewayInitLoad(A) = FreewayInitLoad
         'gFreewayInitLoadType(A) = FreewayInitLoadType
      Next A
      For A = 0 To 15
         Input #FileNum, Dumm, gUsePol(A * 3 + 1), gUsePol(A * 3 + 2), gUsePol(A * 3 + 3)
      Next A
      For A = 1 To 15
         Input #FileNum, Dumm, gStreetLen(A), gAStAcc(A), gBStAcc(A), gCStAcc(A), gInitStLoad(A), _
                    gStDirtAccType(A)
         Input #FileNum, gPrkCon$(A), gStClProd(A), gM(A), gB(A), gPrkDen(A), gStTexture(A),
gInitStDirtType(A), _
                    gStCleanSchedChanges(A)
         'Input #filenum, gStCleanFreq(0, A), gStCleanFreq(1, A), gStCleanFreq(2, A), gStCleanFreq(3,
A), _
                    gStCleanFreq(4, A), gStCleanFreq(5, A), gStCleanFreq(6, A), gStCleanFreq(7, A), _
                    gStCleanFreq(8, A), gStCleanFreq(9, A), gStCleanFreq(10, A)
         Input #FileNum, Dumm, gStCleanFreq(0, A), gStCleanFreq(1, A), gStCleanFreq(2, A),
gStCleanFreq(3, A), _
                    gStCleanFreq(4, A), gStCleanFreq(5, A), gStCleanFreq(6, A), gStCleanFreq(7, A), _
                    gStCleanFreq(8, A), gStCleanFreq(9, A)
         Input #FileNum, gStCleanDate$(0, A), gStCleanDate$(1, A), gStCleanDate$(2, A),
gStCleanDate$(3, A), _
                    gStCleanDate$(4, A), gStCleanDate$(5, A)
         Input #FileNum, gStCleanDate$(6, A), gStCleanDate$(7, A), gStCleanDate$(8, A),
gStCleanDate$(9, A), _
                    gStCleanDate$(10, A)
      Next A
      For DrainType = 1 To 5
         Input #FileNum, gDrainArea(DrainType)
      Next DrainType
      'fDum = 99999
      For A = 6 To 14
         Input #FileNum, Dumm
      Next A
      Dumm = 0
   Close #FileNum

   proLandUseAreaSum

   Exit Sub                        ' JM8

LoadDatFileError:                  ' JM8
```

```
    Select Case Err.Number
      Case 53       ' File not found
          ErrorMsg = "The file you selected was not found."
          MsgBox ErrorMsg, vbCritical, "File Not Found"
          Exit Sub
      Case Else
          ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
            & Chr(10) & Chr(10) & "Procedure proDatFileV62Load"
          MsgBox ErrorMsg, vbCritical, "Error Trap"
          Exit Sub
    End Select

End Sub



Public Sub proClearSAVariable(SANum As Integer)

    gTSArea(SANum) = 0
    gSAName(SANum) = 0
    gIDPRate(SANum) = 0
    gIDAServ(SANum) = 0
    gIDArea(SANum) = 0
    gIDWToD(SANum) = 0
    gOtherConcRed(SANum) = 0
    gPorPavPercRate(SANum) = 0
    gPorPavArea(SANum) = 0
    gPondAreaServ(SANum) = 0
    gOtherVolRed(SANum) = 0
    gOtherAServed(SANum) = 0
    gI$(SANum) = ""
    gW$(SANum) = ""
    gOth$(SANum) = ""
    gP$(SANum) = ""
    gD$(SANum) = ""
    gS$(SANum) = ""
    gSpreadingArea$(SANum) = ""
    gRoof(SANum) = 0
    gTypeSA(SANum) = 0
    gDirt(SANum) = 0
    gAlley(SANum) = 0
    gDensity(SANum) = 0

End Sub

Public Sub proClearStreetVariable(SANum As Integer, StNum As Integer)

    Dim A

    gTSArea(SANum) = 0
    gSAName(SANum) = 0
    gS$(SANum) = ""
```

```
    gStreetLen(StNum) = 0
    gAStAcc(StNum) = 0
    gBStAcc(StNum) = 0
    gCStAcc(StNum) = 0
    gInitStLoad(StNum) = 0
    gStDirtAccType(StNum) = 0
    gPrkCon$(StNum) = ""
    gStClProd(StNum) = 0
    gM(StNum) = 0
    gB(StNum) = 0
    gPrkDen(StNum) = 0
    gStTexture(StNum) = 0
    gInitStDirtType(StNum) = 0
    gStCleanSchedChanges(StNum) = 0
    For A = 0 To 10
       gStCleanFreq(A, StNum) = 0
       gStCleanDate$(A, StNum) = ""
    Next   'A

End Sub

Public Sub proClearOutfallVariable()

    Dim fDrainType As Integer

    gSwlInfilRate = 0
    gSwlDensity = 0
    gSwlWidth = 0
    gG$ = ""
    gSwlAreaServedBy = 0
    gC$ = ""
    gTtlSumpVol = 0
    gCBAreaServ = 0
    gPCSumpVolFull = 0
    gSumpDepth = 0
    gNumCBClngs = 0
    For A = 1 To 5
       gCBCleanDate$(A) = ""
    Next  ' A
    For fDrainType = 1 To 5
       gDrainArea(fDrainType) = 0
    Next   'fDrainType

End Sub

Public Sub proClearFreewayVariable(SANum As Integer)

    gTSArea(SANum) = 0
    gSAName(SANum) = 0  '  gSAName == gCO
    gIDPRate(SANum) = 0
    gIDAServ(SANum) = 0
    gIDArea(SANum) = 0
    gIDWToD(SANum) = 0
```

```
    gOtherConcRed(SANum) = 0
    gPorPavPercRate(SANum) = 0
    gPorPavArea(SANum) = 0
    gPondAreaServ(SANum) = 0
    gOtherVolRed(SANum) = 0
    gOtherAServed(SANum) = 0
    gI$(SANum) = ""
    gW$(SANum) = ""
    gOth$(SANum) = ""
    gP$(SANum) = ""
    gSpreadingArea$(SANum) = ""
    If SANum > 150 And SANum < 156 Then
        gFreewayText(SANum - 150) = 0
        gAvgDailyTraf(SANum - 150) = 0
        gFreewayLen(SANum - 150) = 0
        gFreewayInitLoad(SANum - 150) = 0
        gFreewayInitLoadType(SANum - 150) = 0
    End If

End Sub

Public Sub proClearFileVariable()

    gSADF$ = ""
    gRainFile$ = ""
    gPolProbDistF$ = ""
    gPartResDelF$ = ""
    gRSubVF$ = ""
    gPSCncF$ = ""
    gStartDate$ = ""
    gEndDate$ = ""
    gJulianStartDate$ = ""
    gJulianEndDate$ = ""
    gOutOption = 4
    gSeed = 42
    gOutOpt$ = "Default option - Print outfall summaries only"
    gNumAreas = 0
    gSiteDes$ = ""
    For A = 0 To 15
        gUsePol(A * 3 + 1) = 0
        gUsePol(A * 3 + 2) = 0
        gUsePol(A * 3 + 3) = 0
    Next   'A

End Sub

Public Function funJulianDate(DateCheck As String) As Single

    Dim Y, M, D

    Y = Val(Mid$(DateCheck$, 7, 2))
    M = Val(Mid$(DateCheck$, 1, 2))
    D = Val(Mid$(DateCheck$, 4, 2))
    Y = Y - 52
```

```
    'removed hour and minute values from complete julian date calc
    funJulianDate = (Y) * 365 + Int((Y - 1) / 4) + (M - 1) * 28 + Val(Mid$("000303060811131619212426",
(M - 1) * 2 + 1, 2)) + D - ((M > 2) And (((Y) And Not -4) = 0))
'    funJulianDate = (Y) * 365 + Int((Y - 1) / 4) + (M - 1) * 28 + Val(Mid$("000303060811131619212426",
(M - 1) * 2 + 1, 2)) + D + ((H + Min / 60) / 24) - ((M > 2) And (((Y) And Not -4) = 0))

End Function


Public Sub proClearPondVariable()

    'JV2 -11 / 29 / 96

    Dim PN As Integer '    PN==Pond Number
    Dim ONm As Integer    '  ONm==Outlet Number
    Dim M As Integer    '  M==Month
    Dim SE As Integer   '  SE==Stage Elevation

    For PN = 1 To gTtlNumDP
            gDPSANumMatch(PN).PndIndex = 0
            gPndLUNum(PN) = 0
            gSACO(PN) = 0
            gInitStage(PN) = 0
            gStageIncVarOrConst(PN) = 0
            gStageIncr(PN) = 0
            gPondDepth(PN) = 0
            gPartSizeF$(PN) = ""
            For SE = 0 To gNumIncAr(PN)
                gStageAr(PN, SE) = 0
                gPndAreaAr(PN, SE) = 0
            Next 'SE
            For ONm = 1 To gNumOutlets(PN)
                gWeirHeight(PN, ONm) = 0
                gInvertElev(PN, ONm) = 0
                gWeirLength(PN, ONm) = 0
                gVWeirAngle(PN, ONm) = 0
                gOrificeDia(PN, ONm) = 0
                gInfilRate(PN, ONm) = 0
                gSeepWidth(PN, ONm) = 0
                gSeepLen(PN, ONm) = 0
                If gOutletType(PN, ONm) = 5 Then
                    For SE = 0 To gNumIncAr(PN)
                        gNaturalSeep(SE, PN, ONm) = 0
                    Next  'SE
                End If
                If gOutletType(PN, ONm) = 6 Then
                    For M = 1 To 12
                        gEvap(M, PN, ONm) = 0
                    Next 'M
                End If
                If gOutletType(PN, ONm) = 7 Then
                    For SE = 0 To gNumIncAr(PN)
                        gStageAr(PN, SE) = 0
                        gQOutOther(SE, PN, ONm) = 0
```

```
                Next 'SE
            End If
            gOutletType(PN, ONm) = 0
        Next 'ONm
        gNumIncAr(PN) = 0
        gNumOutlets(PN) = 0
    Next ' PN
    gTtlNumDP = 0

End Sub

Public Sub proLandUseAreaSum()

    Dim ResArea As Single
    Dim InsArea As Single
    Dim ComArea As Single
    Dim IndArea As Single
    Dim OpeArea As Single
    Dim FreArea As Single
    Dim TtlArea As Single
    Dim Counter As Integer

    For Counter = 1 To 30
        ResArea = ResArea + gTSArea(Counter)
        InsArea = InsArea + gTSArea(Counter + 30)
        ComArea = ComArea + gTSArea(Counter + 60)
        IndArea = IndArea + gTSArea(Counter + 90)
        OpeArea = OpeArea + gTSArea(Counter + 120)
        If Counter < 11 Then
            FreArea = FreArea + gTSArea(Counter + 150)
        End If
    Next Counter
    TtlArea = ResArea + InsArea + ComArea + IndArea + OpeArea + FreArea

    frmMainMenu.lblResArea1.Caption = Format(ResArea, " ###0.00") & " Acres"
    frmMainMenu.lblInsArea1.Caption = Format(InsArea, " ###0.00") & " Acres"
    frmMainMenu.lblComArea1.Caption = Format(ComArea, " ###0.00") & " Acres"
    frmMainMenu.lblIndArea1.Caption = Format(IndArea, " ###0.00") & " Acres"
    frmMainMenu.lblOpeArea1.Caption = Format(OpeArea, " ###0.00") & " Acres"
    frmMainMenu.lblFreArea1.Caption = Format(FreArea, " ###0.00") & " Acres"
    frmMainMenu.lblTtlArea1.Caption = Format(TtlArea, " ####0.00") & " Acres"

      If ResArea > 0 Then
            frmMainMenu.mnuResidential.Checked = True
        Else
            frmMainMenu.mnuResidential.Checked = False
    End If
    If InsArea > 0 Then
            frmMainMenu.mnuInstitutional.Checked = True
        Else
            frmMainMenu.mnuInstitutional.Checked = False
    End If
    If ComArea > 0 Then
            frmMainMenu.mnuCommercial.Checked = True
```

```
    Else
        frmMainMenu.mnuCommercial.Checked = False
  End If
  If IndArea > 0 Then
        frmMainMenu.mnuIndustrial.Checked = True
    Else
        frmMainMenu.mnuIndustrial.Checked = False
  End If
  If OpeArea > 0 Then
        frmMainMenu.mnuOpenSpace.Checked = True
    Else
        frmMainMenu.mnuOpenSpace.Checked = False
  End If
  If FreArea > 0 Then
        frmMainMenu.mnuFreeways.Checked = True
    Else
        frmMainMenu.mnuFreeways.Checked = False
  End If


End Sub

Public Sub proAbout()
  Dim MyStamp As String
  Dim pos As Integer

  MyStamp = FileDateTime(gAppPath & "WinSLAMM.exe")

  MsgBox "WinSLAMM version " & Format(App.Major) & "." & Format(App.Minor) _
        & "." & Format(App.Revision) & vbCrLf & _
        Format$(MyStamp, "Long Date") & ".", vbOKOnly, "Version Number"


End Sub



Public Sub proOutput5RunoffFlowSum()

  Dim Col1 As String * 6
  Dim Col2 As String * 12
  Dim Col3 As String * 12
  Dim Col4 As String * 12
  Dim Col5 As String * 12
  Dim Col6 As String * 12
  Dim Col7 As String * 12
  Dim Col8 As String * 12
  Dim Col9 As String * 12
  Dim Col10 As String * 12
  Dim Col11 As String * 12
  Dim Col12 As String * 12
  Dim Col13 As String * 12
  Dim Col14 As String * 12
  Dim s As String * 2
```

```
Dim OutputFileName As String
Dim FileNum As Integer
Dim AppPath As String
Dim OFNum As Integer
Dim AvgFlow As Single
Dim PeakFlow As Single
Dim RainDur As Single
Dim RunDur As Single
Dim RSubv As Single

AppPath = App.Path
If Right$(AppPath, 1) <> "\" Then
   AppPath = AppPath & "\"
End If

s = Chr$(32) & Chr$(32)

OutputFileName$ = Left(gSADF$, Len(gSADF$) - 4) & ".OUT"
   'Me.FontName = "Lineprinter"
   FileNum = FreeFile

   Col1 = "Event"
   RSet Col2 = "Rain Start"
   RSet Col3 = "Rain Start"
   RSet Col4 = "Julian"
   RSet Col5 = "Rain"
   RSet Col6 = "Rain"
   RSet Col7 = "Runoff"
   RSet Col8 = "Rain"
   RSet Col9 = "Runoff"
   RSet Col10 = "R sub v"
   RSet Col11 = "Average"
   RSet Col12 = "Peak"
   RSet Col13 = "Suspended"
   RSet Col14 = "Suspended"

   Open OutputFileName For Output As #FileNum

   Print #FileNum, Col1 & s & Col2 & s & Col3 & s & Col4 & s & Col5 & s & Col6 & s & _
            Col7 & s & Col8 & s & Col9 & s & Col10 & s & Col11 & s & Col12 & s & Col13 & s & Col14

   Col1 = "Number"
   RSet Col2 = "Start"
   RSet Col3 = "Start"
   RSet Col4 = "Start Date"
   RSet Col5 = "Duration"
   RSet Col6 = "Interevent"
   RSet Col7 = "Duration"
   RSet Col8 = "Depth"
   RSet Col9 = "Volume"
   RSet Col10 = ""
   RSet Col11 = "Flow"
   RSet Col12 = "Flow"
   RSet Col13 = "Solids"
```

```
    RSet Col14 = "Solids"

    Print #FileNum, Col1 & s & Col2 & s & Col3 & s & Col4 & s & Col5 & s & Col6 & s & _
          Col7 & s & Col8 & s & Col9 & s & Col10 & s & Col11 & s & Col12 & s & Col13 & s & Col14

    Col1 = ""
    RSet Col2 = "Date"
    RSet Col3 = "Time"
    RSet Col4 = "& Time"
    RSet Col5 = "(hrs)"
    RSet Col6 = "Period(days)"
    RSet Col7 = "(hrs)"
    RSet Col8 = "(in)"
    RSet Col9 = "(cf)"
    RSet Col10 = ""
    RSet Col11 = "(cfs)"
    RSet Col12 = "(cfs)"
    RSet Col13 = "Conc(mg/L)"
    RSet Col14 = "Mass(lbs)"


    Print #FileNum, Col1 & s & Col2 & s & Col3 & s & Col4 & s & Col5 & s & Col6 & s & _
          Col7 & s & Col8 & s & Col9 & s & Col10 & s & Col11 & s & Col12 & s & Col13 & s & Col14

    'Print #FileNum, Chr$(13);

    OFNum = gNumAreas
    For A = gFirstRainNum To gLastRainNum     '1 To gNumRains
      LSet Col1 = Format$(A, "##,###")
      RSet Col2 = gRainEventStartDate(A)
        'gPartSolConc(A, OFNum) = gPartSolConc(A, OFNum - 1) * (1 - TtlPCConcRed)
        'gPartSolYield(A, OFNum) = gPartSolConc(A, OFNum) * gRunoffVol(A, OFNum) * (28.32 /
454000!)
      RSet Col3 = gStartTime(A)
      RSet Col4 = Format$(gJulDPStartDate(A), "#,##0.00")
      RainDur = gRainDur(A) * 24
      RSet Col5 = Format$(RainDur, "#,##0.00")
      RSet Col6 = Format$(gJulInterEventPer(A), "#,##0.00")
      RunDur = RainDur * 1.2
      RSet Col7 = Format$(RunDur, "#,##0.00")
      RSet Col8 = Format$(gRain(A), "#0.00")
      RSet Col9 = Format$(gRunoffVol(A, OFNum), "##,###,##0")
      RSubv = gRunoffVol(A, OFNum) / (gRain(A) * gTtlBasinArea * 43560! / 12)     '[cu ft / (in *acres *
43560 sf / acre / 12 in / ft)]
      RSet Col10 = Format$(RSubv, "0.00")
      AvgFlow = gRunoffVol(A, OFNum) / (1.2 * gRainDur(A) * 86400)     '[cu ft / (days * 24 hrs/day * 60
min/hr * 60 sec/min)]
      RSet Col11 = Format$(AvgFlow, "#,##0.00")
      PeakFlow = AvgFlow * 2
      RSet Col12 = Format$(PeakFlow, "#,##0.00")
      RSet Col13 = Format$(gPartSolConc(A, OFNum), "##,###,##0")
      RSet Col14 = Format$(gPartSolYield(A, OFNum), "##,###,##0")

      Print #FileNum, Col1 & s & Col2 & s & Col3 & s & Col4 & s & Col5 & s & Col6 & s & _
```

```
                Col7 & s & Col8 & s & Col9 & s & Col10 & s & Col11 & s & Col12 & s & Col13 & s & Col14

        Next A

    Close #FileNum

End Sub

Public Sub proTriHydrograph()

    Dim NumOfTimeIncs As Long
    Dim TimeInc As Single
    Dim FlowRate As Single
    Dim PeakFlow As Single
    Dim AvgFlow As Single
    Dim FileNum As Integer
    Dim RunDur As Single    'Runoff Duration
    Dim PeakTime As Single
    Dim i As Long
    Dim ModelRunTime As Single
    Dim ModelRunTimeIncCounter As Long
    Dim AppPath As String
    Dim OutputFileName As String
    Dim TimeIncAfterPeak As Integer
    Dim PrevRunoffEndsAfterCurrentRainStarts As Boolean
    Dim PrevEventPeakFlow As Single
    Dim PrevTimeIncAfterPeak As Integer
    Dim PrevPeakTime As Single
    Dim PrevNumOfTimeIncs As Integer
    Dim PrevFlowRate As Single
    Dim PolNum As Integer
    Dim intPrnPol As Integer
    Dim PollNames() As String
    Dim PollUnits() As String
    Dim SWMMPollUnit() As String

    FileNum = FreeFile
    OutputFileName$ = Left(gSADF$, Len(gSADF$) - 4) & ".HYD"
    Open OutputFileName$ For Output As #FileNum
    ModelRunTimeIncCounter = 0

    Select Case gOutOption
        Case 6
            TimeInc = 6 / 60 / 24 '6 minute increments [days]
        Case 7
            TimeInc = 15 / 60 / 24 '15 minute increments [days]
        Case 8
            TimeInc = 60 / 60 / 24 '60 minute increments [days]
    End Select

    For A = gFirstRainNum To gLastRainNum

        PrevEventPeakFlow = PeakFlow
        PrevTimeIncAfterPeak = TimeIncAfterPeak
```

```
    PrevPeakTime = PeakTime
    AvgFlow = gRunoffVol(A, gNumAreas) / (1.2 * gRainDur(A) * 86400)     '[cu ft / (days * 24 hrs/day *
60 min/hr * 60 sec/min)]
    PeakFlow = AvgFlow * 2
    RunDur = 1.2 * gRainDur(A)
    PeakTime = 0.5 * RunDur
    TimeIncAfterPeak = 0
    PrevRunoffEndsAfterCurrentRainStarts = False

    If A < gLastRainNum Then
        NumOfTimeIncs = ((gJulDPStartDate(A + 1) - gJulDPStartDate(A)) / TimeInc) - 1
      ElseIf A = gLastRainNum Then
        NumOfTimeIncs = RunDur / TimeInc + 1
    End If

    If A > gFirstRainNum Then                    'to test for two events occuring at the same time
      If (gJulDPStartDate(A - 1) + 1.2 * gRainDur(A - 1)) > gJulDPStartDate(A) Then
        PrevRunoffEndsAfterCurrentRainStarts = True
      End If
    End If

    For i = 0 To NumOfTimeIncs
      If (i * TimeInc) <= ((1.2 * gRainDur(A)) / 2) Then
          FlowRate = PeakFlow / (PeakTime) * (TimeInc * i)
          If PrevRunoffEndsAfterCurrentRainStarts = True Then
            If PrevEventPeakFlow - PrevEventPeakFlow / (PrevPeakTime) * (TimeInc *
PrevTimeIncAfterPeak) > 0 Then
              PrevTimeIncAfterPeak = PrevTimeIncAfterPeak + 1
              PrevFlowRate = PrevEventPeakFlow - PrevEventPeakFlow / (PrevPeakTime) *
(TimeInc * PrevTimeIncAfterPeak)
              FlowRate = FlowRate + PrevFlowRate
            End If
          End If
        ElseIf (i * TimeInc) > ((1.2 * gRainDur(A)) / 2) And (i * TimeInc) < (1.2 * gRainDur(A)) Then
          TimeIncAfterPeak = TimeIncAfterPeak + 1
          FlowRate = PeakFlow - PeakFlow / (PeakTime) * (TimeInc * TimeIncAfterPeak)
        ElseIf (i * TimeInc) >= (1.2 * gRainDur(A)) Then
          FlowRate = 0
      End If
      If FlowRate < 0 Then FlowRate = 0
      ModelRunTime = ModelRunTimeIncCounter * TimeInc

      ' Print headings
      If gPrnHeadings = False Then
        gPrnHeadings = True
        Write #FileNum, funTrimPath(Left(gSADF$, Len(gSADF$) - 4))
        If gNumOfPol = 0 Then
              Write #FileNum, "TIME (days)", "FLOW (cfs)", "PART. SOLIDS (mg/L)"
          Else
            ReDim PollNames(1 To gNumOfPol)
            ReDim PollUnits(1 To gNumOfPol)
            ReDim SWMMPollUnit(1 To gNumOfPol)
            Call proGetPollutantNames(PollNames(), PollUnits(), SWMMPollUnit())
            Write #FileNum, "TIME (days)", "FLOW (cfs)", "PART. SOLIDS (mg/L)";
```

```
                For intPrnPol = 1 To gNumOfPol - 1
                    If gPrintPol(intPrnPol) = True Then
                        Write #FileNum, PollNames(intPrnPol) & " " & PollUnits(intPrnPol);
                    End If
                Next intPrnPol
                Write #FileNum, PollNames(gNumOfPol) & " " & PollUnits(intPrnPol)
            End If
        End If

        '  Print hydrograph and pollutant data
        If gNumOfPol = 0 Then
            If FlowRate > 0 Then
                Write #FileNum, Val(Format$(ModelRunTime, "0.0000")), _
                        Val(Format$(FlowRate, "0.0000")), _
                        Val(Format$(gPartSolConc(A, gNumAreas), "0.0000"))
              ElseIf FlowRate = 0 Then
                Write #FileNum, Val(Format$(ModelRunTime, "0.0000")), _
                        Val(Format$(FlowRate, "0.0000")), 0
            End If
          Else
            If FlowRate > 0 Then
                Write #FileNum, Val(Format$(ModelRunTime, "0.0000")), _
                        Val(Format$(FlowRate, "0.0000")), _
                        Val(Format$(gPartSolConc(A, gNumAreas), "0.0000"));
              ElseIf FlowRate = 0 Then
                Write #FileNum, Val(Format$(ModelRunTime, "0.0000")), _
                        Val(Format$(FlowRate, "0.0000")), 0;
            End If
            For intPrnPol = 1 To gNumOfPol - 1
                If gPrintPol(intPrnPol) = True And FlowRate > 0 Then
                    Write #FileNum, Val(Format$(gPolConc(A, gNumAreas, intPrnPol), "0.0000"));
                  ElseIf gPrintPol(intPrnPol) = True And FlowRate = 0 Then
                    Write #FileNum, 0;
                End If
            Next intPrnPol
            If FlowRate > 0 Then
                Write #FileNum, Val(Format$(gPolConc(A, gNumAreas, gNumOfPol), "0.0000"))
              ElseIf FlowRate = 0 Then
                Write #FileNum, 0
            End If
        End If

        ModelRunTimeIncCounter = ModelRunTimeIncCounter + 1

    Next i
    PrevNumOfTimeIncs = NumOfTimeIncs
  Next A

  Close #FileNum

End Sub

Public Sub proGetPollutantNames(PollutantNames() As String, PollutantUnit() As String,
SWMMPollUnit() As String)
```

```
Dim i As Integer
Dim intArrayPtr As Integer

On Error GoTo ErrorTrap

intArrayPtr = 1
For i = 2 To 48              ' Don't start with 1, because Particulate Residues don't count as a pollutant.
   'If gUsePol(i) = 1 Then
   If gPolCalc(i) > 0 Then
      Select Case i
         ''Case 1
         ''   PollutantNames(intArrayPtr) = "PARTICULATE SOLIDS"
         Case 2
            PollutantNames(intArrayPtr) = "FILTERABLE SOLIDS"
            PollutantUnit(intArrayPtr) = "(mg/L)"
            SWMMPollUnit(intArrayPtr) = "(mg/L)"
         Case 3
            PollutantNames(intArrayPtr) = "TOTAL SOLIDS"
            PollutantUnit(intArrayPtr) = "(mg/L)"
            SWMMPollUnit(intArrayPtr) = "(mg/L)"
         Case 4
            PollutantNames(intArrayPtr) = "PARTICULATE PHOSPHORUS"
            PollutantUnit(intArrayPtr) = "(mg/L)"
            SWMMPollUnit(intArrayPtr) = "(mg/L)"
         Case 5
            PollutantNames(intArrayPtr) = "FILTERABLE PHOSPHORUS"
            PollutantUnit(intArrayPtr) = "(mg/L)"
            SWMMPollUnit(intArrayPtr) = "(mg/L)"
         Case 6
            PollutantNames(intArrayPtr) = "TOTAL PHOSPHORUS"
            PollutantUnit(intArrayPtr) = "(mg/L)"
            SWMMPollUnit(intArrayPtr) = "(mg/L)"
         Case 7
            PollutantNames(intArrayPtr) = "N/A"
            PollutantUnit(intArrayPtr) = "N/A"
            SWMMPollUnit(intArrayPtr) = "N/A"
         Case 8
            PollutantNames(intArrayPtr) = "NITRATES"
            PollutantUnit(intArrayPtr) = "(mg/L)"
            SWMMPollUnit(intArrayPtr) = "(mg/L)"
         Case 9
            PollutantNames(intArrayPtr) = "N/A"
            PollutantUnit(intArrayPtr) = "N/A"
            SWMMPollUnit(intArrayPtr) = "N/A"
         Case 10
            PollutantNames(intArrayPtr) = "PARTICULATE TKN"
            PollutantUnit(intArrayPtr) = "(mg/L)"
            SWMMPollUnit(intArrayPtr) = "(mg/L)"
         Case 11
            PollutantNames(intArrayPtr) = "FILTERABLE TKN"
            PollutantUnit(intArrayPtr) = "(mg/L)"
            SWMMPollUnit(intArrayPtr) = "(mg/L)"
         Case 12
```

```
    PollutantNames(intArrayPtr) = "TOTAL TKN"
    PollutantUnit(intArrayPtr) = "(mg/L)"
    SWMMPollUnit(intArrayPtr) = "(mg/L)"
Case 13
    PollutantNames(intArrayPtr) = "PARTICULATE CHEMICAL OXYGEN DEMAND"
    PollutantUnit(intArrayPtr) = "(mg/L)"
    SWMMPollUnit(intArrayPtr) = "(mg/L)"
Case 14
    PollutantNames(intArrayPtr) = "FILTERABLE CHEMICAL OXYGEN DEMAND"
    PollutantUnit(intArrayPtr) = "(mg/L)"
    SWMMPollUnit(intArrayPtr) = "(mg/L)"
Case 15
    PollutantNames(intArrayPtr) = "TOTAL CHEMICAL OXYGEN DEMAND"
    PollutantUnit(intArrayPtr) = "(mg/L)"
    SWMMPollUnit(intArrayPtr) = "(mg/L)"
Case 16
    PollutantNames(intArrayPtr) = "N/A"
Case 17
    PollutantNames(intArrayPtr) = "FILTERABLE FECAL COLIFORM BACTERIA"
    PollutantUnit(intArrayPtr) = "(#/100 ml)"
    SWMMPollUnit(intArrayPtr) = "(mg/L)"
Case 18
    PollutantNames(intArrayPtr) = "N/A"
    PollutantUnit(intArrayPtr) = "N/A"
    SWMMPollUnit(intArrayPtr) = "N/A"
Case 19
    PollutantNames(intArrayPtr) = "PARTICULATE CHROMIUM"
    PollutantUnit(intArrayPtr) = "(ug/L)"
    SWMMPollUnit(intArrayPtr) = "(ug/L)"
Case 20
    PollutantNames(intArrayPtr) = "FILTERABLE CHROMIUM"
    PollutantUnit(intArrayPtr) = "(ug/L)"
    SWMMPollUnit(intArrayPtr) = "(ug/L)"
Case 21
    PollutantNames(intArrayPtr) = "TOTAL CHROMIUM"
    PollutantUnit(intArrayPtr) = "(ug/L)"
    SWMMPollUnit(intArrayPtr) = "(ug/L)"
Case 22
    PollutantNames(intArrayPtr) = "PARTICULATE COPPER"
    PollutantUnit(intArrayPtr) = "(ug/L)"
    SWMMPollUnit(intArrayPtr) = "(ug/L)"
Case 23
    PollutantNames(intArrayPtr) = "FILTERABLE COPPER"
    PollutantUnit(intArrayPtr) = "(ug/L)"
    SWMMPollUnit(intArrayPtr) = "(ug/L)"
Case 24
    PollutantNames(intArrayPtr) = "TOTAL COPPER"
    PollutantUnit(intArrayPtr) = "(ug/L)"
    SWMMPollUnit(intArrayPtr) = "(ug/L)"
Case 25
    PollutantNames(intArrayPtr) = "PARTICULATE LEAD"
    PollutantUnit(intArrayPtr) = "(ug/L)"
    SWMMPollUnit(intArrayPtr) = "(ug/L)"
Case 26
```

```
            PollutantNames(intArrayPtr) = "FILTERABLE LEAD"
            PollutantUnit(intArrayPtr) = "(ug/L)"
            SWMMPollUnit(intArrayPtr) = "(ug/L)"
        Case 27
            PollutantNames(intArrayPtr) = "TOTAL LEAD"
            PollutantUnit(intArrayPtr) = "(ug/L)"
            SWMMPollUnit(intArrayPtr) = "(ug/L)"
        Case 28
            PollutantNames(intArrayPtr) = "PARTICULATE ZINC"
            PollutantUnit(intArrayPtr) = "(ug/L)"
            SWMMPollUnit(intArrayPtr) = "(ug/L)"
        Case 29
            PollutantNames(intArrayPtr) = "FILTERABLE ZINC"
            PollutantUnit(intArrayPtr) = "(ug/L)"
            SWMMPollUnit(intArrayPtr) = "(ug/L)"
        Case 30
            PollutantNames(intArrayPtr) = "TOTAL ZINC"
            PollutantUnit(intArrayPtr) = "(ug/L)"
            SWMMPollUnit(intArrayPtr) = "(ug/L)"
'gUDPartPolUnit (31 + (Other - 1) * 3), gUDPartPolName$(31 + (Other - 1) * 3), gUDFiltPolName$(32 +
(Other - 1) * 3), gUDFiltPolUnit(32 + (Other - 1) * 3)

        Case 31
            PollutantNames(intArrayPtr) = "PARTICULATE " & gUDPartPolName$(31)
            PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDPartPolUnit(31))
            SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDPartPolUnit(31))
        Case 32
            PollutantNames(intArrayPtr) = "FILTERABLE " & gUDFiltPolName$(32)
            PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(32))
            SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(32))
        Case 33
            PollutantNames(intArrayPtr) = "TOTAL " & gUDPartPolName$(31)
            PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(32))
            SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(32))
        Case 34
            PollutantNames(intArrayPtr) = "PARTICULATE " & gUDPartPolName$(34)
            PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDPartPolUnit(34))
            SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDPartPolUnit(34))
        Case 35
            PollutantNames(intArrayPtr) = "FILTERABLE " & gUDFiltPolName$(35)
            PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(35))
            SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(35))
        Case 36
            PollutantNames(intArrayPtr) = "TOTAL " & gUDPartPolName$(34)
            PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(35))
            SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(35))
        Case 37
            PollutantNames(intArrayPtr) = "PARTICULATE " & gUDPartPolName$(37)
            PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDPartPolUnit(37))
            SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDPartPolUnit(37))
        Case 38
            PollutantNames(intArrayPtr) = "FILTERABLE " & gUDFiltPolName$(38)
            PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(38))
            SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(38))
```

```
            Case 39
               PollutantNames(intArrayPtr) = "TOTAL " & gUDPartPolName$(37)
               PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(38))
               SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(38))
            Case 40
               PollutantNames(intArrayPtr) = "PARTICULATE " & gUDPartPolName$(40)
               PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDPartPolUnit(40))
               SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDPartPolUnit(40))
            Case 41
               PollutantNames(intArrayPtr) = "FILTERABLE " & gUDFiltPolName$(41)
               PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(41))
               SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(41))
            Case 42
               PollutantNames(intArrayPtr) = "TOTAL " & gUDPartPolName$(40)
               PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(41))
               SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(41))
            Case 43
               PollutantNames(intArrayPtr) = "PARTICULATE " & gUDPartPolName$(43)
               PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDPartPolUnit(43))
               SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDPartPolUnit(43))
            Case 44
               PollutantNames(intArrayPtr) = "FILTERABLE " & gUDFiltPolName$(44)
               PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(44))
               SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(44))
            Case 45
               PollutantNames(intArrayPtr) = "TOTAL " & gUDPartPolName$(43)
               PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(44))
               SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(44))
            Case 46
               PollutantNames(intArrayPtr) = "PARTICULATE " & gUDPartPolName$(46)
               PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDPartPolUnit(46))
               SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDPartPolUnit(46))
            Case 47
               PollutantNames(intArrayPtr) = "FILTERABLE " & gUDFiltPolName$(47)
               PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(47))
               SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(47))
            Case 48
               PollutantNames(intArrayPtr) = "TOTAL " & gUDPartPolName$(46)
               PollutantUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(47))
               SWMMPollUnit(intArrayPtr) = gUDPolUnitLabel$(gUDFiltPolUnit(47))
            Case Else
               PollutantNames(intArrayPtr) = "N/A"
         End Select

         intArrayPtr = intArrayPtr + 1
      End If
   Next i

   Exit Sub
'For fCounter = 1 To 6
'   If gUDFiltPolName$(32 + (fCounter - 1) * 3) <> "" Then
'      lblOther(fCounter) = gUDFiltPolName$(32 + (fCounter - 1) * 3)
'   End If
'   If gUDPartPolName$(31 + (fCounter - 1) * 3) <> "" Then
```

```
'       lblOther(fCounter) = gUDPartPolName$(31 + (fCounter - 1) * 3)
'    End If
'Next fCounter



ErrorTrap:

    DisplayErrorMessage "proGetPollutantNames"
    Exit Sub

End Sub



Public Sub proConvertHydroToEvenTimeSteps()

    Dim TimeInc As Single
    Dim FileNum1 As Integer
    Dim FileNum2 As Integer
    Dim i As Long
    Dim A As Integer    ' A == RainNumber
    Dim ModelRunTime As Single
    Dim ModelRunTimeIncCounter As Long
    Dim AppPath As String
    Dim OutputFileName As String
    Dim TimeStep As Single
    Dim HydQOut As Single
    Dim NumOfTimeIncs As Long
    Dim TimeIncNum As Single
    Dim FirstHydQOut As Single
    Dim FirstModelRunTime As Single
    Dim FirstTimeIncNum As Single
    Dim Slope As Single
    Dim HydQOutInterpolated As Single
    Dim PrevModelRunTime As Single
    Dim FirstZeros As Boolean
    Dim Counter As Integer
    Dim PollNames() As String
    Dim PollUnits() As String
    Dim SWMMPollUnit() As String
    Dim intPrnPol As Integer

    'OutputFileName$ = Left(gSADF$, Len(gSADF$) - 4) & ".HYD"
    'Open OutputFileName$ For Output As #FileNum2
    'ModelRunTimeIncCounter = 0

    Select Case gOutOption
        Case 6
            TimeInc = 6 / 60 / 24 '6 minute increments [days]
        Case 7
            TimeInc = 15 / 60 / 24 '15 minute increments [days]
        Case 8
            TimeInc = 60 / 60 / 24 '60 minute increments [days]
```

```
End Select

FirstZeros = False
TimeIncNum = 0
FileNum1 = FreeFile
Counter = 0
Open "ModelHydrograph.TMP" For Input As #FileNum1
FileNum2 = FreeFile
OutputFileName$ = Left(gSADF$, Len(gSADF$) - 4) & ".HYD"
Open OutputFileName$ For Output As #FileNum2

    ' Print headings
    If gPrnHeadings = False Then
        gPrnHeadings = True
        Write #FileNum2, funTrimPath(Left(gSADF$, Len(gSADF$) - 4))
        If gNumOfPol = 0 Then
                Write #FileNum2, "TIME (days)", "FLOW (cfs)", "PART. SOLIDS (mg/L)"
            Else
                ReDim PollNames(1 To gNumOfPol)
                ReDim PollUnits(1 To gNumOfPol)
                ReDim SWMMPollUnit(1 To gNumOfPol)
                Call proGetPollutantNames(PollNames(), PollUnits(), SWMMPollUnit())
                Write #FileNum2, "TIME (days)", "FLOW (cfs)", "PART. SOLIDS (mg/L)";
                For intPrnPol = 1 To gNumOfPol - 1
                    If gPrintPol(intPrnPol) = True Then
                        Write #FileNum2, PollNames(intPrnPol) & " " & PollUnits(intPrnPol);
                    End If
                Next intPrnPol
                Write #FileNum2, PollNames(gNumOfPol) & " " & PollUnits(intPrnPol)
        End If
    End If

    'Print data
    If gNumOfPol = 0 Then
            Do While Not EOF(FileNum1) ' Check for end of file.
                Input #FileNum1, A, ModelRunTime, HydQOut
                Do While ModelRunTime > TimeIncNum
                    If ModelRunTime = TimeIncNum Then
                            'Write #FileNum2, TimeIncNum, HydQOut
                            If HydQOut > 0 Then
                                Write #FileNum2, Val(Format$(TimeIncNum, "0.0000")), _
                                        Val(Format$(HydQOut, "0.0000")), _
                                        Val(Format$(gPartSolConc(A, gNumAreas), "0.0000"))
                              ElseIf HydQOut = 0 Then
                                Write #FileNum2, Val(Format$(TimeIncNum, "0.0000")), _
                                        Val(Format$(HydQOut, "0.0000")), 0
                            End If
                        ElseIf ModelRunTime > TimeIncNum Then
                            Slope = (HydQOut - FirstHydQOut) / (ModelRunTime - FirstModelRunTime)
                            HydQOutInterpolated = Slope * (TimeIncNum - FirstModelRunTime) +
FirstHydQOut
                            'Write #FileNum2, TimeIncNum, HydQOutInterpolated
                            If HydQOutInterpolated > 0 Then
                                Write #FileNum2, Val(Format$(TimeIncNum, "0.0000")), _
```

```
                        Val(Format$(HydQOutInterpolated, "0.0000")), _
                        Val(Format$(gPartSolConc(A, gNumAreas), "0.0000"))
                ElseIf HydQOutInterpolated = 0 Then
                    Write #FileNum2, Val(Format$(TimeIncNum, "0.0000")), _
                        Val(Format$(HydQOutInterpolated, "0.0000")), 0
            End If
                    'Counter = Counter + 1
                    'Debug.Print Counter, ModelRunTime, HydQOut, TimeIncNum,
HydQOutInterpolated
        End If
        TimeIncNum = TimeIncNum + TimeInc
      Loop
      FirstHydQOut = HydQOut
      FirstModelRunTime = ModelRunTime
      FirstTimeIncNum = TimeIncNum
    Loop
  Else
    Do While Not EOF(FileNum1) ' Check for end of file.
      Input #FileNum1, A, ModelRunTime, HydQOut
      Do While ModelRunTime > TimeIncNum
        If ModelRunTime = TimeIncNum Then
            If HydQOut > 0 Then
                Write #FileNum2, Val(Format$(TimeIncNum, "0.0000")), _
                    Val(Format$(HydQOut, "0.0000")), _
                    Val(Format$(gPartSolConc(A, gNumAreas), "0.0000"));
              ElseIf HydQOut = 0 Then
                Write #FileNum2, Val(Format$(TimeIncNum, "0.0000")), _
                    Val(Format$(HydQOut, "0.0000")), 0;
            End If
            For intPrnPol = 1 To gNumOfPol - 1
              If gPrintPol(intPrnPol) = True And HydQOut > 0 Then
                  Write #FileNum2, Val(Format$(gPolConc(A, gNumAreas, intPrnPol),
"0.0000"));
                ElseIf gPrintPol(intPrnPol) = True And HydQOut = 0 Then
                  Write #FileNum2, 0;
              End If
            Next intPrnPol
            If HydQOut > 0 Then
                Write #FileNum2, Val(Format$(gPolConc(A, gNumAreas, gNumOfPol),
"0.0000"))
              ElseIf HydQOut = 0 Then
                Write #FileNum2, 0
            End If
          ElseIf ModelRunTime > TimeIncNum Then
            Slope = (HydQOut - FirstHydQOut) / (ModelRunTime - FirstModelRunTime)
            HydQOutInterpolated = Slope * (TimeIncNum - FirstModelRunTime) +
FirstHydQOut
            'Write #FileNum2, TimeIncNum, HydQOutInterpolated
            If HydQOutInterpolated > 0 Then
                Write #FileNum2, Val(Format$(TimeIncNum, "0.0000")), _
                    Val(Format$(HydQOutInterpolated, "0.0000")), _
                    Val(Format$(gPartSolConc(A, gNumAreas), "0.0000"));
              ElseIf HydQOutInterpolated = 0 Then
                Write #FileNum2, Val(Format$(TimeIncNum, "0.0000")), _
```

```
                    Val(Format$(HydQOutInterpolated, "0.0000")), 0;
               End If
                    'Counter = Counter + 1
                    'Debug.Print Counter, ModelRunTime, HydQOut, TimeIncNum,
HydQOutInterpolated
               For intPrnPol = 1 To gNumOfPol - 1
                  If gPrintPol(intPrnPol) = True And HydQOutInterpolated > 0 Then
                        Write #FileNum2, Val(Format$(gPolConc(A, gNumAreas, intPrnPol),
"0.0000"));
                     ElseIf gPrintPol(intPrnPol) = True And HydQOutInterpolated = 0 Then
                        Write #FileNum2, 0;
                  End If
               Next intPrnPol
               If HydQOutInterpolated > 0 Then
                     Write #FileNum2, Val(Format$(gPolConc(A, gNumAreas, gNumOfPol),
"0.0000"))
                  ElseIf HydQOutInterpolated = 0 Then
                     Write #FileNum2, 0
               End If

             End If
             TimeIncNum = TimeIncNum + TimeInc
          Loop
          FirstHydQOut = HydQOut
          FirstModelRunTime = ModelRunTime
          FirstTimeIncNum = TimeIncNum
      Loop

   End If

 Close #FileNum1
 Close #FileNum2

End Sub


Public Sub proDatFileLoadVersionDetermination()

 Dim FileNum As Integer
 Dim Dum As String
 Dim Version As String
 Dim Msg As String
 Dim Counter As Integer

 '*****************************************************************************************************
 'Version Testing. DON'T FORGET TO ADD CODE TO
 'funReadSLUFile, frmBatchMain:lstAvailLUTypes_DblClick, funTestForSLUFile
 'and funWriteNewDATFile WHEN UPDATING VERSIONS
 '*****************************************************************************************************

 FileNum = FreeFile
 Open gSADF$ For Input As #FileNum
    Input #FileNum, Dum$
    Input #FileNum, Dum$
```

```
      Input #FileNum, Dum$
      Input #FileNum, Dum$
      Input #FileNum, Dum$, Dum$
      Input #FileNum, Version$
   Close #FileNum

   If Version$ = "V8.1" Then
         proDatFileV81Load
      ElseIf Version$ = "V8.0" Then
         proDatFileV80Load
         For Counter = 1 To 162
                  If gW$(Counter) = "W" Then
                     gFirstPond = False
                     frmWetDetention.proPndLoadFile   ' load detention pond file
                     Counter = 162
                  End If
         Next Counter
      ElseIf Version$ = "V6.2" Then
         proDatFileV62Load
         For Counter = 1 To 162
                  If gW$(Counter) = "W" Then
                     gFirstPond = False
                     frmWetDetention.proPndLoadFile   ' load detention pond file
                     Counter = 162
                  End If
         Next Counter

      Else
         Msg = "The version " & Version$ & "file you want to open is not" & Chr(10) & _
         "compatible with the current version " & "V" & Format(App.Major) & "." & Format(App.Minor)
         MsgBox Msg, vbCritical, "Incompatible Data File"
   End If

   Call proTestAvailablePols

End Sub

Public Sub proDatFileSaveAsCurrentVersion()

   Dim ErrorMsg As String            ' JM8
   Dim SAIndex As Integer    'Source Area index number counter
   Dim Blank As String
   Dim E As Integer
   Dim DrainType As Integer
   Dim A As Integer
   Dim Dum As Long
   Dim Dumm As String
   Dim FileNum As Integer

   If gSADF$ = "Cancel" Then   ' User clicked Cancel button in "Save As" common dialog box
      Exit Sub
   End If

   On Error GoTo SaveDatFileError     ' JM8
```

```
    FileNum = FreeFile

    SAIndex = 1
    Blank$ = "   "
    gUsePol(1) = 1
    gTSArea(161) = funTtlBasinArea
    gTSArea(162) = funTtlBasinArea
    gSwlAreaServedBy = gTSArea(161) * gDrainArea(1)
    If gCBAreaServ = 0 Then
       gCBAreaServ = gTSArea(161)
    End If

    If gSeed = "" Then gSeed = 0

    gNumAreas = 2
    For E = 1 To 160
       If gTSArea(E) <> 0 Then
          gNumAreas = gNumAreas + 1
          If gIDAServ(E) = 0 Then gIDAServ(E) = gTSArea(E)
          If gPorPavArea(E) = 0 Then gPorPavArea(E) = gTSArea(E)
          If gPondAreaServ(E) = 0 Then gPondAreaServ(E) = gTSArea(E)
          If gOtherAServed(E) = 0 Then gOtherAServed(E) = gTSArea(E)
       End If
    Next E

    If gSADF$ = "" Then
       frmMainMenu.proSaveFile  ' JM8 - if cancel out of save dialog, then gSADF$ = ""
    End If

    'MsgBox "Saving File " & gSADF$, vbOKOnly, "WinSLAMM"

    Open gSADF$ For Output As #FileNum
          Write #FileNum, gRainFile$
          Write #FileNum, gPolProbDistF$
          Write #FileNum, gPartResDelF$
          Write #FileNum, gRSubVF$
          Write #FileNum, gPSCncF$, Dumm$
          Write #FileNum, gVersion$
          Write #FileNum, gStartDate$, gEndDate$, gJulianStartDate$, gJulianEndDate$
          Write #FileNum, gOutOption, gSeed, Dum, Dumm$, gOutOpt$, Dum, gNumAreas
          Write #FileNum, gSiteDes$
          Write #FileNum, gG$, gSwlInfilRate, gSwlDensity, gSwlWidth, gSwlAreaServedBy
          Write #FileNum, gC$, gTtlSumpVol, gCBAreaServ, gPCSumpVolFull, gNumCBClngs,
gSumpDepth

          ' JM30
          'ReDim gSAArNum(gNumAreas - 2)  ' Do not include S.A.'s 161 and 162.  ' JM7/20/97-A
          ReDim gSAArNum(gNumAreas)  ' Added S.A.'s 161 and 162. to get outfall calcs to work '
JV5/16/98


          For A = 1 To 162
             If gTSArea(A) = 0 Then GoTo 22160
```

```
            Write #FileNum, A, gTSArea(A), gSAName(A), gIDPRate(A), gIDAServ(A), gIDArea(A),
gIDWToD(A), gOtherConcRed(A), _
                        gPorPavPercRate(A), gPorPavArea(A), gPondAreaServ(A)
            Write #FileNum, Blank$, gOtherVolRed(A), gOtherAServed(A), gI$(A), gW$(A), gOth$(A),
gP$(A), gD$(A), gS$(A), _
                        gSpreadingArea$(A)
            Write #FileNum, Blank$, gRoof(A), gTypeSA(A), gDirt(A), gAlley(A), gDensity(A)

            ' JM7/20/97  This array is used with getting the S.A. name (text) for use in the Windows
            ' Calc module.  The text serves as column headers.
            'If A < 161 Then   ' JM30  Remove the If test.
               gSAArNum(SAIndex) = A
               SAIndex = SAIndex + 1
            ' End If
22160  Next A
         For A = 1 To 5
            Write #FileNum, A, gCBCleanDate$(A), gFreewayText(A), gAvgDailyTraf(A), gFreewayLen(A),
gFreewayInitLoad(A), gFreewayInitLoadType(A)
         Next A
         For A = 0 To 15
            Write #FileNum, A + 1, gUsePol(A * 3 + 1), gUsePol(A * 3 + 2), gUsePol(A * 3 + 3)
         Next A
         For A = 1 To 15
            Write #FileNum, A, gStreetLen(A), gAStAcc(A), gBStAcc(A), gCStAcc(A), gInitStLoad(A),
gStDirtAccType(A)
            Write #FileNum, gPrkCon$(A), gStClProd(A), gM(A), gB(A), gPrkDen(A), gStTexture(A),
gInitStDirtType(A), gStCleanSchedChanges(A)
            'Write #filenum, gStCleanFreq(0, A), gStCleanFreq(1, A), gStCleanFreq(2, A), gStCleanFreq(3,
A), gStCleanFreq(4, A), gStCleanFreq(5, A), _
                     gStCleanFreq(6, A), gStCleanFreq(7, A), gStCleanFreq(8, A), gStCleanFreq(9, A),
gStCleanFreq(10, A)
            Write #FileNum, 0, gStCleanFreq(0, A), gStCleanFreq(1, A), gStCleanFreq(2, A),
gStCleanFreq(3, A), gStCleanFreq(4, A), gStCleanFreq(5, A), _
                     gStCleanFreq(6, A), gStCleanFreq(7, A), gStCleanFreq(8, A), gStCleanFreq(9, A)
            Write #FileNum, gStCleanDate$(0, A), gStCleanDate$(1, A), gStCleanDate$(2, A),
gStCleanDate$(3, A), gStCleanDate$(4, A), gStCleanDate$(5, A)
            Write #FileNum, gStCleanDate$(6, A), gStCleanDate$(7, A), gStCleanDate$(8, A),
gStCleanDate$(9, A), gStCleanDate$(10, A)
         Next A
         For DrainType = 1 To 5
            Write #FileNum, gDrainArea(DrainType)
         Next DrainType
         Dum = 99999
         For A = 6 To 14
            Write #FileNum, Dum
         Next A
         Dum = 0
   Close #FileNum

   Exit Sub              ' JM8

SaveDatFileError:        ' JM8

   Select Case Err.Number
```

```
        Case 53       ' File not found
            ErrorMsg = "The file you selected was not found."
            MsgBox ErrorMsg, vbCritical, "File Not Found"
            Exit Sub
        Case Else
            ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
              & Chr(10) & Chr(10) & "Procedure proDatFileSaveAsCurrentVersion"
            MsgBox ErrorMsg, vbCritical, "Error Trap"
            Exit Sub
    End Select

End Sub

Public Sub proDatFileSaveAsDOSVersion()

    Dim ErrorMsg As String             ' JM8
    Dim SAIndex As Integer    'Source Area index number counter
    Dim Blank As String
    Dim E As Integer
    Dim DrainType As Integer
    Dim A As Integer
    Dim Dum As Long
    Dim Dumm As String

    If gSADF$ = "Cancel" Then   ' User clicked Cancel button in "Save As" common dialog box
        Exit Sub
    End If

    On Error GoTo SaveDatFileError     ' JM8

    SAIndex = 1
    Blank$ = "   "
    gUsePol(1) = 1
    gTSArea(161) = funTtlBasinArea
    gTSArea(162) = funTtlBasinArea
    gSwlAreaServedBy = gTSArea(161) * gDrainArea(1)
    If gCBAreaServ = 0 Then
        gCBAreaServ = gTSArea(161)
    End If

    If gSeed = "" Then gSeed = 0

    gNumAreas = 2
    For E = 1 To 160
        If gTSArea(E) <> 0 Then
            gNumAreas = gNumAreas + 1
            If gIDAServ(E) = 0 Then gIDAServ(E) = gTSArea(E)
            If gPorPavArea(E) = 0 Then gPorPavArea(E) = gTSArea(E)
            If gPondAreaServ(E) = 0 Then gPondAreaServ(E) = gTSArea(E)
            If gOtherAServed(E) = 0 Then gOtherAServed(E) = gTSArea(E)
        End If
    Next 'E

    If gSADF$ = "" Then
```

```
        frmMainMenu.proSaveFile    ' JM8 - if cancel out of save dialog, then gSADF$ = ""
    End If

    MsgBox "Saving File " & gSADF$, vbOKOnly, "WinSLAMM"

    Open gSADF$ For Output As #1
        Write #1, funTrimPath(gRainFile$)                    'gRainFile$
        Write #1, funTrimPath(gPolProbDistF$)                    'gPolProbDistF$
        Write #1, funTrimPath(gPartResDelF$)                    'gPartResDelF$
        Write #1, funTrimPath(gRSubVF$)                    'gRSubVF$
        Write #1, funTrimPath(gPSCncF$), Dumm$            'gPSCncF$, Dumm$
        Write #1, "V6.2"
        Write #1, gStartDate$, gEndDate$, gJulianStartDate$, gJulianEndDate$
        Write #1, gOutOption, gSeed, Dum, Dumm$, gOutOpt$, Dum, gNumAreas
        Write #1, gSiteDes$
        Write #1, gG$, gSwlInfilRate, gSwlDensity, gSwlWidth, gSwlAreaServedBy
        Write #1, gC$, gTtlSumpVol, gCBAreaServ, gPCSumpVolFull, gNumCBClngs

        ' JM30
        'ReDim gSAArNum(gNumAreas - 2)  ' Do not include S.A.'s 161 and 162.  ' JM7/20/97-A
        ReDim gSAArNum(gNumAreas)  ' Added S.A.'s 161 and 162. to get outfall calcs to work '
JV5/16/98


        For A = 1 To 162
          If gTSArea(A) = 0 Then GoTo 22160
          Write #1, A, gTSArea(A), gSAName(A), gIDPRate(A), gIDAServ(A), gIDArea(A), gIDWToD(A),
gOtherConcRed(A), _
                    gPorPavPercRate(A), gPorPavArea(A), gPondAreaServ(A)
          Write #1, Blank$, gOtherVolRed(A), gOtherAServed(A), gI$(A), gW$(A), gOth$(A), gP$(A),
gD$(A), gS$(A), gSpreadingArea$(A)
          Write #1, Blank$, gRoof(A), gTypeSA(A), gDirt(A), gAlley(A), gDensity(A)

          ' JM7/20/97  This array is used with getting the S.A. name (text) for use in the Windows
          ' Calc module.  The text serves as column headers.
          'If A < 161 Then   ' JM30  Remove the If test.
             gSAArNum(SAIndex) = A
             SAIndex = SAIndex + 1
          ' End If
22160      Next A
        For A = 1 To 5
          Write #1, A, gCBCleanDate$(A), gFreewayText(A), gAvgDailyTraf(A), gFreewayLen(A),
gFreewayInitLoad(A), gFreewayInitLoadType(A)
        Next A
        For A = 0 To 15
          Write #1, A + 1, gUsePol(A * 3 + 1), gUsePol(A * 3 + 2), gUsePol(A * 3 + 3)
        Next A
        For A = 1 To 15
          Write #1, A, gStreetLen(A), gAStAcc(A), gBStAcc(A), gCStAcc(A), gInitStLoad(A),
gStDirtAccType(A)
          Write #1, gPrkCon$(A), gStClProd(A), gM(A), gB(A), gPrkDen(A), gStTexture(A),
gInitStDirtType(A), gStCleanSchedChanges(A)
          'Write #1, gStCleanFreq(0, A), gStCleanFreq(1, A), gStCleanFreq(2, A), gStCleanFreq(3, A),
gStCleanFreq(4, A), gStCleanFreq(5, A), _
```

```
                        gStCleanFreq(6, A), gStCleanFreq(7, A), gStCleanFreq(8, A), gStCleanFreq(9, A),
gStCleanFreq(10, A)
            Write #1, 0, gStCleanFreq(0, A), gStCleanFreq(1, A), gStCleanFreq(2, A), gStCleanFreq(3, A),
gStCleanFreq(4, A), gStCleanFreq(5, A), _
                        gStCleanFreq(6, A), gStCleanFreq(7, A), gStCleanFreq(8, A), gStCleanFreq(9, A)
            Write #1, gStCleanDate$(0, A), gStCleanDate$(1, A), gStCleanDate$(2, A), gStCleanDate$(3,
A), gStCleanDate$(4, A), gStCleanDate$(5, A)
            Write #1, gStCleanDate$(6, A), gStCleanDate$(7, A), gStCleanDate$(8, A), gStCleanDate$(9,
A), gStCleanDate$(10, A)
        Next A
        For DrainType = 1 To 5
            Write #1, gDrainArea(DrainType)
        Next DrainType
        Dum = 99999
        For A = 6 To 14
            Write #1, Dum
        Next 'A
        Dum = 0
    Close #1

    Exit Sub            ' JM8

SaveDatFileError:           ' JM8

    Select Case Err.Number
      Case 53       ' File not found
        ErrorMsg = "The file you selected was not found."
        MsgBox ErrorMsg, vbCritical, "File Not Found"
        Exit Sub
      Case Else
        ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
          & Chr(10) & Chr(10) & "Procedure proDatFileSaveAsDOSVersion"
        MsgBox ErrorMsg, vbCritical, "Error Trap"
        Exit Sub
    End Select


End Sub


Public Function funTrimPath(FileName As String)

    Dim FileNameLength As Integer
    Dim Counter As Integer

    For Counter = Len(FileName) - 1 To 1 Step -1
        FileNameLength = Counter
        If Mid(FileName, FileNameLength, 1) = "\" Then
            Exit For
        End If
    Next Counter
    If Counter > 1 Then
            funTrimPath = UCase(Right(FileName, Len(FileName) - FileNameLength))
        Else
```

```
        funTrimPath = UCase(FileName)
    End If

End Function



Public Sub proTestAvailablePols()

    Dim Index As Integer

    '   this procedure corrects the .dat file if it contains a gpolcntr value =1 when there is no pollutant
    '     data in the .ppd file for that pollutant.

    proLoadPolFile

    For Index = 1 To 16
        If gPolCntr(Index) = 0 And gUsePol(3 * Index - 2) = 1 Then
            gUsePol(3 * Index - 2) = 0
            gUsePol(3 * Index) = 0
        End If
    Next Index
    For Index = 17 To 32
         If gPolCntr(Index) = 0 And gUsePol(3 * (Index - 16) - 1) = 1 Then
            gUsePol(3 * (Index - 16) - 1) = 0
            gUsePol(3 * (Index - 16)) = 0
        End If
    Next Index

End Sub
```

Attribute VB_Name = "CalcWetDetention"

```
Option Explicit

   Dim mMaxQIn As Single    'DOS == MAXQIN
   Dim mMaxQOut As Single   'DOS == MAXQOUT
   Dim mTtlQOut As Single     'DOS == TOTQOUT
   Dim mSumWghtPartSize As Single     'DOS = SUMWGHTPSIZ
   Dim mSumWghtControl As Single      'DOS == SUMWGHTDCONT
   Dim mSumHydQOut As Single      'DOS == SUMHYDQOUT
   Dim mSumQOut As Single     'DOS == SUMQOUT
   Dim mSumVolOut As Single    'DOS == SUMVOLOUT
   Dim mVolSeepOut As Single     'DOS == VOLSEEPOUT
   Dim mVolEvapOut As Single      'DOS == VOLEVAPOUT
   Dim mHydVolOut As Single        'DOS == HYDVOLOUT
   Dim mSumQIn As Single       'DOS == SUMQIN
   Dim mMaxCritPartSize As Single    'DOS == MAXCRITPSIZ
   Dim mBetweenRains As Boolean     'DOS == BTWNRNS$
   Dim mNumInc As Integer    'DOS == NUMINC
   Dim mTimeInc As Single    '  Time Increment step for detention calcs  DOS == TIMINC
   Dim mFirstEvent As Boolean    'DOS == FIRSTEVENT$
   Dim mLastValue As Integer     'DOS == LASTVALUE
   Dim mNumIncToLarge As Boolean    'DOS == NUMINCTOLRG$
   Dim mRestartTime As Boolean    'DOS == RESTRTIME$
   Dim mNumIncBetweenRains As Integer      'DOS == NUMINCBTWNRAINS
   Dim mTtlQOutAr() As Single     'DOS == TOTQOUT
   Dim mEvapOutNumber As Integer        'DOS == EVAPOUTNMBR
   Dim mLastTimeInc As Single




Public Sub proMainWetDet(FROMCALC As String)

     Dim LowestOutletElev As Single   '  DOS == LOWOUTELEV
     Dim OutletNum As Integer   '  DOS == OUTNMBR
     Dim NSN As Integer   ' New Stage Number   DOS == NSN
     Dim OSN As Integer    ' Old Stage Number   DOS  == OSN
     Dim EnteredproMainWetDet As Boolean    '  DOS == DPC2   marker to indicate that this program was
used
     'DPInOutfall as boolean  DOS == DP162
     Dim PondVolBelowInv As Single   'Pond Volume Below Invert   DOS == PVBELINVi
     Dim s As Integer
     Dim A As Integer
     Dim i As Integer
     Dim j As Integer
     Dim F As Integer
     Dim DPE As Integer
     Dim RunDur As Single    'Runoff Duration   DOS == RUNDUR
     Dim PeakTime As Single    'DOS == PEAKTIME
     Dim QOut As Single    'DOS == QOUT
     Dim QAve As Single    'DOS == QAVE
     Dim QPeak As Single   'DOS == QPEAK
```

```
    Dim Stage As Single    'DOS == STAGE
'     Dim OSN As Integer     'DOS == OSN  Old Stage Number
'     Dim NSN As Integer       'New Stage Number   DOS == NSN
    Dim UpQRatio As Single    'DOS == UPQRATIO
    Dim CritPSizRatio As Single    'DOS == CRITPSIZRATIO
    Dim SPQOutRatio As Single    'DOS == SPQOUTRATIO
    Dim StageRatio As Single     'DOS == STAGERATIO
    Dim EarlyNextRain As Boolean    'DOS == EARLYNEXTRAIN
    Dim InterEventDur As Single     'DOS == INTEVENTDUR
    Dim EventDur As Single      'DOS == EVENTDUR
    Dim TimeIncBetweenRains   'DOS == TIMINCBTWNRAINS
    Dim InflowHydrograph As String     'DOS == INFHYDROG$
    Dim ZeroStage As Boolean      'DOS == ZEROSTAGE
    Dim RestartLoop As Boolean    'DOS == restartloop
    Dim TmpStorage          'DOS == TMPSTORAGE
    Dim TmpPndStage   'DOS == TMPNDSTAGE
    Dim TmpPndArea      'DOS == TMPNDAREA
    Dim TmpTotQOut    'DOS == TMPTOTQOUT
    Dim TmpNSeepOut      'DOS == TMPNSEEPOUT
     Dim TmpEvapOut      'DOS == TMPEVAPOUT
     Dim TmpHydQOut     'DOS == TMPHYDQOUT
     Dim TmpUpQVel      'DOS == TMPUPQVEL
     Dim TmpCritPSiz      'DOS == TMPCRITPSIZ
     Dim TmpWghtPSiz     'DOS == TMPWGHTPSIZ
     Dim TmpPcPCont      'DOS == TMPPCPCONT
     Dim TmpWghtdCont     'DOS == TMPWGHTDCONT
     Dim StartTime As Single    'DOS == STARTIME
     Dim TMaxQOut As Single    'DOS == TMAXQOUT
     Dim TSumQOut As Single    'DOS == TSUMQOUT
     Dim TSumWghtPSiz As Single    'DOS == TSUMWGHTPSIZ
     Dim TSumWghtdCont As Single    'DOS == TSUMWGHTDCONT
     Dim TSumVolOut As Single    'DOS == TSUMVOLOUT
     Dim TVolSeepOut As Single    'DOS == TVOLSEEPOUT
     Dim TVolEvapOut As Single    'DOS == TVOLEVAPOUT
     Dim THydVolOut As Single    'DOS == THYDVOLOUT
     Dim TSumHydQOut As Single    'DOS == TSUMHYDQOUT
     Dim PrevQPeak As Single    'DOS == PREVQPEAK
     Dim PrevPeakTime As Single      'DOS == PREVPEAKTIME
     Dim M As Integer     'DOS == M
     Dim CurTime As Single     'DOS == CURTIME
     Dim N As Integer    'DOS == N
     Dim fDummy As Single
     Dim NumInc As Integer
     Dim MOY As Integer      '  Month Of Year
     Dim FileNum As Integer

    If FROMCALC$ = "outfall" And EnteredproMainWetDet = True Then GoTo 1340
    Rem $DYNAMIC
    Rem    dim format:  (number of detention ponds allowed in file-DPE)
'     ReDim gNumOutlets(10), gInitStage(10), gPondLUNum(10), gSACO(10)
'     ReDim gNumIncAr(10), gStageIncr(10), gPondDepth(10), gPartSizeF$(10)
    Rem   dim format:  (number of detention ponds allowed in file-DPE,
    Rem                number of outlets per pond-gNumOutlets)
    Rem   dim format:  (stage elevation number-gNumIncAr,
```

```
    Rem             number of detention ponds allowed in file-DPE,
    Rem             number of outlets per pond-gNumOutlets)
    Rem   dim format:  (number of rains,
    Rem             number of detention ponds allowed in file - DPE)
    ReDim gWghtdTSReduct(gFirstRainNum To gLastRainNum, gTtlNumDP)
    ReDim gPCDPVolReduct(1, 1)
    ReDim gPndOverflowMsg(1, 1)
    ReDim gTimeStep(1), gQIn(1)
'     ReDim gUpFlowVelStokes(30), gCritPartSizeStokes(30), gPCGreaterThanCritPartSize(31),
gCritPartSizeData(31)
    ReDim gCumStorage(1), gSPQOutAr(1), gQOutAr(1)
    'ReDim gRainEventStartDate(1), gRain(1), gJulStartDate(1), gPondRainDur(1)
    ReDim gPondRainDur(1)
    Rem   the following variables may be eliminated as arrays after testing
    ReDim gQInAve(1), gAveVol(1), gStorMinusQOut(1)
    ReDim gTtlStorageVol(1), mTtlQOutAr(1), gSPQOut(1)
    ReDim gNatSeepOut(1), gEvapOut(1), gNatSeepQ(1), gHydQOut(1)
    ReDim gPondStage(1)
    ReDim gPondArea(1)
    ReDim gPrevQIn(1)
    ReDim gQIn(1)
    ReDim gPCPartControl(1)
    ReDim gWeightedControl(1)
    ReDim gUpQVel(1)
    ReDim gCritPartSize(1)
    ReDim gWeightedCritPartSize(1)
    ReDim gPndAreaArSF(10, 40) As Single  'gPndAreaAr() in square feet


     ReDim gPondRainDur(gFirstRainNum To gLastRainNum)   '8600
     For A = gFirstRainNum To gLastRainNum
          gPondRainDur(A) = gRainDur(A) * 24
     Next A    '8640
     Call proInitCritPartSizeData 'GoSub 10080:    Rem    variable initialization
     For DPE = 1 To gTtlNumDP
        For NumInc = 0 To gNumIncAr(DPE)
          gPndAreaArSF(DPE, NumInc) = 43560 * gPndAreaAr(DPE, NumInc)
          Rem    pndareaar[sqft]=pndareaar[acres]*[43560ftsq/acre]
        Next NumInc
     Next DPE

     ReDim gWghtdTSReduct(gFirstRainNum To gLastRainNum, gTtlNumDP),
gPndOverflowMsg(gFirstRainNum To gLastRainNum, gTtlNumDP)
     ReDim gPCDPVolReduct(gFirstRainNum To gLastRainNum, gTtlNumDP)
1340  If FROMCALC$ = "outfall" Then
        gSANum = 162
        ReDim gFlushRatio(gFirstRainNum To gLastRainNum)
        ReDim gWAvgCritPartSiz(gFirstRainNum To gLastRainNum)
        ReDim gPeakFlowRed(gFirstRainNum To gLastRainNum)
        ReDim gWeightedTtlSolRed162(gFirstRainNum To gLastRainNum)
        ReDim gDPVolRed162(gFirstRainNum To gLastRainNum)
    End If
    EnteredproMainWetDet = True     '  marker to indicate that this program was used
    For DPE = 1 To gTtlNumDP
```

```
    If gDPSANumMatch(DPE).SANum = 0 Then GoTo 1900
    Call proLoadCPZFile(DPE)   'GoSub 8300:     Rem    load particle size file
    s = 1
    mFirstEvent = True
    mRestartTime = True
    Do Until gSAArNum(s) = gDPSANumMatch(DPE).SANum
      s = s + 1
    Loop
    If gDPSANumMatch(DPE).SANum = 162 And FROMCALC$ = "landuses" Then GoTo 1900
    If gDPSANumMatch(DPE).SANum < 162 And FROMCALC$ = "outfall" Then GoTo 1900
    GoSub 4800:     Rem   increase number of stage increments by factor of 10
    Call proLowestInvElev(DPE, LowestOutletElev)    'GoSub 5000:     Rem   find lowest invert elevation
    A = 1:          Rem   to set Month for evap calc
    GoSub 5200:     Rem   to stage and surface area calcs
    For A = gFirstRainNum To gLastRainNum
         mTimeInc = 3 * gPondRainDur(A) * 60 / 100
         If mTimeInc > 15 Then mTimeInc = 15
         Rem GOSUB 24425  :  REM  print heading
         GoSub 5900:     Rem   re-initialize pond stats
         If gInitStage(DPE) > 0 And A = 1 Then GoSub 5950:  Rem    calc initial values for loop
         GoSub 2000:     Rem   to main calc loop
         Rem GOSUB 25300   :  REM  print summary
1860     Next A
1900  Next DPE
      mLastTimeInc = 0
   Exit Sub:      Rem   end subroutine


2000 Rem ***********  BEGIN gRain LOOP  **************************************
   mNumIncToLarge = False
   mNumIncBetweenRains = 0
   If i > 1 Then GoSub 5900:   Rem   initialize pond performance statistics
   RunDur = 1.2 * gPondRainDur(A)
   PeakTime = 0.5 * RunDur
   If gDPSANumMatch(DPE).SANum = 162 Then
      QAve = gRunoffVol(A, s - 1) / (RunDur * 3600) * (gPondAreaServ(gSAArNum(s)) / gTtlBasinArea)
    Else
      QAve = gRunoffVol(A, s) / (RunDur * 3600) * (gPondAreaServ(gSAArNum(s)) /
gTSArea(gSAArNum(s)))
   End If
   QPeak = 2 * QAve
   If M <> Val(Left$(gRainEventStartDate(A), 2)) Then
      M = Val(Left$(gRainEventStartDate(A), 2))
      GoSub 5200: Rem   recalc outflow to account for change in evap rate
   End If
   Call proCalcgSPQOutAr(DPE)     '   calc gSPQOutAr  gosub 6000
   If mFirstEvent = True Then
     mFirstEvent = False
     mLastValue = 0
     GoSub 7300      'save temp values
    ElseIf mFirstEvent = False Then
     mLastValue = mNumInc
     GoSub 7300
   End If
```

```
    GoSub 6350:      Rem   to check when next rain is
    GoSub 6300:      Rem   redim arrays
    GoSub 7350:      Rem   apply tmp values to redimed arrays
4200 Rem   return to here to restart loop if time inc adjusted
    mBetweenRains = False
    GoSub 6500:      Rem  main calc loop
    If RestartLoop = True Then
        GoSub 6300:   Rem   redim arrays
        Call proCalcgSPQOutAr(DPE)     '  recalc gSPQOutAr   gosub 6000
        GoSub 7350:   Rem   apply tmp values to redimed arrays
        GoSub 5900:   Rem   re-initialize pond performance stats
        GoTo 4200: Rem   restart loop with shorter time increment
    End If
    GoSub 23170:     Rem   initialize values to deal with early next rain
      If mRestartTime = True Then
           gTimeStep(0) = 0
           mRestartTime = False
        Else
           gTimeStep(0) = CurTime
      End If
    GoSub 23000:     Rem   calc time()
    If gOutOption > 5 And gW$(gSAArNum(gNumAreas)) = "W" Then Call proSaveHydrographData(A)
    '     TRINP is only valid in DETPOND
'      If TRINP <> 3 And A < N Then CurTime = gTimeStep(0) + (gJulStartDate(A + 1) - gJulStartDate(A))
    If A < gLastRainNum Then CurTime = gTimeStep(0) + (gJulDPStartDate(A + 1) -
gJulDPStartDate(A))
    '      JV5    If A < N Then CurTime = gTimeStep(0) + (gJulDPStartDate(A + 1) - gJulDPStartDate(A))

    GoSub 23025:   Rem   calc total qin and qout
    Rem GOSUB 24200:   REM   printout subroutine
4350  If mNumIncBetweenRains > 0 Then GoSub 10000: Rem  calculations for between events
    GoSub 23700:   Rem   summary pond perform stats
    Rem GOSUB 24350:   REM   print interevent per results
4400  Return
    Rem  ****  end rain loop, return to main menu  **************


3760 Rem   particle calc gosub
      If gPondArea(i) = 0 Then
          gUpQVel(i) = 0
         Else
          gUpQVel(i) = gHydQOut(i) / gPondArea(i) * 3600
      End If
      Rem  gUpQVel[ft/hr]=HYDQOUT[cfs]/gPondArea[sqft]*[3600sec/hr]
      j = 1
      While gUpQVel(i) > gUpFlowVelStokes(j)
          j = j + 1
      Wend
      UpQRatio = (gUpQVel(i) - gUpFlowVelStokes(j - 1)) / (gUpFlowVelStokes(j) - gUpFlowVelStokes(j -
1))
      gCritPartSize(i) = gCritPartSizeStokes(j - 1) + (gCritPartSizeStokes(j) - gCritPartSizeStokes(j - 1)) *
UpQRatio
      gWeightedCritPartSize(i) = gHydQOut(i) * gCritPartSize(i)
      j = 1
```

```
      While gCritPartSize(i) > gCritPartSizeData(j)
        j = j + 1
      Wend
      CritPSizRatio = (gCritPartSize(i) - gCritPartSizeData(j - 1)) / (gCritPartSizeData(j) -
gCritPartSizeData(j - 1))
      gPCPartControl(i) = gPCGreaterThanCritPartSize(j - 1) + (gPCGreaterThanCritPartSize(j) _
                        - gPCGreaterThanCritPartSize(j - 1)) * CritPSizRatio
      gWeightedControl(i) = gHydQOut(i) * gPCPartControl(i)
      If gPondStage(i) < 3 Then gWeightedControl(i) = 0
   Return

4800 Rem   increase number of stage increments by factor of 10
   OSN = 0: Rem  osm==oldstagenumber
   gNumIncAr10(DPE) = 10 * gNumIncAr(DPE)
   ReDim gTStageAr(gNumIncAr10(DPE)) As Single
   ReDim gTPondAreaAr(gNumIncAr10(DPE)) As Single
   ReDim gTNatSeep(gNumIncAr10(DPE), gNumOutlets(DPE)) As Single
   ReDim gTQOutOther(gNumIncAr10(DPE), gNumOutlets(DPE)) As Single
   gTStageAr(0) = gStageAr(DPE, 0)
   gTPondAreaAr(0) = gPndAreaArSF(DPE, 0)
   For j = 1 To gNumOutlets(DPE)
      gTNatSeep(0, j) = gNaturalSeep(0, DPE, j)
      gTQOutOther(0, j) = gQOutOther(0, DPE, j)
   Next j
   For NSN = 1 To gNumIncAr10(DPE): Rem   NSN==newstagenumber
      If NSN Mod 10 = 0 Then
            OSN = OSN + 1
            gTStageAr(NSN) = gStageAr(DPE, OSN)
            gTPondAreaAr(NSN) = gPndAreaArSF(DPE, OSN)
            For j = 1 To gNumOutlets(DPE)
               gTNatSeep(NSN, j) = gNaturalSeep(OSN, DPE, j)
               gTQOutOther(NSN, j) = gQOutOther(OSN, DPE, j)
            Next j
         Else
            gTStageAr(NSN) = gTStageAr(NSN - 1) + 0.1 * (gStageAr(DPE, OSN + 1) - gStageAr(DPE,
OSN))
            gTPondAreaAr(NSN) = gTPondAreaAr(NSN - 1) + 0.1 * (gPndAreaArSF(DPE, OSN + 1) -
gPndAreaArSF(DPE, OSN))
            For j = 1 To gNumOutlets(DPE)
               gTNatSeep(NSN, j) = gTNatSeep(NSN - 1, j) + 0.1 * (gNaturalSeep(OSN + 1, DPE, j) -
gNaturalSeep(OSN, DPE, j))
               gTQOutOther(NSN, j) = gTQOutOther(NSN - 1, j) + 0.1 * (gQOutOther(OSN + 1, DPE, j) -
gQOutOther(OSN, DPE, j))
            Next j
      End If
   Next NSN
   ReDim gNStageAr(gNumIncAr10(DPE)) As Single
   ReDim gNPondAreaAr(gNumIncAr10(DPE)) As Single
   ReDim gNatSeepRate(gNumIncAr10(DPE), gNumOutlets(DPE)) As Single
   ReDim gNQOutOther(gNumIncAr10(DPE), gNumOutlets(DPE)) As Single
   For NSN = 0 To gNumIncAr10(DPE)
      gNStageAr(NSN) = gTStageAr(NSN)
      gNPondAreaAr(NSN) = gTPondAreaAr(NSN)
      For j = 1 To gNumOutlets(DPE)
```

```
        gNQOutOther(NSN, j) = gTQOutOther(NSN, j)
        gNatSeepRate(NSN, j) = gTNatSeep(NSN, j)
      Next j
    Next NSN
    Erase gTStageAr, gTPondAreaAr, gTNatSeep, gTQOutOther
    Return


5200 Rem   stage and surface area calcs   new version
     ReDim gCumStorage(gNumIncAr10(DPE)), gSPQOutAr(gNumIncAr10(DPE))
     ReDim gQOutAr(gNumIncAr10(DPE)), gNatSeepQ(gNumIncAr10(DPE))
     Rem    to save memory i did not redim the above 4 variables for # of detention ponds
     PondVolBelowInv = 0
     For i = 0 To gNumIncAr10(DPE)
       If i = 0 Then
           Rem continue
         ElseIf gNStageAr(i) <= LowestOutletElev Then
           PondVolBelowInv = (gNStageAr(i) - gNStageAr(i - 1)) * gNPondAreaAr(i) + PondVolBelowInv
           gCumStorage(i) = (gNStageAr(i) - gNStageAr(i - 1)) * gNPondAreaAr(i) + gCumStorage(i - 1)
         ElseIf gNStageAr(i) > LowestOutletElev Then
           gCumStorage(i) = (gNStageAr(i) - gNStageAr(i - 1)) * gNPondAreaAr(i) + gCumStorage(i - 1)
       End If
       Stage = gNStageAr(i)
       Call proQOutCalcs(QOut, DPE, Stage, i, M)     'GoSub 5300: Rem   to calculate the outflow value
       gQOutAr(i) = QOut
     Next i
     Return

5900 Rem   initialize pond performance statistics
      mMaxQIn = 0: mSumQIn = 0: mMaxQOut = 0
      mSumQOut = 0: mSumWghtPartSize = 0: mSumWghtControl = 0: mSumVolOut = 0
      mMaxCritPartSize = 0: mSumHydQOut = 0
      mTtlQOut = 0
      mVolSeepOut = 0: mVolEvapOut = 0: mHydVolOut = 0
      If gPondStage(0) = 0 Then
         gPondArea(0) = gNPondAreaAr(0)
         gPCPartControl(0) = gPCGreaterThanCritPartSize(0)
      End If
    Return

5950  Rem    calc initial values for loop
      Stage = gInitStage(DPE): F = 0: i = 0
      gPondStage(0) = gInitStage(DPE)
      gTtlStorageVol(0) = 0
      While gInitStage(DPE) > gNStageAr(F)
         If F >= gNumIncAr10(DPE) Then
            F = gNumIncAr10(DPE)
            GoSub 6740: Rem  overflow label
            Return
         End If
         F = F + 1
      Wend
      For i = 1 To F - 1
         gTtlStorageVol(0) = gTtlStorageVol(0) + (gNStageAr(i) - gNStageAr(i - 1)) * gNPondAreaAr(i)
```

```
      Rem LPRINT I, F, STORAGE(0), gInitStage, gNStageAr(I), gNStageAr(I - 1), gNPondAreaAr(I)
    Next i
    i = 0
    StageRatio = (gPondStage(0) - gNStageAr(F - 1)) / (gNStageAr(F) - gNStageAr(F - 1))
    mTtlQOutAr(0) = gQOutAr(F - 1) + (gQOutAr(F) - gQOutAr(F - 1)) * StageRatio
    gPondArea(0) = gNPondAreaAr(F - 1) + (gNPondAreaAr(F) - gNPondAreaAr(F - 1)) * StageRatio
    gTtlStorageVol(0) = gTtlStorageVol(0) + (gPondStage(0) - gNStageAr(F - 1)) * gPondArea(0)
    gNatSeepOut(0) = gNatSeepQ(F - 1) + (gNatSeepQ(F) - gNatSeepQ(F - 1)) * StageRatio
    gEvapOut(0) = gEvap(M, DPE, mEvapOutNumber) * gPondArea(0) / 24 / 3600 / 12
    gHydQOut(0) = mTtlQOutAr(0) - gEvapOut(0) - gNatSeepOut(0)
    GoSub 3760:     Rem  particle size calcs
    GoSub 23600:     Rem  calc statistics
   Return

6300  Rem  redim arrays for calcs
   ReDim gQInAve(mNumInc), gAveVol(mNumInc), gStorMinusQOut(mNumInc)
   ReDim gTtlStorageVol(mNumInc), mTtlQOutAr(mNumInc), gSPQOut(mNumInc)
   ReDim gNatSeepOut(mNumInc), gEvapOut(mNumInc), gHydQOut(mNumInc)
   ReDim gPondStage(mNumInc), gPondArea(mNumInc)
   ReDim gTimeStep(mNumInc + 10), gPrevQIn(mNumInc + 10), gQIn(mNumInc + 10)
   ReDim gUpQVel(mNumInc), gCritPartSize(mNumInc)
   ReDim gWeightedCritPartSize(mNumInc), gPCPartControl(mNumInc), gWeightedControl(mNumInc)
   Return

6350 Rem   to check when next rain is
   EarlyNextRain = False
   If A = gLastRainNum Then
      mNumInc = Int(RunDur * 60 / mTimeInc * 3)
      mNumIncBetweenRains = 0
      InterEventDur = 0
     ElseIf gJulDPStartDate(A + 1) < gJulDPStartDate(A) + RunDur / 24 Then
      mNumInc = Int((gJulDPStartDate(A + 1) - gJulDPStartDate(A)) * 24 * 60 / mTimeInc)
      EarlyNextRain = True
      EventDur = (gJulDPStartDate(A + 1) - gJulDPStartDate(A))
      InterEventDur = 0
     ElseIf gJulDPStartDate(A + 1) >= gJulDPStartDate(A) + RunDur / 24 And gJulDPStartDate(A + 1)
<= gJulDPStartDate(A) + (3 * RunDur / 24) Then
      mNumInc = Int((gJulDPStartDate(A + 1) - gJulDPStartDate(A)) * 24 * 60 / mTimeInc)
      EventDur = (gJulDPStartDate(A + 1) - gJulDPStartDate(A))
      InterEventDur = 0
     ElseIf gJulDPStartDate(A + 1) > gJulDPStartDate(A) + 3 * RunDur / 24 Then
      mNumInc = Int(RunDur * 60 / mTimeInc * 3)
      TimeIncBetweenRains = ((gJulDPStartDate(A + 1) - (gJulDPStartDate(A) + 3 * RunDur / 24)) * 24
* 60) / 200
      If TimeIncBetweenRains > 60 Then
         TimeIncBetweenRains = 60
        ElseIf TimeIncBetweenRains < 10 Then
         TimeIncBetweenRains = 10
      End If
      mNumIncBetweenRains = Int(((gJulDPStartDate(A + 1) - (gJulDPStartDate(A) + 3 * RunDur / 24))
* 24 * 60) / (TimeIncBetweenRains))
      EventDur = RunDur / 24
      InterEventDur = gJulDPStartDate(A + 1) - (gJulDPStartDate(A) + 3 * RunDur / 24)
   End If
```

```
    Return

6500  Rem   main calc loop   ***************************
    'LOCATE 4, 1: Print "Main Calculation Loop gTimeStep Increment (min):  ";: Print USING; "###.#";
mTimeInc
    For i = 1 To mNumInc
      'LOCATE 5, 1: Print "Increment #:  "; i; " of "; mNumInc
      GoSub 23200:    Rem   calc inflow hydrograph
      gQInAve(i) = (gQIn(i) + gQIn(i - 1)) / 2
      gAveVol(i) = gQInAve(i) * mTimeInc * 60
      gStorMinusQOut(i) = gTtlStorageVol(i - 1) - 0.5 * mTtlQOutAr(i - 1) * mTimeInc * 60
      If gStorMinusQOut(i) <= 0 And gPondStage(i - 1) < (gNStageAr(1) / 2) And InflowHydrograph$ =
"DOWN" Then
          ZeroStage = True
        ElseIf mNumIncToLarge = True Then
          Rem   continue
        ElseIf gStorMinusQOut(i) < 0 Then
          i = mNumInc: mNumInc = mNumInc * 2: mTimeInc = mTimeInc / 2: RestartLoop = True
6550         If A = gLastRainNum And mNumInc > 3500 Then           '  JV5  If A = N And mNumInc > 3500
Then
              mTimeInc = mTimeInc * 1.05
              mNumInc = Int(mNumInc / 1.05)
              mNumIncToLarge = True
              GoTo 6550
            ElseIf A = gLastRainNum Then    '                       JV5                ElseIf A = N Then
              Rem   continue
            ElseIf Int((gJulDPStartDate(A + 1) - gJulDPStartDate(A)) * 24 * 60 / mTimeInc) > 3500 Then
              mTimeInc = mTimeInc * 1.05
              mNumIncToLarge = True
              mNumInc = Int(mNumInc / 1.05): Rem GOSUB 6350:     REM  recalc mnuminc
              GoTo 6550
          End If
          RestartLoop = True
          If mTimeInc >= 1 Then GoTo 6650
          If mTimeInc < 1 Then
            mTimeInc = 1
            GoSub 6350:     Rem  recalc mnuminc
            mNumIncToLarge = True
            RestartLoop = True
            GoTo 6650
          End If
      End If
      RestartLoop = False
      gSPQOut(i) = gAveVol(i) + gStorMinusQOut(i)
      j = 1
      Do While gSPQOut(i) >= gSPQOutAr(j)
        If j >= gNumIncAr10(DPE) Then GoSub 6740: Exit Do
        j = j + 1
      Loop
      If ZeroStage = False Then
          SPQOutRatio = (gSPQOut(i) - gSPQOutAr(j - 1)) / (gSPQOutAr(j) - gSPQOutAr(j - 1))
          gPondStage(i) = gNStageAr(j - 1) + (gNStageAr(j) - gNStageAr(j - 1)) * SPQOutRatio
          gTtlStorageVol(i) = gCumStorage(j - 1) + (gCumStorage(j) - gCumStorage(j - 1)) * SPQOutRatio
          gPondArea(i) = gNPondAreaAr(j - 1) + (gNPondAreaAr(j) - gNPondAreaAr(j - 1)) * SPQOutRatio
```

```
            gNatSeepOut(i) = gNatSeepQ(j - 1) + (gNatSeepQ(j) - gNatSeepQ(j - 1)) * SPQOutRatio
            gEvapOut(i) = gEvap(M, DPE, mEvapOutNumber) * gPondArea(i) / 24 / 3600 / 12
            mTtlQOutAr(i) = gQOutAr(j - 1) + (gQOutAr(j) - gQOutAr(j - 1)) * SPQOutRatio
            gHydQOut(i) = mTtlQOutAr(i) - gEvapOut(i) - gNatSeepOut(i)
          ElseIf ZeroStage = True Then:        Rem   inflow hydrograph zero or decreasing
            gPondStage(i) = 0
            gTtlStorageVol(i) = 0
            gPondArea(i) = gNPondAreaAr(0)
            gNatSeepOut(i) = 0
            gEvapOut(i) = 0
            mTtlQOutAr(i) = 0
            gHydQOut(i) = 0
        End If
        ZeroStage = False
        GoSub 3760:     Rem  particle size calcs
        GoSub 23600:     Rem  calc statistics
6650  Next i
     Return:    Rem   **********************************

6740 Rem  overflow labeling
      j = gNumIncAr10(DPE)
      gPndOverflowMsg(A, DPE) = (Str$(gPondLUNum(DPE)) + " -" + Str$(gSACO(DPE)))
      If gSANum >= 150 And gSANum <= 155 Then gPndOverflowMsg(A, DPE) = (Str$(gPondLUNum) + "
-" + Str$(gSACO(DPE) + 150))
      If gSANum = 162 Then gPndOverflowMsg(A, DPE) = "8 - 162"
 '      Print "Outlet structure capacity exceeded - pond "; gPndOverflowMsg(A, DPE); " is overflowing"
    Return

7300  Rem   temporary values for between events
     TmpStorage = gTtlStorageVol(mLastValue)
     TmpPndStage = gPondStage(mLastValue)
     TmpPndArea = gPondArea(mLastValue)
     TmpTotQOut = mTtlQOutAr(mLastValue)
     TmpNSeepOut = gNatSeepOut(mLastValue)
     TmpEvapOut = gEvapOut(mLastValue)
     TmpHydQOut = gHydQOut(mLastValue)
     TmpUpQVel = gUpQVel(mLastValue)
     TmpCritPSiz = gCritPartSize(mLastValue)
     TmpWghtPSiz = gWeightedCritPartSize(mLastValue)
     TmpPcPCont = gPCPartControl(mLastValue)
     TmpWghtdCont = gWeightedControl(mLastValue)
     Return
7350 Rem   pass tmp values to new arrays
     gTtlStorageVol(0) = TmpStorage
     gPondStage(0) = TmpPndStage
     gPondArea(0) = TmpPndArea
     mTtlQOutAr(0) = TmpTotQOut
     gNatSeepOut(0) = TmpNSeepOut
     gEvapOut(0) = TmpEvapOut
     gHydQOut(0) = TmpHydQOut
     gUpQVel(0) = TmpUpQVel
     gCritPartSize(0) = TmpCritPSiz
     gWeightedCritPartSize(0) = TmpWghtPSiz
     gPCPartControl(0) = TmpPcPCont
```

```
     gWeightedControl(0) = TmpWghtdCont
     Return


    Rem ***********   file management section   ***************************

8000 Rem   re-loading dpinff$
     gDPInpF$ = Left$(gSADF$, (Len(gSADF$) - 4)) + ".SDP"
     Open gDPInpF$ For Input As #1
        Input #1, gTtlNumDP, gVersion$
        For DPE = 1 To gTtlNumDP
          Input #1, DPE, gDPSANumMatch(DPE).SANum, gPondLUNum(DPE), gSACO(DPE),
gInitStage(DPE), fDummy
          Input #1, gNumIncAr(DPE), gStageIncr(DPE), gPondDepth(DPE), gPartSizeF$(DPE)
          For NumInc = 0 To gNumIncAr(DPE)
             Input #1, DPE, NumInc, gStageAr(DPE, NumInc), gPndAreaAr(DPE, NumInc)
             gPndAreaAr(DPE, NumInc) = 43560 * gPndAreaAr(DPE, NumInc)
             Rem    pndareaar[sqft]=pndareaar[acres]*[43560ftsq/acre]
          Next NumInc
          Input #1, DPE, gNumOutlets(DPE)
          For OutletNum = 1 To gNumOutlets(DPE)
             Input #1, DPE, OutletNum, gOutletType(DPE, OutletNum)
             Input #1, gWeirHeight(DPE, OutletNum), gInvertElev(DPE, OutletNum)
             Input #1, gWeirLength(DPE, OutletNum), gVWeirAngle(DPE, OutletNum), gOrificeDia(DPE,
OutletNum)
             Input #1, gInfilRate(DPE, OutletNum), gSeepWidth(DPE, OutletNum), gSeepLen(DPE,
OutletNum)
             If gOutletType(DPE, OutletNum) = 5 Then      'GoTo 8100
                For NumInc = 0 To gNumIncAr(DPE)
                  Input #1, NumInc, OutletNum, gNaturalSeep(NumInc, DPE, OutletNum)
                Next NumInc
             End If
             If gOutletType(DPE, OutletNum) = 6 Then       '  GoTo 8150  line number 8100
                For MOY = 1 To 12
                  Input #1, MOY, OutletNum, gEvap(MOY, DPE, OutletNum)
                Next MOY
             End If
             If gOutletType(DPE, OutletNum) = 7 Then   'GoTo 8200     line number 8150
                For NumInc = 0 To gNumIncAr(DPE)
                  Input #1, NumInc, DPE, OutletNum, gStageAr(DPE, NumInc), gQOutOther(NumInc, DPE,
OutletNum)
                Next NumInc
             End If
          Next OutletNum     '8200
       Next DPE
    Close #1
    ReDim gWghtdTSReduct(gFirstRainNum To gLastRainNum, gTtlNumDP)
    ReDim gPndOverflowMsg(gFirstRainNum To gLastRainNum, gTtlNumDP)
    ReDim gPCDPVolReduct(gFirstRainNum To gLastRainNum, gTtlNumDP)
    Return


10000 Rem  calculations for between events
       'LOCATE 3, 1: Print "Interevent Loop between Rains "; A; " and "; A + 1
```

```
    Rem BTWNRNS = 1
    mLastValue = mNumInc
    mBetweenRains = True
    GoSub 7300:    Rem   save temp values
    GoSub 22000:   Rem   save final rain event stats
    mTimeInc = TimeIncBetweenRains
    mNumInc = mNumIncBetweenRains
10100 GoSub 6300:    Rem   redim arrays
    GoSub 7350:    Rem   apply tmp values to redimed arrays
    Call proCalcgSPQOutAr(DPE)     '  recalc gSPQOutAr    gosub 6000
    gTimeStep(0) = StartTime
    QPeak = 0
    GoSub 6500:    Rem   main calc loop
    If RestartLoop = True Then
      mLastValue = 0:  Rem   to restart at 0th array value
      GoSub 7300:     Rem   save temp values
      GoSub 22100:    Rem   re-initialize inter-event period stats
      GoTo 10100:     Rem   restart interevent loop
    End If
    GoSub 23000:    Rem   calc time()
    If gOutOption > 5 And gW$(gSAArNum(gNumAreas)) = "W" Then Call proSaveHydrographData(A)

    mTtlQOut = 0: GoSub 23025: Rem   calc inter-event mttlqout
    mBetweenRains = False
   Return

22000 Rem   save initial stats for inter-event period
   TMaxQOut = mMaxQOut
   TSumQOut = mSumQOut
   TSumWghtPSiz = mSumWghtPartSize
   TSumWghtdCont = mSumWghtControl
   TSumVolOut = mSumVolOut
   TVolSeepOut = mVolSeepOut
   TVolEvapOut = mVolEvapOut
   THydVolOut = mHydVolOut
   TSumHydQOut = mSumHydQOut
   Return

22100 Rem   re-initialize inter-event period stats
   mMaxQOut = TMaxQOut
   mSumQOut = TSumQOut
   mSumWghtPartSize = TSumWghtPSiz
   mSumWghtControl = TSumWghtdCont
   mSumVolOut = TSumVolOut
   mVolSeepOut = TVolSeepOut
   mVolEvapOut = TVolEvapOut
   mHydVolOut = THydVolOut
   mSumHydQOut = TSumHydQOut
   Return

23000 Rem   calc time()
   For i = 1 To mNumInc
    gTimeStep(i) = gTimeStep(i - 1) + mTimeInc / 60 / 24
   Next i
```

```
    StartTime = gTimeStep(i - 1)
    Return

23025 Rem  calc inflow and outflow totals
  For i = 0 To mNumInc: Rem  changed 1 to 0 on 8/12/88
    mTtlQOut = mTtlQOut + mTtlQOutAr(i)
  Next i
    Return

23170 Rem  initilize values to deal with early next rain
    If EarlyNextRain = False Then
        Return
      Else
        ReDim gPrevQIn(mNumInc)
        PrevQPeak = QPeak
        gPrevQIn(0) = gQIn(mNumInc)
        PrevPeakTime = PeakTime
      End If
  Return

23200 Rem   calc inflow hydrograph
    If (i * mTimeInc / 60) <= ((1.2 * gPondRainDur(A)) / 2) And mBetweenRains = False Then
        InflowHydrograph$ = "UP"
        gQIn(i) = QPeak / (PeakTime * 60) * mTimeInc + gQIn(i - 1)
     ElseIf (i * mTimeInc / 60) > ((1.2 * gPondRainDur(A)) / 2) Then
        InflowHydrograph$ = "DOWN"
        gQIn(i) = gQIn(i - 1) - QPeak / (PeakTime * 60) * mTimeInc
       If gPrevQIn(i - 1) > 0 Then GoSub 23215
        gQIn(i) = gQIn(i) + gPrevQIn(i)
       If gQIn(i) < 0 Then gQIn(i) = 0
    End If
    Return

23215 Rem  calc additional runoff from previous rain
    gPrevQIn(i) = gPrevQIn(i - 1) - PrevQPeak / (PrevPeakTime * 60) * mTimeInc
    If gPrevQIn(i) < 0 Then gPrevQIn(i) = 0
    Return

23600 Rem   array pond performance statistics
    If gQIn(i) > mMaxQIn Then mMaxQIn = gQIn(i)
    If mTtlQOutAr(i) > mMaxQOut Then mMaxQOut = mTtlQOutAr(i)
    mSumWghtPartSize = mSumWghtPartSize + gWeightedCritPartSize(i)
    mSumWghtControl = mSumWghtControl + gWeightedControl(i)
    mSumHydQOut = mSumHydQOut + gHydQOut(i)
    mSumQOut = mSumQOut + mTtlQOutAr(i)
    mSumVolOut = mSumVolOut + mTtlQOutAr(i) * mTimeInc * 60
    mVolSeepOut = mVolSeepOut + gNatSeepOut(i) * mTimeInc * 60
    mVolEvapOut = mVolEvapOut + gEvapOut(i) * mTimeInc * 60
    mHydVolOut = mHydVolOut + gHydQOut(i) * mTimeInc * 60
    mSumQIn = mSumQIn + gQIn(i) * mTimeInc * 60
    If gCritPartSize(i) > mMaxCritPartSize Then mMaxCritPartSize = gCritPartSize(i)
    Return

23700 Rem   summary pond perform stats
```

```
    If mSumQIn = 0 Then
        gPCDPVolReduct(A, DPE) = 0
      Else
        gPCDPVolReduct(A, DPE) = 1 - (mSumQIn - (mVolSeepOut + mVolEvapOut)) / mSumQIn
    End If
    If gPCDPVolReduct(A, DPE) < 0 Then gPCDPVolReduct(A, DPE) = 0
    If gPCDPVolReduct(A, DPE) > 1 Then gPCDPVolReduct(A, DPE) = 1
    If gSANum < 162 Then
        If mSumHydQOut = 0 Then
             gWghtdTSReduct(A, DPE) = 1
          Else
             gWghtdTSReduct(A, DPE) = mSumWghtControl / (mSumHydQOut * 100)
        End If
      Else
        If mMaxQIn = 0 Then gPeakFlowRed(A) = 1 Else gPeakFlowRed(A) = 1 - mMaxQOut / mMaxQIn
        If mSumQIn = 0 Then gDPVolRed162(A) = 0 Else gDPVolRed162(A) = 1 - (mSumQIn -
(mVolSeepOut + mVolEvapOut)) / mSumQIn
        If mSumHydQOut = 0 Then
            gWAvgCritPartSiz(A) = 0
            gWeightedTtlSolRed162(A) = 100
          Else
            gWAvgCritPartSiz(A) = mSumWghtPartSize / mSumHydQOut
            gWeightedTtlSolRed162(A) = mSumWghtControl / (mSumHydQOut * 100)
        End If
        If PondVolBelowInv = 0 Then gFlushRatio(A) = 0 Else gFlushRatio(A) = mSumQIn /
PondVolBelowInv
    End If
    Return

End Sub

Private Sub proInitCritPartSizeData()

    Rem   particle size and percent control data
    Rem   first column:  upflow (ft/hr)  -  gUpFlowVelStokes(I)
    Rem   second column:  critical size (microns)  -  gCritPartSizeStokes(I)

'101  Rem   beginning of particle size data
     gUpFlowVelStokes(1) = 0.05
     gUpFlowVelStokes(2) = 0.2
     gUpFlowVelStokes(3) = 0.49
     gUpFlowVelStokes(4) = 0.89
     gUpFlowVelStokes(5) = 1.3
     gUpFlowVelStokes(6) = 2#
     gUpFlowVelStokes(7) = 2.6
     gUpFlowVelStokes(8) = 3.3
     gUpFlowVelStokes(9) = 4.3
     gUpFlowVelStokes(10) = 4.9
     gUpFlowVelStokes(11) = 6.6
     gUpFlowVelStokes(12) = 7.5
     gUpFlowVelStokes(13) = 9.2
     gUpFlowVelStokes(14) = 11
     gUpFlowVelStokes(15) = 12
     gUpFlowVelStokes(16) = 18
```

```
        gUpFlowVelStokes(17) = 31
        gUpFlowVelStokes(18) = 43
        gUpFlowVelStokes(19) = 56
        gUpFlowVelStokes(20) = 69
        gUpFlowVelStokes(21) = 98
        gUpFlowVelStokes(22) = 125
        gUpFlowVelStokes(23) = 210
        gUpFlowVelStokes(24) = 270
        gUpFlowVelStokes(25) = 490
        gUpFlowVelStokes(26) = 660
        gUpFlowVelStokes(27) = 1080

        gCritPartSizeStokes(1) = 1.65
        gCritPartSizeStokes(2) = 3.3
        gCritPartSizeStokes(3) = 4.9
        gCritPartSizeStokes(4) = 6.7
        gCritPartSizeStokes(5) = 8
        gCritPartSizeStokes(6) = 10
        gCritPartSizeStokes(7) = 11.5
        gCritPartSizeStokes(8) = 13
        gCritPartSizeStokes(9) = 15
        gCritPartSizeStokes(10) = 16
        gCritPartSizeStokes(11) = 19
        gCritPartSizeStokes(12) = 20
        gCritPartSizeStokes(13) = 21
        gCritPartSizeStokes(14) = 22.4
        gCritPartSizeStokes(15) = 26.2
        gCritPartSizeStokes(16) = 30
        gCritPartSizeStokes(17) = 45
        gCritPartSizeStokes(18) = 55
        gCritPartSizeStokes(19) = 66
        gCritPartSizeStokes(20) = 77
        gCritPartSizeStokes(21) = 96
        gCritPartSizeStokes(22) = 117
        gCritPartSizeStokes(23) = 178
        gCritPartSizeStokes(24) = 215
        gCritPartSizeStokes(25) = 380
        gCritPartSizeStokes(26) = 510
        gCritPartSizeStokes(27) = 910


End Sub

Public Sub proLoadCPZFile(DPE As Integer)

    ' Load the Critical Particle size (.CPZ) file.
    Dim Row As Integer
    Dim FileNum As Integer
    Dim Dum As String
    Dim MissingFile As String
    Dim ErrorMsg As String

    On Error GoTo ErrorTrap
```

```
    FileNum = FreeFile
    MissingFile$ = gPartSizeF$(DPE)

    Open gPartSizeF$(DPE) For Input As #FileNum
        'Input #FileNum, gPartSizeF$, CPSDES$
        Input #FileNum, Dum$, Dum$
        For Row = 0 To 31
            Input #FileNum, Row, gCritPartSizeData(Row), gPCGreaterThanCritPartSize(Row)
        Next Row
    Close #FileNum
    MissingFile$ = ""

    Exit Sub

ErrorTrap:
    Select Case Err.Number
       Case 53       ' Object doesn't support this property or method
            ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
              & Chr(10) & Chr(10) & "Procedure proLoadCPZFile in CalcWetDetention" _
                & Chr(10) & Chr(10) & "File " & MissingFile$ & " was not found."
            MsgBox ErrorMsg, vbCritical, "File Not Found Error"
            Close   'Close all files
            Exit Sub  ' e.g., the text box was disabled just as the focus shifted there.
       Case Else
            ErrorMsg = "Error number " & Format$(Err.Number) & ":  " & Err.Description _
              & Chr(10) & Chr(10) & "Procedure proLoadCPZFile in CalcWetDetention"
            MsgBox ErrorMsg, vbCritical, "Error Trap"
            Exit Sub
    End Select

End Sub

Public Sub proQOutCalcs(QOut As Single, DPE As Integer, Stage As Single, i As Integer, M As Integer)

    Dim OutFlow As Single   'DOS == OUTFLOW
    Dim OutletNumber As Integer    '  DOS == outletnum
    Dim NetStage As Single   '  DOS == NETSTAGE

'5300 Rem  outflow calcs
    QOut = 0
    For OutletNumber = 1 To gNumOutlets(DPE)
        NetStage = Stage - gInvertElev(DPE, OutletNumber)
        'PRINT gNumOutlets(DPE), Outletnumber, NETSTAGE, STAGE, gInvertElev(Outletnumber),
gWeirHeight(Outletnumber)
        If NetStage < 0 Then GoTo 5350
        If gOutletType(DPE, OutletNumber) > 2 And gOutletType(DPE, OutletNumber) < 6 Then GoTo 5330
        If NetStage > gWeirHeight(DPE, OutletNumber) Then NetStage = gWeirHeight(DPE, OutletNumber)
5330      'On gOutletType(DPE, OutletNumber) GoSub 5375, 5400, 5500, 5550, 5600, 5700, 5800
            Select Case gOutletType(DPE, OutletNumber)
                Case 1
                    '5375 Rem  rectangular weir
                    OutFlow = 3.33 * (gWeirLength(DPE, OutletNumber) - 0.2 * NetStage) * NetStage ^ 1.5
                Case 2
                    '5400 Rem   v-notch weir
```

```
            Select Case gVWeirAngle(DPE, OutletNumber)
               Case 1
                  OutFlow = 0.497 * NetStage ^ 2.5
               Case 2
                  OutFlow = 0.676 * NetStage ^ 2.5
               Case 3
                  OutFlow = 1.035 * NetStage ^ 2.5
               Case 4
                  OutFlow = 1.443 * NetStage ^ 2.5
               Case 5
                  OutFlow = 2.5 * NetStage ^ 2.5
               Case 6
                  OutFlow = 4.4 * NetStage ^ 2.5
            End Select
         Case 3
            '5500 Rem   orifice   Q[cfs] = C * A * (2*g*h)^(1/2)  C = 0.60
            OutFlow = 3.78 * gOrificeDia(DPE, OutletNumber) ^ 2 * NetStage ^ 0.5
         Case 4
            '5550 Rem   seepage basin outflow values
            OutFlow = gSeepWidth(DPE, OutletNumber) * gSeepLen(DPE, OutletNumber) *
gInfilRate(DPE, OutletNumber) / 12 / 3600
         Case 5
            '5600 Rem   natural seepage
            'OUTFLOW[cfs]=NATSEEP[in/hr]*gPndAreaArSF[sq ft]*[1hr/3600sec]*[1ft/12in]
            gNatSeepQ(i) = gNatSeepRate(i, OutletNumber) * gNPondAreaAr(i) / 3600 / 12
            OutFlow = gNatSeepQ(i)
         Case 6
            '5700 Rem   evaporation
            OutFlow = gEvap(M, DPE, OutletNumber) * gNPondAreaAr(i) / 24 / 3600 / 12
            mEvapOutNumber = OutletNumber
            'OUTFLOW[cfs]=EVAP[in/hr]*gPndAreaArSF[sq ft]*[1day/24hr]*[1hr/3600sec]*[1ft/12in]
         Case 7
            '5800 Rem   other outflow device
            OutFlow = gNQOutOther(i, OutletNumber)
      End Select
      QOut = QOut + OutFlow
5350  Next OutletNumber

   End Sub

Public Sub proLowestInvElev(DPE As Integer, LowestOutletElev As Single)

   Dim OutletNum As Integer
   Dim LowestStageInc As Integer  ' DOS == LOWESTGINC
   Dim SN As Integer     '  SN == Stage Number

5000 Rem    find lowest invert elevation
     LowestOutletElev = 999
     SN = 0
     For OutletNum = 1 To gNumOutlets(DPE)
        If gOutletType(DPE, OutletNum) < 5 Or gOutletType(DPE, OutletNum) > 6 Then      'GoTo 5020
           If gOutletType(DPE, OutletNum) = 7 Then
              Do
                gInvertElev(DPE, OutletNum) = gNStageAr(SN)
```

```
                SN = SN + 1
              Loop Until gNQOutOther(SN, OutletNum) > 0
            End If
            If gInvertElev(DPE, OutletNum) < LowestOutletElev Then LowestOutletElev = gInvertElev(DPE,
OutletNum)
          End If
        Next OutletNum    '5020
        If LowestOutletElev = 999 Then LowestOutletElev = gNStageAr(gNumIncAr10(DPE)) - 0.001
        Rem   above line prevents crashing if there is no hydraulic outlet
        LowestStageInc = 1
        While LowestOutletElev > gNStageAr(LowestStageInc)
          LowestStageInc = LowestStageInc + 1
        Wend

End Sub

Public Sub proCalcgSPQOutAr(DPE As Integer)

    Dim i As Integer

    '6000  Rem   calc gSPQOutAr
     For i = 1 To gNumIncAr10(DPE)
       gSPQOutAr(i) = gCumStorage(i) + 0.5 * gQOutAr(i) * 60 * mTimeInc
     Next i

End Sub

Public Sub proSaveHydrographData(RainNumber As Integer)

    Dim TimeInc As Single
    Dim FileNum As Integer
    Dim i As Long
    Dim ModelRunTime As Single
    Dim ModelRunTimeIncCounter As Long
    Dim AppPath As String
    Dim OutputFileName As String
    Dim TimeStep As Single

    FileNum = FreeFile
    OutputFileName$ = "ModelHydrograph.TMP"
    Open OutputFileName$ For Append As #FileNum

    'Write #FileNum, "Entered proSaveHydrographData"
        If gTimeStep(0) > 0 Then mLastTimeInc = mLastTimeInc - gTimeStep(0)

        For i = 0 To mNumInc
          TimeStep = gTimeStep(i) + mLastTimeInc
          Write #FileNum, RainNumber, TimeStep, gHydQOut(i)
        Next i

        mLastTimeInc = TimeStep
    Close #FileNum

End Sub
```

Attribute VB_Name = "WetDetentionProcedures"

```
Option Explicit

  Dim fAreaSum, fCounter
  Global Response As String
  Private Index As Integer

  '  move these variables to the appropriate place in WSLAMM70 when
  '  this detention pond program is integrated

  '12==  number of months in a year
  '10==  number of detention ponds allowed in file
  ' 5==   number of outlets allowed in detention pond

  Global gEvap(12, 10, 5) As Single
  Global gQOutOther(40, 10, 5) As Single
  Global gNaturalSeep(40, 10, 5) As Single
  Global gInvertElev(10, 5) As Single
  Global gOrificeDia(10, 5) As Single
  Global gVWeirAngle(10, 5) As Single
  Global gWeirHeight(10, 5) As Single
  Global gWeirLength(10, 5) As Single
  Global gInfilRate(10, 5) As Single
  Global gSeepWidth(10, 5) As Single
  Global gSeepLen(10, 5) As Single
  Global gPndOutNum(10, 5) As Integer ' Pond Outlet Number

  Global gOutletType(10, 5) As Integer  'Pond Outlet Type
  Global gNumOutlets(10) As Integer  ' Number of Pond Outlets

  Public gNumIncAr(10) As Integer
  Public gNumIncAr10(10) As Integer       ' 'value of gNumIncAr(10) * 10
  Public gStageIncVarOrConst(10) As Integer  'Pond stage increments variable(1) or constant(2)
  Public gStageIncr(10) As Single  '  fixed increment between stages
  Public gPondDepth(10) As Integer  'depth of pond
  Public gStageAr(10, 40) As Single
  Public gPndAreaAr(10, 40) As Single
  'Public gQOutOther(10, 40) As Single

  Global gOutletNum As Integer
  Global gDPNum As Integer  '  current detention pond number
  Global gTtlNumDP As Integer  '  Number of Detention Ponds
  Global gPndLUNum(10) As Integer  'land use number for pond
  Global gPndSAName(10) As Integer  'name of source area pond is in
  Global gSACO(10) As Integer  '  equivlent of CO in DOS version


  Type PondNumMap
     SANum As Integer
     PndIndex As Integer
  End Type
  Global gDPSANumMatch(10) As PondNumMap  'DPondNum and matching SANum
```

```
   Global gStageAreaEntered(10) As Boolean
   Global gBeenInThisPondBefore(10) As Boolean
   Global gPondsPresent As Boolean  '  check if any pond exists in the current run
   Global gFirstPond As Boolean   ' check if this is the first pond being edited or created in the run
   Global gFromcmdDeleteRow As Boolean   ' test to indicate if control is coming from insert row or delete
row

   Global gPartSizeF(10) As String
   Global gDPInpF As String
   Global gInitStage(10) As Single
   Global gOutletLabel(7) As String

   Global gAddingOutlet As Boolean   'check to see if an


   '  remove these variables from this list before transfering to WSLAMM.
   '  they are duplicated in the WSLAMM program
   'Global gSANum, gLUNum, gTSArea(162), gFileType$, gPathAndName$
   'Global gRainFile$   ', gPolProbDistF$, gRSubVF$, gPSCncF$, gPartResDelF$



Public Sub proGetScreenResolution()
Dim WidthResolution, HeightResolution

WidthResolution = Screen.Width / Screen.TwipsPerPixelX
HeightResolution = Screen.Height / Screen.TwipsPerPixelY

'gScreenResolution = Format$(WidthResolution) & "x" & Format$(HeightResolution)


End Sub




Public Function funDigitFilter(KeyAscii As Integer)
' Ascii 8 = backspace key

If (KeyAscii >= Asc("0") And KeyAscii <= Asc("9")) Or (KeyAscii = 8) Then
   funDigitFilter = KeyAscii
Else
   funDigitFilter = 0
End If

End Function


Public Sub proDeleteOutlet()

   Dim iMonth As Integer
   Dim iStage As Integer

   'shift variables from next pond to current pond, to remove current pond
```

```
For fCounter = gOutletNum To gNumOutlets(gDPNum) - 1
   Select Case gOutletType(gDPNum, fCounter + 1)
      Case 1
         gWeirLength(gDPNum, fCounter) = gWeirLength(gDPNum, fCounter + 1)
         gWeirHeight(gDPNum, fCounter) = gWeirHeight(gDPNum, fCounter + 1)
         gInvertElev(gDPNum, fCounter) = gInvertElev(gDPNum, fCounter + 1)
         gOutletType(gDPNum, fCounter) = gOutletType(gDPNum, fCounter + 1)
      Case 2
         gVWeirAngle(gDPNum, fCounter) = gVWeirAngle(gDPNum, fCounter + 1)
         gWeirHeight(gDPNum, fCounter) = gWeirHeight(gDPNum, fCounter + 1)
         gInvertElev(gDPNum, fCounter) = gInvertElev(gDPNum, fCounter + 1)
         gOutletType(gDPNum, fCounter) = gOutletType(gDPNum, fCounter + 1)
      Case 3
         gOrificeDia(gDPNum, fCounter) = gOrificeDia(gDPNum, fCounter + 1)
         gInvertElev(gDPNum, fCounter) = gInvertElev(gDPNum, fCounter + 1)
         gOutletType(gDPNum, fCounter) = gOutletType(gDPNum, fCounter + 1)
      Case 4
         gInfilRate(gDPNum, fCounter) = gInfilRate(gDPNum, fCounter + 1)
         gInvertElev(gDPNum, fCounter) = gInvertElev(gDPNum, fCounter + 1)
         gSeepWidth(gDPNum, fCounter) = gSeepWidth(gDPNum, fCounter + 1)
         gSeepLen(gDPNum, fCounter) = gSeepLen(gDPNum, fCounter + 1)
         gOutletType(gDPNum, fCounter) = gOutletType(gDPNum, fCounter + 1)
      Case 5
         For iStage = 1 To gNumIncAr(gDPNum)
            gNaturalSeep(iStage, gDPNum, fCounter) = gNaturalSeep(iStage, gDPNum, fCounter + 1)
         Next  'iStage
         gOutletType(gDPNum, fCounter) = gOutletType(gDPNum, fCounter + 1)
      Case 6
         For iMonth = 1 To 12
            gEvap(iMonth, gDPNum, fCounter) = gEvap(iMonth, gDPNum, fCounter + 1)
         Next  'iMonth
         gOutletType(gDPNum, fCounter) = gOutletType(gDPNum, fCounter + 1)
      Case 7
         For iStage = 1 To gNumIncAr(gDPNum)
            gQOutOther(iStage, gDPNum, fCounter) = gQOutOther(iStage, gDPNum, fCounter + 1)
         Next  'iStage
         gOutletType(gDPNum, fCounter) = gOutletType(gDPNum, fCounter + 1)
   End Select
Next ''fCounter

'remove values of last pond
Select Case gOutletType(gDPNum, gNumOutlets(gDPNum))
      Case 1
         gWeirLength(gDPNum, gNumOutlets(gDPNum)) = 0
         gWeirHeight(gDPNum, gNumOutlets(gDPNum)) = 0
         gInvertElev(gDPNum, gNumOutlets(gDPNum)) = 0
         gOutletType(gDPNum, gNumOutlets(gDPNum)) = 0
      Case 2
         gVWeirAngle(gDPNum, gNumOutlets(gDPNum)) = 0
         gWeirHeight(gDPNum, gNumOutlets(gDPNum)) = 0
         gInvertElev(gDPNum, gNumOutlets(gDPNum)) = 0
         gOutletType(gDPNum, gNumOutlets(gDPNum)) = 0
      Case 3
         gOrificeDia(gDPNum, gNumOutlets(gDPNum)) = 0
```

```
            gInvertElev(gDPNum, gNumOutlets(gDPNum)) = 0
            gOutletType(gDPNum, gNumOutlets(gDPNum)) = 0
        Case 4
            gInfilRate(gDPNum, gNumOutlets(gDPNum)) = 0
            gInvertElev(gDPNum, gNumOutlets(gDPNum)) = 0
            gSeepWidth(gDPNum, gNumOutlets(gDPNum)) = 0
            gSeepLen(gDPNum, gNumOutlets(gDPNum)) = 0
            gOutletType(gDPNum, gNumOutlets(gDPNum)) = 0
        Case 5
            For iStage = 1 To gNumIncAr(gDPNum)
                gNaturalSeep(iStage, gDPNum, gNumOutlets(gDPNum)) = 0
            Next  'iStage
            gOutletType(gDPNum, gNumOutlets(gDPNum)) = 0
        Case 6
            For iMonth = 1 To 12
                gEvap(iMonth, gDPNum, gNumOutlets(gDPNum)) = 0
            Next  'iMonth
            gOutletType(gDPNum, gNumOutlets(gDPNum)) = 0
        Case 7
            For iStage = 1 To gNumIncAr(gDPNum)
                gQOutOther(iStage, gDPNum, gNumOutlets(gDPNum)) = 0
            Next  'iStage
            gOutletType(gDPNum, gNumOutlets(gDPNum)) = 0
    End Select

    gNumOutlets(gDPNum) = gNumOutlets(gDPNum) - 1

End Sub

Public Sub proCritPartSizeFile()

    gFileType$ = "*.CPZ"
    frmFileSelect.cboFileType.AddItem "Crit Part files (*.CPZ)"

    frmFileSelect.Caption = "Critical Particle Size File Name"

    proShowCentered frmFileSelect, vbModal, frmWetDetention ', Me

End Sub


Public Sub proCancelAddOutlet()
    Dim HoldNumOutlets As Integer

    '  Used to reset the number of outlets for a pond to the previous value
    '  if the pond outlet form was canceled rather than continued while we
    '  are adding a new outlet.

    HoldNumOutlets = gNumOutlets(gDPNum)
    gNumOutlets(gDPNum) = gNumOutlets(gDPNum) - 1
    gPndOutNum(gDPNum, HoldNumOutlets) = 0

End Sub
```

```
End Sub

Public Sub proCritPartSizeFile()

    gFileType$ = "*.CPZ"
    frmFileSelect.cboFileType.AddItem "Crit Part files (*.CPZ)"

    frmFileSelect.Caption = "Critical Particle Size File Name"

    proShowCentered frmFileSelect, vbModal, frmWetDetention ', Me

End Sub


Public Sub proCancelAddOutlet()
    Dim HoldNumOutlets As Integer

    '  Used to reset the number of outlets for a pond to the previous value
    '  if the pond outlet form was canceled rather than continued while we
    '  are adding a new outlet.

    HoldNumOutlets = gNumOutlets(gDPNum)
    gNumOutlets(gDPNum) = gNumOutlets(gDPNum) - 1
    gPndOutNum(gDPNum, HoldNumOutlets) = 0

End Sub
```