R. Pitt
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Module 8
Overall Drainage Design Approach

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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 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 was 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 the 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:

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.

Figure 1. Survey on Storm Drainage Design Procedures.

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 could 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. 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 (WWF) 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 discussion, the topic cannot be ignored when addressing wet weather flows. 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. 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 that 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.* (1993): 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.* (1993) 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 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, 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.

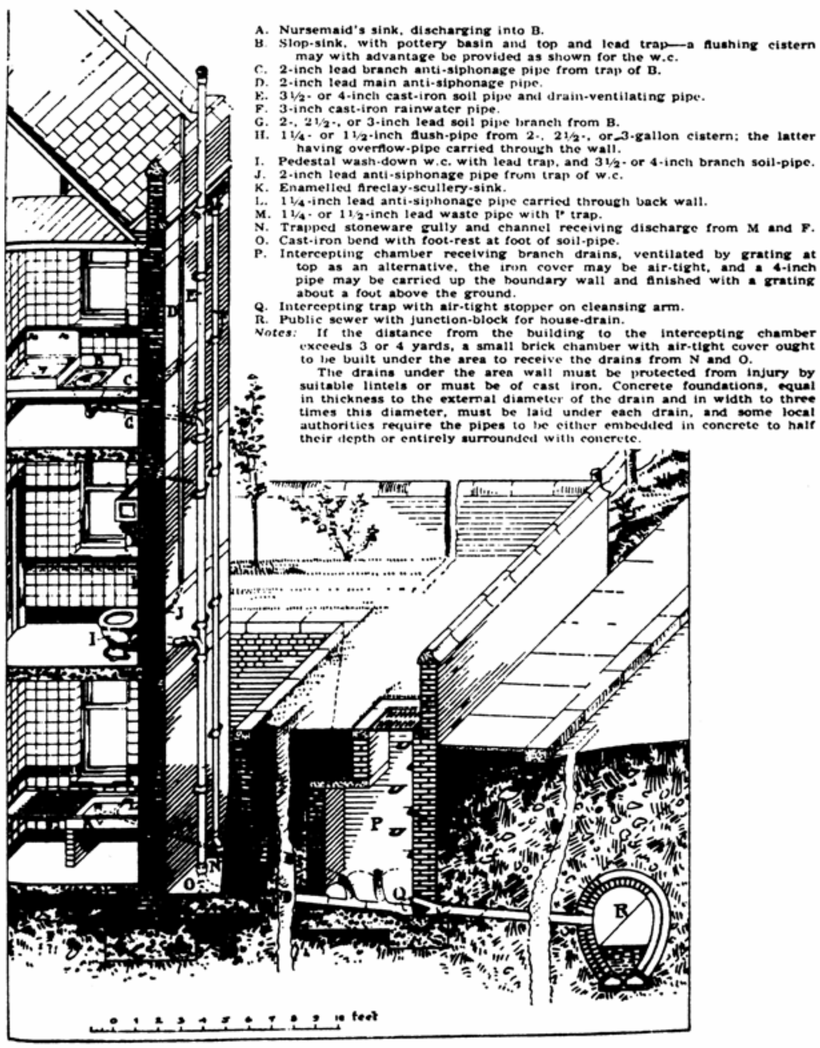

Figure 2. Nineteenth century English household holding tank located before sanitary sewerage (Reyburn 1989).

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 that 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 sedimentation in sewers (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 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 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.

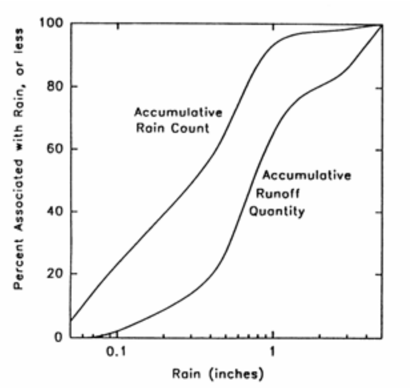

Figure 3. Milwaukee rainfall and runoff probability distributions.

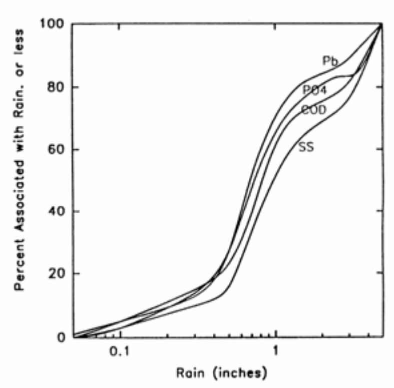

Figure 4. Milwaukee pollutant mass probability distributions.

• >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 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. 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.

Historical Developments in Urban Drainage
Reviews of historical developments in urban drainage practices, and examinations of current practices, are necessary prerequisites to producing useful tools for drainage design in the future. Historical information is 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 is necessary in order to formulate and substantiate our design approach for the future.

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. SLAMM can be 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.

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 of 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, during the past 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 5. 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. In addition, it is clear 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) can 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 5 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 6. 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 7. 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 8 (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 9). 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 10.

Other recent presentations on optimization of control practices are shown on Figures 11 and 12 (Field, *et al*. 1994). Figure 11 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 12 shows another example where the most cost-effective solution for storage-treatment is likely at some mid-point requiring a combination of both practices.

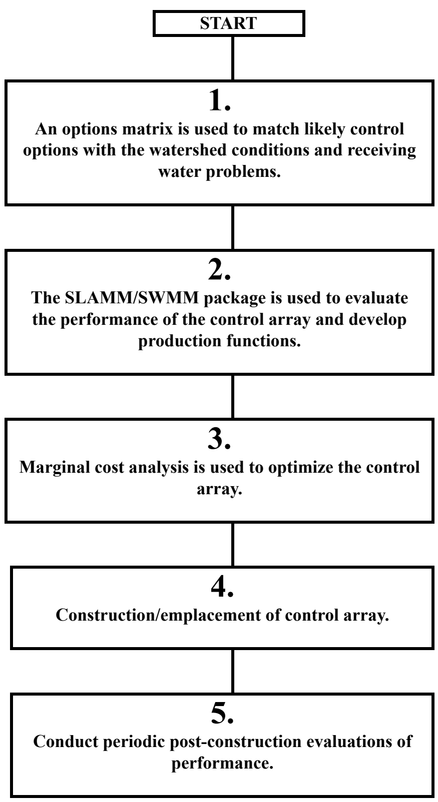

Figure 5. Flowchart of outline of design methodology.

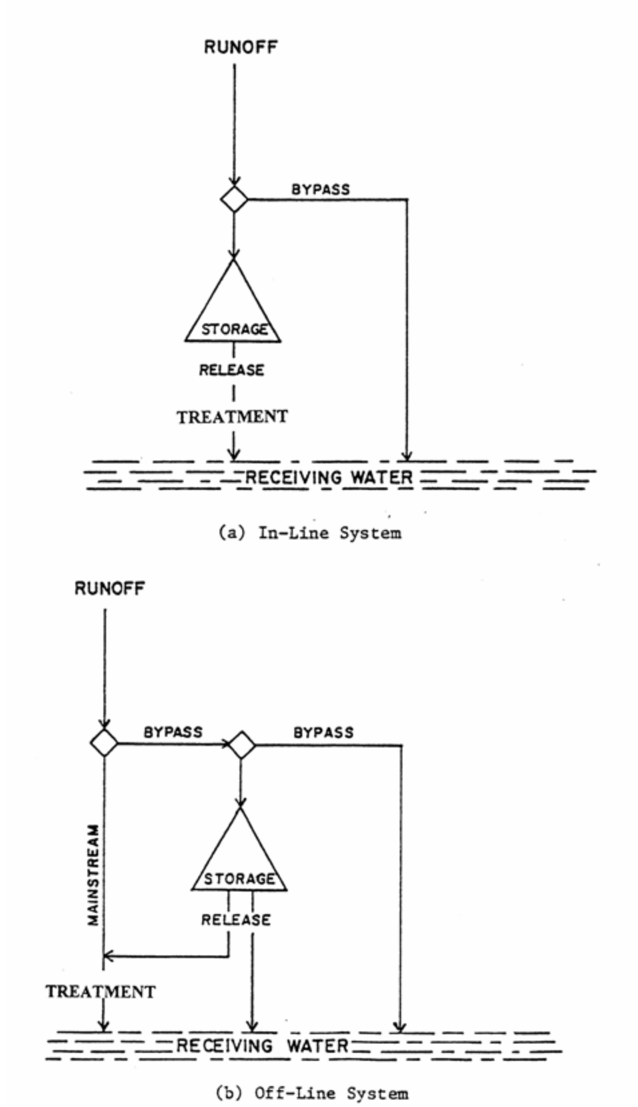

Figure 6. Basic storage/treatment system configurations.

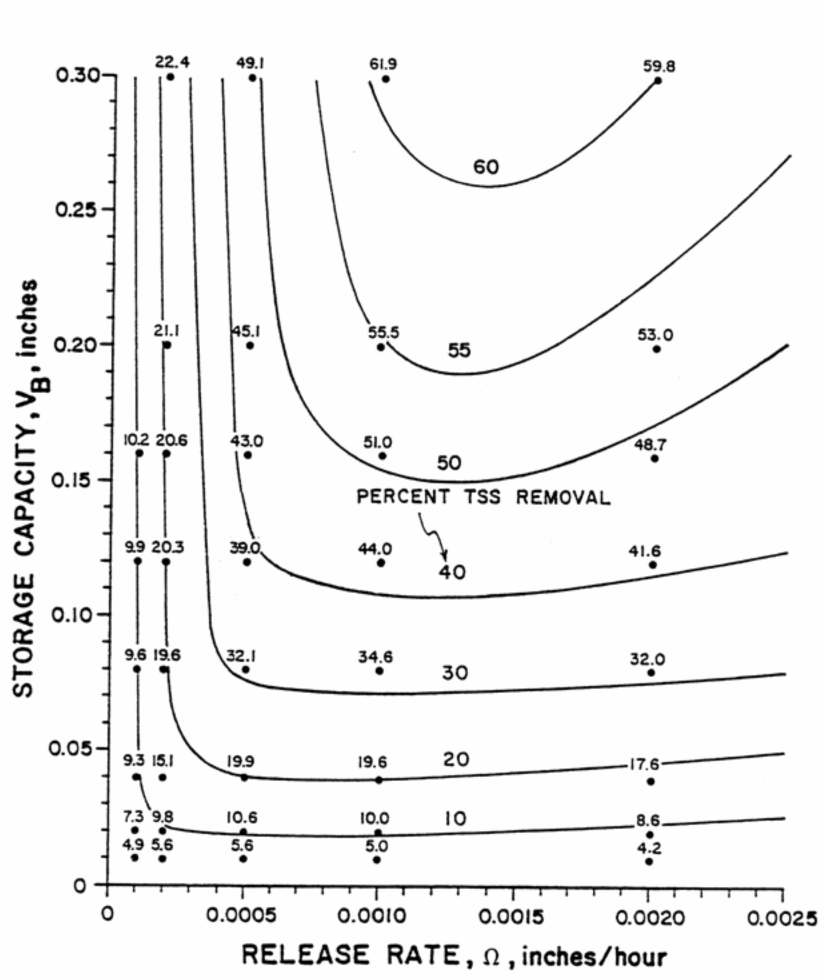

Figure 7. Percent TSS removal production function, results of S/T block simulation.

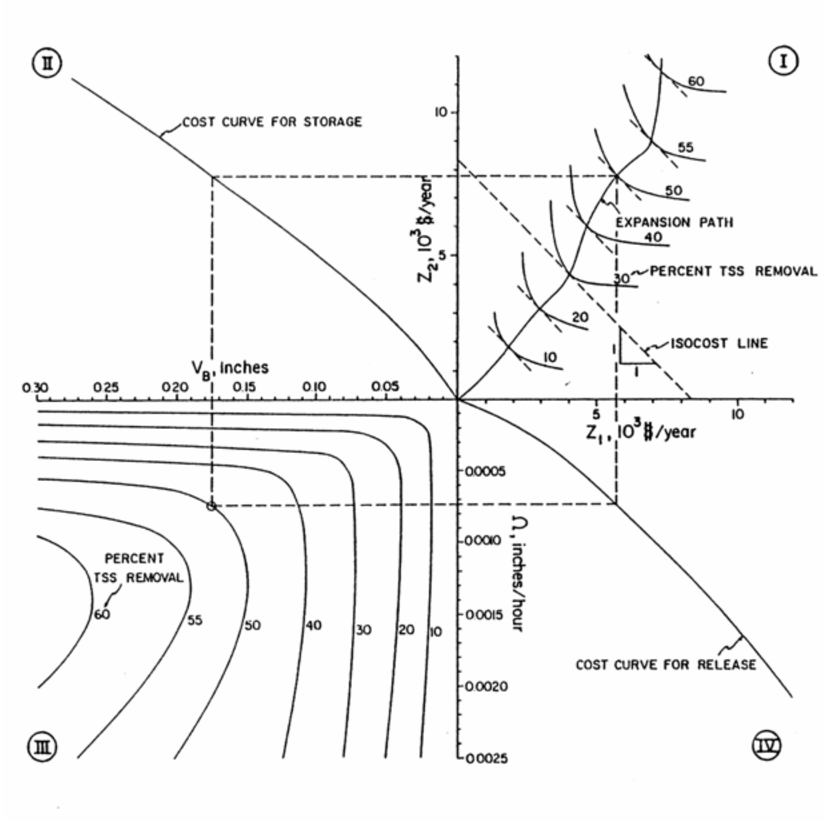

Figure 8. Application of storage/treatment optimization procedure (Nix and Heaney 1988).

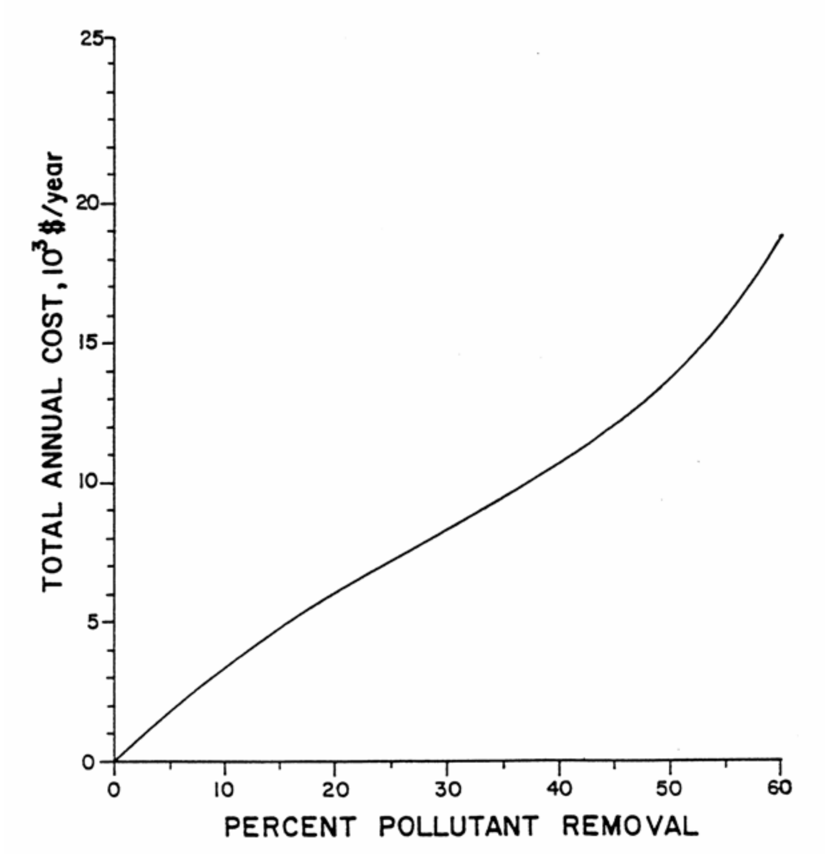

Figure 9. Final cost curve.

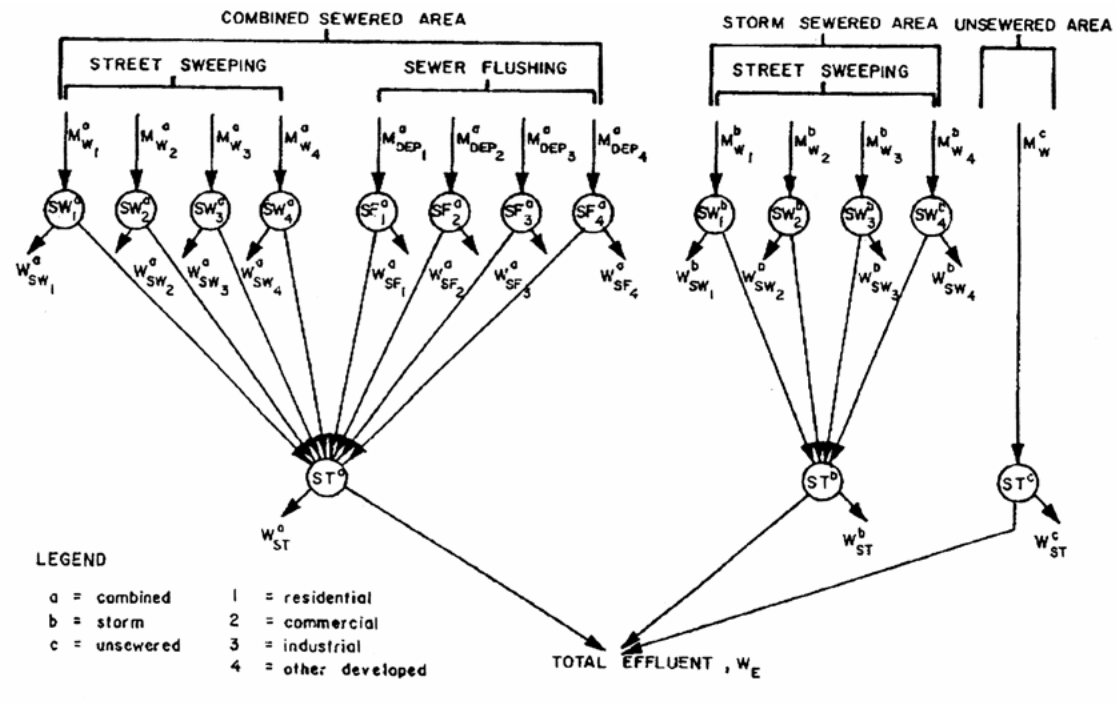

Figure 10. Stormwater pollution control network for Anytown, U.S.A. (Heaney and Nix 1977).

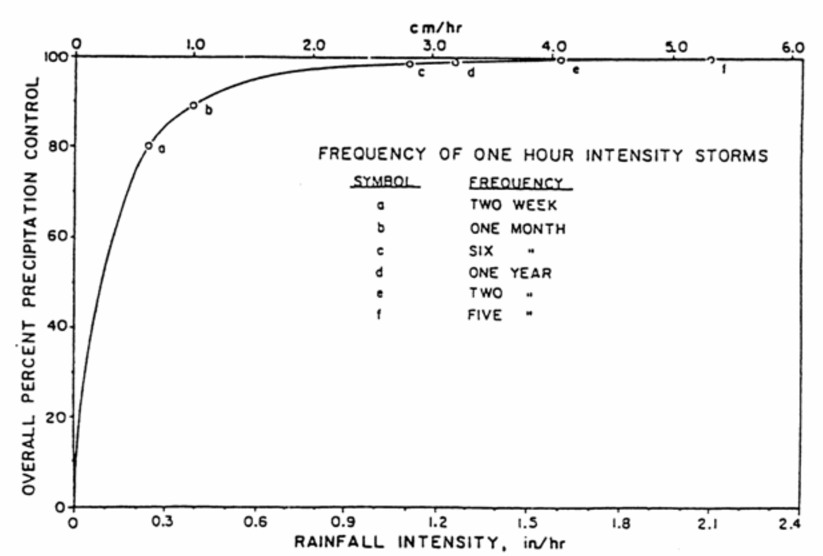

Figure 11. Overall percent precipitation control vs. rainfall intensity - Atlanta, Georgia (1948-1972) (Heaney, *et al.* 1977).

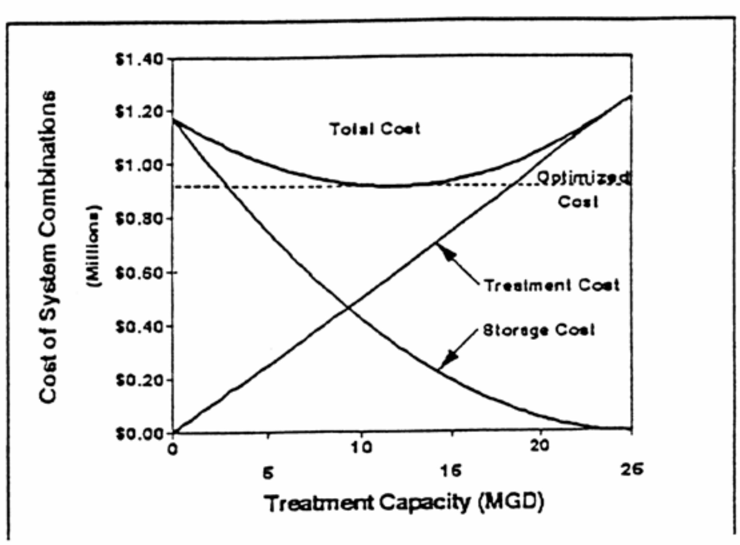

Figure 12. Storage/Treatment example – Cost for all combinations (Field, *et al.* 1994).

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 8, and
- creating an updated compendium of cost information for control technologies.

System Modeling Methodology

The system model that can be used in the proposed methodology is 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 heavily 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) 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.

It is proposed to 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

An improved methodology can be used to design wet weather flow drainage systems that consider 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 is the integration of two available computer models to assist designers, SWMM and SLAMM. A marginal cost algorithm is also used 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 the type of development occurring in most of the U.S. -- relatively unplanned, uncontrolled urbanization proceeding a few acres at time.

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