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SLAMM, the Source Loading and Management Model

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Introduction

The Source Loading and Management Model (SLAMM) was originally developed to better understand the relationships between sources of urban runoff pollutants and runoff quality. It has been continually expanded since the late 1970s and now includes a wide variety of source area and outfall control practices (infiltration practices, wet detention ponds, porous pavement, street cleaning, catchbasin cleaning, and grass swales). SLAMM is strongly based on actual field observations, with minimal reliance on pure theoretical processes that have not been adequately documented or confirmed in the field. SLAMM is mostly used as a planning tool, to better understand sources of urban runoff pollutants and their control.

Special emphasis has been placed on small storm hydrology and particulate washoff in SLAMM, common areas of misuse in many stormwater quality models. Many currently available urban runoff models have their roots in drainage design where the emphasis is with very large and rare rains. In contrast, stormwater quality problems are mostly associated with common and relatively small rains. The assumptions and simplifications that are legitimately used with drainage design models are not appropriate for water quality models. SLAMM therefore incorporates unique process descriptions to more accurately predict the sources of runoff pollutants and flows for the storms of most interest in stormwater quality analyses. However, SLAMM can be effectively used in conjunction with drainage design models to incorporate the mutual benefits of water quality controls on drainage design.

SLAMM has been used in many areas of North America and has been shown to accurately predict stormwater flows and pollutant characteristics for a broad range of rains, development characteristics, and control practices. As with all stormwater models, SLAMM needs to be accurately calibrated and then tested (verified) as part of any local stormwater management effort.

SLAMM is unique in many aspects. One of its most important feature 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.

History of SLAMM and Typical Uses

The Source Loading and Management Model (SLAMM) was initially developed to more efficiently evaluate stormwater control practices. It soon became evident that in order to accurately evaluate the effectiveness of stormwater controls at an outfall, the sources of the pollutants or problem water flows must be known. SLAMM has evolved to include a variety of source area and end-of-pipe controls and the ability to predict the concentrations and loadings of many different pollutants from a large number of potential source areas. SLAMM calculates mass balances for both particulate and dissolved pollutants and runoff flow volumes for different development characteristics and rainfalls. It was designed to give relatively simple answers (pollutant mass discharges and control measure effects for a very large variety of potential conditions).

SLAMM was developed primarily as a planning level tool, such as to generate information needed to make planning level decisions, while not generating or requiring superfluous information. Its primary capabilities include predicting flow and pollutant discharges that reflect a broad variety of development conditions and the use of many combinations of common urban runoff control practices. Control practices evaluated by SLAMM include detention ponds, infiltration devices, porous pavements, grass swales, catchbasin cleaning, and street cleaning. These controls can be evaluated in many combinations and at many source areas as well as the outfall location. SLAMM also predicts the relative contributions of different source areas (roofs, streets, parking areas, landscaped areas, undeveloped areas, etc.) for each land use investigated. As an aid in designing urban drainage systems, SLAMM also calculates correct NRCS curve numbers that reflect specific development and control characteristics. These curve numbers can then be used in conjunction with available urban drainage procedures to reflect the water quantity reduction benefits of stormwater quality controls.

SLAMM is normally used to predict source area contributions and outfall discharges. However, SLAMM has been used in conjunction with a receiving water model (HSPF) to examine the ultimate receiving water effects of urban runoff (Ontario 1986), and has been recently been modified to be integrated with SWMM (Pitt, *et al.* 1999c) to more accurately consider the joint benefits of source area controls on drainage design.

The development of SLAMM began in the mid 1970s, primarily as a data reduction tool for use in early street cleaning and pollutant source identification projects sponsored by the EPA's Storm and Combined Sewer Pollution Control Program (Pitt 1979; Pitt and Bozeman 1982; Pitt 1984). Additional information contained in SLAMM was obtained during the EPA's Nationwide Urban Runoff Program (NURP) (EPA 1983), especially the early Alameda County, California (Pitt and Shawley 1982), and the Bellevue, Washington (Pitt and Bissonnette 1984) projects. The completion of the model was made possible by the remainder of the NURP projects and additional field studies and programming support sponsored by the Ontario Ministry of the Environment (Pitt and McLean 1986), the Wisconsin Department of Natural Resources (Pitt 1986), and Region V of the U.S. Environmental Protection Agency. Early users of SLAMM included the Ontario Ministry of the Environment's Toronto Area Watershed Management Strategy (TAWMS) study (Pitt and McLean 1986) and the Wisconsin Department of Natural Resources' Priority Watershed Program (Pitt 1986). SLAMM can now be effectively used as a tool to enable watershed planners to obtain a better understanding of the effectiveness of different control practice programs.

Some of the major users of SLAMM have been associated with the Nonpoint Source Pollution Control Program of the Wisconsin Department of Natural Resources, where SLAMM has been used for a number of years to support their extensive urban stormwater planning and cost-sharing program (Thum, *et al*. 1990, Kim, *et al.* 1993a and 1993b, Ventura and Kim 1993, Bachhuber 1996, Bannerman, *et al*. 1996, Haubner and Joeres 1996, and Legg, *et al.* 1996). Many of these applications have included the integrated use of SLAMM with GIS models.

A logical approach to stormwater management requires knowledge of the problems that are to be solved, the sources of the problem pollutants, and the effectiveness of stormwater management practices that can control the problem pollutants at their sources and at outfalls. SLAMM is designed to provide information on these last two aspects of this approach.

SLAMM Process Descriptions

Linsley (1982), in a paper summarizing urban runoff models, defined a model as a mathematical or physical system obeying certain conditions. The behavior of a model must be analogous to the system under study. Linsley felt that a comprehensive literature search would uncover at least several hundred, if not several thousand, models that have been used to predict runoff from rainfall information. He included in his review paper an interesting set of definitions for the many adjectives that have been used to describe hydraulic models:

> "• Deterministic-- Based on the assumption that the process can be defined in physical terms without a random component.
> • Stochastic-- Based on the assumption that the flow at any time is a function of the antecedent flows and a random component.

- Conceptual-- Model is designed according to a conceptual understanding of the hydraulic cycle with empirically determined functions to describe the various sub-processes.
- Theoretical-- Model is written as a series of mathematical functions describing a theoretical concept of the hydologic cycle.
- Black box-- Model uses an appropriate mathematical function or functions which is fitted to the data without regard to the processes it represents.
- Continuous-- Model is designed to simulate long periods of time without being reset to the observed data. Such models require some form of moisture storage accounting.
- Event-- Designed to simulate a single runoff event given the initial conditions.
- Complete-- Includes algorithms for computing the volume of runoff from rainfall and distributing this volume into the form of a hydrograph.
- Routing-- Model contains no algorithms for rainfall-runoff but simply distributes a given volume of runoff in time by routing or unit-hydrograph computations.
- Simplified-- Uses algorithms which have been deliberately simplified, or uses large time increments to minimize computer running time."

These labels may create more confusion than insight. Many relatively simple models not only have numerous descriptions for different model elements, but they also have conflicting descriptions as well. As an example, theoretical process descriptions are commonly coupled with conceptual and statistical (black box) descriptions. This is much more common with water quality models that have been constructed based on older hydraulic models (such as the development of HSPF from HSP from SWM). Each process contained in a model should have its own unique set of descriptors (deterministic or stochastic; and conceptual, theoretical, or black box), while the overall model design also dictates another set of descriptors (continuous or event; plus possibly complete, routing, and simplified). A complete set of descriptors would therefore become very confusing. It would be much better if the processes and the model design were well documented.

Troutman (1985) described the preconceived differences between deterministic models or black box models. He concluded that the distinction between these two seemingly conflicting categories of models was not at all clear, or important, when analyzing errors. He found that some of the confusion in these model categories was because some users categorized statistical models as black box models (such as defined above by Linsley in 1982). He gives as an example the general assumption of runoff that tends to vary proportionally with rainfall. This conceptual relationship is typically reflected by a very simple statistical black box model. He further shows that many of the most complex physically based conceptual hydrologic models currently used contain many process descriptions where some of the variables are simply statistically related to other variables. Because these models are large and complex, these relationships are commonly overlooked. His major conclusion is that any rainfall-runoff model can be defined as a conceptual model, and that the distinctions between black box and physically based (conceptual) models are not clear or useful. He states that every model becomes a statistical model when the errors are rigorously and objectively examined by representing the errors as random variables having a probabilistic structure.

Like many models, SLAMM has attributes that fit many of Linsley's descriptors. Table 1 is a matrix showing these different attributes for different processes in the model.

All components and processes in SLAMM have residual errors that cannot be completely explained through calibration. SLAMM therefore includes Monte Carlo simulation techniques and batch processing to consider this residual so model results reflect these uncertainties. Some of the model input parameters are directly measured, such as the areas and characteristics of the contributing areas in the watershed, and the pollutant associations with particulate solids from these areas. The rainfall-runoff components, particulate accumulation rates, and street cleaning effects are based on conceptual models, and have been extensively verified through many prior studies and don't require local measurements. Infiltration, grass swale, and detention pond effects are based on standard theoretical approaches that have also been verified under many conditions. Particulate washoff and catchbasin cleaning are based on statistical curve-fits, based on measured parameters (street dirt loading, street texture, flow rate, prior accumulation, etc.). Many of the processes are continuous in that variations in runoff, particulate loadings, water in ponds, water in infiltration devices, etc. are continuously modeled throughout the study period, with inter-event effects on the device performance considered during subsequent wet weather events. Other processes are only event-based, in that field measurements in urban areas have not shown important or significant benefits of continuous simulations. Interestingly, rainfall-runoff processes are not continuously modeled in SLAMM, but are only based on conditions present at the time of rainfall initiation. Antecedent soil moisture has little effect on disturbed urban soils, compared to soil compaction, and the large amount of pavement dominating runoff processes for the common small and medium-sized rains that SLAMM was designed to simulate. SLAMM has been shown to very accurately predict runoff volumes for many rain types throughout the US with this simplification. Runoff is converted to hydrograph representations where rate of flow changes have important effects on performance of control devices, such as detention ponds, swales, and infiltration devices.

Table 1. Major Process Descriptions in SLAMM (attributes total 10 for each process)

Process or Input Parameters	Deter-ministic	Stoch-astic	Con-ceptual	Theor-etical	Statis-tical	Contin-uous	Event	Complete	Simplified
Source areas	9	1				n/a			
Development characteristics	9	1				n/a			
Rainfall-runoff		2	8				yes	yes	yes
Particulate accumulation		3	7			yes			
Particulate washoff		2			8		yes		
Pollutant associations	7	3					yes		
Street cleaning		3	7			yes			yes
Catchbasin cleaning		2			8	yes			yes
Infiltration		2		8		yes		yes	
Grass swales		2		8			yes	yes	
Detention		1		9		yes		yes	

Use of SLAMM requires careful measurements of contributing areas and characteristics, from watershed surveys and aerial photographs. Calibrations of the rainfall-runoff, particulate accumulation and washoff processes, and pollutant associations, are based on regional data. Model verification is based on a set of observed outfall events.

Unique Attributes of SLAMM

The following paragraphs discuss two important aspects included in SLAMM that are incorrectly considered in most currently used stormwater models, the runoff predictions associated with small and moderate sized events associated with the majority of receiving water problems, and the washoff of particulate pollutants from urban surfaces.

Small Storm Hydrology

One of the major problems with conventional stormwater models concerns runoff volume estimates associated with small and moderate-sized storms. Figures 1 and 2 show the importance of common small storms when considering total annual pollutant discharges. Figure 1 shows the accumulative rain count and the associated accumulative runoff volume for a medium density residential area in Milwaukee, Wisconsin, based on 1983 monitored data (Bannerman, *et al*. 1983). This figure shows that the median rain, by count, was about 0.3 inches (7.5 mm), while the rain associated with the median runoff quantity is about 0.75 inches (20 mm). 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 (20 mm). The 1983 rains (which were monitored during the Milwaukee NURP project) included several very large storms which are also shown on Figure 1. These large storms (of 3 to 5 inches, or 75 to 125 mm in depth) distort Figure 1 because, on average, the Milwaukee area only can expect one 3.5 inch (90 mm) storm every five years. In most years, these large rains would not occur and the significance of the smaller rains would be even greater.

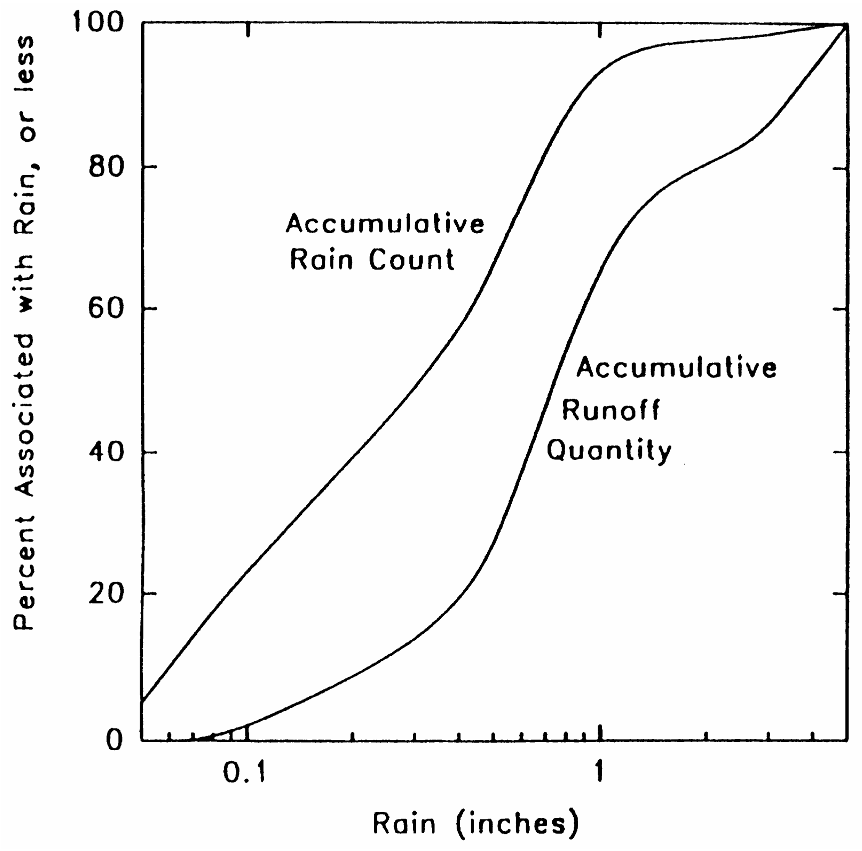


Figure 1. Accumulative rain count and associated runoff volumes for medium density residential areas monitored in Milwaukee, WI (from Bannerman, *et al*. 1983).

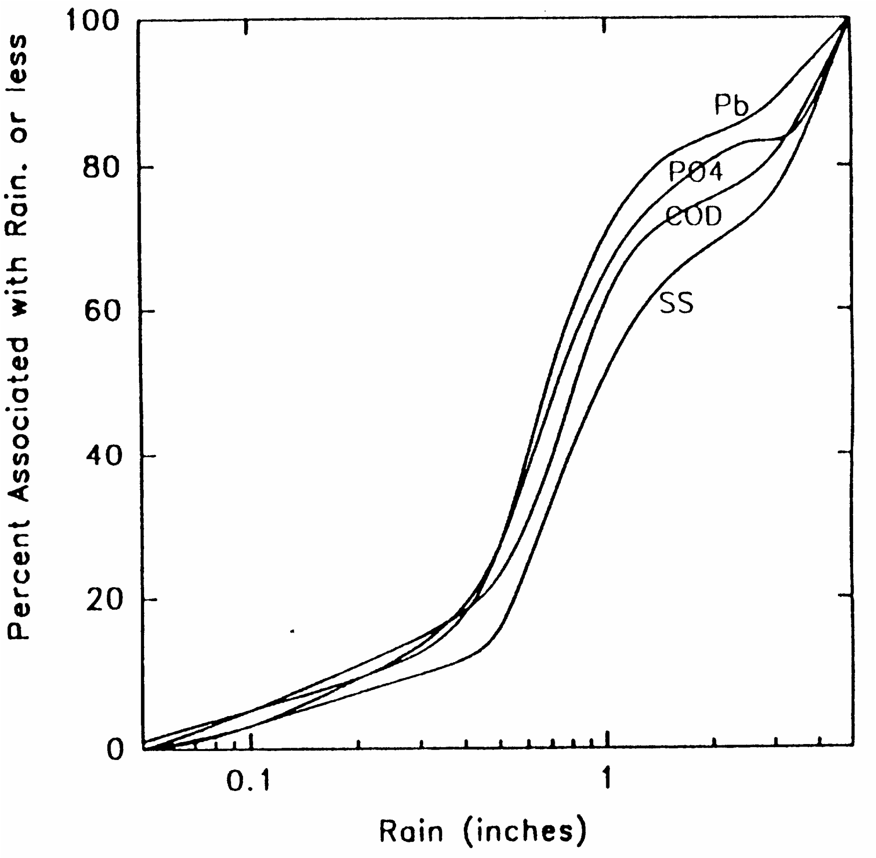


Figure 2. Accumulative pollutant loadings for medium density residential areas monitored in Milwaukee, WI (from Bannerman, *et al*. 1983).

Figure 2 shows the accumulative loadings of different pollutants (suspended solids, COD, phosphates, and lead) monitored during 1983 in Milwaukee at the same site as the rain and runoff data shown in Figure 1 (Bannerman, *et al*. 1983). When Figure 2 is compared to Figure 1, it is seen that the runoff and discharge distributions are very similar. This is a simple way of indicating that there were no significant trends of stormwater concentrations for different size events. There were substantial variations in pollutant concentrations observed, but they were random and not related to storm size. Similar conclusions were noted when all of the NURP data was evaluated (EPA 1983). Therefore, accurately knowing the runoff volume is most important when studying pollutant discharges, not runoff flow rates. By better understanding the significance and runoff generation potential of these small rains, runoff problems would be better understood.

By knowing the relative contributions of water and pollutants from each source area, it is possible to evaluate potential source area runoff controls for different rains. Figure 3 illustrates the concept of variable contributing areas as applied to urban watersheds. This figure indicates the relative significance of three major source areas (street surfaces, other impervious surfaces, and pervious surfaces) in an urban area. The individual flow rates associated with each of these source areas increase until their time of concentrations are met. The flow rate then remains constant for each source area until the rain event ends. When the rain stops, runoff recession curves occur, draining the individual source areas. The three component hydrographs are then added together to form the complete hydrograph for the area. Calculating the percentage of the total hydrograph associated with each individual source area enables estimates of the relative importance of each source area to be quantified. The relative pollutant discharges from each area can then be calculated from the runoff pollutant strengths associated with each area.

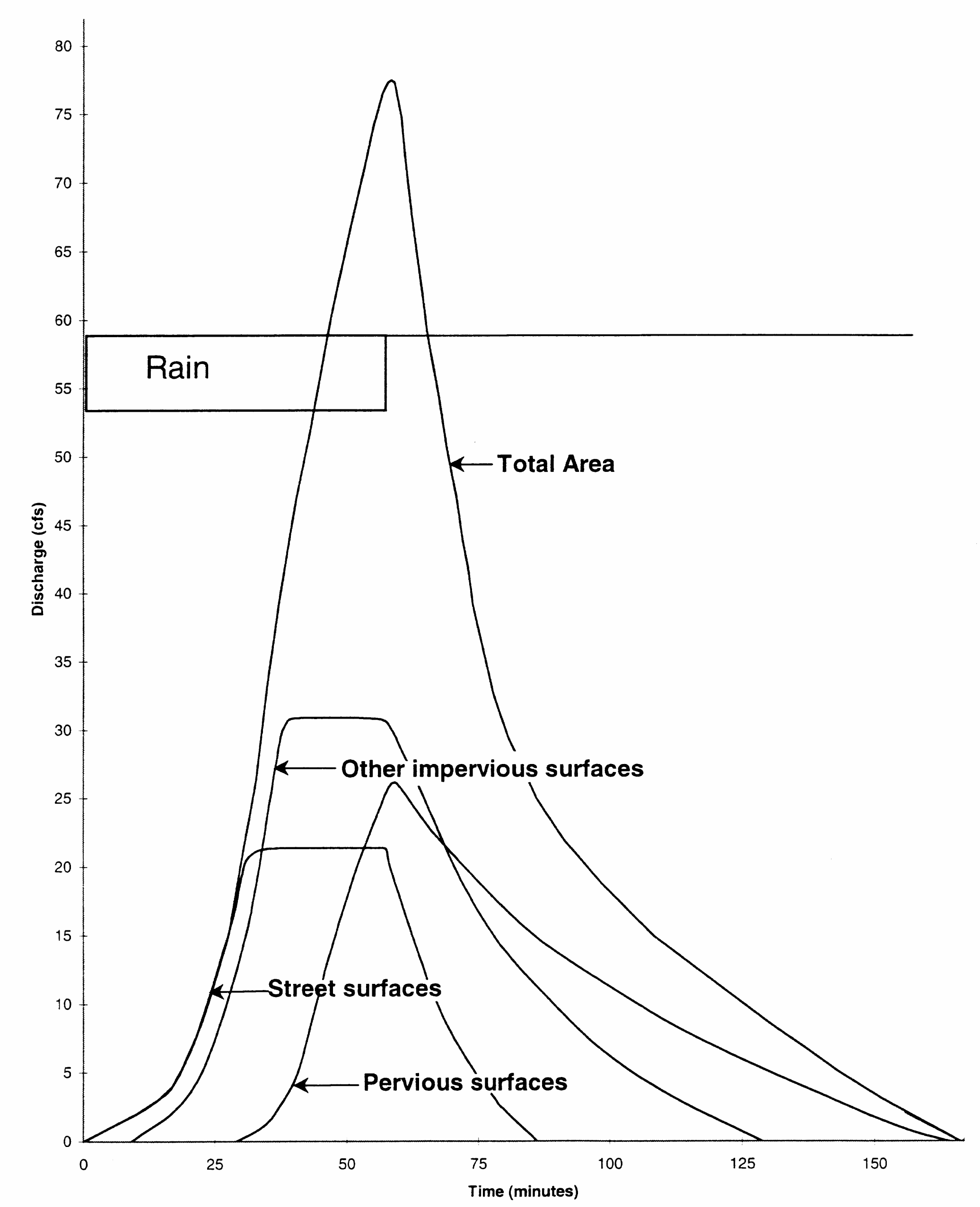


Figure 3. Variable contributing areas in urban watersheds.

When the time of concentration and the rain duration are equal for an area, the maximum runoff rate for that rain intensity is reached. The time of concentration occurs when the complete drainage area is contributing runoff to the point of concern. If the rain duration exceeds the time of concentration, then the maximum runoff rate is maintained until the rain ends. When the rain ends, the runoff rate decreases according to a recession curve for that surface. The example shown in Figure 3 is for a rain duration greater than the times of concentrations for the street surfaces and other impervious areas, but shorter than the time of concentration for the pervious areas. Similar runoff quantities originated from each of the three source areas for this example. If the same rain intensity occurs, but lasts for twice the duration (a less frequent storm), the runoff rates for the street surfaces and other impervious surfaces will be the same until the end of the rain, when their recession curves would begin. However, the relative runoff contribution from the pervious surfaces would increase substantially. If the same rain intensity occurs, but only for half of the original duration, the street surfaces time of concentration is barely met, and the other impervious surfaces would not have reached their time of concentration. In this last example, the pervious surfaces would barely begin to cause runoff, and the street surfaces are the dominant source of runoff water.

Figure 4 shows monitored rainfall-runoff results from one of a series of tests conducted to investigate runoff losses associated with common small rains on pavement (Pitt 1987). This figure indicates that initial abstractions (measured to be detention storage associated with street texture and pavement slope) for this pavement totaled about 0.04 in. (1 mm), while the total rainfall losses were about 0.25 in. (6 mm). The other losses after the initial abstractions were mostly associated with infiltration through the relatively thin and porous pavement material and through cracks and seams. These maximum losses occurred after about 0.8 in. (20 mm) of rain. For a relatively small rain of about 0.3 in. (7 mm), almost one-half of the rain falling on this pavement did not contribute to runoff. During smaller storms, the majority of the rainfall did not contribute to runoff. These rainfall losses for pavement are similar for most city streets and are substantially greater than commonly considered in stormwater models. Runoff yields from large expanses of pavement (such as parking areas) and for high use roadways (highways) are much greater than for most roadways. Large parking areas have minimal infiltration losses because of the long horizontal flow distances to the edge of the pavement, while the thicker and more dense pavements of high-use roadways allow only minimal amounts of water infiltration. Only special pavement base materials are capable of allowing significant water infiltration. Normally, the pavement bases therefore typically act as the “aquaclude” for pavement structures. The water entering a pavement is therefore restricted to the storage volume in the pavement, plus the effects of the drainage of water from the pavement. In-pavement storage volume is usually very small. For relatively narrow streets, pavement drainage through the pavement edges (following Darcy’s law) allows more rainfall losses than for the longer flow paths associated with parking lots, for example.

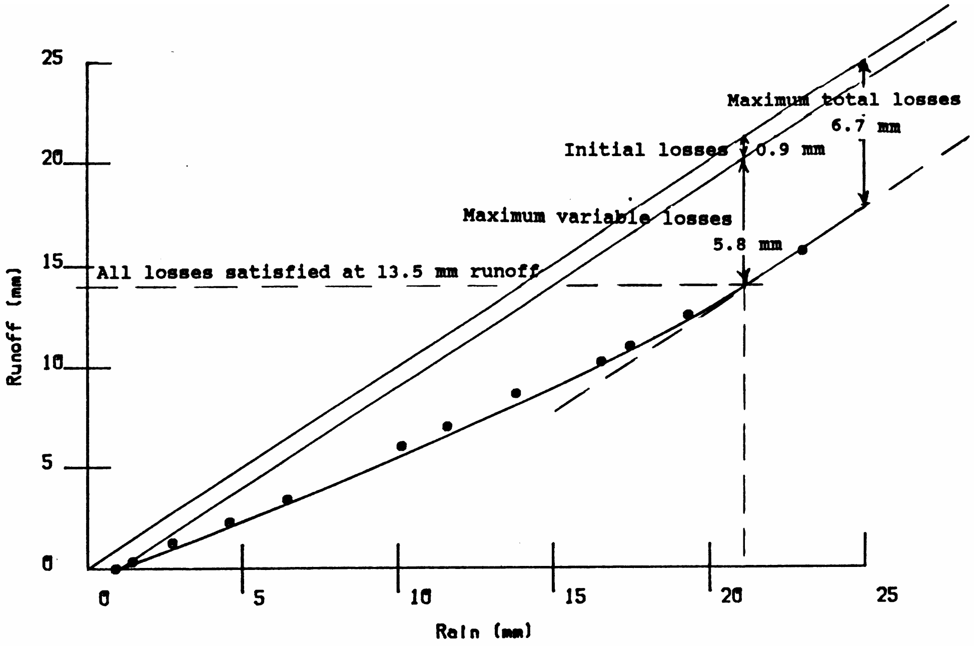


Figure 4. Measured rainfall-runoff from a typical city street (Pitt 1987).

Most stormwater models use rainfall-runoff relationships that have been developed and used for many years for drainage design. Drainage design is concerned with rain depths of at least several inches (hundreds of mm). When these same procedures are used to estimate the runoff associated with common small storms (which are the most important in water quality investigations), the runoff predictions can be highly inaccurate. As an example, the volumetric runoff coefficient (the ratio of the runoff to the rain depth) observed at outfalls varies for each rain depth. This ratio can be about 0.1 for storms of about 0.5 inches (12 mm) but may approach about 0.4 for a moderate size storm of 2.5 inches (65 mm) or greater that is typically associated with drainage events for medium density residential areas. However, the NURP study (EPA 1983) recommended the use of constant (average) volumetric runoff coefficients for the stormwater permit process. Therefore, common small storms would likely have their runoff volumes over-predicted.

During recent research on the infiltration rates of disturbed urban soils, it was found that compaction was much more significant than moisture for many conditions (Pitt, *et al.* 1999b). Figures 5 and 6 are 3D plots of the observed infiltration data, illustrating effects of soil-water levels and compaction, for both sand and clay. Four general conditions were observed to be statistically unique. Compaction has the greatest effect on infiltration rates in sandy soils, with little detrimental effects associated with higher soil-water content. Clay soils, however, are affected by both compaction and soil-water content. Compaction was seen to have about the same effect as saturation on these soils, with saturated and compacted clayey soils having very little effective infiltration. Therefore, if common occurring compaction was ignored, runoff from pervious areas could be over-predicted.

Figure 7 shows the actual calculated Natural Resources Conservation Service (SCS 1986) curve numbers (CN) associated with different storms at a medium density residential site in Milwaukee. This figure shows that the actual CN values vary dramatically for the different rain depths that actually occurred at this site. The actual CN values approach the CN values that would be selected for this type of site only for rains greater than several inches (hundreds of mm) in depth. The actual CN values are substantially greater for the smaller common storms, especially for rains less than the one inch (25 mm) minimum rain criteria given by NRCS (SCS 1986) for the use of this procedure. These results are similar to those obtained at many other sites. In almost all cases, the CN values for storms of less than a 0.5 inch (12 mm) are 90, or greater. Therefore, the smaller storms actually contribute much more runoff than would typically be assumed if using NRCS procedures. The curve number method was initially developed, and is most appropriate, for use in the design of drainage systems associated with storms of much greater size than those of interest in stormwater quality investigations.

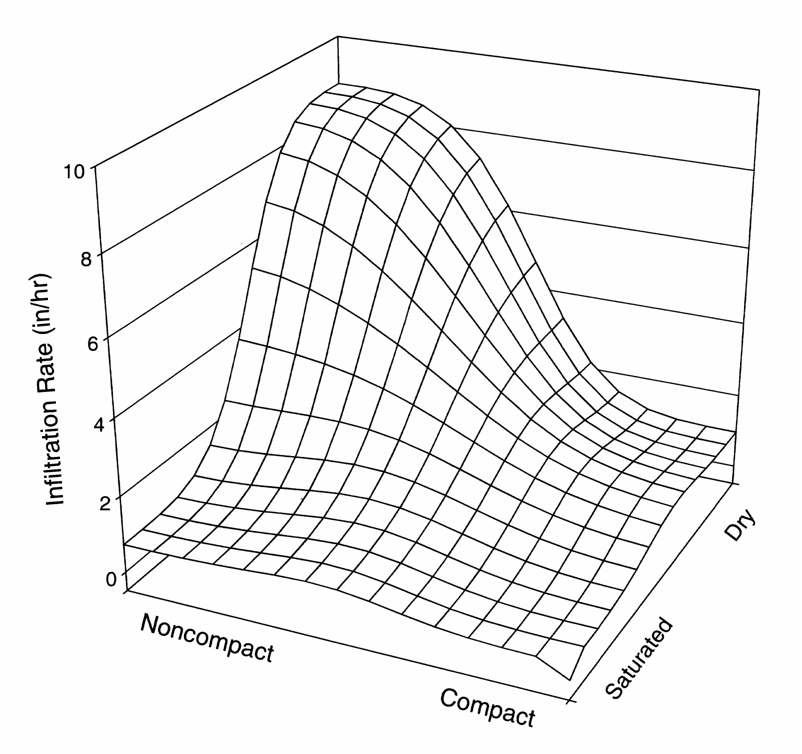


Figure 5. Effects of compaction and moisture on clayey urban soils (Pitt, *et al*. 1999b).

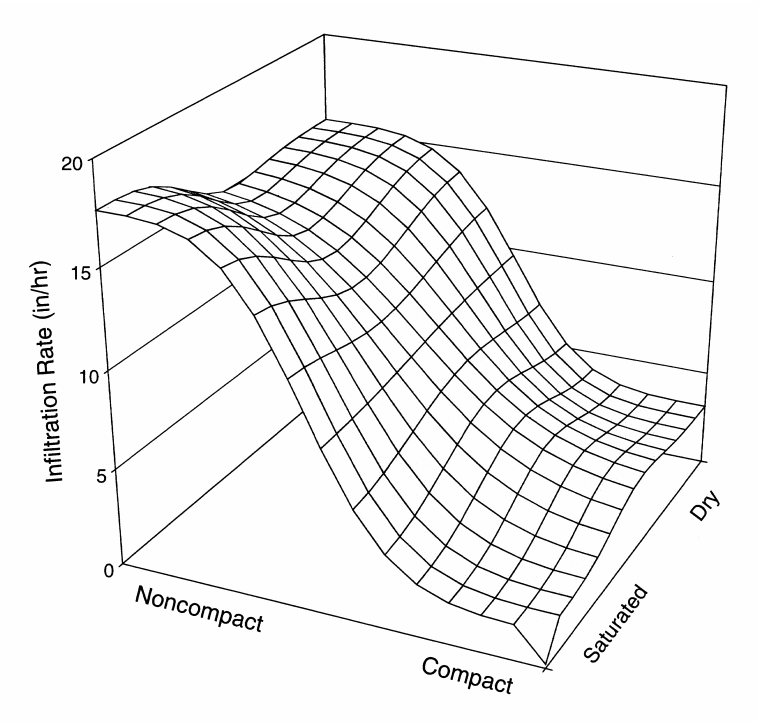


Figure 6. Effects of compaction and moisture on sandy urban soils (Pitt, *et al.* 1999b).

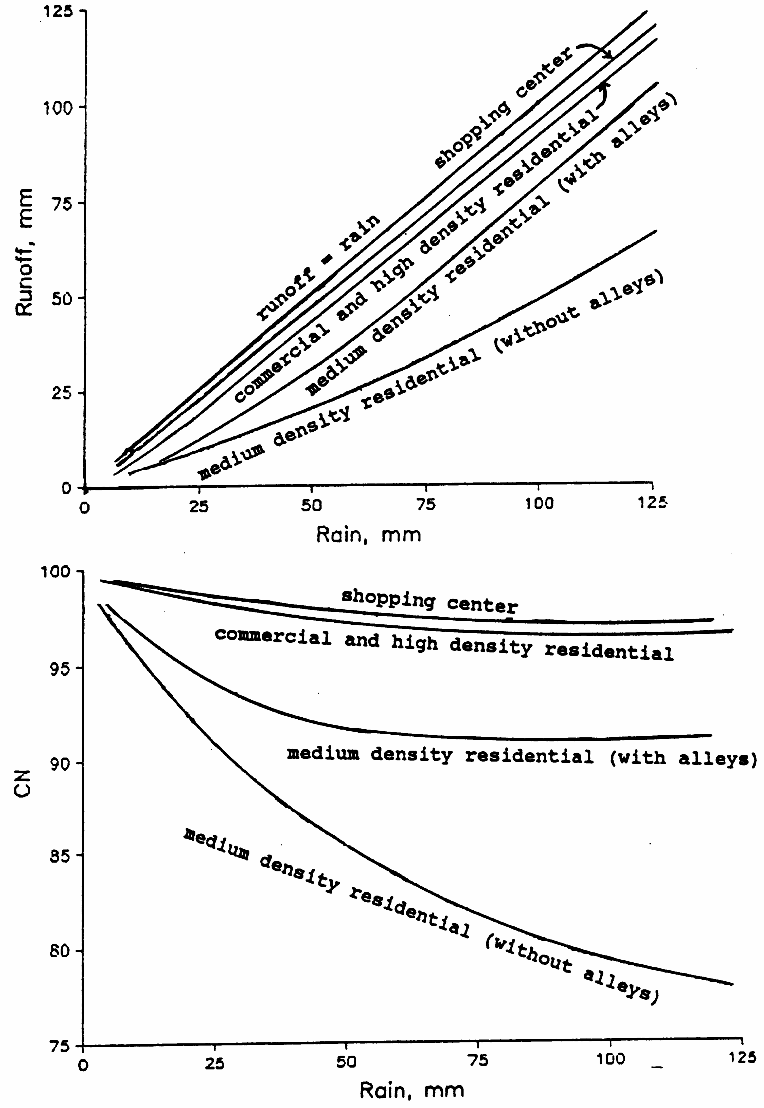


Figure 7. Actual NRCS curve numbers from monitored Milwaukee, WI (from Bannerman, *et al.* 1983).

SLAMM makes runoff predictions using the small storm hydrology methods developed by Pitt (1987). Figure 8 shows the verification of the small storm hydrology method used in SLAMM for storms from a commercial area in Milwaukee. This figure shows that the calculated runoff for many storms over a wide range of conditions was very close to the actual observed runoff. Figure 9 shows a similar plot of the predicted versus observed runoff for a Milwaukee medium density residential area. These two sites were substantially different from each other in the amount of impervious surfaces and how these areas were connected to the drainage system. Similar satisfactory comparisons using these small storm hydrology models for a wide range of rain events have been made for other locations, including Portland, Oregon (Sutherland 1993) and Toronto, Canada (Pitt and McLean 1986).

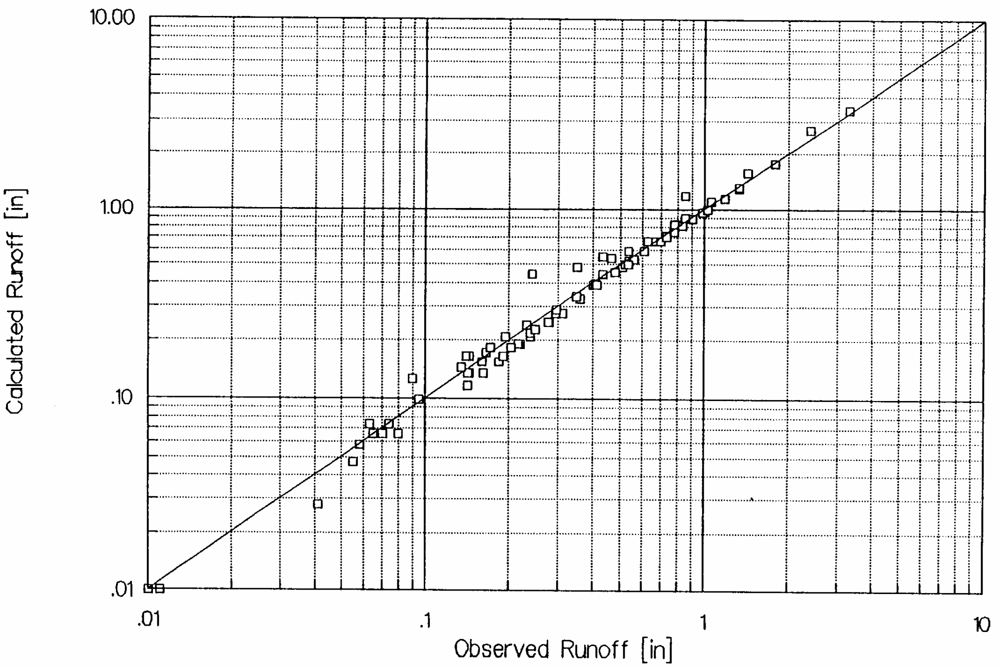


Figure 8. Verification of the small storm hydrology components of SLAMM for a commercial site in Milwaukee, WI.

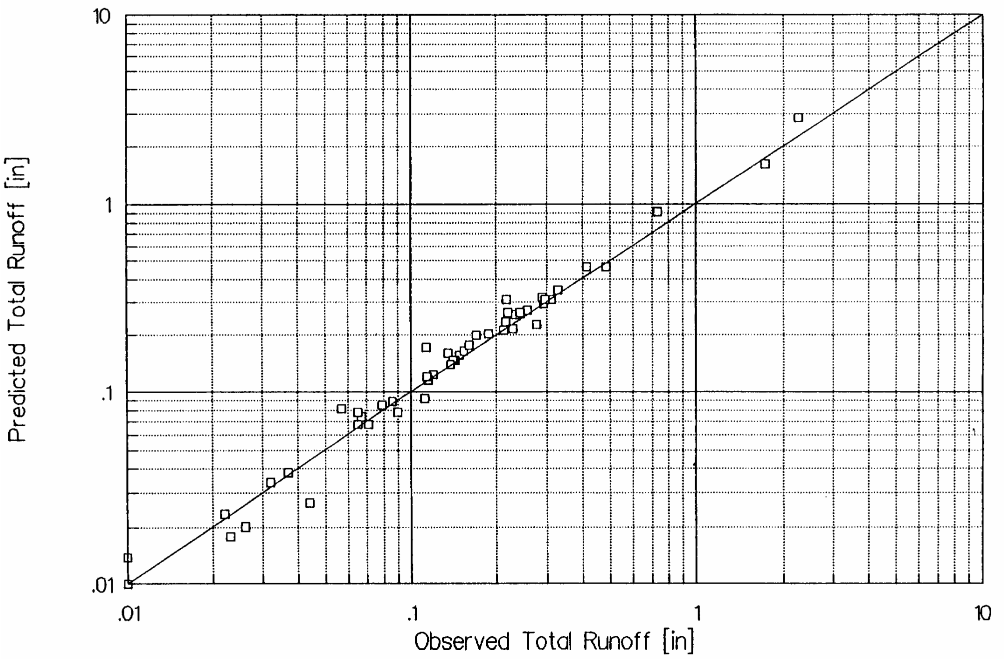


Figure 9. Verification of the small storm hydrology components of SLAMM for a medium residential area in Milwaukee, WI.

Particulate Washoff

Another unique feature of SLAMM is its correct use of a washoff model to predict the losses of suspended solids from different surfaces. SLAMM calculates suspended solids washoff based on individual first-flush (exponential) relationships for each surface. These relationships were derived from observations during both controlled tests and during actual rains for individual homogeneous surfaces (Pitt and McLean 1986 and Pitt 1987). These washoff relationships have been verified during runoff observations from large and complex drainages (Pitt 1987). Figure 10 shows washoff plots for total solids, suspended solids (>0.45 µm), and dissolved solids (<0.45µm) during an example controlled street surface washoff test (Pitt 1987). These plots indicate the accumulative (g/m^2) washoff as a function of rain depth. Also shown on these plots are the total street dirt loadings. As an example, 13.8 g/m^2 of total solids were on the street surfaces before the controlled rain event. After about 15 mm of rain fell on the test sites, almost 90 percent of the particulates that would wash off (about 3 g/m^2) did, similar to the rain depth needed for "complete" washoff as reported by earlier studies by Sartor and Boyd (1972). However, the total quantity of material that could possibly wash off (about 3 g/m^2) is a small fraction of the total loading that was on the street (13.8 g/m^2). If the relationship between total available loading and total loading of particulates is not considered (as in many stormwater models), then the predicted washoff would be greatly in error.

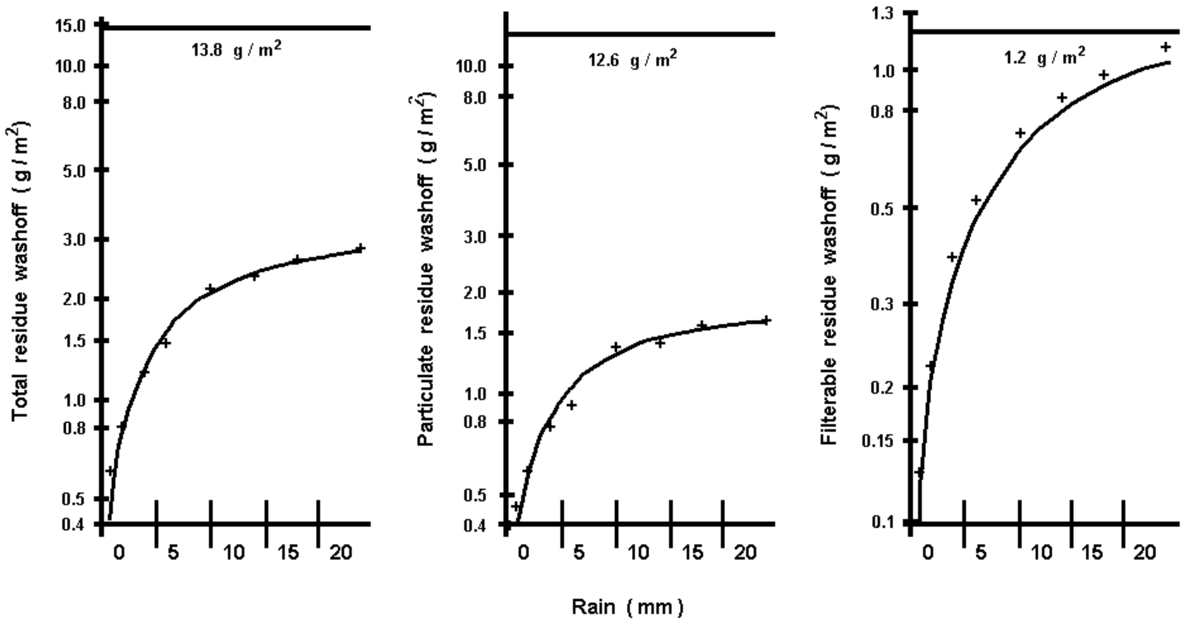


Figure 10. Washoff plots for HDS test (high rain intensity, dirty, and smooth street) (Pitt 1987).

Figure 10 also shows washoff of the smallest particle sizes ("dissolved solids", <0.45 µm) as a function of total rain. Here the total loading of the filterable solids on the streets was only about 1 g/m^2 and almost all of these small particles were available for washoff during these rains. Figure 10 also shows the washoff of the largest particles ("suspended solids", >0.45 µm) on the street. Here, the street loading was 12.6 g/m^2, with only about 1.8 g/m^2 available for washoff.

The predicted washoff of suspended solids could be in error by 700 percent if the total loading on the street was assumed to be removable by rains. SLAMM uses test results from Pitt (1987) that measured the washoff and street dirt loading availability relationships for many street surfaces, rain intensities, and street dirt loadings to more accurately predict the amount of washoff.

Another common problem with stormwater models is the use of incorrect particulate accumulation rates for different surfaces. Figure 11 shows an example of the accumulation and deposition of street surface particulates for two residential areas monitored in San Jose, California (Pitt 1979). The two areas were very similar in land use, but the street textures were quite different. The good-condition asphalt streets were quite smooth, while the oil and screens overlaid streets were very rough. Immediately after intensive street cleaning, the rough streets still had substantial particulate loadings, while the smooth streets had substantially less. The accumulation of debris on the streets also increased the street dirt loadings over time. The accumulation rates were very similar for these two different streets having the same land uses. However, the loadings on the streets at any time were quite different because of the greatly different initial loading values (permanent storage loadings). If infrequent street dirt loading observations are made, the true shape of the accumulation rate curve may not be accurately known. As an example, the early Sartor and Boyd (1972) test results that have been used in many stormwater models assumed that the initial loading values after rains were close to zero, instead of the actual substantial initial loadings. The accumulation rates were calculated by using the slope between each individual loading value and the origin (zero time and zero loading), rather than between loadings from adjacent sampling times. This can easily result in accumulation rates many times greater than actually occurred.

The street dirt deposition rates were found to only be a function of the land uses, but the street dirt loadings were a function of the land use and street texture. The accumulation rates slowly decreased as a function of time and eventually became zero, with the loading remaining constant, after a period of about one month of either no street cleaning or no rains. Figure 11 shows that the deposition and accumulation rates on the streets were about the same until about one or two weeks after a rain. If the streets were not cleaned for longer periods, then the accumulation rate decreased because of fugitive dust losses of street dirt to surrounding areas by winds or vehicle turbulence. In most areas of the US. (having rains at least every week or two), the actual accumulation of material on street surfaces is likely constant, with little fugitive dust losses (Pitt 1979). SLAMM includes a large number of street dirt accumulation and deposition rate relationships that have been obtained for many monitoring sites throughout the US and in Canada. The accumulation rates are a function of the land uses, while the initial loadings on the streets are a function of street texture. The decreasing accumulation rate is also a function of the time after a street cleaning or large rain event.

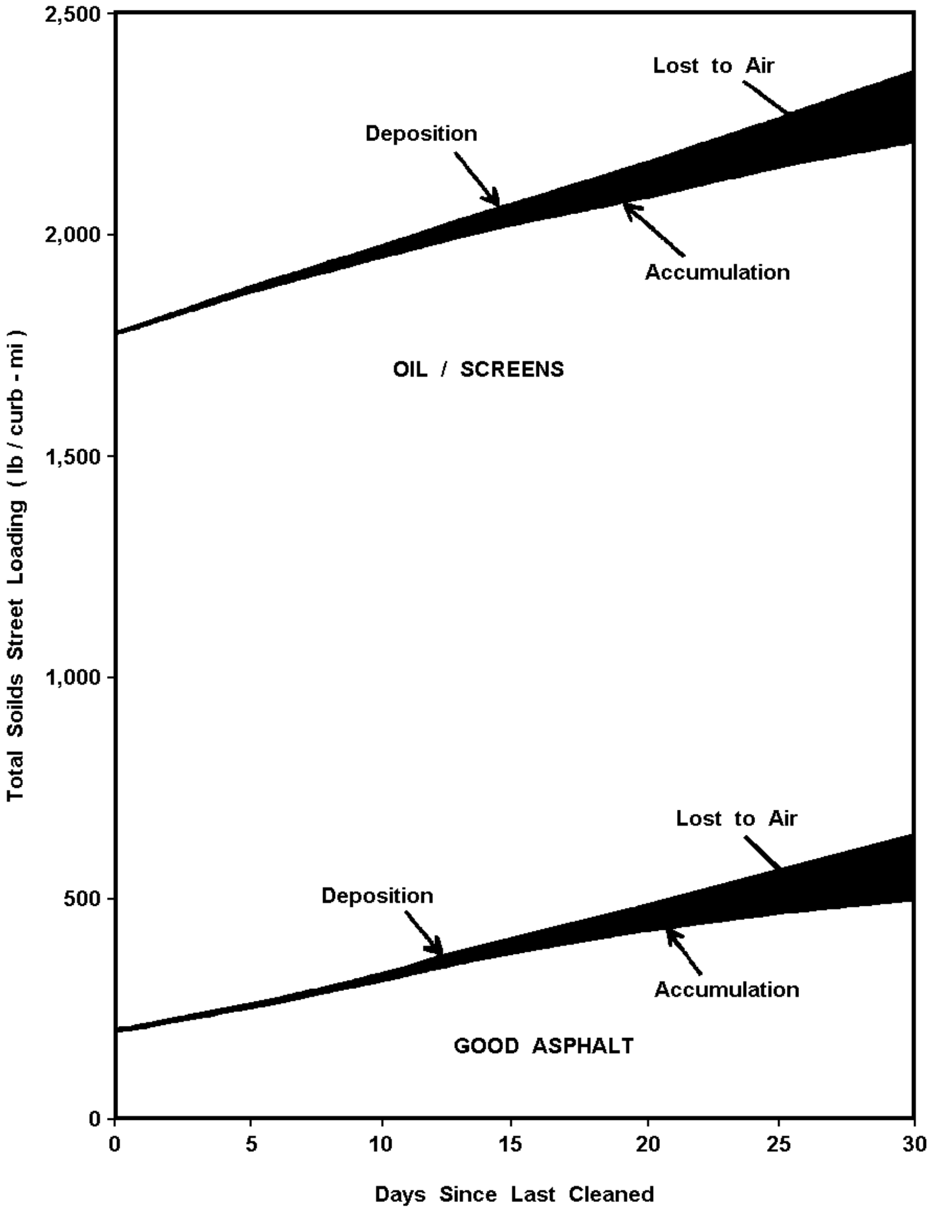


Figure 11. Deposition and accumulation of street dirt.

SLAMM Computational Processes

In most urban areas, there is a wide variety of drainage systems from concrete curb and gutters to grass swales, along with directly connected roof drainage systems and drainage systems that drain to pervious areas. “Development characteristics” define the magnitude of these drainage efficiency attributes, along with the areas associated with each surface type (road surfaces, roofs, landscaped areas, etc.). The use of SLAMM shows that these characteristics greatly affect runoff quality and quantity. Land use alone is usually not sufficient to describe these characteristics.

The types of the drainage system (curbs and gutters or grass swales) and roof connections (directly connected or draining to pervious area), are probably the most important attributes affecting runoff characteristics. These attributes are not directly related to land use, but some trends are obvious: most roofs in strip commercial and shopping center areas are directly connected, and the roadside is most likely drained by curbs and gutters, for example. Different land uses, of course, are also associated with different levels of pollutant generation. For example, industrial areas usually have the greatest pollutant accumulations due to material transfer and storage, and heavy truck traffic.

SLAMM uses the water volume and suspended solids concentrations at the outfall to calculate the other pollutant concentrations and loadings. SLAMM keeps track of the portion of the total outfall suspended solids loading and runoff volume that originated from each source area. The suspended solids fractions are then used to develop weighted loading factors associated with each pollutant. In a similar manner, dissolved pollutant concentrations and loadings are calculated based on the percentage of water volume that originates from each of the source areas within the drainage system.

SLAMM predicts urban runoff discharge parameters (total storm runoff flow volume, flow-weighted pollutant concentrations, and total storm pollutant yields) for many individual storms and for the complete study period. It has built-in Monte Carlo sampling procedures to consider many of the uncertainties common in model input values. This enables the model output to be expressed in probabilistic terms that more accurately represent the likely range of results expected.

Early versions of SLAMM only used average concentration factors for different land use areas and source areas. This was satisfactory for predicting the event mean concentrations (EMCs, as used by NURP, EPA 1983) for an extended period of time and in calculating the unit area loadings for different land uses. However, in order to predict the probability distributions of the concentrations, it was necessary to include probability information for the concentrations found in the different source areas. Statistical analyses of concentration data (attempting to relate concentration trends to rain depths and season, for example) from these different source areas have not been able to explain all of the variation in concentrations that have been observed (Pitt, *et al.* 1999c). The statistical analyses also indicate that most pollutant concentration values from individual source areas are distributed log-normally (EPA 1983). Therefore, log-normally distributed random concentration values are used in SLAMM for these different areas. The result is much more reasonable predictions for concentration distributions at the outfall when compared to actual observed conditions. This provides more accurate estimates of criteria violations for different stormwater pollutants at an outfall for long continuous simulations.

Use of SLAMM to Identify Pollutant Sources and to Evaluate Different Control Programs

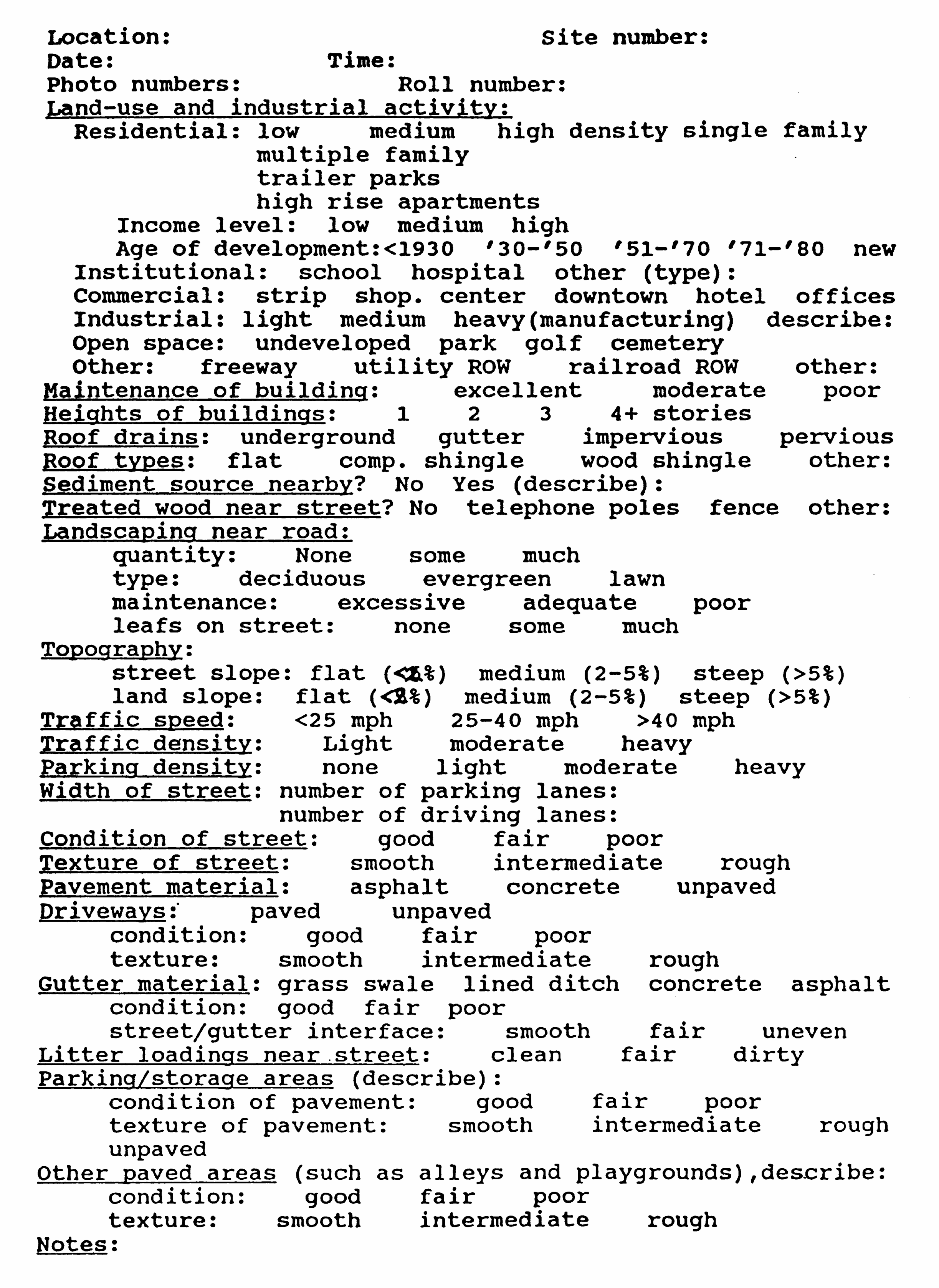
Table 2 is a field sheet that has been developed to assist users of SLAMM describe test watershed areas. This sheet is mostly used to evaluate stormwater control retrofit practices in existing developed areas, and to examine how different new development standards effect runoff conditions. Much of the information on the sheet is not actually required to operate SLAMM, but is very important when considering additional control programs (such as public education and good housekeeping practices) that are not quantified by SLAMM. The most important information shown on this sheet is the land use, the type of the gutter or drainage system, and the method of drainage from roofs and large paved areas to the drainage system. The efficiency of drainage in an area, specifically if roof runoff or parking runoff drains across grass surfaces, can be very important when determining the amount of water and pollutants that enter the outfall system. Similarly, the presence of grass swales in an area may substantially reduce the amount of pollutants and water discharged. This information is therefore required to use SLAMM.

The areas of the different surfaces in each land use is also very important for SLAMM. Figure 12 is an example showing the areas of different surfaces for a medium density residential area in Milwaukee. As shown in this example, streets make up between 10 and 20 percent of the total area, while landscaped areas can make up about half of the drainage area. The variation of these different surfaces can be very large within a designated area. The analysis of many candidate areas may therefore be necessary to understand how effective or how consistent the model results may be for a general land use classification.

One of the first problems in evaluating an urban area for stormwater controls is the need to understand where the pollutants of concern are originating under different rain conditions. Figure 13 is an example for a typical medium density residential area showing the percentage of runoff originating from different major sources, as a function of rain depth. For storms of up to about 0.1 inch in depth, street surfaces contribute about one-half to the total runoff to the outfall. This contribution decreased to about 20 percent for storms greater than about 0.25 inch in depth. This decrease in the significance of streets as a source of water is associated with an increase of water contributions from landscaped areas (which make up more than 75% of the area and have clayey soils). Similarly, the significance of runoff from driveways and roofs also starts off relatively high and then decreases with increasing storm depth. Obviously, this is just an example plot and the source contributions would vary greatly for different land uses/development conditions, rainfall patterns, and the use of different source area controls.

A major use of SLAMM is to better understand the role of different sources of pollutants. As an example, to control suspended solids, street cleaning (or any other method to reduce the washoff of particulates from streets) may be very effective for the smallest storms, but would have very little benefit for storms greater than about 0.25 inches in depth. However, erosion control from landscaped surfaces may be effective over a wider range of storms. The following list shows the different control programs that were investigated in this hypothetical medium density residential area:

Table 2. Study Area Description Field Sheet



Location: Site number:
Date: Time:
Photo numbers: Roll number:
Land-use and industrial activity:
Residential: low medium high density single family
multiple family
trailer parks
high rise apartments
Income level: low medium high
Age of development:<1930 '30-'50 '51-'70 '71-'80 new
Institutional: school hospital other (type):
Commercial: strip shop. center downtown hotel offices
Industrial: light medium heavy(manufacturing) describe:
Open space: undeveloped park golf cemetery
Other: freeway utility ROW railroad ROW other:
Maintenance of building: excellent moderate poor
Heights of buildings: 1 2 3 4+ stories
Roof drains: underground gutter impervious pervious
Roof types: flat comp. shingle wood shingle other:
Sediment source nearby? No Yes (describe):
Treated wood near street? No telephone poles fence other:
Landscaping near road:
quantity: None some much
type: deciduous evergreen lawn
maintenance: excessive adequate poor
leafs on street: none some much
Topography:
street slope: flat (<2%) medium (2-5%) steep (>5%)
land slope: flat (<2%) medium (2-5%) steep (>5%)
Traffic speed: <25 mph 25-40 mph >40 mph
Traffic density: Light moderate heavy
Parking density: none light moderate heavy
Width of street: number of parking lanes:
number of driving lanes:
Condition of street: good fair poor
Texture of street: smooth intermediate rough
Pavement material: asphalt concrete unpaved
Driveways: paved unpaved
condition: good fair poor
texture: smooth intermediate rough
Gutter material: grass swale lined ditch concrete asphalt
condition: good fair poor
street/gutter interface: smooth fair uneven
Litter loadings near street: clean fair dirty
Parking/storage areas (describe):
condition of pavement: good fair poor
texture of pavement: smooth intermediate rough
unpaved
Other paved areas (such as alleys and playgrounds),describe:
condition: good fair poor
texture: smooth intermediate rough
Notes:

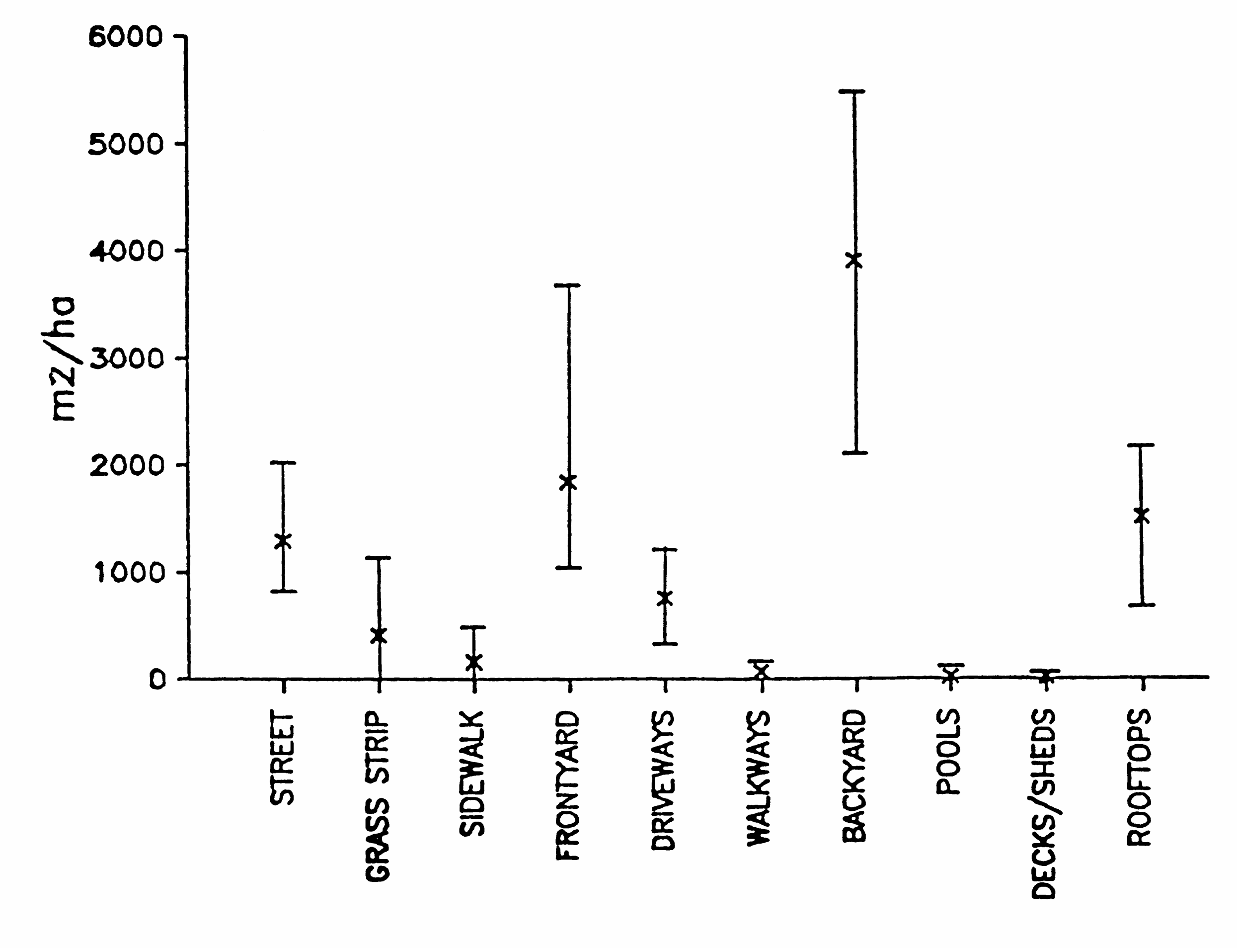


Figure 12. Source areas – Milwaukee medium density residential areas (without alleys) (Pitt 1987).

- Base level (as built in 1961-1980 with no additional controls)
- Catchbasin cleaning
- Street cleaning
- Grass swales
- Roof disconnections
- Wet detention pond
- Catchbasin and street cleaning combined
- Roof disconnections and grass swales combined
- All of the controls combined

This residential area, which was based upon actual Birmingham, Alabama, field observations for homes built between 1961 to 1980, has no controls, including no street cleaning or catchbasin cleaning. The use of catchbasin cleaning in the area, in addition to street cleaning was evaluated. Grass swale use was also evaluated, but swales are an unlikely retrofit option, and would only be appropriate for newly developing areas. However, it is possible to disconnect some of the roof drainages and divert the roof runoff away from the drainage system and onto grass surfaces for infiltration in existing developments. In addition, wet detention ponds can be retrofitted in different areas and at outfalls. Besides those controls examined individually, catchbasin and street cleaning controls combined were also evaluated, in addition to the combination of disconnecting some of the rooftops and the use of grass swales. Finally, all of the controls together were also examined.

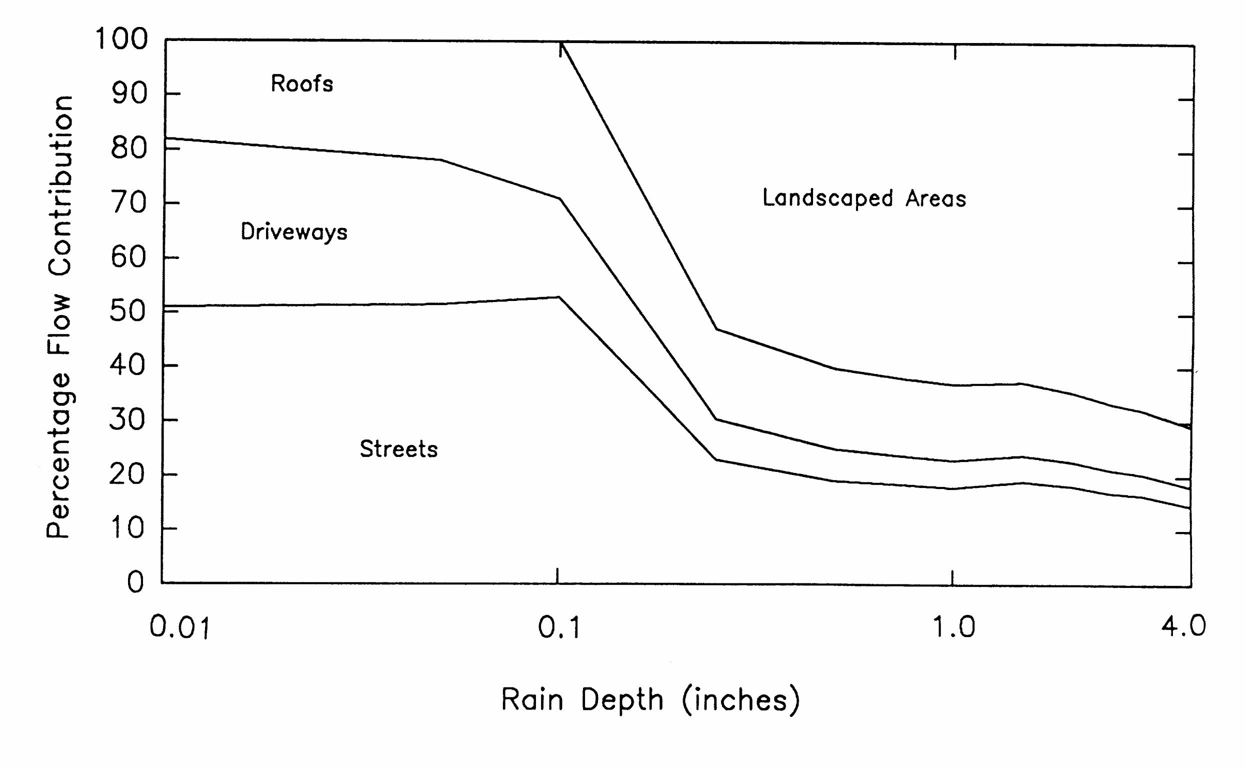


Figure 13. Flow sources for example medium density residential area having clayey soils (Pitt and Voorhees 1995).

The following list shows a general description of this hypothetical area:

- all curb and gutter drainage (in fair condition)
- 70% of roofs drain to landscaped areas
- 50% of driveways drain to lawns
- 90% of streets are intermediate texture (remaining are rough)
- no street cleaning
- no catchbasins

About one-half of the driveways currently drain to landscaped areas, while the other half drain directly to the pavement or the drainage system. Almost all of the streets are of intermediate texture, and about 10 percent are rough textured. As noted earlier, there currently is no street cleaning or catchbasin cleaning.

The level of catchbasin use that was investigated for this site included 950 ft^3 of total sump volume per 100 acres (typical for this land use), with a cost of about $50 per catchbasin cleaning. Typically, catch basins in this area could be cleaned about twice a year for a total annual cost of about $85 per acre of the watershed.

Street cleaning could also be used with a monthly cleaning effort for about $30 per year per watershed acre. Light parking and no parking restrictions during cleaning is assumed, and the cleaning cost is estimated to be $80 per curb mile.

Grass swale drainage was also investigated, assuming that swales could be used throughout the area, there could be 350 feet of swales per acre (typical for this land use), and the swales were 3.5 ft. wide. Because of the clayey soil conditions, an average infiltration rate of about 0.5 inch per hour was used in this analysis, based on many different double ring infiltrometer tests of typical soil conditions. Swales cost much less than conventional curb and gutter systems, but have an increased maintenance frequency. Again, the use of grass swales is appropriate for new development, but not for retrofitting in this area.

Roof disconnections could also be utilized as a control measure by directing all roof drains to landscaped areas. The objective would be to direct all the roof drains to landscaped areas. Since 70 percent of the roofs already drain to the landscaped areas, only 30 percent could be further disconnected, at a cost of about $125 per household. The estimated total annual cost would be about $10 per watershed acre.

An outfall wet detention pond suitable for 100 acres of this medium density residential area would have a wet pond surface of 0.5% of drainage area to provide about 90% suspended solids control. It would need 3 ft. of dead storage and live storage equal to runoff from 1.25" rain. A 90° V notch weir and 5 ft. wide emergency spillway could be used. No seepage or evaporation was assumed. The total annual cost was estimated to be about $ 130 per watershed acre.

Table 3 summarizes the SLAMM results for runoff volume, suspended solids, filterable phosphate, and total lead for 100 acres of this medium density residential area. The only control practices evaluated that would reduce runoff volume are the grass swales and roof disconnections. All of the other control practices evaluated do not infiltrate stormwater. Table 3 also shows the total annual average volumetric runoff coefficient (Rv) for these different options. The base level of control has an annual flow-weighted Rv of about 0.3, while the use of swales would reduce the Rv to about 0.1. Only a small reduction of Rv (less than 10 percent) would be associated with complete roof disconnections compared to the existing situation because of the large amount of roof disconnections that already occur. The suspended solids analyses shows that catchbasin cleaning alone could result in about 14 percent suspended solids reductions. Street cleaning would have very little benefit, while the use of grass swales would reduce the suspended solids discharges by about 60 percent. Grass swales would have minimal effect on the reduction of suspended solids concentrations at the outfall (they are primarily an infiltration device, having very little filtering benefits). Wet detention ponds would remove about 90 percent

Table 3. SLAMM Predicted Runoff and Pollutant Discharge Conditions for Example[1] (Pitt and Voorhees 1995)

Birmingham 1976 rains: (112 rains, 55 in. total 0.01-3.84 in. each)	Runoff Volume			Suspended Solids		Filterable Phosphate		Total Lead	
	annual ft3/acre	flow-wtg. Rv	CN range	flow-wtg. mg/L	annual lbs/acre	flow-wtg. µg/L	annual lbs/acre	flow-wtg. µg/L	annual lbs/acre
Base (no controls)	59800	0.3	77-100	385	1430	157	0.58	543	2.0
Catchbasin cleaning	59800	0.3	77-100	331	1230	157	0.58	468	1.7
reduction (lbs or ft3)	0				200		0		0.29
reduction (%)	0			14	14	0	0	14	14
cost ($/lb or $/ft3)	N/A				0.43		N/A		293
($85/acre/yr)									
Street cleaning	59800	0.3	77-100	385	1430	157	0.58	543	2.0
reduction (lbs or ft3)	0				0		0		0.01
reduction (%)	0			0	0	0	0	0	0.49
cost ($/lb or $/ft3)	N/A				N/A		N/A		3000
($30/acre/yr)									
Grass swales	23300	0.12	63-100	380	554	151	0.22	513	0.75
reduction (lbs or ft3)	36500				876		0.36		1.28
reduction (%)	61			1	61	4	62	6	63
cost ($/lb or $/ft3)	minimal				minimal		minimal		minimal
($minimal/acre/yr)									
Roof disconnections	56000	0.28	76-100	410	1430	156	0.55	443	1.6
reduction (lbs or ft3)	3800				0		0.03		0.48
reduction (%)	6			-6	0	1	5	18	24
cost ($/lb or $/ft3)	0				N/A		333		21
($10/acre/yr)									
Wet detention pond	59800	0.3	77-100	49	185	157	0.58	69	0.26
reduction (lbs or ft3)	0				1250		0		1.8
reduction (%)	0			87	87	0	0	87	87
cost ($/lb or $/ft3)	N/A				0.10		N/A		73
($130/acre/yr)									
CB & street cleaning	59800	0.3	77-100	331	1230	157	0.58	468	1.7
reduction (lbs or ft3)	0				200		0		0.29
reduction (%)	0			14	14	0	0	14	14
cost ($/lb or $/ft3)	N/A				0.58		N/A		397
($115/acre/yr)									
Roof dis. & swales	20900	0.1	63-100	403	526	139	0.18	352	0.46
reduction (lbs or ft3)	38900				904		0.40		1.6
reduction (%)	65			-5	63	11	69	35	77
cost ($/lb or $/ft3)	0.00026				0.01		25		6.4
($10/acre/yr)									
All above controls	20900	0.1	63-100	42	55	139	0.18	36	0.05
reduction (lbs or ft3)	38900				1375		0.40		1.98
reduction (%)	65			89	96	11	69	93	97
cost ($/lb or $/ft3)	0.0066				0.19		638		129
($255/acre/yr)									

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[1] Medium density residential area, developed in 1961-1980, with clayey soils (curbs & gutters); new development controls (not retro-fit)

of the mass and concentrations of suspended solids. Similar observations can be made for filterable phosphates and lead.

Figures 14 through 17 show the maximum percentage reductions in runoff volume and pollutants, along with associated unit removal costs. As an example, Figure 14 shows that roof disconnections would have a very small potential maximum benefit for runoff volume reduction and at a very high unit cost compared to the other practices. The use of grass swales could have about a 60 percent reduction at minimal cost. The use of roof disconnection plus swales would slightly increase the maximum benefit to about 65 percent, at a small unit cost. Obviously, the use of roof disconnections alone, or all controlled practices combined, are very inefficient for this example. For suspended solids control, catchbasin cleaning and street cleaning would have minimal benefit at high cost, while the use of grass swales would produce a substantial benefit at very small cost. However, if additional control is necessary, the use of wet detention ponds may be necessary at a higher cost. If close to 95 percent reduction of suspended solids were required, then all of the controls investigated could be used together, but at substantial cost.

Future Directions for SLAMM

Recent EPA-funded research has developed a framework for future modifications to the SLAMM model. Emerging control technologies (especially for critical source area controls in ultra urban areas) have included: inlets and inlet inserts (Pitt and Field 1998), stormwater filtration (Clark and Pitt 1999), and treatment trains (Pitt, *et al.* 1999a). The information obtained during these projects is being used to modify SLAMM to include these control technologies. In addition, EPA-funded research on infiltration in disturbed urban soils and demonstrations of infiltration benefits through soil amendments (Pitt, *et al.* 1999b) is being used to further advance the urban hydrology aspects of the model. Finally, a modification of SLAMM has been made to enable its integration with SWMM to more accurately consider the benefits of source area controls for stormwater quality objectives on drainage objectives (Pitt, *et al*. 1999c).

This recently completed project will basically substitute the RUNOFF Block in SWMM with SLAMM in order to better account for small storm processes and for its greater flexibility in evaluating source area flow and pollutant controls. The SWMM EXTRAN and TRANSPORT

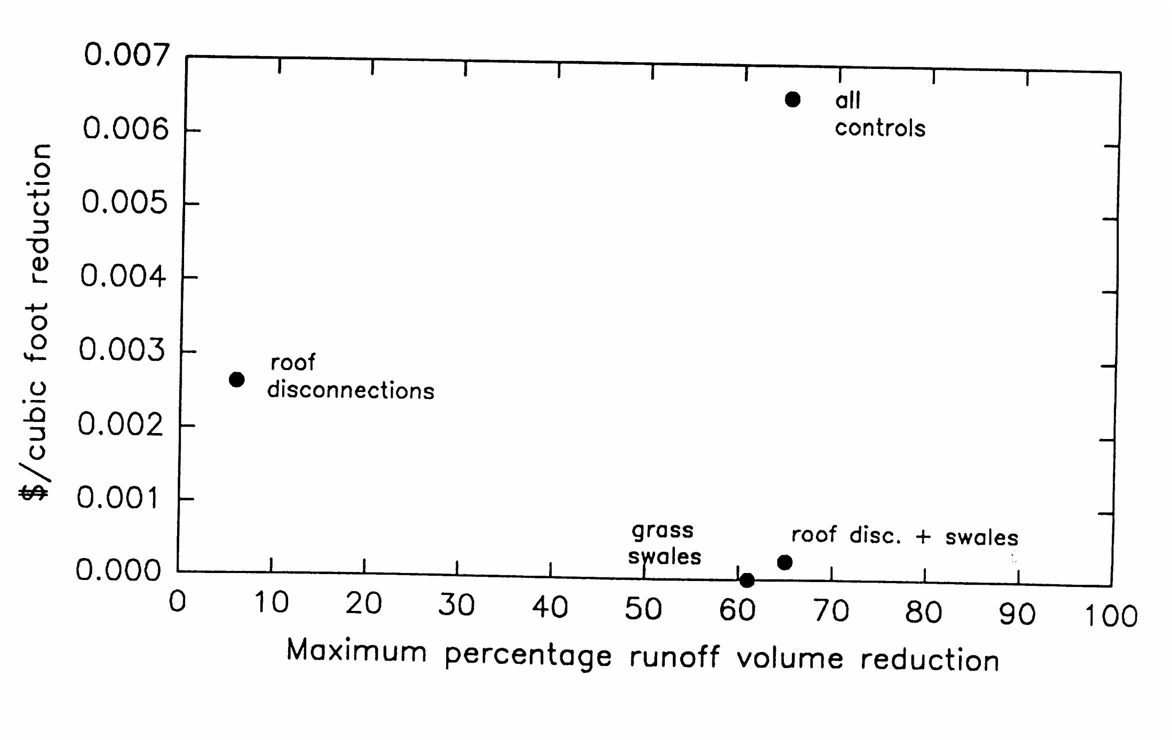

Figure 14. Cost-effectiveness data for runoff volume reduction benefits (Pitt and Voorhees 1995).

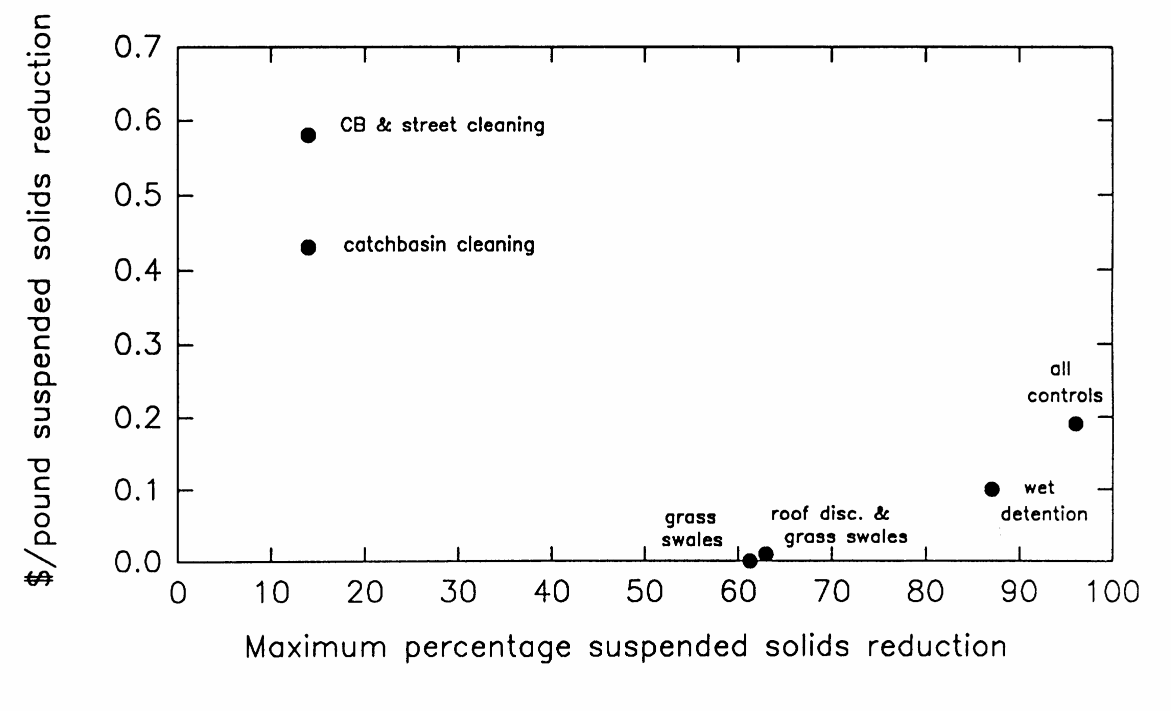

Figure 15. Cost-effectiveness data for suspended solids reduction benefits (Pitt and Voorhees 1995).

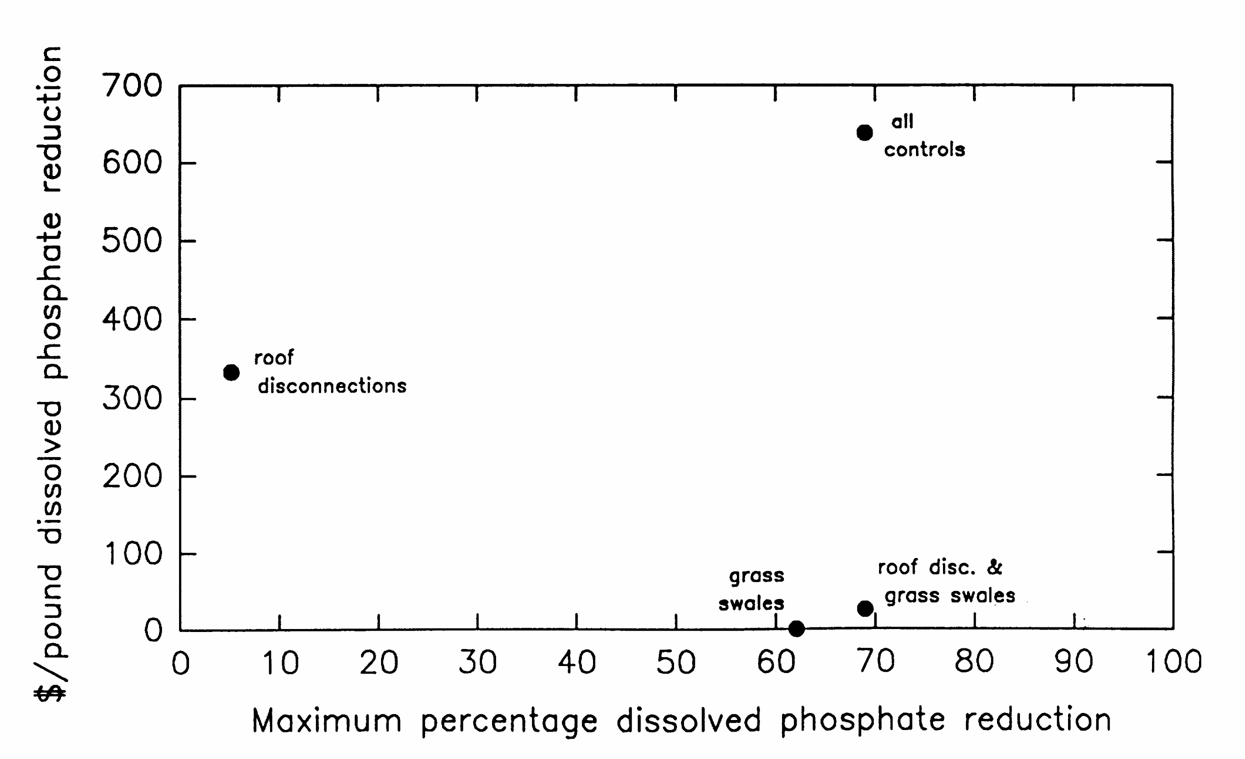

Figure 16. Cost-effectiveness data for dissolved phosphate reduction benefits (Pitt and Voorhees 1995).

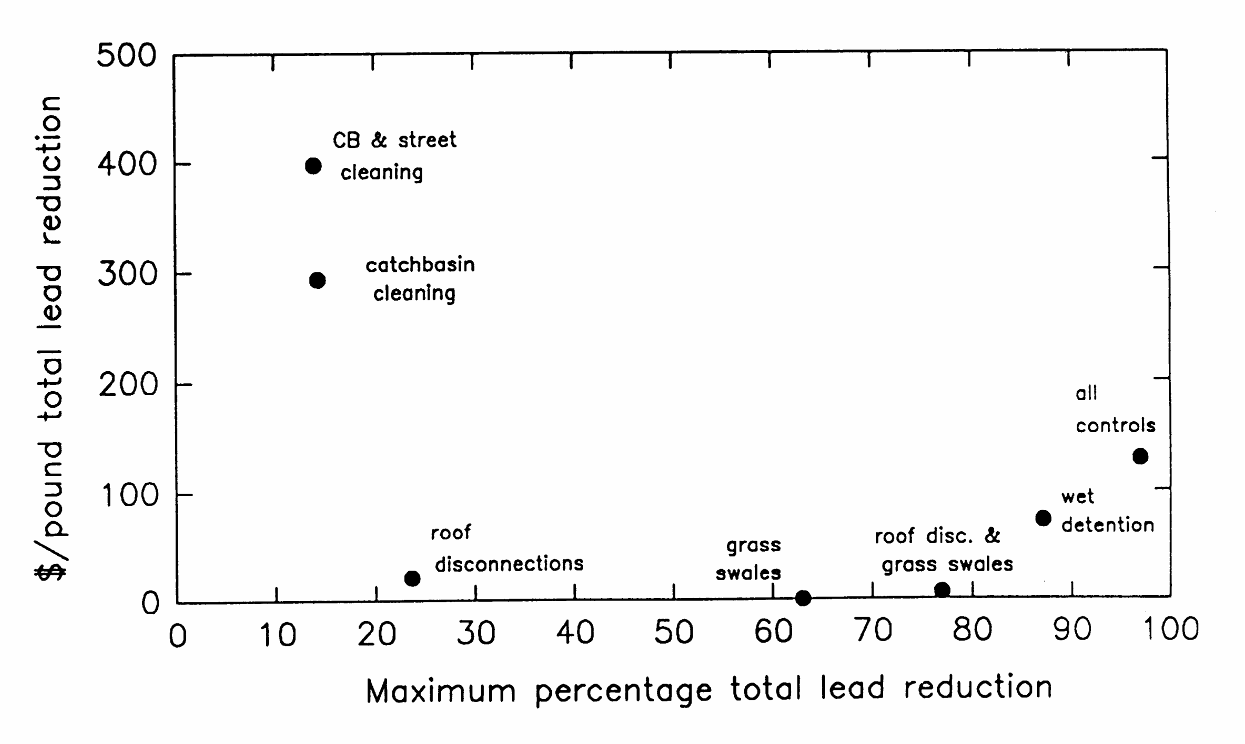

Figure 17. Cost-effectiveness data for total lead reduction benefits (Pitt and Voorhees 1995).

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. Overall, Pitt, *et al*. (1999c) developed an improved methodology to design wet weather flow drainage systems that considers both water quality and drainage benefits. A review of past, present, and emerging control technologies was conducted to present suitable combinations of practices that may be most suitable for many different conditions.

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