Chapter 2

Unique Features of the Source Loading and Management Model (SLAMM)

Robert Pitt

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 can be an important component, along with local receiving water studies, of an effective watershed management program.

SLAMM was initially developed to evaluate stormwater control practices more efficiently. 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). Basic types of control practices evaluated by SLAMM include detention ponds, percolation ponds, infiltration devices, porous pavements, grass swales, catchbasin cleaning, and street cleaning, plus different development alternatives. Most of these controls can be evaluated in many combinations and

---

Pitt, R.E. 1998. "Unique Features of the Source Loading and Management Model (SLAMM)." *Journal of Water Management Modeling* R200-02. doi: 10.14796/JWMM.R200-02.

ISSN: 2292-6062 (Formerly in Advances in Modeling the Management of Stormwater Impacts. ISBN: 0-9697422-8-2)

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. An early version of SLAMM was described by Pitt and Shawley (1982) as part of the Nationwide Urban Runoff Program study conducted in Castro Valley, CA. A detailed description of SLAMM, including examples of its use, was presented by Pitt and Voorhees (1995).

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). Much of the 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 (WI DNR) (Pitt 1986), and the U.S. Environmental Protection Agency (EPA) (Pitt and Voorhees 1995).

SLAMM has been commonly used as a planning level model for large watershed projects. As an example, SLAMM has been extensively used by the Wisconsin Nonpoint Source Program in its evaluation of urban areas, as described by Pitt (1986). The WI DNR uses SLAMM to identify sources of pollutants, quantify their discharges, and to evaluate alternative control practices. Its use in Wisconsin in conjunction with geographical information systems (GIS) has also been described by several authors (Thum, *et al.* 1990; Ventura and Kim 1993; Kim and Ventura 1993; Kim, *et al.* 1993; and Haubner and Joeres 1996). Another early use of SLAMM on a watershed scale was during the Toronto Area Watershed Management Strategy program (TAWMS). In this project, SLAMM was used to predict drainage area pollutant and flow discharges, SWMM was used to predict combined sewer overflow (CSO) discharges from the older sections of the city, and HSPF was used to evaluate receiving water conditions resulting from these discharges (TAWMS 1986).

SLAMM is used 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. SLAMM is strongly based on field observations, with minimal reliance on theoretical processes that have not been adequately documented or confirmed in the field. 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 on 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.

2.1 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 hydrologic cycle.
>
> Black box-- Model uses an appropriate mathematical function or functions which is fitted to he 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 others). 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) discussed 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 that runoff 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 2.1 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 areas and characteristics of the contributing areas in the watershed, and 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

Table 2.1 Major process descriptions in SLAMM (attributes total 10 for each process)

Process or Input Parameters	Deterministic	Stochastic	Conceptual	Theoretical	Statistical	Continuous	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	

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 during wet weather. 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 onset of rainfall. 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.

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.

2.2 Unique Attributes of SLAMM

The following paragraphs discuss two important aspects included in SLAMM that are incorrectly considered in most currently used stormwater models:

1. runoff predictions associated with small and moderate sized events associated with the majority of receiving water problems, and
2. washoff of particulate pollutants from urban surfaces.

2.2.1 Small Storm Hydrology

One of the major problems with conventional stormwater models concerns runoff volume estimates associated with small and moderate-sized storms. Figures 2.1 and 2.2 show the importance of common small storms when considering total annual pollutant discharges. Figure 2.1 shows the accumulative rain count and the associated cumulative runoff volume for a medium density residential area in Milwaukee, Wisconsin, based on 1983 observations (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 2.1. 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 2.2 shows the cumulative 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 2.1 (Bannerman, *et al.* 1983). When Figure 2.2 is compared to Figure 2.1, 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 in stormwater concentrations for different size events. Substantial variations in pollutant concentrations were 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 very important when studying pollutant discharges. By better understanding the significance and runoff generation potential of these small rains, runoff problems can be better understood.

Figure 2.3 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 are used for 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 the relative importance of each source area to be estimated. The relative pollutant discharges from each area can then be calculated from the runoff pollutant strengths associated with each area.

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

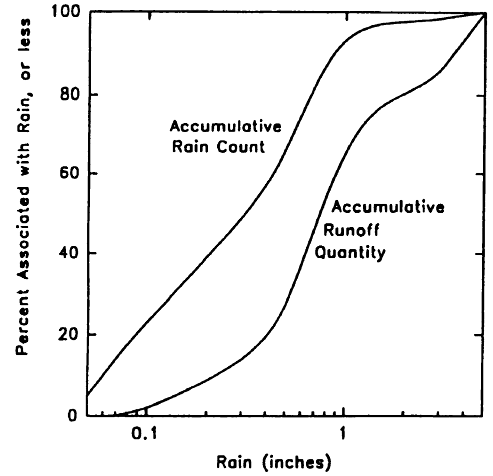

Figure 2.1 Milwaukee rain and runoff distributions (medium-density residential area) (Pitt and Voorhees, 1995).

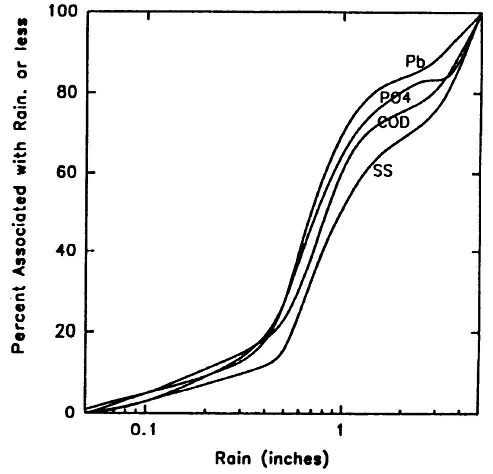

Figure 2.2 Milwaukee pollutant discharge distributions (medium-density residential area) (Pitt and Voorhees, 1995).

runoff rate decreases according to a recession curve for that surface. The example shown in Figure 2.3 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

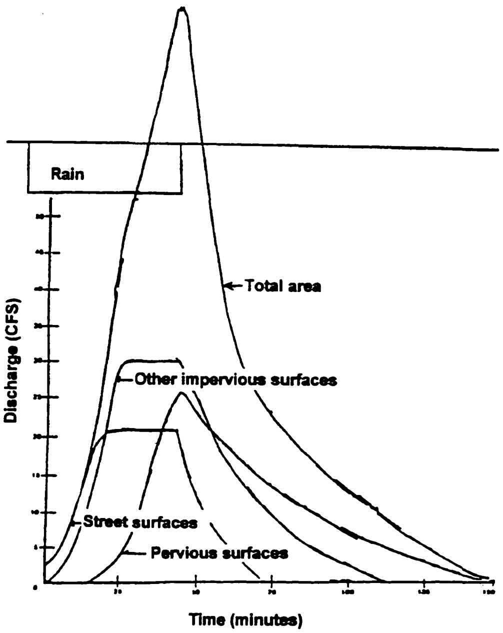

Figure 2.3 Variable contributing areas in urban watersheds (Pitt and Voorhees, 1995).

street surfaces and other impervious surfaces will be the same until the end of the rain, when their recession curves would begin. However, the pervious surface contribution would increase substantially because its time of concentration may be exceeded by the longer rain duration. 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. In this last case, the street surfaces are the dominant source of runoff water. 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 2.4 shows observed rainfall-runoff 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. (8 mm), almost one-half of the rain falling on this pavement did not contribute to runoff. During smaller storms, most of the rainfall did not contribute to runoff. These rainfall losses for pavement are similar for most city streets and are substantially greater than is 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 and they 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.

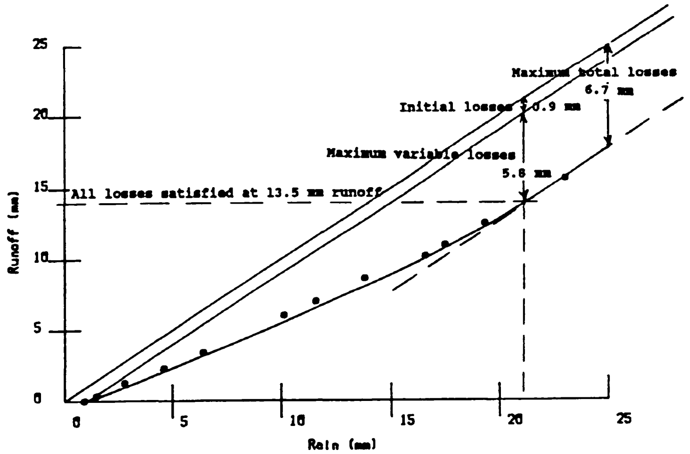

Figure 2.4 Rainfall-runoff plot (example for high-intensity rains, clean and rough streets) (Pitt, 1987).

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 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 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, 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.

Figure 2.5 shows the 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 calculated CN values vary dramatically for the different rain depths that occurred at this site. The calculated 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 calculated 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 contribute much more runoff than would typically be estimated 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.

SLAMM makes runoff predictions using the small storm hydrology methods developed by Pitt (1987). Figure 2.6 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 observed runoff. Figure 2.7 shows

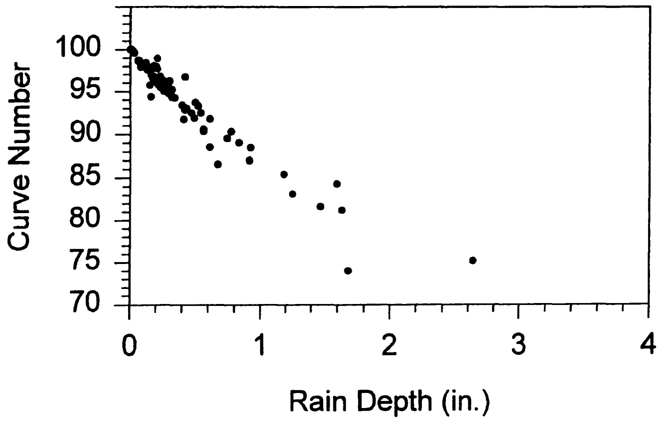

Figure 2.5 Curve number variations for different rain depths (medium density area with clayey soils) (Pitt and Voorhees, 1995).

a similar plot of the computed versus observed runoff for a Milwaukee medium density residential area. These two sites were substantially different from one another in the amount of impervious surfaces and in their connection 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).

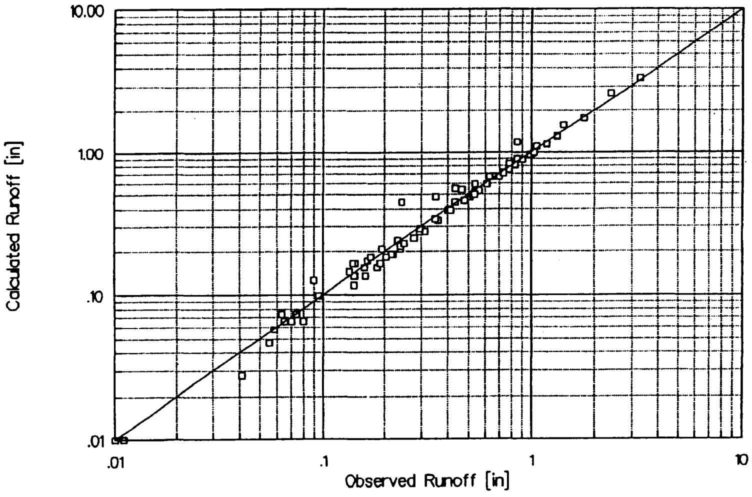

Figure 2.6 Commercial shopping center runoff verification (Pitt, 1987)

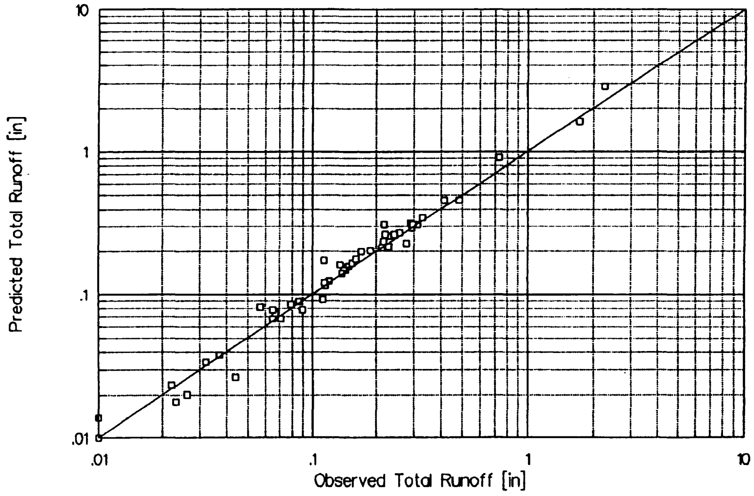

Figure 2.7 Medium-density residential area runoff verification (Pitt, 1987).

2.2.2 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. Figure 2.8 is a plot of the suspended solids concentrations for different rain depths for sheetflow runoff from paved surfaces during controlled tests in Toronto (Pitt 1987). This figure shows local "first-flush" effects, with a decreasing trend of suspended solids concentration with increasing rain depth. During the smallest rains, these concentrations are shown to be several hundred mg/L, and as high as 4000 mg/L. The suspended solids concentrations during the largest events (about 1 inch, or 25 mm, in depth) decreased rapidly to about 10 mg/L. These data were obtained during rainfall-runoff and particulate washoff tests using carefully controlled and constant rain intensities. A first flush of pollutants, as seen in this figure, is likely only to occur for relatively small homogeneous surfaces subjected to relatively constant rain intensities. First flushes at storm drain outfalls may not be commonly observed because of the routing of many different individual first flush flows that become mixed. Because the highest concentrations associated with these individual flows reach the outfall at different time periods, these individual first flushes are mixed and lost. More significantly, later times during a rain may have periods of very high peak rain intensities, resulting in high suspended solids concentrations later in a storm. These periods of high rain intensities therefore can cause localized periods of high runoff pollutant concentrations that may occur long after the beginning of the rain. Therefore, first-flush situations are most likely to occur for small, homogeneous drainage areas (such as for large paved areas or roofs) during relatively constant rain intensities.

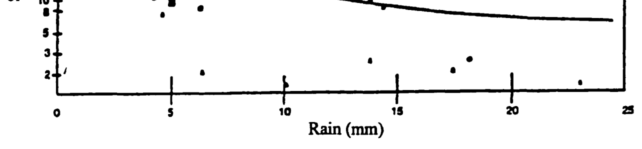

Figure 2.8 Pavement "first-flush" suspended solids concentrations (Pitt, 1987).

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 real 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). Figures 2.9 through 2.11 show washoff plots for total solids, suspended solids (>0.45 μm), and dissolved solids (<0.45 μm) during a controlled street surface washoff test (Pitt 1987). These plots indicate the cumulative (g/m^2) washoff as a function of rain depth. Also shown on these figures are the total street dirt loadings. For example, Figure 2.9 shows that 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% of the particulates that would wash off (about 3 g/m^2) did, similar to the rain depth needed for "complete" washoff as reported in 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 2.10 is similar to Figure 2.9, but 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 2.11 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 computed washoff of suspended solids could be in error by 700% if the total loading on the street was assumed to be removable by rains. SLAMM uses observations by 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 compute the amount of washoff.

Another common problem with stormwater models is the use of incorrect particulate accumulation rates for different surfaces. Figure 2.12 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

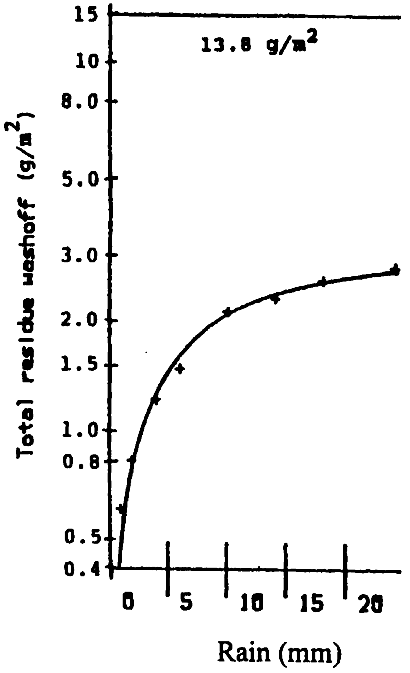

Figure 2.9 Total solids washoff test results (Pitt, 1987).

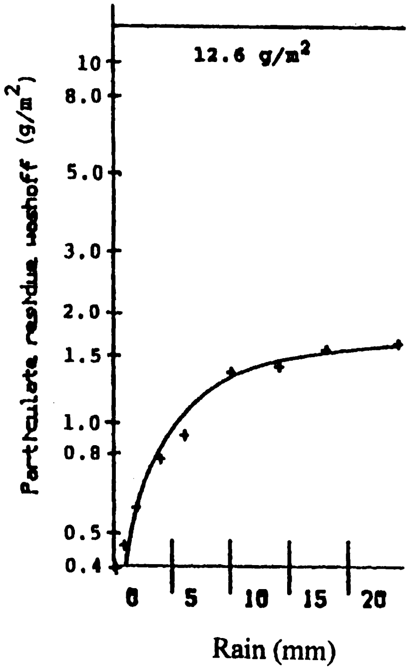

Figure 2.10 Dissolved solids washoff test results (Pitt, 1987).

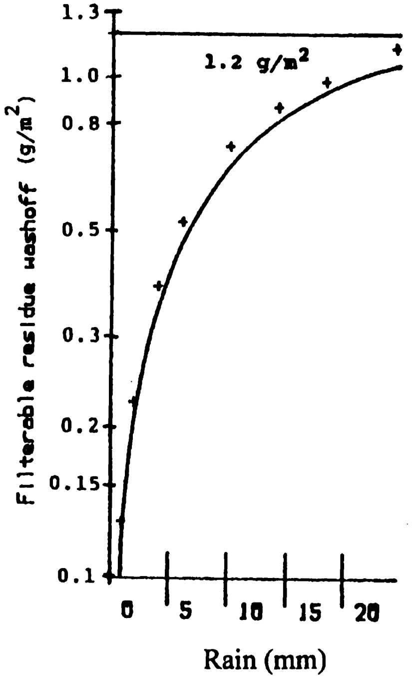

Figure 2.11 Suspended solids washoff test results (Pitt, 1987).

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 loadings after rains were close to zero, instead of the real and substantial initial loadings. The accumulation rates were calculated by using the slope between each individual loading 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.

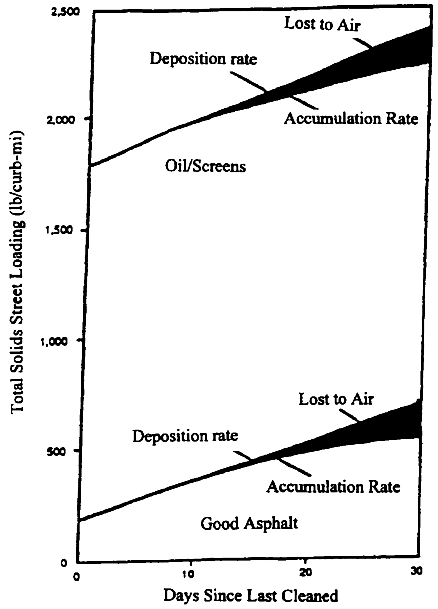

Figure 2.12 Deposition and accumulation rates of street dirt (Pitt, 1979).

The street dirt deposition rates were found to be only 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 2.12 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 from 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.

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

The most important information needed by SLAMM 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 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. 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. The control options available for each source area are illustrated in Table 2.2. These facilities can be used singly or in combination, at source areas or at the outfalls or, in the case of grass swales and catchbasins, within the drainage system. In addition, SLAMM provides a great deal of flexibility in describing the sizes and other design aspects of these different practices. Newly developing source area and outfall controls (such as different filtration media) are currently being added to SLAMM, based on recent EPA research.

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 from under different rain conditions. Figures 2.13 through 2.15 are examples for a typical medium density residential area showing the percentage of different pollutants originating from different major sources, as a function of rain depth. For example, Figure 2.13 shows the areas where water is originating. For storms of up to about 0.1 inch (2.5 mm) in depth, street surfaces contribute about one-half to the total runoff to the outfall. This contribution decreased to about 20% for storms greater than about 0.25 inch (6 mm) 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 which has clayey soils). Similarly, the significance of runoff from driveways and roofs also starts off relatively high and then decreases with increasing storm depth. Figure 2.14 is a similar plot for suspended solids. This shows that streets

Table 2.2 Source area, drainage system, and outfall control options available in SLAMM (1).

	Infiltr-ation device	Wet detention pond	Grass drainage swale	Street cleaning	Catch - basin cleaning	Porous pave-ment
Roof	X	X				
Paved parking/ storage	X	X				X
Unpaved parking/ storage	X	X				
Playgrounds	X	X				X
Driveways						X
Sidewalks/ walks						X
Streets/alleys				X		
Undeveloped areas	X	X				
Small landscaped areas	X					
Other pervious areas	X	X				
Other impervious areas	X	X				X
Freeway lanes/ shoulders	X	X				
Large turf areas	X	X				
Large landscaped areas	X	X				
Drainage system			X		X	
Outfall	X	X				

(1) Development characteristics affecting runoff, such as roof and pavement draining to grass instead of being directly connected to the drainage system, are included in the individual source area descriptions.

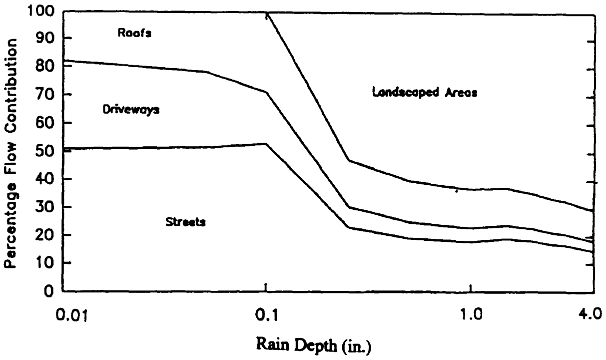

Figure 2.13 Flow sources for example medium-density residential area having clayey soils (Pitt and Voorhees, 1995).

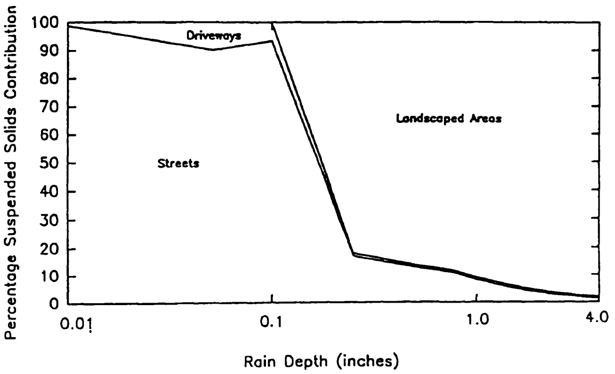

Figure 2.14 Suspended solids sources for example medium-density residential area having clayey soils (Pitt and Voorhees, 1995).

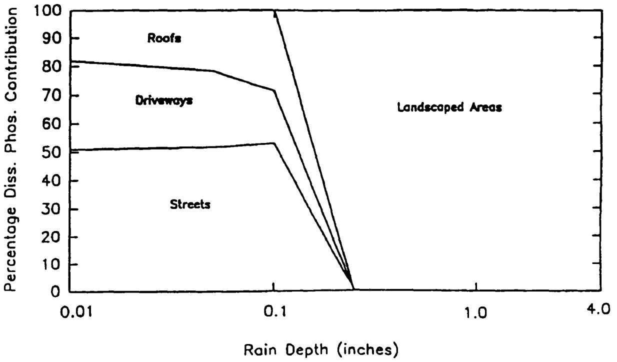

Figure 2.15 Dissolved phosphate sources for example medium-density residential area having clayey soils (Pitt and Voorhees, 1995).

contribute almost all of the suspended solids for the smallest storms, up to about 0.1 inch (2.5 mm). The contributions from landscaped areas then become dominant. Figure 2.15 shows that the contributions of phosphates are more evenly distributed between streets, driveways, and rooftops for the small storms, but the contributions from landscaped areas completely dominate for storms greater than about 0.25 inch (6 mm) in depth.

Obviously, the specific contributions from different areas and for different pollutants vary dramatically, depending upon the characteristics of development for the area and the source controls used. Again, a major use of SLAMM is to better understand the role of different sources of pollutants. For 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 (6 mm) 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 a medium density residential area having clayey soils:

- base level (as built in 1961-1980 with no additional controls)
- catchbasin cleaning
- street cleaning
- grass swales
- roof disconnections
- wet detention pond
- catchbasin and street cleaning combined
- roof disconnections and grass swales combined, and
- all of the controls combined.

This residential area, which was based upon field observations for homes built between 1961 to 1980, in Birmingham, Alabama, has no controls, 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.

The following list shows a general description of this 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

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. *(In this chapter $=US$)*

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 ($50/km).

Grass swale drainage was also investigated. Assuming that swales could be used throughout the area, there would be about 45 m per ha (350 feet per acre) of swales (typical for this land use), and the swales would be 1.1 m (3.5 ft.) wide. Because of the clayey soil conditions, an average infiltration rate of about 12 mm (0.5 inch) per hour was assumed. Infiltration tests in disturbed urban soils indicate that compaction and texture have the greatest influence on infiltration rate, with less influence from time or rain. The observed rates are mostly random for a single site, with average rates being suitable for most situations. 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. Since 70% of the roofs already drain to the landscaped areas, only 30% 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 (40 ha) of this medium density residential area would have a wet pond surface of 0.5% of drainage area for approximately 90% suspended solids control. It would need 3 ft. (0.9 m) of dead storage and live storage equal to runoff from 1.25 in.(32 mm) rain. A 90° V notch weir and 5 ft. (1.5 m) 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.

As indicated in the following summary graphs, the only control practices evaluated that would reduce runoff volume (Rv) are the grass swales and roof disconnections. All other control practices evaluated do not infiltrate stormwater. The base level for this development 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%) would be associated with complete roof disconnections compared to the existing situation because of the large amount of roof disconnections that already exist. The suspended solids analyses shows that catchbasin cleaning alone could result in about 14% 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%, mostly from infiltration of water. Wet detention ponds would remove about 90% of the mass and concentrations of suspended solids. Similar observations can be made for filterable phosphates and lead.

Figures 2.16 and 2.17 show the maximum percentage reductions in runoff volume and suspended solids, along with associated unit removal costs. For example, Figure 2.16 shows that roof disconnections would have a very small potential maximum benefit for runoff volume reduction and a very high unit cost compared to the other practices. The use of grass swales could have about a 60% reduction at minimal cost. The use of roof disconnection plus swales would slightly increase the maximum benefit to about 65%, at a small unit cost. Obviously, the use of roof disconnections alone, or all controlled practices combined, is very inefficient for this example. For suspended solids control,

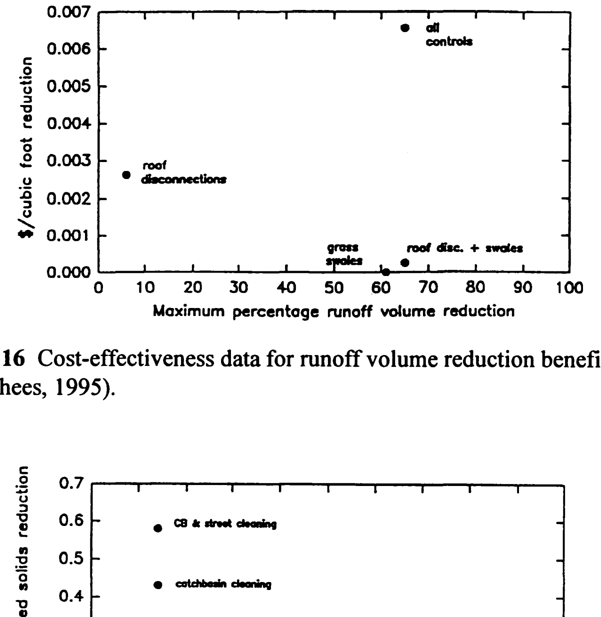

Figure 2.16 Cost-effectiveness data for runoff volume reduction benefits (Pitt and Voorhees, 1995).

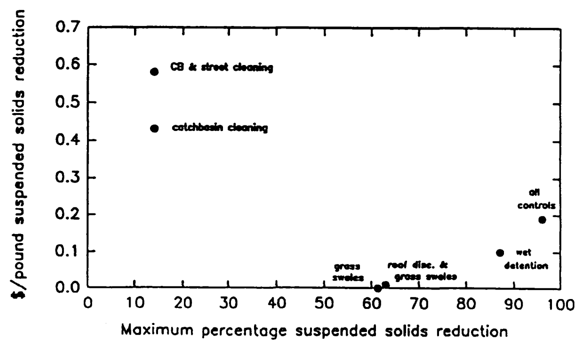

Figure 2.17 Cost-effectiveness data for suspended solids reduction benefits (Pitt and Voorhees, 1995).

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% reduction of suspended solids were required, then all of the controls investigated could be used together, but at substantial cost.

2.3 Current Work

We are currently making numerous enhancements to SLAMM, in conjunction with the Wisconsin DNR and the EPA, and with private funding. Most significantly, we are just completing a complete re-writing of SLAMM using Visual Basic, making the program a Windows application. This will enable important changes to be made with less restrictions from computer resources, greatly enhance error trapping and ease of use, and enable much more powerful interfacing with other programs. We are also adding results from recent stormwater management research to consider new critical source area practices (different filter media, different inlet options, additional infiltration device options, and greater flexibility in combining controls).

We are also integrating the use of SLAMM with geographic information systems (GIS) for watershed evaluations of stormwater pollutant impacts, sources, and control. The Alabama Department of Environmental Management (ADEM) contracted with the Department of Civil and Environmental Engineering to model stormwater nutrient sources and control in the Cahaba River watershed (about 700 km^2 in area). Stormwater was collected from six major land uses over four seasons and analyzed for nitrogen and phosphorus compounds. A WI Dept. of Natural Resources project funded modifications to SLAMM to enable batch operations. The batch generated SLAMM output will be formatted to enable easy integration with a GIS by the ADEM funded project. This will result in a generic GIS interface for easier customization by other users, according to their specific data availability and project objectives. SLAMM is currently freely available from the WI DNR WWW page (http://www.dnr.state.wi.us/eq/wq/nps/slamm.htm) and is also available on the CD ROM for PCSWMM.

References

Bannerman, R., K. Baun, M. Bohn, P.E. Hughes, and D.A. Graczyk. *Evaluation of Urban Nonpoint Source Pollution Management in Milwaukee County, Wisconsin*, Vol. I. Grant No. P005432-01-5, PB 84-114164. US Environmental Protection Agency, Water Planning Division, November 1983.

EPA (U.S. Environmental Protection Agency). *Final Report for the Nationwide Urban Runoff Program*. Water Planning Division, Washington, D.C., December 1983.

Haubner, S.M. and E.F. Joeres. "Using a GIS for estimating input parameters in urban stormwater quality modeling." *Water Resources Bulletin*. Vol. 32, no. 6, pp. 1341 - 1351. Dec. 1996.

Kim, K., and S.J. Ventura. "Large-scale modeling of urban nonpoint source pollution using a geographical information system." *Photogrammetric Engineering & Remote Sensing*. Vol. 59, no. 10, pp. 1539 - 1544. Oct. 1993.

Kim, K., S.J. Ventura, and P.M. Harris. "Urban son-point source pollution assessment using a geographical information system." *Journal of Environmental Management*. Vol. 39. Pp. 157 - 170. 1993.

Linsley, R.K. "Rainfall-runoff models - An overview." In: *Rainfall-Runoff Relationships*. Edited by V.P. Singh. Water Resources Publications. 1982.

McCuen, R.H. *Hydrologic Analysis and Design*. Prentice Hall. Englewood Cliffs, New Jersey. 1989.

Pitt, R. *Demonstration of Nonpoint Pollution Abatement Through Improved Street Cleaning Practices*. EPA-600/2-79-161, U.S. Environmental Protection Agency, Cincinnati, Ohio, August 1979.

Pitt, R. Characterization, *Sources, and Control of Urban Runoff by Street and Sewerage Cleaning*. Contract No. R-80597012, U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, Ohio, 1984.

Pitt, R. "Runoff Controls in Wisconsin's Priority Watersheds", *Conference on Urban Runoff Quality - Impact and Quality Enhancement Technology*, Henniker, New Hampshire, Edited by B. Urbonas and L.A. Roesner, Proceedings published by the American Society of Civil Engineering, New York, June 1986.

Pitt, R. Small Storm Flow and Particulate Washoff Contributions to Outfall Discharges. Ph.D. dissertation, Department of Civil and Environmental Engineering, the University of Wisconsin - Madison, November 1987.

Pitt, R. and G. Shawley. *A Demonstration of Non-Point Source Pollution Management on Castro Valley Creek*. Alameda County Flood Control and Water Conservation District (Hayward, CA) for the Nationwide Urban Runoff Program, U.S. Environmental Protection Agency, Water Planning Division, Washington, D.C., June 1982.

Pitt, R. and M. Bozeman. *Sources of Urban Runoff Pollution and Its Effects on an Urban Creek*. EPA-600/S2-82-090, U.S. Environmental Protection Agency, Cincinnati, Ohio, December 1982.

Pitt, R. and P. Bissonnette. *Bellevue Urban Runoff Program, Summary Report*. Storm and Surface Water Utility, Bellevue, Washington, November 1984.

Pitt, R. and J. McLean. Toronto Area Watershed Management Strategy Study - Humber River Pilot Watershed Project". Ontario Ministry of the Environment, Toronto, Ontario, June 1986.

Pitt, R., and J. Voorhees. "Source loading and management model (SLAMM)." *National Conference on Urban Runoff Management: Enhancing Urban Watershed Management at the Local, County, and State Levels*. EPA/625/R-95/003. Center for Environmental Research Information, U.S. Environmental Protection Agency. Cincinnati, Ohio. pp. 225 - 243. April 1995.

Sartor, J.D. and G.B. Boyd. *Water Pollution Aspects of Street Surface Contaminants*. EPA-R2-72-081, U.S. Environmental Protection Agency, November 1972.

SCS (U.S. Soil Conservation Service, now Natural Resources Conservation Service). *Urban Hydrology for Small Watersheds*. U.S. Dept. of Agriculture Tech. Release No. 55 (revised), June 1986.

Sutherland, R. *Portland Stormwater Quality using SIMPTM*. Draft report. OTAK, Inc. Lake Oswego, OR. 1993.

TAWMS (Toronto Area Watershed Management Strategy). *Humber River Water Quality Management Plan*. Ontario Ministry of the Environment. Toronto, Ontario. 186 pgs. 1986.

Thum, P.G., S.R. Pickett, B.J. Niemann, Jr., and S.J. Ventura. "LIS/GIS: Integrating nonpoint pollution assessment with land development planning." *Wisconsin Land Information Newsletter*. Vol. 5, no. 2, pp. 1 - 12. 1990.

Troutman, B.M. "Errors and parameter estimation in precipitation-runoff modeling: 2-case study.: *Water Resources Research*, Vol. 21, no. 8, pp. 1195 - 1213. August 1985.

Ventura, S.J. and K. Kim. "Modeling urban nonpoint source pollution with a geographical information system." *Water Resources Bulletin*. Vol. 29, no. 2, pp. 189 - 198. April 1993.