Module 9
The Integration of Urban Water Systems Modeling and Analysis

Introduction

The use of computers has become common in many aspects of engineering practice, including wet weather management. In fact, no reasonable methodology can be conducted without the analytical and modeling capabilities of a computer. Unfortunately, no currently available software package adequately integrates wet weather quantity and quality objectives. The integration of two currently used computer models – the EPA's Storm Water Management Model (SWMM) (Huber, *et al.* 1988) and the Source Loading and Management Model (SLAMM) (Pitt and Voorhees 1995) will meet this need. These two popular models have unique characteristics that when merged will create the kind of tool needed for effective wet weather management. *The integrated model will form the principal analytical tool used in the design methodology.*

SWMM (The Storm Water Management Model)

The U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) is a large and relatively complex software package capable of simulating the movement of precipitation and pollutants from the ground surface, through pipe/channel networks and storage/treatment facilities, and finally to receiving waters. The model can be used to simulate a single event or a long, continuous period.

SWMM is probably the most popular of all urban runoff models. Unfortunately, it has a reputation for being a difficult model to use. This is not necessarily the case if one knows the fundamentals of how it works and if the parts of the model not needed in a particular application are simply not used. SWMM uses well-known hydrologic and hydraulic concepts to simulate the urban drainage system. Its reputation for sophistication (and difficulty) derives more from the numerical algorithms necessary to solve the rather straightforward governing equations that are trying to simulate a complex system (i.e., the urban stormwater drainage system) driven by a highly dynamic input (i.e., precipitation).

SWMM is divided into several "blocks". The major blocks, i.e., RUNOFF, TRANSPORT, EXTRAN, and STORAGE/REATMENT are computational blocks responsible for the hydrologic, pollutant generation and transport, and hydraulic calculations. Others, *i.e*., EXECUTIVE, STATISTICAL, RAIN, TEMP, GRAPH, and COMBINE, perform various auxiliary functions, and are known as service blocks. The ability of SWMM to route flows and pollutants through a drainage and/or sewer system is its strength. While not very user friendly, it is not overly difficult to manage and use. A few "preprocessing" packages are available to help prepare the input data. The recently developed Windows-based SWMM5 (described earlier in module 8) has a much easier to use interface, but is still lacking the implementation of some historically available processes and options available in earlier SWMM versions.

SLAMM (The Source Loading and Management Model)

SLAMM (see Module 4 for a more complete model description and user guide) was originally developed to better understand the relationships between sources of urban runoff pollutants and runoff quality. It has been continually expanded since the late 1970s and now includes a wide variety of source area and outfall control practices (infiltration practices, wet detention ponds, porous pavement, street cleaning, catchbasin cleaning, and grass swales). SLAMM is strongly based on actual field observations, with minimal reliance on theoretical processes that have not been adequately documented or confirmed in the field. SLAMM is mostly used as a planning tool, to better understand sources of urban runoff pollutants and their control. Special emphasis has been placed on small storm hydrology and particulate washoff in SLAMM. Many currently available urban runoff models have their roots in drainage design where the emphasis is with very large and rare rains. In contrast, many stormwater quality problems are mostly associated with common and relatively small rains. The assumptions and simplifications that are legitimately used with drainage design models are not appropriate for water quality models. SLAMM therefore incorporates unique process descriptions to more accurately predict the sources of runoff pollutants and flows for the storms of most interest in stormwater quality analyses. However, SLAMM can be effectively used in conjunction with hydraulic models (such as SWMM as in this module) to incorporate the mutual benefits of water quality controls and drainage design. SLAMM has been used in many areas of North America and has been shown to accurately predict stormwater flows and pollutant characteristics for a broad range of rains, development characteristics, and control practices.

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

SLAMM was described in more detail in Module 4.

SLAMM/SWMM Interface

In this project, SLAMM is used in place of SWMM's RUNOFF Block to provide the runoff and pollutant loads for input into the TRANSPORT, EXTRAN, or STORAGE/TREATMENT Blocks of SWMM. This approach better accounts for small storm processes and adds greater flexibility in evaluating source area flow and pollutant controls. SWMM has a well-developed Windows-based interface. The output from SLAMM will be manipulated so that it is acceptable for SWMM. The principal manipulation is to convert the event volume and load into event hydrographs and pollutographs. Secondarily, the flows and loads must be assigned to various locations in the sewer system, or storage/treatment system, simulated by SWMM.

SLAMM currently provides the following output, in a one line per event format:

	Event characteristic
1.	Event number
2.	Rain start date
3.	Rain start time
4.	Julian start date and time
5.	Rain duration (hrs)
6.	Rain interevent period (days)
7.	Runoff duration (hrs)
8.	Rain depth (in)
9.	Runoff volume (ft^3)
10.	Volumetric runoff coefficient (R_v)
11.	Average flow (cfs)
12.	Peak flow (cfs)
13.	Suspended solids concentration (mg/L)
14.	Suspended solids mass (pounds)

The interface package developed for SLAMM-SWMM will include the following capabilities:

- Ability to develop alternative hydrograph shapes for SLAMM runoff events.
- Assignment of source area hydrographs and pollutographs to specific locations on a sewer system or storage/treatment system simulated by SWMM.
- Ability to create a long time series of flows and loads from SLAMM (including dry periods) for effective long-term continuous simulation in SWMM.

SWMM, The EPA's Storm Water Management Model

The U.S. Environmental Protection Agency Storm Water Management Model - or SWMM - is a large, relatively complex software package capable of simulating the movement of precipitation and pollutants from the ground surface, through pipe/channel networks and storage/treatment facilities, and finally to receiving waters. The model can be used to simulate a single event or a long, continuous period. Nix (1994) provided a summary of SWMM use and components. James, *et al.* (2002 and 2003) also frequently publishes comprehensive guides to the hydraulic and hydrology elements of SWMM.

SWMM has been released under several different "official" versions (Metcalf and Eddy, Inc., *et al.* 1971; Huber, *et al.* 1975, 1984; Huber and Dickinson, 1988; Roesner, *et al.* 1984, 1988) and there are many "unofficial" versions modified for specific purposes (some offered by private vendors). The original versions were designed for mainframe use, but the later versions can be executed on a personal computer. The current version of SWMM (Version 4.4; Huber and Dickinson, 1988 and Roesner, *et al.* 1988) may be obtained (along with the

documentation) from the Center for Exposure Assessment Modeling (CEAM), U.S. Environmental Protection Agency, College Station Road, Athens, Georgia 30613. The web site, from which the SWMM package can be downloaded, is ftp://ftp.epa.gov/epa_ceam/wwwhtml/ceamhome.htm. The CEAM phone number is 1-706-546-3549.

SWMM is probably the most popular of all urban runoff models. Unfortunately, it has a reputation for being a difficult model to use. This is not necessarily the case if one knows the fundamentals of how it works and if the parts of the model not needed in a particular application are discarded. SWMM uses well-known hydrologic and hydraulic concepts to simulate the urban watershed. Its reputation for sophistication (and difficulty) derives more from the numerical algorithms necessary to solve the rather straightforward governing equations that are trying to simulate a complex system (i.e., the urban watershed) being driven by a highly dynamic input (i.e., precipitation).

There is an extensive body of literature describing SWMM and a wide range of applications. Interested readers should begin their review of this literature by referring to a document prepared by Huber, *et al.* (1985). This large body of experience is an advantage that SWMM probably enjoys over all other urban runoff models. The SWMM internet user's group, through the University of Guelph, also offers a great deal of SWMM support.

SWMM is divided into several "blocks". The major blocks - i.e., RUNOFF, TRANSPORT, STORAGE/TREATMENT, and EXTRAN - are *computational blocks* responsible for the hydrologic, pollutant generation and transport, and hydraulic calculations. Others blocks - i.e., EXECUTIVE, STATISTICAL, RAIN, TEMP, GRAPH, and COMBINE - perform various auxiliary functions, and are known as *service blocks*. A general operational schematic of SWMM is shown in Figure 9-1. The computational blocks, RUNOFF, TRANSPORT, EXTRAN, and STORAGE/TREATMENT are described below. The RUNOFF Block is only summarized here so as to provide a comparison with SLAMM, recalling that SLAMM is replacing the RUNOFF Block.
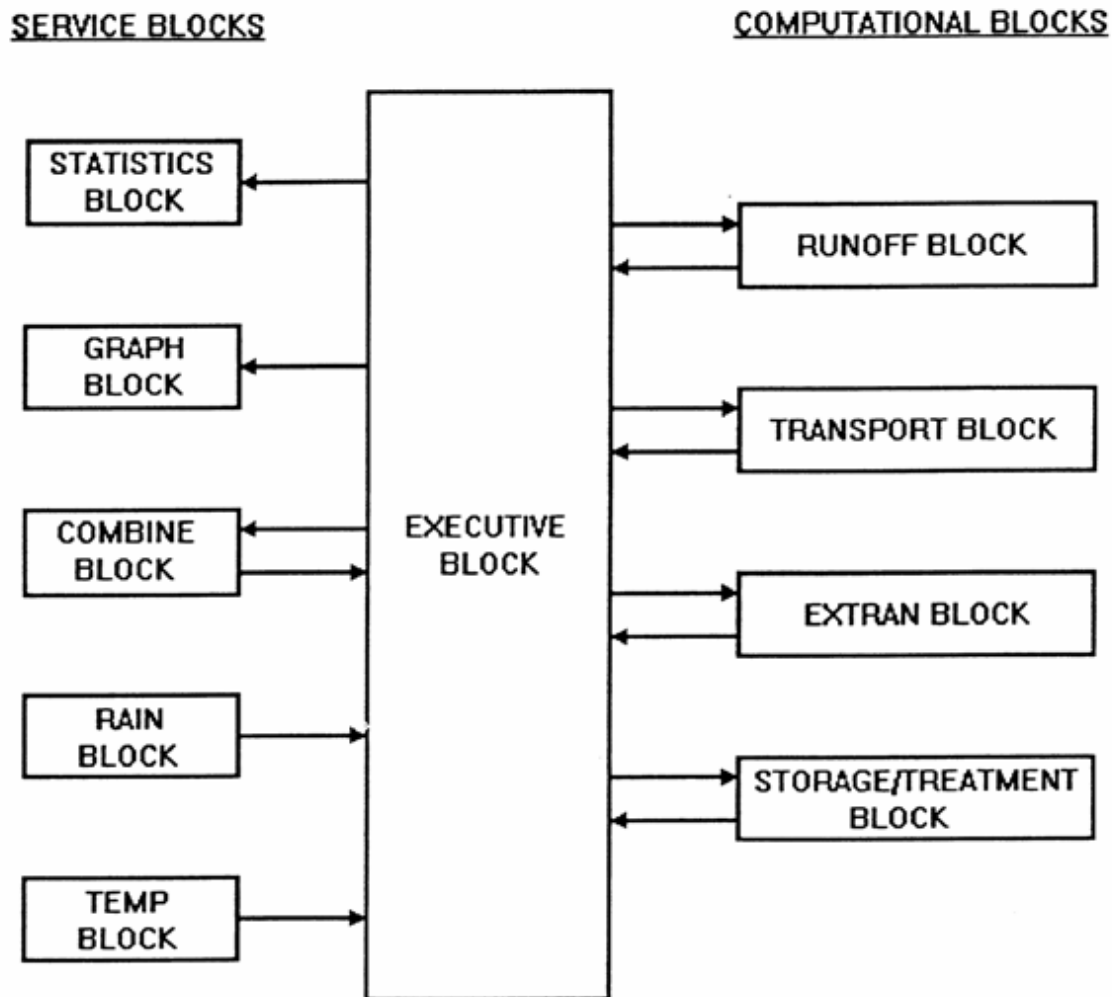
Figure 9-1. SWMM, the Storm Water Management Model, program configuration (after Huber and Dickinson 1988).

RUNOFF Block

The RUNOFF Block generates surface runoff and pollutant loads in response to precipitation and surface pollutant accumulations (Huber and Dickinson, 1988). The key to applying RUNOFF is the division of the watershed into a number of subwatersheds (or subcatchments). Each subwatershed should be relatively homogeneous (i.e., the physical characteristics should be consistent). Just how homogeneous each subwatershed should be depends on how finely characterized the watershed must be to meet the modeling objectives. Dividing the watershed into a large number of subwatersheds implies that each is probably very homogeneous; a smaller number implies less homogeneity.

Runoff Simulation. The conceptual view of surface runoff used by the RUNOFF Block is quite simple and is summarized in Figure 9-2. Essentially, each subwatershed surface is treated as a nonlinear reservoir with a single inflow – precipitation. There are several "discharges" including infiltration, evaporation, and surface runoff. The capacity of this "reservoir" is the maximum depression storage, which is the maximum surface storage provided by

ponding, surface wetting, and interception. Surface runoff occurs only when the depth of water in the "reservoir" exceeds the maximum depression storage.
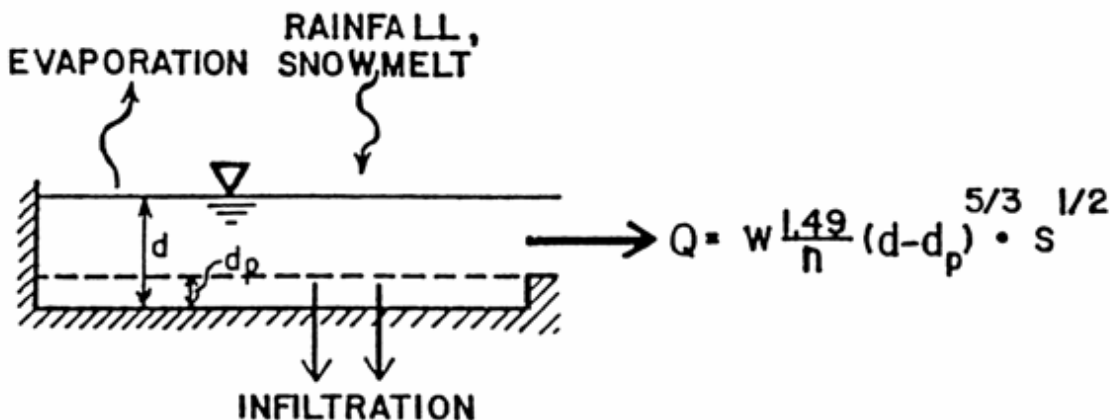

Figure 9-2. Nonlinear reservoir representation of a subwatershed, RUNOFF Block, SWMM (Huber and Dickinson 1988).

The water in storage is also being depleted by infiltration and evaporation. Infiltration occurs only if the ground surface is pervious (as opposed to an impervious surface, such as a paved parking lot, which by definition allows no infiltration). The infiltration process is modeled by one of two methods (Horton's equation or the Green-Ampt equation), which can be selected by the user. Infiltrated water is routed through upper and lower subsurface zones and may contribute to total runoff through ground water flow (this capability is a relatively new addition to SWMM). Monthly average evaporation rates (provided by the user) are directly employed to calculate the amount of water evaporated from the surface (and indirectly to calculate evapotranspiration from the subsurface zones). The precipitation intensity, less the rates of infiltration and evaporation, is known as the *rainfall excess*.

The entire process is repeated for each subwatershed (each having its own unique set of physical characteristics) and is modeled by two equations. One is the continuity of mass equation, which tracks the volume or depth of water on the surface of the subwatershed:

change in volume stored on the subwatershed per unit time		*rainfall excess(net inflow to the subwatershed)*	*Runoff (outflow from the subwatershed)*	
$dV/dt = d(A \cdot d)/dt$	$=$	$(A \cdot i_e)$	$- Q$	(9-1)

where $V = A \cdot d$ = volume of water on the subwatershed, feet^3 or meters^3;

A = area of the subwatershed, feet^2 or meters^2;

d = depth of water on the subwatershed, feet or meters;

t = time, seconds;

I_e = rainfall excess, which is the rainfall intensity less the evaporation/infiltration rate, feet/second or meters/second; and

Q = runoff flow rate from the subwatershed, feet^3/second or meters^3/second.

The second equation is based on Manning's equation and is used to model the rate of surface runoff (i.e., the outflow rate from the reservoir) as a function of the depth of flow above the maximum depression storage depth. Manning's equation can be stated as:

$$Q = A_c \cdot (\beta/n) \cdot R^{2/3} \cdot S_o^{1/2} \tag{9-2}$$

where
- A_c = cross-sectional area of flow over the subwatershed, $feet^2$ or $meters^2$;
- n = Manning's roughness coefficient;
- R = hydraulic radius of flow over the watershed, feet or meters;
- S_o = slope of the subwatershed, feet/foot or meters/meter (which is assumed to equal the friction or energy slope); and
- β = 1.49 if U.S. customary units are used or 1.0 if metric units are used.

The cross-sectional area of flow is:

$$A_c = W \cdot (d - d_p) \tag{9-3}$$

where
- W = width of flow over the subwatershed, or the width of overland flow, feet or meters; and
- d_p = depth of maximum depression storage, feet or meters.

The hydraulic radius is the cross-sectional area of flow divided by the wetted perimeter. Since the depth of flow is very small, the wetted perimeter can be approximated by W. Thus, R can be calculated as:

$$R = [W \cdot (d - d_p)]/W = d - d_p \tag{9-4}$$

Substituting Equations 9-3 and 9-4 into Equation 9-2 yields:

$$Q = W \cdot (\beta/n) \cdot (d - d_p)^{5/3} \cdot S_o^{1/2} \tag{9-5}$$

Substituting Equation 9-5 into Equation 9-1 and dividing by A produces:

$$dd/dt = i_e - [(\beta \cdot W)/(A \cdot n)] \cdot (d - d_p)^{5/3} \cdot S_o^{1/2} \tag{9-6}$$

Equation 9-6 is the second governing equation used in RUNOFF.

The two governing equations are solved numerically as follows. Equation 9-1 can be approximated by:

$$(d_{n+1} - d_n)/dt = i_e - Q/A \tag{9-7}$$

where
- Δt = $t_{n+1} - t_n$, time step size, seconds;

- $n, n+1$ = subscripts indicating conditions at the end of time step n (or start of time step n+1) and the end of time step n+1 (e.g., d_{n+1} is the depth at the end of time step n+1);
- i_e = average precipitation intensity during time step n+1, feet/second or meters/second; and
- Q = average runoff flow rate during time step n+1, $feet^3$/second or $meters^3$/second.

Equation 9-7 shows the differential term dd/dt approximated by a finite difference of values for depth at two points in time separated by Δt. The value of the differential term is then approximated by the average of the terms on the right-hand side evaluated at the beginning and end of Δt. If the average runoff flow rate is calculated as a function of the average depth of flow Equation 9-7 becomes:

$$(d_{n+1}-d_n)/dt \quad = \quad I_e - [(\beta \cdot W)/(A \cdot n)] \cdot (d-d_p)^{5/3} \cdot S_o^{1/2} \qquad\qquad (9\text{-}8)$$

where d = $(d_n + d_{n+1})/2$, average depth of flow during time step n+1, feet or meters.

Equation 9-8 is a relatively simple nonlinear, algebraic relationship with one unknown at any time, d_{n+1}. (The value of d_n is, of course, known from the end of the previous time step.) The Newton-Raphson technique for numerically solving a nonlinear equation is used to solve for d_{n+1}. The calculated value of d_{n+1} is then used in Equation 9-5 to calculate the value of Q at the end of the time step. For all intents and purposes, Equation 9-8 is the core of the RUNOFF Block.

The most perplexing parameter in Equation 9-8 is the width of overland flow, W. Essentially, it is the width over which surface runoff occurs. Again, using the reservoir analogy, this width is similar to the length of a weir or spillway. An idealized view is shown in Figure 9-3. In this schematic, surface runoff is being discharged to a drainage channel running down the center of the subwatershed. In this situation, the two halves are symmetrical and, thus, the total length of overland flow is twice the length of the channel. Of course, this idealized case never occurs, but it demonstrates the concept.

The width of overland flow primarily affects the rapidity of runoff. Recall the weir analogy. In this case, though, when the weir width is enlarged, the length of the "reservoir" is shortened so that the surface area and depth of flow behind the weir remain constant for a given volume of water. As a result, a shorter width will delay runoff; a longer width will facilitate runoff.

The RUNOFF Block has a limited ability to route flows through simple gutter and pipes using the nonlinear reservoir technique. However, the more sophisticated routines in TRANSPORT and EXTRAN Blocks are almost always employed for this purpose.

The surface flows generated by the RUNOFF Block are concentrated at nodes. In other words, the flows are not distributed along gutters or pipes (as implied by Figure 9-3). The width of overland flow is used as a computational tool but the flow is not actually distributed over this distance.

Pollutant Load Simulation
The accumulation of pollutants on the subwatershed surface is modeled in a number of ways. Pollutants can be accumulated as "dust and dirt" on streets or as a simple areal load. Loads may be accumulated in a linear or nonlinear fashion. The different methods (essentially four different equations) are summarized in Figure 9-4 along with a visualization of the accumulation modeled by each.

The washoff of accumulated pollutants is handled in one of two ways. One method applies the following "first-order" relationship to each subwatershed:

$$-P_{off} = dP_p/dt \quad = \quad -K \cdot P_p \qquad\qquad (9\text{-}9)$$

where P_{off} = rate at which pollutant is washed off the subwatershed at time t, quantity/second;
                   P_p = amount of pollutant p on the subwatershed surface at time t, quantity; and
                   K = coefficient, 1/second.
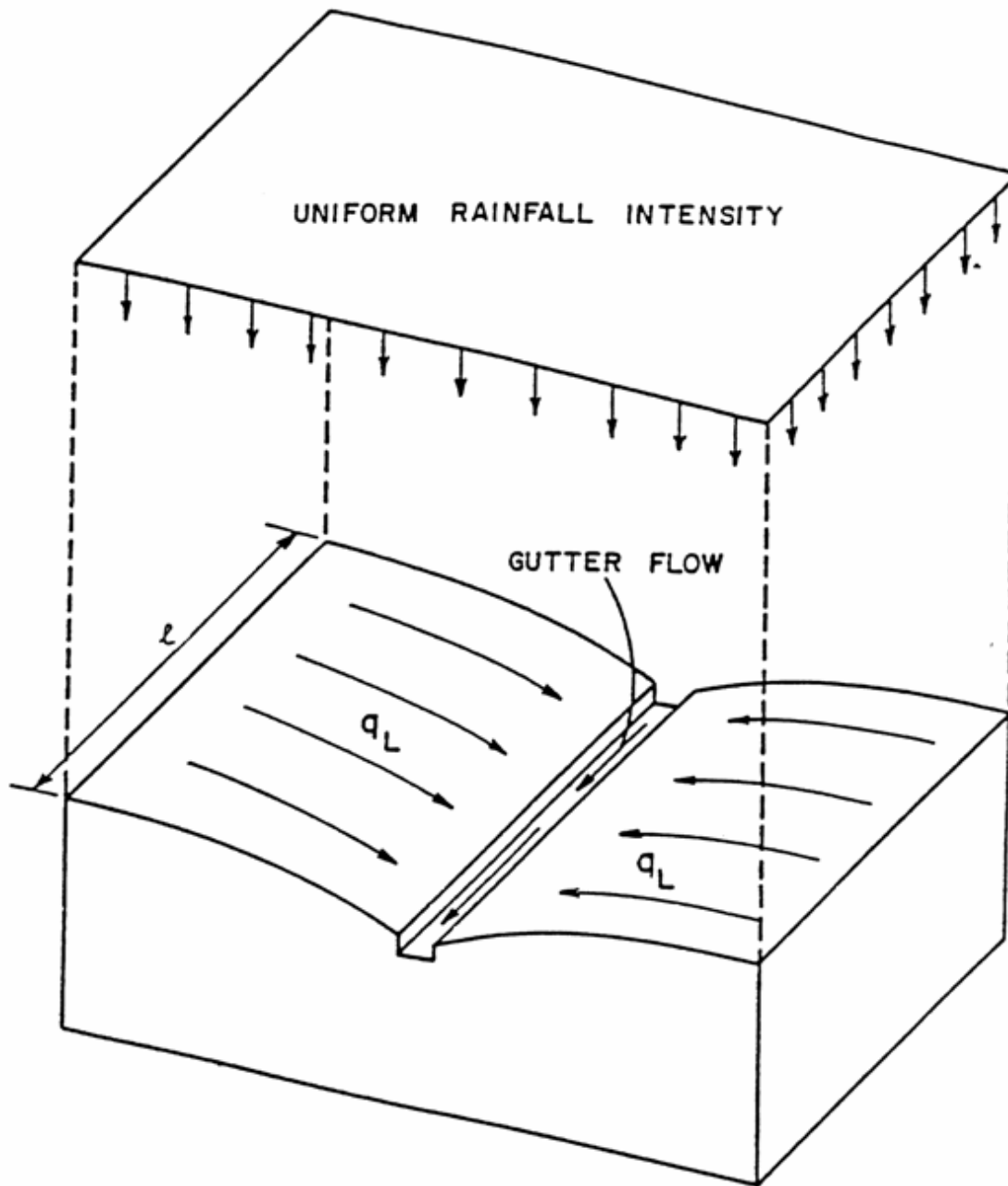
q_L = RATE OF OVERLAND FLOW/UNIT WIDTH.

W = 2ℓ = TOTAL WIDTH OF OVERLAND FLOW

Figure 9-3. Idealized subwatershed-gutter arrangement illustrating the subwatershed width of overland flow, RUNOFF Block, SWMM (Huber and Dickinson 1988).
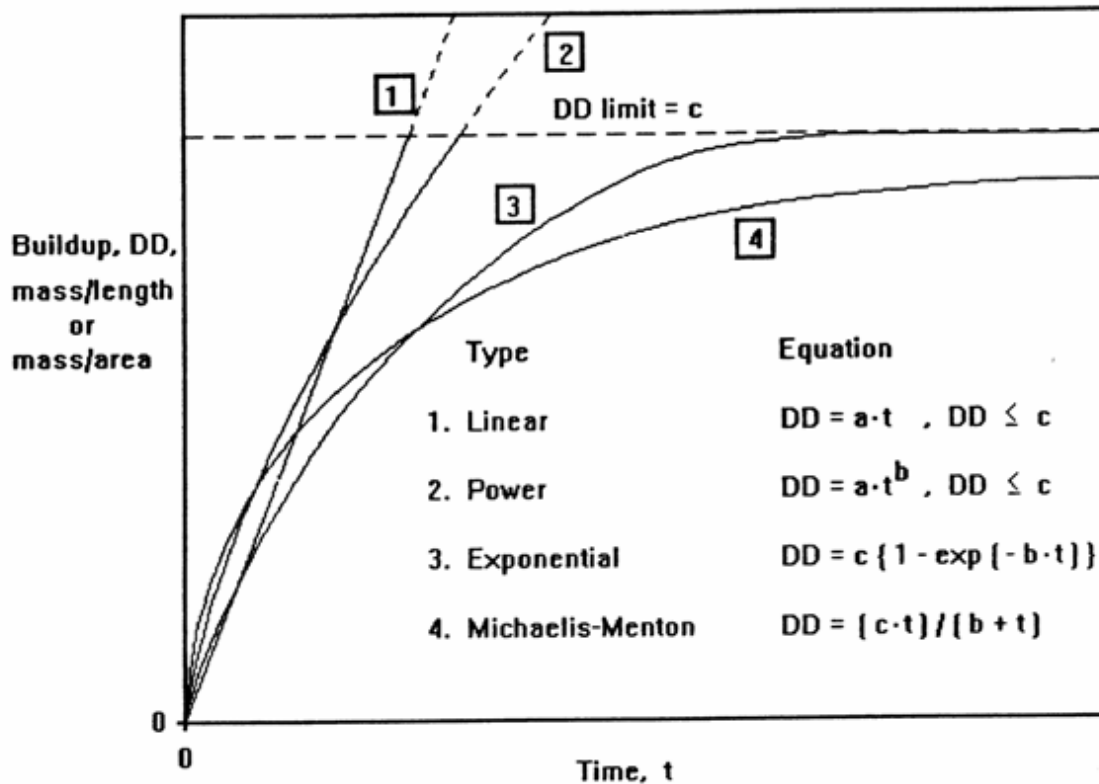
Figure 9-4. Buildup equations, RUNOFF Block, SWMM (after Huber and Dickinson 1988).

The term "quantity" is used in the definitions of P_{off} and P_p because the pollutants modeled by SWMM can be characterized with a variety of units (e.g. milligrams, MPN for coliform bacteria, NTU for turbidity, etc.). Equation 9-9 says that the rate at which a pollutant disappears from a subwatershed surface is proportional to the amount remaining on the subwatershed surface. The coefficient K is assumed to be proportional to the runoff rate:

$$K \quad = \quad R_c \cdot r \tag{9-10}$$

where $\quad R_c \quad$ = washoff coefficient, inches^{-1} or millimeters^{-1}; and
$\quad\quad r \quad$ = runoff rate over the subwatershed at time t, inches/second or millimeters/second
$\quad\quad\quad$ (calculated from Q in Equation 9-5, r = Q/A).

Substituting Equation 9-10 into Equation 9-9 and multiplying by -1 yields:

$$P_{off} = -dP_p/dt \quad = \quad R_c \cdot r \cdot P_p \tag{9-11}$$

A major deficiency of Equation 9-11 is that the runoff pollutant concentrations are forced to decrease over the course of a runoff event. Equation 9-11 shows the washoff rate increasing with runoff, but dividing Equation 9-11 by the runoff flow, Q, yields:

$$C = P_{off}/Q \quad = \quad conv(R_c \cdot r \cdot P_p)/(A \cdot r) = conv(R_c \cdot P_p)/A \tag{9-12}$$

where C = concentration, quantity/volume;
               Q = $A \cdot r$, runoff flow rate, feet^3/second or meters^3/second;
               A = subwatershed area, acres or hectares; and
             conv = a constant containing a number of conversion factors.

Note that the runoff rate, r, disappears in Equation 9-12. Thus, the concentration, C, become independent of the runoff rate and directly proportional to a decreasing amount of pollutant remaining on the watershed. A decreasing concentration, while fairly common, is certainly not the only possible trend. Concentrations can increase during a runoff event. To overcome this problem, an exponent other than one is allowed for r:

$$P_{off} = -dP_p/dt \qquad = \qquad R_c \cdot r^n \cdot P_p \qquad\qquad (9\text{-}13)$$

where n = exponent for the runoff rate.

The load calculated by Equation 9-13 is combined with the runoff flow rate to calculate the concentration, i.e., $C = P_{off}/Q$. If $n = 1$, Equation 9-13 reverts to Equation 11 and the concentration will decrease over the course of an event. Otherwise, concentration is proportional to r^{n-1} (recall Equation 9-12) and as such it may increase if the runoff rate is large enough to offset the reduced value of P_p.

The solution to Equation 9-13 is determined from a finite difference approximation that produces:

$$P_p(t+\Delta t) \qquad = \qquad P_p(t) \cdot \exp\{-R_c \cdot 0.5 \cdot [r(t)^n + r(t+\Delta t)^n]\Delta t\} \qquad\qquad (9\text{-}14)$$

where $0.5[r(t)^n + r(t+\Delta t)^n]$ = average runoff rate over Δt, inches/second or millimeters/second.

The second method allows the user to simulate the washoff as a simple function of the runoff rate:

$$P_{off} \qquad = \qquad R_c \cdot Q^n \qquad\qquad (9\text{-}15)$$

where coefficients R_c and n are assigned particular values for each pollutant. In this method, the simulation of pollutant load washoff may be totally independent of the amount accumulated on the surface (i.e., the load is a function of the runoff flow rate only) or may be linked to the accumulated amount by not allowing the total load discharged during a particular storm to exceed the amount present on the surface at the beginning of the storm.

Other Capabilities and Summary
There are many other capabilities not discussed here, most notably snowmelt simulation. The RUNOFF Block consumes a considerable portion of the SWMM user's manual, making it seem more profound and difficult than it is. Recall that the heart of the block is a very simple nonlinear reservoir representation of the surface runoff process, rudimentary nonlinear and linear buildup relationships, and a first-order washoff process.

Unfortunately, many users incorrectly use RUNOFF through misinterpretation of the early stormwater data that was used in its development, especially the washoff mechanisms and infiltration of water through compacted soils and infiltration through pavement. In addition, RUNOFF doesn't allow direct application of many common stormwater control practices. For these reasons, SLAMM is used during this project to replace the RUNOFF block of SWMM.

TRANSPORT Block
The TRANSPORT Block routes flows and pollutant loads through a sewer system (Metcalf and Eddy, Inc., *et al.* 1971; Huber and Dickinson 1988). These flows and loads are generated by the RUNOFF Block (or some other program, e.g., SLAMM) and input to points throughout the system. TRANSPORT also has the ability to simulate

dry-weather or sanitary sewage flows for routing through a sewer system. Hydrographs and pollutographs can also be manually introduced at various points in the system.

The sewer system is viewed as a series of "elements". This is shown in Figure 9-5. Elements may be nodes or conduits. Nodes link conduits and include manholes, pump stations, storage units, and flow dividers (see Table 9-1). Inflows to the system, such as surface runoff, occur at the nodes and may be entered directly by the user or come from other programs such as the RUNOFF Block or SLAMM through an interface file. A conduit may have one of 15 different cross-sectional shapes supplied by the model or two supplied by the user (see Table 9-1). Simple flow diversion devices (e.g., overflow structures) are also allowed.

A user-supplied number identifies each element. The numbering scheme can be arbitrary, for the system elements are fashioned into a connected network by indicating which elements are upstream of each element. In other words, element 11 is not necessarily connected to element 12, nor is element 12 necessarily connected to element 13. But element 119 <u>can</u> be connected to element 1034 if the user specifies that element 1034 is one of the elements immediately upstream of element 119.

Flow Routing

Ideally, flow in sewers can be represented by two partial differential equations: the continuity and momentum equations or, as they are sometimes known, the Saint-Venant equations (Chow, *et al*. 1988):

Momentum:

pressure force	*Convective Acceleration*	*local acceleration*	*gravity force*	*friction force*	
$\delta h/\delta t$ +	$(v/g)\cdot\delta v/\delta x$ +	$(1/g)\cdot\delta v/\delta t$ =	S_o -	S_f	(9-16)

Continuity:

inflows and outflows to and from a control volume	*change in amount of water in control volume*			
$\delta Q/\delta x$ +	$\delta A/\delta t$ =	0		(9-17)

where h = water depth, feet or meters;
v = average flow velocity, feet/second or meters/second;
x = distance along the conduit, feet or meters;
t = time, seconds;
g = acceleration due to gravity, 32.2 feet/second^2 or 9.8 meters/seconds^2;
S_o = invert slope (slope of the conduit), feet/foot or meters/meter;
S_f = friction (energy) slope, feet/foot or meters/meter;
Q = flow rate, feet^3/second or meters^3/second; and
A = cross-sectional area of flow, feet^2 or meters^2.

Unfortunately, the Saint-Venant equations are difficult to manipulate and simplifications are often desirable. TRANSPORT uses a simplified version of the momentum equation in which all terms on the left hand side are neglected, i.e.,

$$S_f \quad = \quad S_o \qquad\qquad\qquad (9\text{-}18)$$
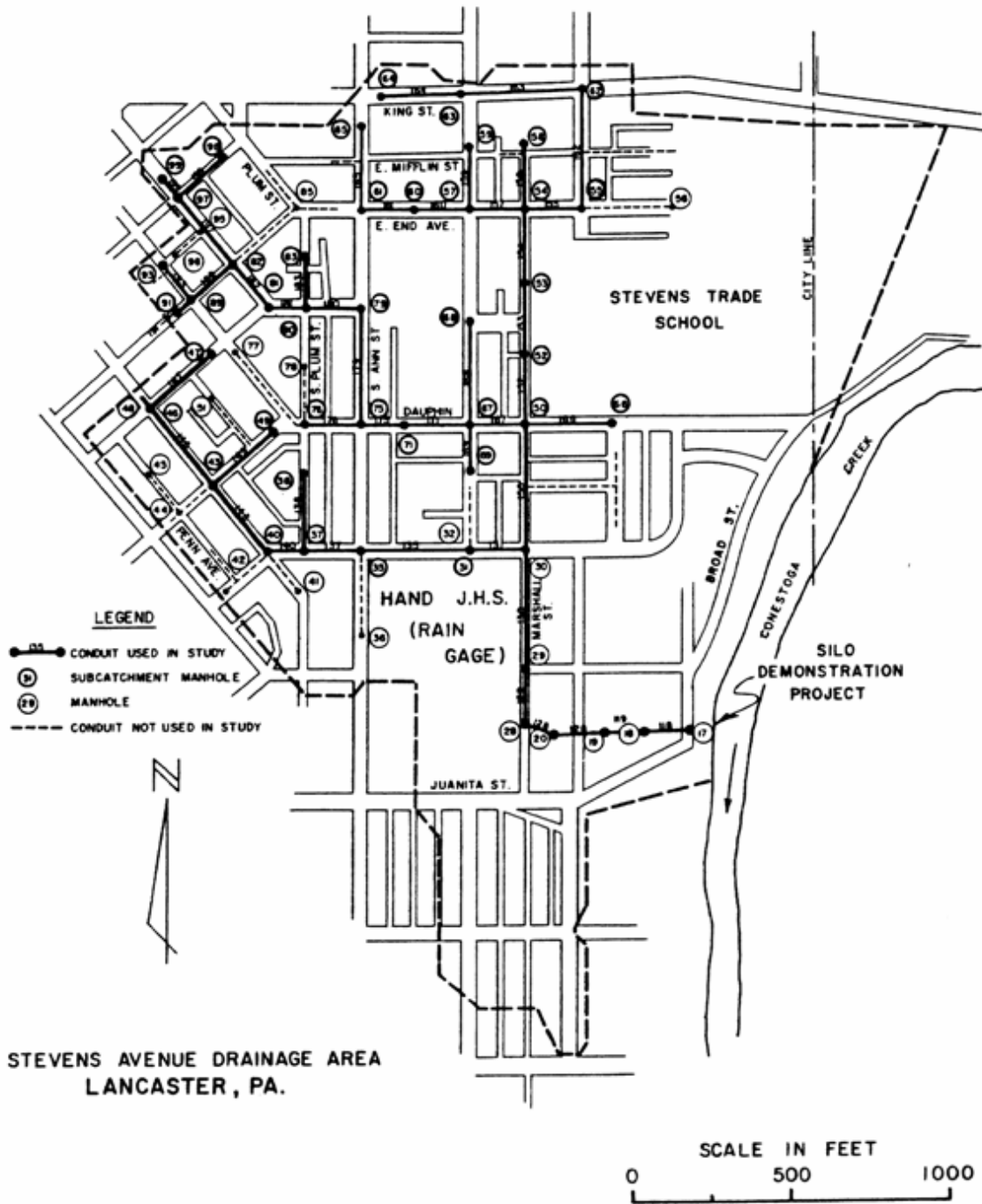
Figure 9-5. Node and conduit representation of a sewer system, TRANSPORT Block, SWMM (Heaney, *et al*. 1975).

Table 9-1. Elements in TRANSPORT Block, SWMM (Huber and Dickinson 1988)

Element Class	Types
Conduits/channels (links)	Circular
	Rectangular
	Phillips standard egg shape
	Boston horseshoe
	Gothic
	Catenary
	Louisville semielliptic
	Basket-handle
	Semicircular
	Modified basket-handle
	Rectangular, triangular bottom
	Rectangular, round bottom
	Trapezoid
	Parabolic
	Power Function
	HEC-2 Format — Natural Channel
	User supplied
Nonconduits (nodes)	
Manhole	Lift station
	Flow divider
	Storage unit
	Flow divider — weir
	Flow divider
	Backwater element

The friction slope, S_f, is estimated from Manning's equation:

$$S_f = Q^2/[(\beta/n)^2 \cdot A^2 \cdot R^{4/3}] \qquad (9\text{-}19)$$

where
n = Manning's roughness coefficient;
R = hydraulic radius, feet or meters; and
β = 1.49 when U.S. customary units are used or 1.0 when metric units are used.

From Equations 9-18 and 9-19,

$$Q = (k/n) \cdot A \cdot R^{2/3} \cdot S_o^{1/2} \qquad (9\text{-}20)$$

Essentially the original momentum equation, Equation 9-16, is replaced with an equation where Q is a function of depth only (recall that the cross-sectional area, A, and the hydraulic radius, R, are functions of depth, h). This *kinematic wave approximation*, as it is commonly known, is what distinguishes the TRANSPORT Block from its more sophisticated cousin, the EXTRAN Block (see the next section). Since flow is a function of depth alone, "disturbances" or changes that occur at one point in a sewer system can only affect what happens at downstream points, not upstream points. The full momentum equation propagates the effects of disturbances in both directions since flow (or velocity) is also a function of local and convective acceleration and pressure. With hydraulic effects propagated in only the downstream direction, backwater conditions cannot be simulated. In addition, the fact that

flow is treated as a function of only depth means that the TRANSPORT Block cannot simulate surcharge conditions (flow under pressure). In summary, the TRANSPORT Block views the system as a simple cascade of conduits with downstream conduits having no effect on upstream conduits.

It is especially important to understand how the TRANSPORT Block behaves when it encounters surcharge conditions. Flows exceeding the open-channel capacity of a conduit are stored at the upstream end of the conduit (at a node) and released when this capacity again becomes available. Hydrographs passing through such a conduit become "clipped" (as shown in Figure 9-6) and, as a result, potential surcharge problems at downstream conduits may be masked.

The continuity equation, Equation 9-17, is approximated by a finite difference relationship:

$$[(1-w_t)(A_{j,n+1} - A_{j,n}) + w_t(A_{j+1,n+1} - A_{j+1,n})]/\Delta t \quad +$$

$$[(1-w_x)(Q_{j+1,n} - Q_{j,n}) + w_x(Q_{j+1,n+1} - Q_{j,n+1})]/\Delta x \quad = \quad 0 \qquad (9\text{-}21)$$

where

Δt	=	$t_{n+1} - t_n$, time step size, seconds;
Δx	=	$x_{j+1} - x_j$, distance interval length (the conduit length), feet or meters;
$j, j+1$	=	subscripts indicating conditions at the upstream end and the downstream end of conduit M, respectively;
$n, n+1$	=	subscripts indicating conditions at the end of time step n (which is also the beginning of time step n+1) and the end of time step n+1, respectively; and
w_t, w_x	=	weights.

The weights w_x and w_t were both set to 0.55 after a series of tests to determine the best values for numerical stability. This numerical approximation and its application are illustrated in Figure 9-7.

Equations 9-20 and 9-21 are used together to route flows through a sewer system. At the end of any time step n+1, the unknown quantities are the flow and cross-sectional area of flow at the downstream end of conduit M, $Q_{j+1,n+1}$ and $A_{j+1,n+1}$. (The variables $Q_{j,n}$ and $A_{j,n}$ are known from the previous time step and conditions at the upstream end of the conduit). With only two unknowns, these two equations are sufficient to determine the value of both. The calculations are carried out from the most upstream conduit to the most downstream conduit during each time step.
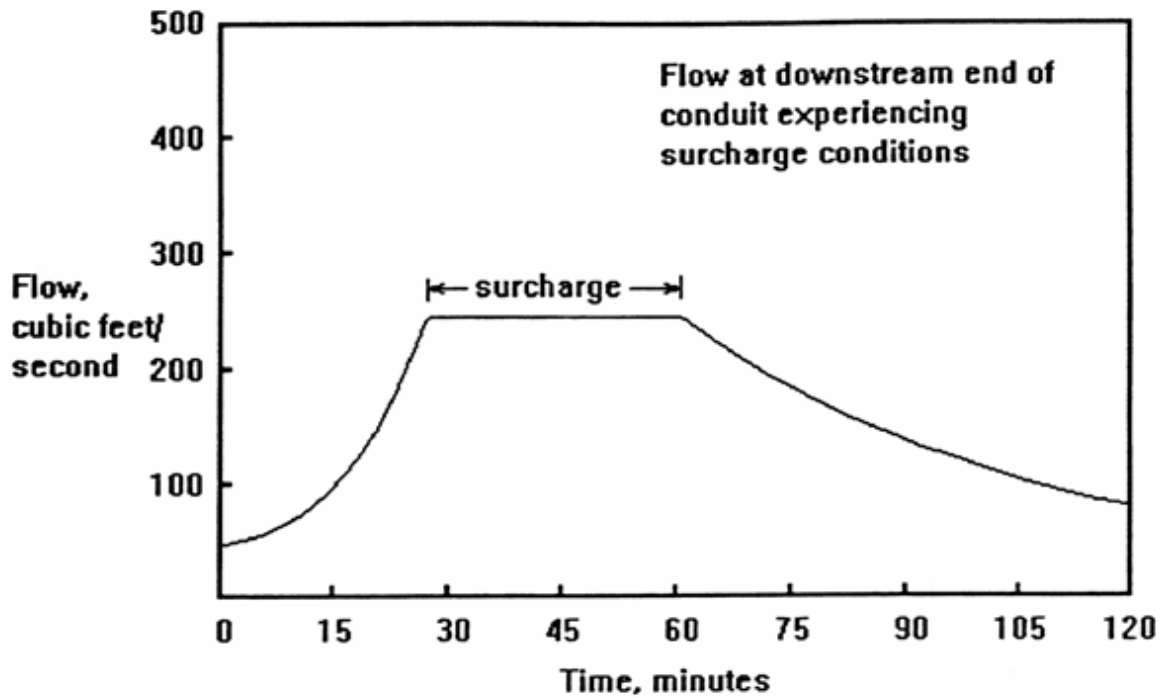
Figure 9-6. Effect of surcharging on downstream hydrograph, TRANSPORT Block, SWMM.

Nodes (e.g., manholes) are treated very simply in the TRANSPORT Block. Flow exiting a node is just the sum of all the flows entering the node.

Although the numbering scheme used to identify the various elements is arbitrary from the user's perspective, the program establishes a separate internal numbering scheme for the routing calculations. Again, this is possible because the user identifies the elements upstream of each element.

It should be noted that several modifications were made to Equations 9-20 and 9-21 to improve model accuracy. These will not be discussed here. It is sufficient to say that these two equations are the heart of the TRANSPORT Block.

Pollutant Routing
Pollutants are routed through the system by treating each conduit as a completely mixed reactor with first-order decay. The governing differential equation is shown below:

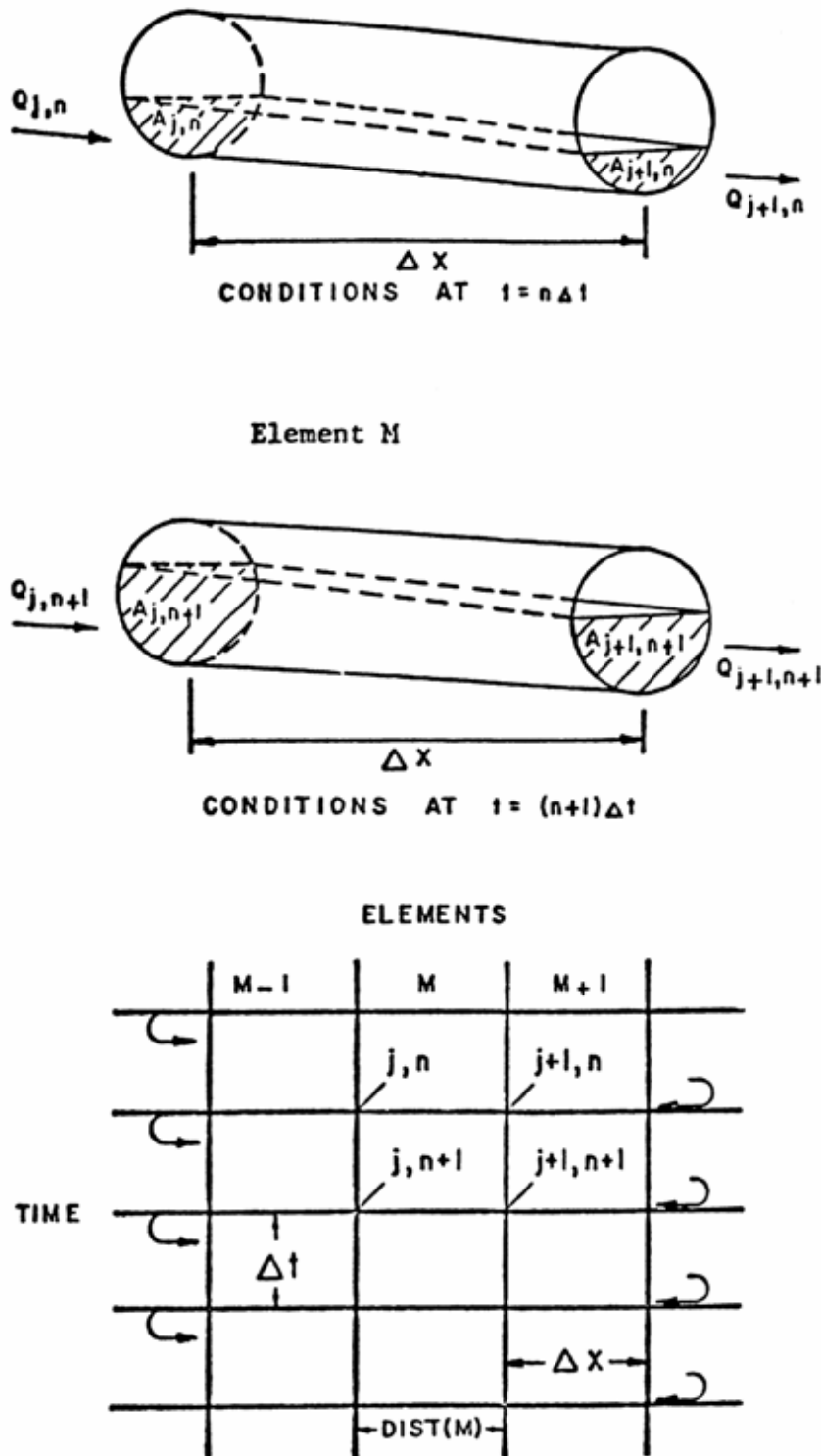| change in mass in conduit per unit time	mass rate to conduit	mass rate from conduit	decay in conduit	mass source or sink	
$d(V \cdot C)/dt = V \cdot dC/dt + C \cdot dV/dt =$	$(Q_i \cdot C_i)$ -	$(Q \cdot C)$ -	$K \cdot C \cdot V$ $\pm$	L	(9-22)

Figure 9-7. Numerical approximation definitions in TRANSPORT Block, SWMM (Metcalf and Eddy, Inc., *et al*. 1971).

where C = pollutant concentration in conduit and discharge from conduit, quantity/volume (e.g.,
           milligrams/liter);

             V = volume of water in conduit, feet^3 or meters^3;

           Q_i = inflow rate to conduit, feet^3/second or meters^3/second;

           C_i = pollutant concentration in inflow, quantity/volume;

           Q = outflow rate from conduit, feet^3/second or meters^3/second;

           K = first-order decay coefficient, seconds^{-1}; and

           L = source (or sink) of pollutant to the conduit, quantity/time.

An integrated form of the solution to this differential equation is used with a simple numerical technique to carry out the estimates for concentration in each conduit.

Other Capabilities and Summary

The TRANSPORT Block has a very simple routine to estimate infiltration into the sewer system. The routine is not very useful and the user can just as easily enter infiltration flows at various nodes in the system. Unfortunately, there is no direct way to generate sewer infiltration from the subsurface flows simulated in the RUNOFF Block.

The TRANSPORT Block also contains a rather data-intensive routine for estimating dry-weather flows and pollutant loads (which would be useful in watersheds with combined sewer systems). The estimates are calculated as functions of land use, population, income levels, and a host of other factors.

In summary, the TRANSPORT Block effectively routes flows and pollutants through a simple sewer system, as long as surcharging is not encountered. Unlike its companion the EXTRAN Block, TRANSPORT is capable of routing pollutants. It is numerically stable and relatively easy to apply.

EXTRAN Block

The EXTRAN Block exceeds the hydraulic capabilities of the TRANSPORT Block, but omits pollutant routing (Roesner, *et al.* 1988). The block has a developmental history that is a little different from the rest of SWMM, joining the software bundle in the latter versions.

<u>Flow Routing</u>. Similar to the TRANSPORT Block, the sewer system is viewed as a network of links and nodes (or, collectively, elements). Inflows to the system occur at the nodes and may be entered directly by the user or come from the RUNOFF Block or other programs (e.g., SLAMM). The number of element types that can be modeled is not as extensive as that of the TRANSPORT Block and the method of linking the system together is slightly different (see Table 9-2). Because hydraulic "signals" are propagated in both directions, upstream <u>and</u> downstream nodes are identified for each link (or conduit).

The EXTRAN Block uses the complete Saint-Venant equations to model the routing of flows through a sewer system. However, the equations are expressed a little differently than in the previous section outlining the TRANSPORT Block (i.e., Equations 9-16 and 9-17):

Momentum:

pressure and gravity force	*convective acceleration*	*local acceleration*	*friction force*		
$g \cdot A \cdot (\delta H / \delta x)$ +	$\delta(Q^2/A)/\delta x$ +	$\delta Q/\delta t$ +	$g \cdot A \cdot S_f$ =	0	(9-23)

Table 9-2. Elements in EXTRAN Block, SWMM (Roesner, *et al*. 1988)

Element Class	Types
Conduits or links	Rectangular
	Circular
	Horseshoe
	Eggshape
	Baskethandle
	Trapezoid
	Power function
	Natural Channel (irregular cross section)
Junctions or nodes	Manholes
Diversion structures	Orifices
	Transverse weirs
	Side-flow weirs
Pump stations	On-line or off-line pump station
Storage basins	On-line, enlarged pipes or tunnels
	On-line or off-line, arbitrary stage-area relationship
Outfall structures	Transverse weir with tide gate
	Transverse weir without tide gate
	Side-flow weir with tide gate
	Side-flow weir without tide gate
	Outfall with tide gate
	Free outfall without tide gate

Continuity:

inflows and outflows to and from a control volume		*change in amount of water in control volume*			
$\delta Q/\delta x$	$+$	$\delta A/\delta t$	$=$	0	(9-24)

where H = z + h, hydraulic head, feet or meters;
z = conduit invert elevation, feet or meters;
h = water depth, feet or meters;
x = distance along the conduit, feet or meters;
t = time, seconds;
g = acceleration due to gravity, 32.2 feet/second^2 or 9.8 meters/seconds^2;
S_f = friction (energy) slope, feet/foot or meters/meter;
Q = flow rate, feet^3/second or meters^3/second; and
A = cross-sectional area of flow, feet^2 or meters^2.

Note that the gravity force term found in Equation 9-16 is incorporated in the first term of Equation 9-23. The friction force term is estimated by Manning's equation:

$$S_f \quad = \quad Q^2/[(\beta/n)^2 \cdot A^2 \cdot R^{4/3}] = \quad Q \cdot |v|/[(\beta/n)^2 \cdot A^2 \cdot R^{4/3}] \qquad (9\text{-}25)$$

where n = Manning's roughness coefficient;
            R = hydraulic radius, feet or meters; and
            β = 1.49 when U.S. customary units are used or 1.0 when metric units are used.

The absolute value sign on velocity, v, insures that the friction force, as expressed by S_f, opposes the direction of flow. For example, if flow is reversed (from the nominal direction of flow) both Q and v would be negative. Taking the absolute value of v allows S_f to become negative as well.

Equations 9-23 and 9-24 are combined through a few algebraic manipulations. These first of these relies on the identity

$$Q^2/A \quad = \quad v^2/A \qquad (9\text{-}26)$$

where v = average flow velocity, feet/second or meters/second.

Substituting Equation 9-26 into the convective acceleration term of the momentum equation (Equation 9-23) yields:

$$g \cdot A \cdot (\delta H/\delta x) + 2A \cdot v \cdot (\delta v/\delta x) + v^2 \cdot (\delta A/\delta x) + \delta Q/\delta t + g \cdot A \cdot S_f \quad = \quad 0 \qquad (9\text{-}27)$$

Noting that $Q = A \cdot v$, the continuity equation, Equation 9-24, can be written as:

$$A \cdot (\delta v/\delta x) + v \cdot (\delta A/\delta x) + \delta A/\delta t = \quad 0 \qquad (9\text{-}28)$$

Multiplying by velocity v and rearranging terms yields:

$$A \cdot v \cdot (\delta v/\delta x) = -v \cdot (\delta A/\delta t) - v^2 \cdot (\delta A/\delta x) \qquad (9\text{-}29)$$

Substituting this result into the second term of the revised momentum equation (Equation 9-27) leads to the basic flow equation used in the EXTRAN Block:

$$g \cdot A \cdot (\delta H/\delta x) - 2v \cdot (\delta A/\delta t) - v^2 \cdot (\delta A/\delta x) + \delta Q/\delta t + g \cdot A \cdot S_f = \quad 0 \qquad (9\text{-}30)$$

Essentially, Equation 9-30 contains two variables, Q and H (v and A are related to Q and H). Therefore, the continuity equation (Equation 9-24) is used to provide a second equation relating Q and H at each node. Finite difference approximations are used to numerically solve the two partial differential equations. The details will not be discussed here. The numerical techniques used in the EXTRAN Block are somewhat unstable and some attention must be paid to the size of the time step and conduit lengths.

Other Capabilities and Summary. The routing of pollutant loads is not modeled. Nor are there routines for estimating sewer infiltration or dry-weather flows.

The EXTRAN Block should be used with care and not undertaken lightly. While hydraulically powerful, it has proven to be numerically "temperamental." Nevertheless, EXTRAN should be used if the sewer system to be modeled is complicated and subject to surcharging.

STORAGE/TREATMENT Block

The STORAGE/TREATMENT Block is designed to route flow and pollutant loads through a storage/treatment facility (Nix 1982; Huber and Dickinson 1988). These flows and loads may come from other blocks in SWMM or other sources. The user is given a great deal of flexibility by the block's ability to connect as many as five storage/treatment units together in a variety of networks. Each unit may be given detention (or storage) characteristics or be modeled as a simple flow-through device.

If a unit is modeled as a detention unit, as shown in Figure 9-8, flows are routed through the unit with a level-surface flow routing procedure (i.e., the modified Puls method). This method is based on yet another version of the continuity of mass equation (Viessman, *et al.* 1988):

change in volume of *water in detention unit* *per unit time*		*flow rate entering the* *detention unit*		*flow rate leaving* *the detention unit*	

$$dV/dt \quad = \quad I \quad - \quad Q \tag{9-31}$$

where
V = volume of water in detention unit, feet^3 or meters^3;
I = inflow rate, feet^3/second or meters^3/second;
Q = outflow rate, feet^3/second or meters^3/second; and
t = time, seconds.

Equation 9-31 is approximated by the following finite difference relationship:

$$(V_{n+1} - V_n)/\Delta t \; = \quad (I_n + I_{n+1})/2 + (Q_n + Q_{n+1})/2 \tag{9-32}$$

where
$n, n+1$ = subscripts indicating conditions at the end of time step n (or the beginning of time step n+1) and the end of time step n+1, respectively; and
Δt = $t_{n+1} - t_n$, time step size, seconds.

At the end of any time step, the values of V_{n+1} and Q_{n+1} are unknown. (The values for V_n and Q_n are known from the previous time step.) A second relationship between storage, V, and discharge, Q, is needed to determine their values. The program gives the user a two ways to provide this relationship. One uses a linear interpolation algorithm to approximate the relationship through a series of volume-discharge data pairs (each pair occurring at a particular depth). With two relationships (Equation 9-32 and the user-supplied volume-discharge information) it is possible to solve for V_{n+1} and Q_{n+1} at each time step.

Pollutants are routed through the detention unit in either a completely mixed or plug-flow manner. In the completely mixed case, all incoming material is instantly distributed throughout the detention unit and, thus, the pollutant concentration is uniform throughout the unit (see Figure 9-9). The following continuity of mass equation is used to simulate the fate of pollutants in the completely mixed detention unit:
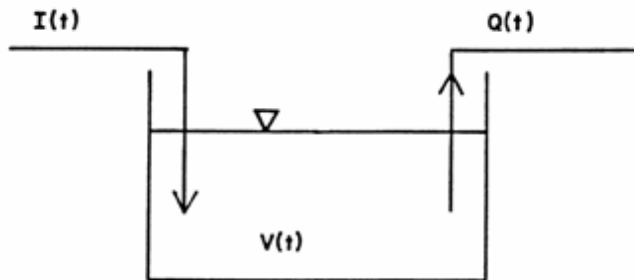
Figure 9-8. Level-surface reservoir, STORAGE/TREATMENT Block, SWMM (after Huber and Dickinson 1988).

change in mass in detention unit per unit time		*mass rate entering the detention unit*		*mass rate leaving the detention unit*		*"reaction" of pollutant by first-order decay*	
$d(CV)/dt$	$=$	$I \cdot C_I$	$-$	$Q \cdot C$	$-$	$K_c \cdot C \cdot V$	(9-33)

where C_I = influent pollutant concentration, quantity/volume (e.g., milligrams/liter);
               C = effluent pollutant concentration, quantity/volume; and
               K_c = decay coefficient, seconds^{-1}.

Equation 9-33 is approximated by a finite difference equation in a manner very similar to that done for Equation 9-31. The result is an algebraic solution for the effluent pollutant concentration at the end of every time step.

In the plug-flow case, the stormwater and pollutants entering the detention unit in a given time step forms a "plug" (see Figure 9-10). The number of plugs (and/or fraction of a plug) leaving the unit in any time step is, of course, directly related to the departing volume (as determined by the flow routing procedure).

Pollutant removal is modeled through the use of "removal equations" or through a set of relationships describing discrete particle settling. In the former the program provides several variables such as detention time, inflow rate, etc. around which the user can build a wide range of removal equations. This is done by providing a generic function that can be manipulated through the assignment of the program variables to the variables in the generic equation and the selection of appropriate values for the equation coefficients. The generic function is:

$$R = [a_{12} \cdot \exp(a_1 x_1) \cdot x_2{}^{a2} + a_{13} \cdot \exp(a_3 x_3) \cdot x_4{}^{a4} + a_{14} \cdot \exp(a_5 x_5) \cdot x_6{}^{a6} +$$

$$a_{15} \cdot \exp(a_7 x_7 + a_8 x_8) \cdot x_9{}^{a9} \cdot x_{10}{}^{a10} \cdot x_{11}{}^{a11}]^{a16} \qquad (9\text{-}34)$$

where x_i = removal equation variable;
             a_j = coefficients; and
             R = removal fraction, $0 \le R \le 1.0$.

As mentioned above, each variable x_i can represent one of a number of variables in the storage/treatment algorithm. The selection varies depending on whether the detention basin is assumed to behave as a plug-flow

reactor or a completely mixed reactor. In the completely mixed mode, Equation 9-34 is really only used to provide a value for K_c in Equation 9-33. In the plug-flow mode, the equation is applied to each plug and many more options are available.
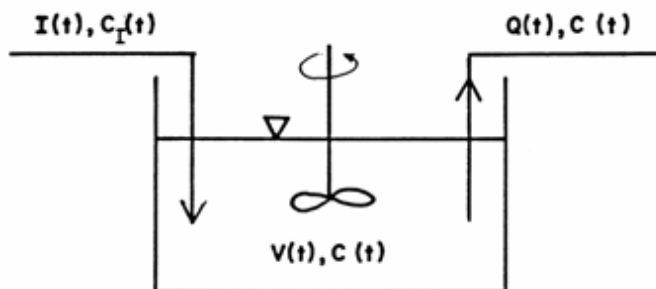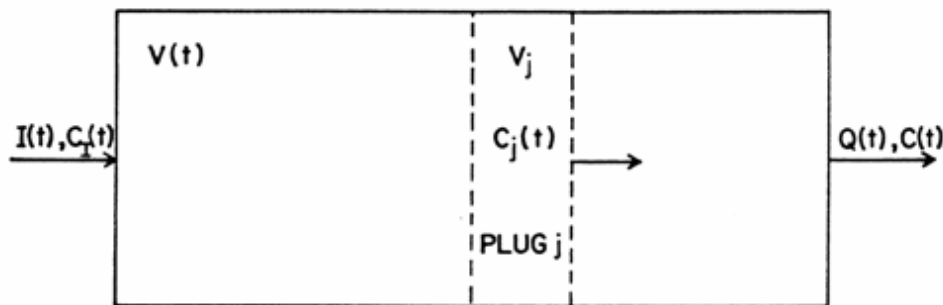

Figure 9-9. Completely mixed detention unit, STORAGE/TREATMENT Block, SWMM (Huber and Dickinson 1988).

Figure 9-10. Plug-flow detention unit, STORAGE/TREATMENT Block, SWMM (Huber and Dickinson 1988).

The particle-settling algorithm can only be used in the plug-flow mode. The size distribution of particles entering the detention unit is assumed to remain constant for all incoming flows. The settling of particles is based on the theory of discrete particle settling modified for the effects of turbulence (Nix 1982). The outgoing size distribution changes over time as differences in flow conditions dictate. The removal (settling) of a particular pollutant is based on its association with particles of various settling velocities or sizes and specific gravities (e.g., 20% of the BOD load is associated with particles that have a given range of settling velocities). This association also remains constant for all incoming pollutant loads. This assumption, and that of a constant particle size distribution, is a major limitation. It should be said, however, that this limitation only exists because the RUNOFF Block does not predict the distribution of particle sizes carried along with stormwater runoff. The algorithms in the STORAGE/TREATMENT Block can handle time-varying distributions.

When a unit is defined as a simple flow-through or non-detention device, flow is routed without delay, i.e., inflow = outflow. Pollutant removal is simulated with Equation 9-34 (again, built by the user with variables provided by the program), or by assuming that all particles of a certain size or larger are removed.

The STORAGE/TREATMENT Block is not intended to be a sophisticated unit operations simulator. There are other models that simulate these processes in great detail. This block is designed to give the user a reasonable prediction of how a wet-weather facility will respond to dynamic stormwater flows and pollutant loads. In order to keep the model tractable, the representation of pollutant routing and removal is fairly simple.

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

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

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

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

In addition to the material presented in this report section, Appendices A and B summarize the small storm hydrology features used in SLAMM (showing how drainage and water quality objectives can be both addressed with the model), Appendix C is a user's guide for using SLAMM, Appendix D describes the source area and outfall controls incorporated in SLAMM, and Appendix E contains the source code for SLAMM.

History of SLAMM and Typical Uses
The Source Loading and Management Model (SLAMM) was initially developed to more efficiently evaluate stormwater control practices. It soon became evident that in order to accurately evaluate the effectiveness of

stormwater controls at an outfall, the sources of the pollutants or problem water flows must be known. SLAMM has evolved to include a variety of source area and end-of-pipe controls and the ability to predict the concentrations and loadings of many different pollutants from a large number of potential source areas. SLAMM calculates mass balances for both particulate and dissolved pollutants and runoff flow volumes for different development characteristics and rainfalls. It was designed to give relatively simple answers (pollutant mass discharges and control measure effects for a very large variety of potential conditions).

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

SLAMM is normally used to predict source area contributions and outfall discharges. However, SLAMM has been used in conjunction with a receiving water model (HSPF) to examine the ultimate receiving water effects of urban runoff (Ontario 1986).

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

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

SLAMM Computational Processes
Figure 9-11 illustrates the wide variety of development characteristics that affect stormwater quality and quantity. This figure shows a variety of drainage systems from concrete curb and gutters to grass swales, along with directly connected roof drainage systems and drainage systems that drain to pervious areas. "Development characteristics" define the magnitude of these drainage efficiency attributes, along with the areas associated with each surface type (road surfaces, roofs, landscaped areas, etc.). The use of SLAMM shows that these characteristics greatly affect runoff quality and quantity. Land use alone is usually not sufficient to describe these characteristics. The types of the drainage system (curbs and gutters or grass swales) and roof connections (directly connected or draining to pervious area), are probably the most important attributes affecting runoff characteristics. These attributes are not directly related to land use, but some trends are obvious: most roofs in strip commercial and shopping center areas are directly connected, and the roadside is most likely drained by curbs and gutters, for example. Different land

uses, of course, are also associated with different levels of pollutant generation. For example, industrial areas usually have the greatest pollutant accumulations due to material transfer and storage, and heavy truck traffic.

Figure 9-12 shows how SLAMM considers a variety of pollutant and flow routings that may occur in urban areas. SLAMM routes material from unconnected sources to the drainage system directly or to adjacent directly connected or pervious areas which in turn drain to the collection system. Each of these areas has pollutant deposition mechanisms in addition to removal mechanisms associated with them. As an example, unconnected sources, which may include rooftops draining to pervious areas or bare ground and landscaped areas, are affected by regional air pollutant deposition (from point source emissions or from fugitive dust) and other aspects that would affect all surfaces. Pollutant losses from these unconnected sources are caused by wind removal and by rain runoff washoff which flow directly to the drainage system, or to adjacent areas. The drainage system may include curbs and gutters where there is limited deposition, and catch basins and grass swales which may remove substantial participates that are transported in the drainage system. Directly connected impervious areas include paved surfaces that drain directly to the drainage system. These source areas are also affected by regional pollutant deposition, in addition to wind removal and controlled removal processes, such as street cleaning. On-site storage is also important on paved surfaces because of the large amount of participate pollutants that are not washed-off, blown-off, or removed by direct cleaning (Pitt 1979; Pitt and Shawley 1982; Pitt 1984).

Figure 9-13 shows how SLAMM proceeds through the major calculations. There is a double set of nested loops in the analyses where runoff volume and suspended solids (particulate residue) are calculated for each source area and then for each rain. These calculations consider the affects of each source area control, in addition to the runoff pattern between areas. Suspended solids washoff and runoff volume from each individual area for each rain are summed for the entire drainage system. The effects of the drainage system controls (catch basins or grass swales, for example) are then calculated. Finally, the effects of the outfall controls are calculated.

SLAMM uses the water volume and suspended solids concentrations at the outfall to calculate the other pollutant concentrations and loadings. SLAMM keeps track of the portion of the total outfall suspended solids loading and runoff volume that originated from each source area. The suspended solids fractions are then used to develop 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.
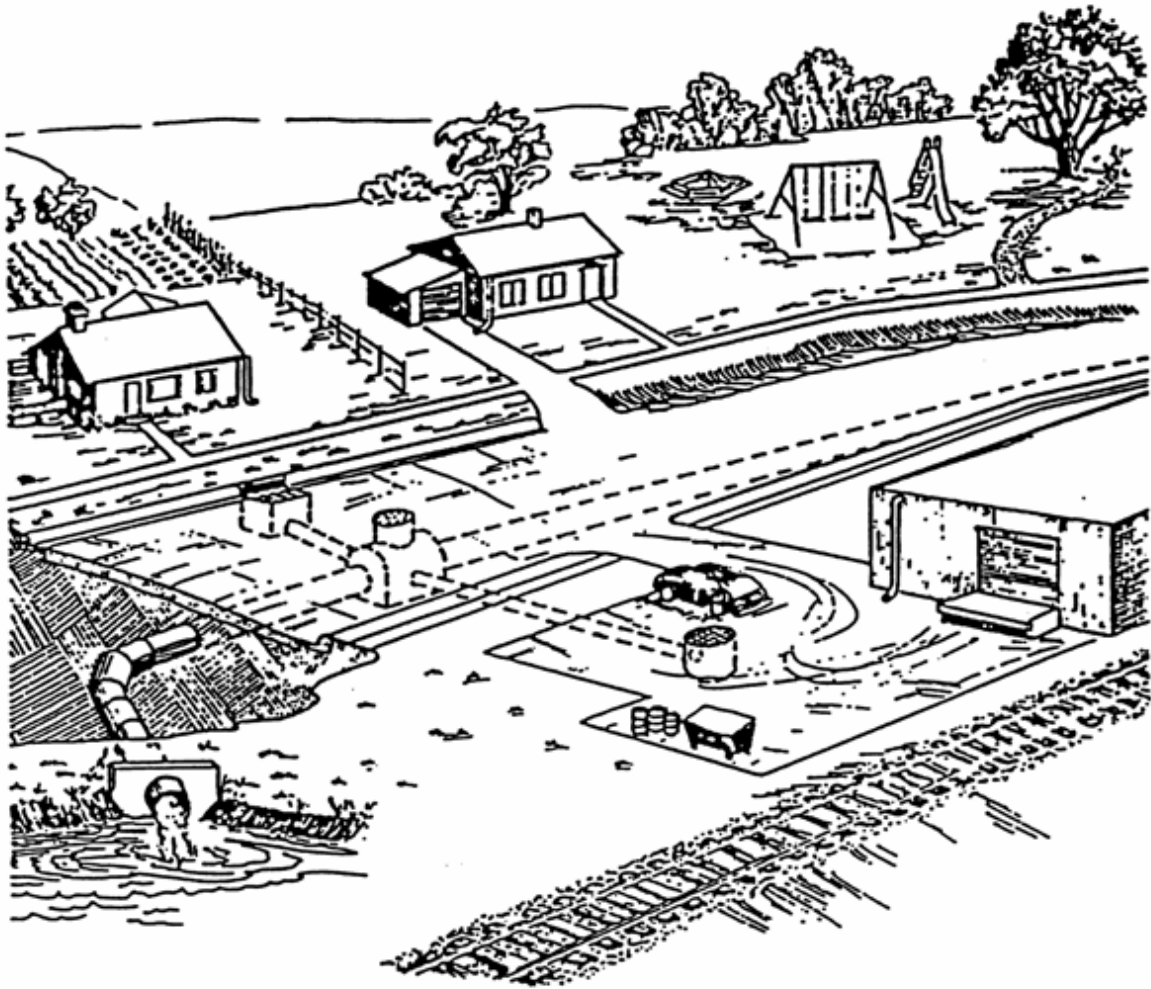
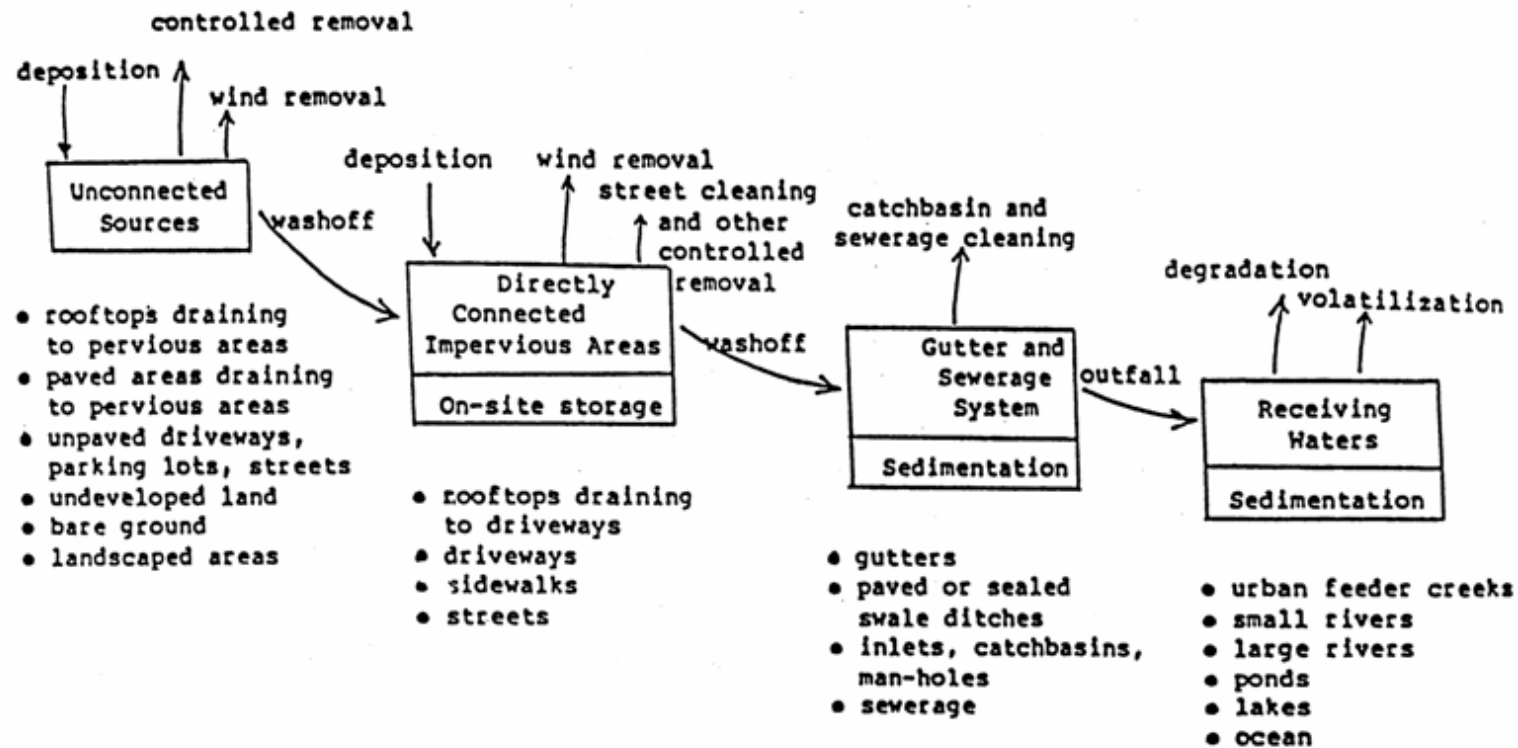**Figure 9-11. Urban runoff source areas and drainage alternatives (Pitt 1986).**

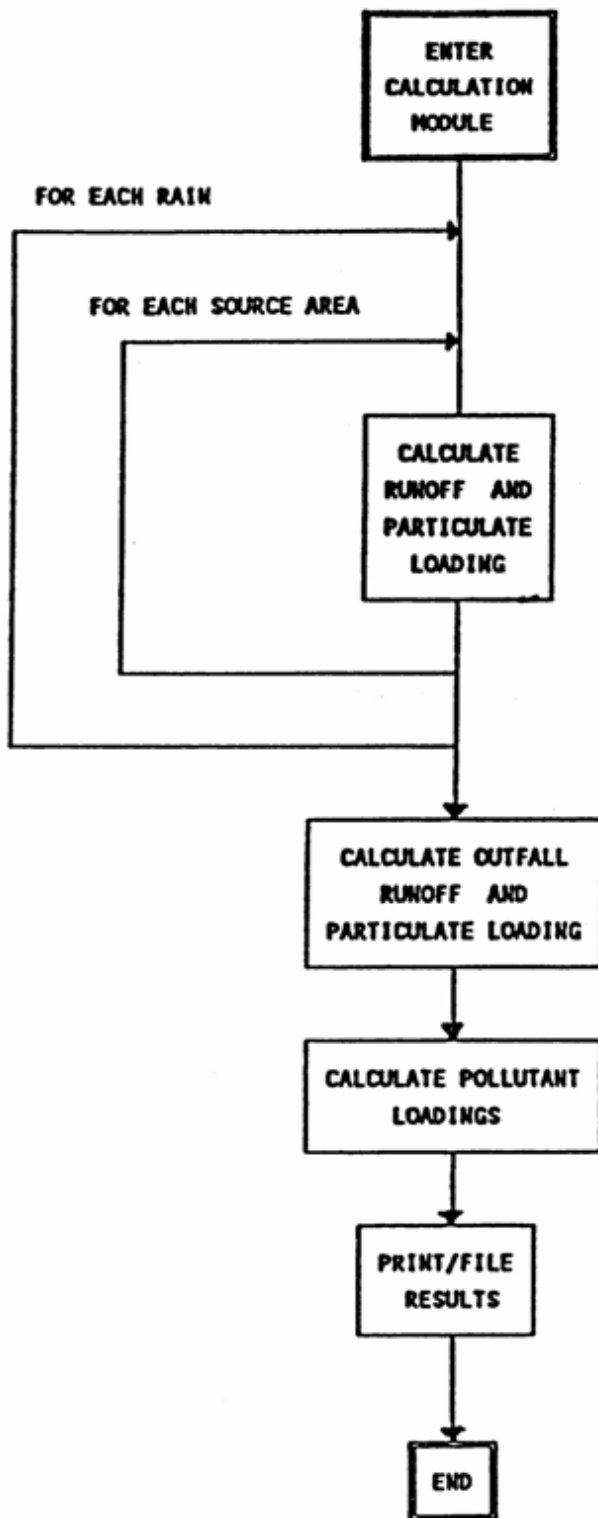**Figure 9-12. Pollutant deposition and removal at source areas (Pitt 1986).**

Figure 9-13. SLAMM calculation flow chart.

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

Monte Carlo Simulation of Pollutants Strengths Associated with Runoff from Various Urban Source Areas

Initial versions of SLAMM only used average concentration factors for different land use areas and source areas. This was satisfactory for predicting the event mean concentrations (EMC, as used by NURP, EPA 1983) for an extended period of time and in calculating the unit area loadings for different land uses. Figure 9-14 is a plot of the event mean concentrations at a Toronto test sites (Pitt and McLean 1986). The observed concentrations are compared to the SLAMM predicted concentrations for a long term simulation. All of the predicted EMC values are very close to the observed EMC values. However, in order to predict the probability distributions of the concentrations, it was necessary to include probability information for the concentrations found in the different source areas. Statistical analyses of concentration data (attempting to relate concentration trends to rain depths and season, for example) from these different source areas have not been able to explain all of the variation in concentrations that have been observed. The statistical analyses also indicate that most pollutant concentration values from individual source areas are distributed log-normally. Therefore, log-normally distributed random concentration values are used in SLAMM for these different areas. The result is much more reasonable predictions for concentration distributions at the outfall when compared to actual observed conditions. This provides more accurate estimates of criteria violations for different stormwater pollutants at an outfall for long continuous simulations.

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

Table 9-3 is a field sheet that has been developed to assist users of SLAMM describe test watershed areas. This sheet is mostly used to evaluate stormwater control retrofit practices in existing developed areas, and to examine how different new development standards effect runoff conditions. Much of the information on the sheet is not actually required to operate SLAMM, but is very important when considering additional control programs (such as public education and good housekeeping practices) that are not quantified by SLAMM. The most important information shown on this sheet is the land use, the type of the gutter or drainage system, and the method of drainage from roofs and large paved areas to the drainage system. The efficiency of drainage in an area, specifically if roof runoff or parking runoff drains across grass surfaces, can be very important when determining the amount of water and pollutants that enter the outfall system. Similarly, the presence of grass swales in an area may substantially reduce the amount of pollutants and water discharged. This information is therefore required to use SLAMM.

The areas of the different surfaces in each land use is also very important for SLAMM. Figure 9-15 is an example showing the areas of different surfaces for a medium density residential area in Milwaukee. As shown in this example, streets make up between 10 and 20 percent of the total area, while landscaped areas can make up about half of the drainage area. The variation of these different surfaces can be very large within a designated area. The analysis of many candidate areas may therefore be necessary to understand how effective or how consistent the model results may be for a general land use classification.

Tables 9-4 and Table 9-5 are coding sheets that have been prepared for SLAMM users. The information on these sheets is used by SLAMM to determine the concentrations and loadings from the different source areas and the effectiveness of different control practices. Table 9-4 shows general information describing the areas and the characteristics of source areas. More information is required for some source areas than others, based upon responses to questions. Table 9-5 contains the coding sheets to describe the types of control practices that are to be investigated using SLAMM in a specific watershed area. Control practices evaluated by SLAMM include infiltration trenches, seepage pits, disconnections of directly connected roofs and paved areas, percolation ponds,

street cleaning, porous pavements, catchbasin cleaning, grass swales, and wet detention ponds. These devices can be used singly or in combination, at source areas or at the outfalls or, in the case of grass swales and catchbasins, within the drainage system. In addition, SLAMM provides a great deal of flexibility in describing the sizes and other design aspects for these different practices.
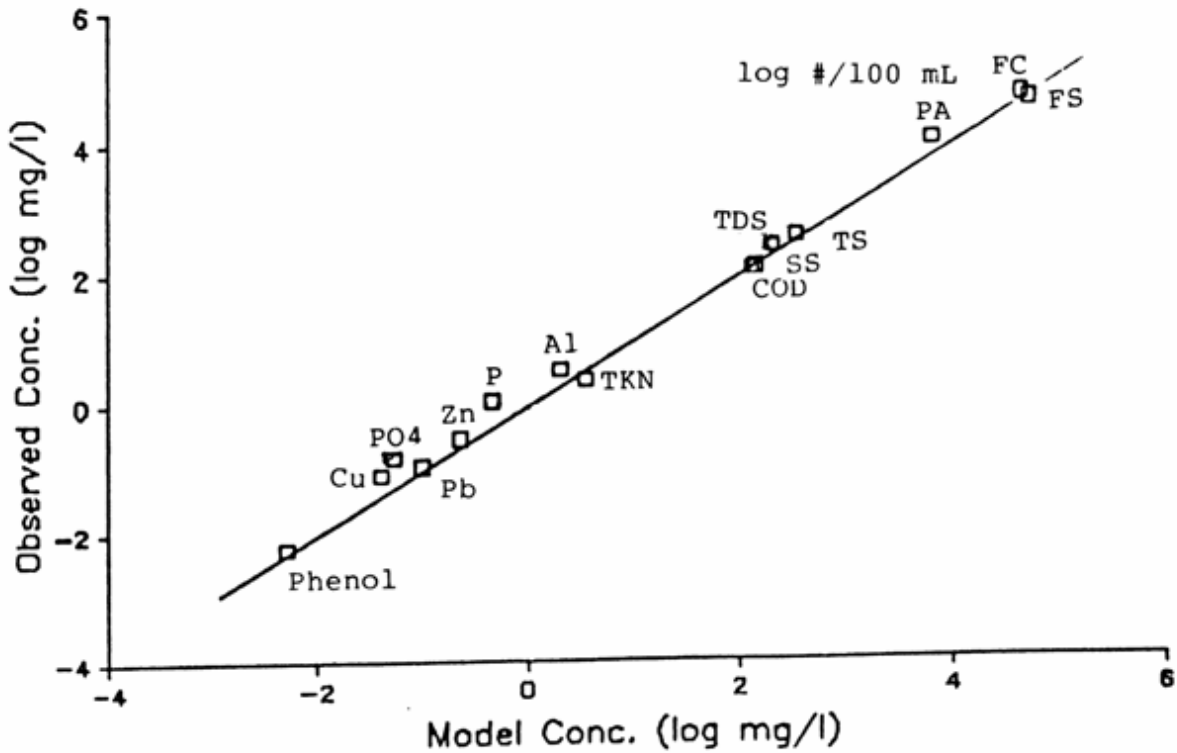

Figure 9-14. Observed and modeled outfall pollutant concentrations – Emery (industrial site) (Pitt 1987).

Table 9-3. Study Area Description Field Sheet

Location: Site number:
Date: Time:
Photo numbers: Roll number:
Land-use and industrial activity:
   Residential: low   medium   high density single family
                  multiple family
                  trailer parks
                  high rise apartments
      Income level: low medium high
      Age of development:<1930 '30-'50 '51-'70 '71-'80 new
   Institutional: school hospital other (type):
   Commercial: strip shop. center downtown hotel offices
   Industrial: light medium heavy(manufacturing) describe:
   Open space: undeveloped park golf cemetery
   Other: freeway   utility ROW   railroad ROW   other:
Maintenance of building: excellent   moderate   poor
Heights of buildings: 1   2   3   4+ stories
Roof drains: underground gutter   impervious   pervious
Roof types: flat   comp. shingle   wood shingle   other:
Sediment source nearby? No   Yes (describe):
Treated wood near street? No telephone poles fence other:
Landscaping near road:
      quantity: None   some   much
      type: deciduous   evergreen   lawn
      maintenance: excessive   adequate   poor
      leafs on street: none   some   much
Topography:
      street slope: flat (<1%) 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
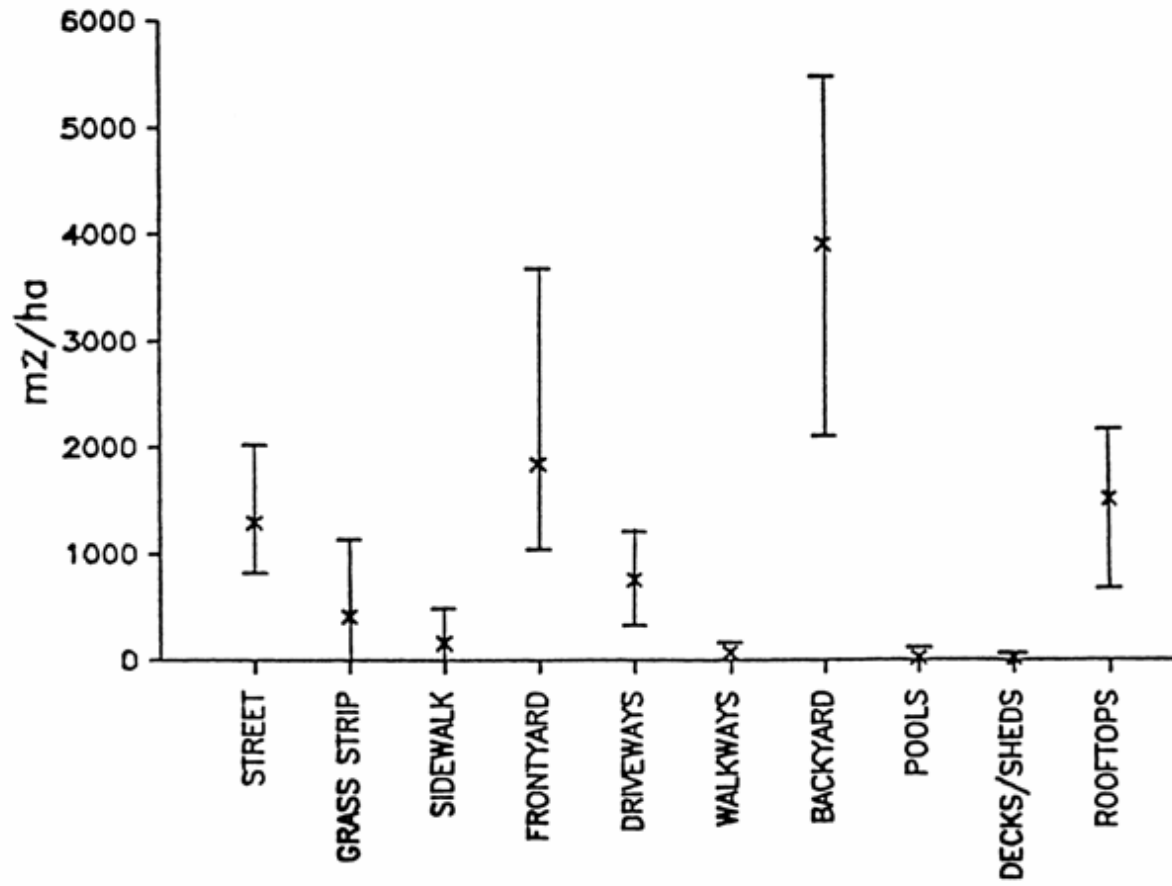   texture: smooth   intermediate   rough
Notes:

Figure 9-15. Source areas – Milwaukee medium density residential areas (without alleys) (Pitt 1987).

Table 9-4a. SLAMM Site Characterization Data Coding Sheet (Pitt and Voorhees 1995)

Nawres.dat: Medium Density Residential, 1961–1980 development, curbs & gutters, clayeys

Land Use: (Residential) / Institutional / Commercial / Industrial / Open Space

Source Area	Area (ac)						
Roofs 1	2.60	Flat/(Pitched)	(Dir Con)/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Roofs 2	6.05	Flat/(Pitched)	Dir Con/(Discon)	Soil: Sandy/(Clayey)	Density: Low/(Med) or High	Alleys: Yes/(No)	IWO
Roofs 3	_____	Flat/Pitched	Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Roofs 4	_____	Flat/Pitched	Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Roofs 5		Flat/Pitched	Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Paved Parking 1	_____		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Paved Parking 2	_____		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Paved Parking 3	_____		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Unpaved Parking 1	_____		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Unpaved Parking 2	_____		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWO
Playground 1	_____		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Playground 2			Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO
Driveways 1	1.19		(Dir Con)/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Driveways 2	1.18		Dir Con/(Discon)	Soil: Sandy/(Clayey)	Density: Low/(Med) or High	Alleys: Yes/(No)	PO
Driveways 3	_____		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Sidewalks 1	_____		Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Sidewalks 2			Dir Con/Discon	Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	PO
Strts/Alleys 1	6.58	2.73 curb-miles (40' wide)	Texture: Smth/(Int)/Rough/ V Rough	Accum: (Default)/A:___ B:___ C:___	Init Load:(Default)/ ___ lbs		S
Strts/Alleys 2	0.65	0.27 curb-miles (40' wide)	Texture: Smth/Int/(Rough)/ V Rough	Accum:(Default)/A:___ B:___ C:___	Init Load:(Default)/ ___ lbs		S
Strts/Alleys 3	_____	curb-miles	Texture: Smth/Int/Rough/ V Rough	Accum: Default/A: B: C:	Init Load: Default/ lbs		S
Lrg Landscapes 1	_____			Soil: Sandy/Clayey			IWO
Lrg Landscapes 2	_____			Soil: Sandy/Clayey			IWO
Undvlpd Area	4.59			Soil: Sandy/(Clayey)			IWO
Sml Landscapes 1	50.94			Soil: Sandy/(Clayey)			IO
Sml Landscapes 2	26.22			Soil: Sandy/(Clayey)			IO
Sml Landscapes 3	_____			Soil: Sandy/Clayey			IO
Isolated Area							
Other Pervious Area	_____			Soil: Sandy/Clayey			IWO
Other Directly Connected Area	_____						IWPO
Other Disconnected Area	_____			Soil: Sandy/Clayey	Density: Low/Med or High	Alleys: Yes/No	IWPO

Σ = 100.00

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Table 9-4b. SLAMM Site Characterization Data Coding Sheet (Pitt and Voorhees 1995)

Source Area	Area (ac)				Land Use: Freeways		
Paved Lanes/Shoulders 1	_____	Texture: Smth/Int/Rough/ V Rough	ADT: _____ veh/day	Highway Length: _____ miles	Init Load: Default/ ____ lbs	IWO
Paved Lanes/Shoulders 2	_____	Texture: Smth/Int/Rough/ V Rough	ADT: _____ veh/day	Highway Length: _____ miles	Init Load: Default/ ____ lbs	IWO
Paved Lanes/Shoulders 3	_____	Texture: Smth/Int/Rough/ V Rough	ADT: _____ veh/day	Highway Length: _____ miles	Init Load: Default/ ____ lbs	IWO
Paved Lanes/Shoulders 4	_____	Texture: Smth/Int/Rough/ V Rough	ADT: _____ veh/day	Highway Length: _____ miles	Init Load: Default/ ____ lbs	IWO
Paved Lanes/Shoulders 5	_____	Texture: Smth/Int/Rough/ V Rough	ADT: _____ veh/day	Highway Length: _____ miles	Init Load: Default/ ____ lbs	IWO
Large Turf Areas	_____	Soil: Sandy/Clayey				IWO
Undeveloped Areas		Soil: Sandy/Clayey				IWO
Other Pervious Area	_____	Soil: Sandy/Clayey				IWO
Other Directly Connected Area	_____					IWPO
Other Disconnected Area	_____	Soil: Sandy/Clayey		Density: Low/Med or High	Alleys: Yes/No	IWPO

Model Run Starting Date : 01 / 01 / 76

Model Run Ending Date: 12 / 31 / 76

Parameter File Names:

Rain File: BHAM 76 .RAN

Runoff Coefficient File: Runoff .RSV

Particulate Solids Concentration File: Part .PSC

Pollutant Relative Concentration File: Poll .PPD   Seed: 01 (5)

Particulate Residue Delivery File: Delivery .PRR

pollutants:
  particulate residue (suspended solids)
  filterable phosphate
  total lead

Table 9-5a. SLAMM Control Device Data Sheet (Pitt and Voorhees 1995)

Control Device for Land Use : ~~Medium Density Residential~~ ; Source Area: _____

File name: ~~Newres~~ .DAT

Infiltration Area or Trench: I
1.   Water percolation rate (in/hr):   _____ ⎫
2.   Area served by device (acres):   _____ ⎪   *total rooftop lender*
3.   Surface area of the device (ft^2):   _____ ⎬   *disconnections :*
4.   Width to Depth Ratio of the Device: _____ ⎭   *eliminate roof 1 .*
                                                          and increase "roof2"
                                                          to 8.65 acres

Street Cleaning ⓢ (*same for both street types*)
1.   Number of Street Cleaning Schedule Changes: *0*   Cleaning Schedule Code
2.   Start Cleaning Date   Cleaning Schedule No.   1.   None
        1 01 / 01 / 76   9 (*every 4 weeks*)   2.   7 Passes/wk
        2 ___/___/___   _____   3.   All weekdays
        3 ___/___/___   _____   4.   4 Passes/wk
        4 ___/___/___   _____   5.   3 Passes/wk
        5 ___/___/___   _____   6.   2 Passes/wk
        6 ___/___/___   _____   7.   1 Pass/wk
        7 ___/___/___   _____   8.   Every two weeks
        8 ___/___/___   _____   9.   Every 4 weeks
        9 ___/___/___   _____   10. Every 8 weeks
       10 ___/___/___   _____   11. Every 12 weeks
3.   Final Street Cleaning Date: 12 / 31 / 76
4.   Overall Street Cleaning Productivity:
        (Default) Cleaning Productivity:
                1.   Parking Density
                        1.   None
                        2.   (Light)
                        3.   Medium
                        4.   Extensive (short term)
                        5.   Extensive (long term)
                2.   Parking Controls: Yes / (No)
        User Defined Cleaning Productivity:
                m   Slope (less than 1): _____
                b   Intercept (greater than or equal to 1): _____

Porous Pavement   P
1.   Infiltration rate of pavement, base, or soil, whichever is the least (in/hr): _____
2.   Porous Pavement Area (acres):   _____

Other Flow or Pollutant Reduction Control   O
1.   Pollutant concentration reduction (fraction):   _____
2.   Water volume (flow) reduction (fraction):   _____
3.   Area served by other control (acres):   _____

Table 9-5b. SLAMM Control Device Data Sheet (Pitt and Voorhees 1995)

Catchbasin Cleaning   ⓒ
1. Total sump volume (ft^3):   950
2. Area served by other control (acres):   100
3. Percentage of sump volume which is
      full at beginning of study period (0 to 100)   30
4. Number of times catchbasin cleaned during
      study period (0 - 5 times):   2
5. Date each time catchbasin is cleaned:
    1 02/ 15 / 76
    2 08/ 15 / 76
    3 ___/___/___
    4 ___/___/___
    5 ___/___/___

Grass Swales   Ⓖ
1. Swale infiltration rate (in/hr):   0.5
2. Swale density (ft/acre):   350
3. Wetted swales width (ft):   3.5
4. Area served by swales (acres):   100

Other Flow or Pollutant Reduction Control at the Outfall   O
1. Particulate Residue Reduction due to rainfall delivery (fraction)

Rain (mm)	Particulate Reduction	Rain (mm)	Particulate Reduction
1	_____	25	_____
2	_____	30	_____
3	_____	40	_____
5	_____	50	_____
10	_____	60	_____
15	_____	70	_____
20	_____	80	_____

2. Water volume (flow) reduction (fraction):   _____
3. Area served by other control (acres):   _____

Drainage System Type   **Fraction of Total Area**
1. Grass Swales: _____
2. Undeveloped roadside: _____
3. Curbs and gutters in poor condition (or flat):   _____
4. Curbs and gutters in fair condition: 1 (except for grass swale test)
5. Curbs and gutters in good condition (or steep):   _____

Table 9-5c. SLAMM Control Device Data Sheet (Pitt and Voorhees 1995)

Wet Detention Ponds $\widehat{D}$

Diagram Outlet Structure in Space Below
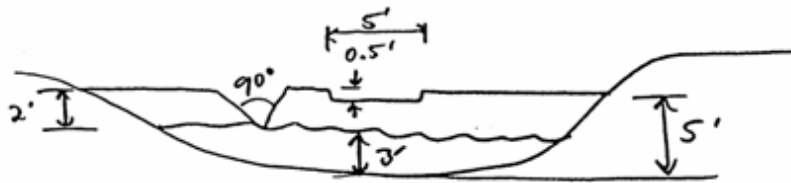
100 acres served

Medium·cpz particle size distribution file

1. Initial Stage Elevation (feet) above datum: _____3_____
2. Number of stage elevation increments required: _____5_____
3. Total number of outlets (maximum: 10): _____2_____
4. Stage, pond area, seepage, and other outlet information:

Entry Number	Stage (ft)	Pond Area (acres)	Natural Seepage (cfs)	Other Outflow (cfs)
0	0.0	0.0	0.0	0.0
1	1	0.1		
2	2	0.2		
3	3	0.5		
4	4	0.7		
5	5	0.9		
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				
25				
26				
27				
28				
29				
30				

Table 9-5d. SLAMM Control Device Data Sheet (Pitt and Voorhees 1995)

Wet Detention Ponds (continued)

5. **Outlet Characteristics**
   1. Rectangular Weir
      1. Weir length (ft) : ___5 ft___
      2. Height from bottom of weir opening (invert) to top of weir: ___0.5 ft___
      3. Height from datum to bottom of weir opening (invert) (ft): ___4.5 ft___
   2. V-Notch Weir
      A) Weir angle
         1. 22.5 degrees
         2. 30 degrees
         3. 45 degrees
         4. 60 degrees
         ⑤ 90 degrees
         6. 120 degrees
      B) Height from bottom of weir opening (invert) to top of weir: ___2 ft___
      C) Height from datum to bottom of weir opening (invert) (ft): ___3 ft___
   3. Orifice
      1. Orifice diameter (ft): _____
      2. Invert elevation above datum (ft): _____
   4. Seepage Basin characteristics
      1. Infiltration rate (in/hr): _____
      2. Width of device (ft): _____
      3. Length of device (ft): _____
      4. Invert elevation of seepage basin inlet above datum (ft): _____
   5. Monthly Evaporation Rate

Month Number	Month	Evaporation (in/day)
1	January	_____
2	February	_____
3	March	_____
4	April	_____
5	May	_____
6	June	_____
7	July	_____
8	August	_____
9	September	_____
10	October	_____
11	November	_____
12	December	_____

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One of the first problems in evaluating an urban area for stormwater controls is the need to understand where the pollutants of concern are originating under different rain conditions. Figures 9-16 through 9-19 are examples for a typical medium density residential area (described in the previous coding sheets) showing the percentage of different pollutants originated from different major sources, as a function of rain depth. As an example, Figure 9-16 shows the areas where water is originating. For storms of up to about 0.1 inch in depth, street surfaces contribute about one-half to the total runoff to the outfall. This contribution decreased to about 20 percent for storms greater than about 0.25 inch in depth. This decrease in the significance of streets as a source of water is associated with an increase of water contributions from landscaped areas (which make up more than 75% of the area and have clayey soils). Similarly, the significance of runoff from driveways and roofs also starts off relatively high and then decreases with increasing storm depth. Figures 9-17, 9-18 and 9-19 are similar plots for suspended solids, phosphorus and lead. These show that streets contribute almost all of these pollutants for the smallest storms up to about 0.1 inch. The contributions from landscaped areas then become dominant. Figure 9-19 shows that the contributions of phosphates are more evenly distributed between streets, driveways, and rooftops for the small storms, but the contributions from landscaped areas completely dominate for storms greater than about 0.25 inch in depth. Obviously, these are just example plots and the source contributions would vary greatly for different land uses/development conditions, rainfall patterns, and the use of different source area controls.
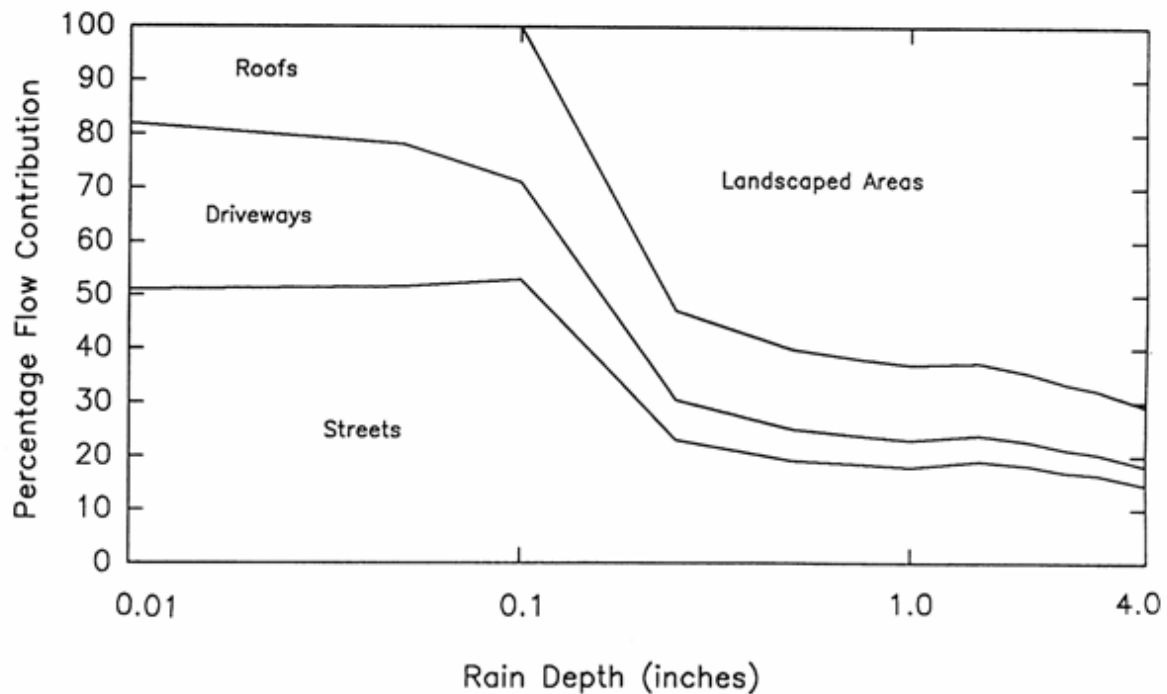

Figure 9-16. Flow sources for example medium density residential area having clayey soils (Pitt and Voorhees 1995).
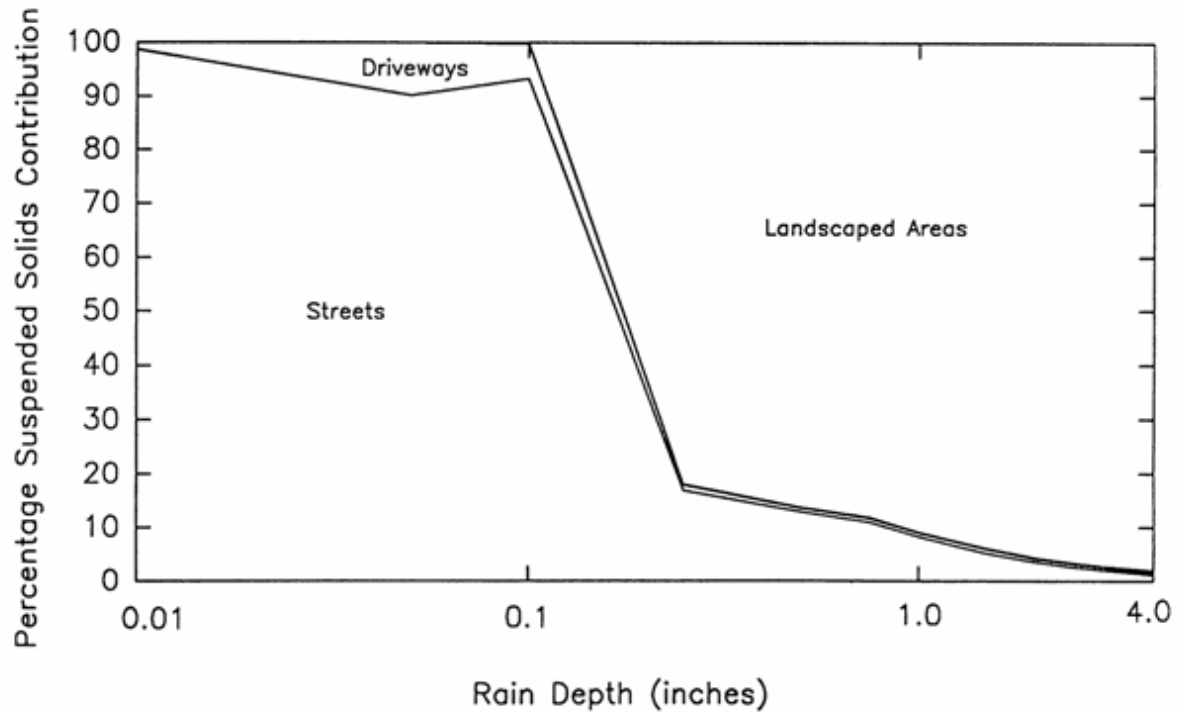
Figure 9-17 Suspended solids sources for example medium density residential area having clayey soils (Pitt and Voorhees 1995).
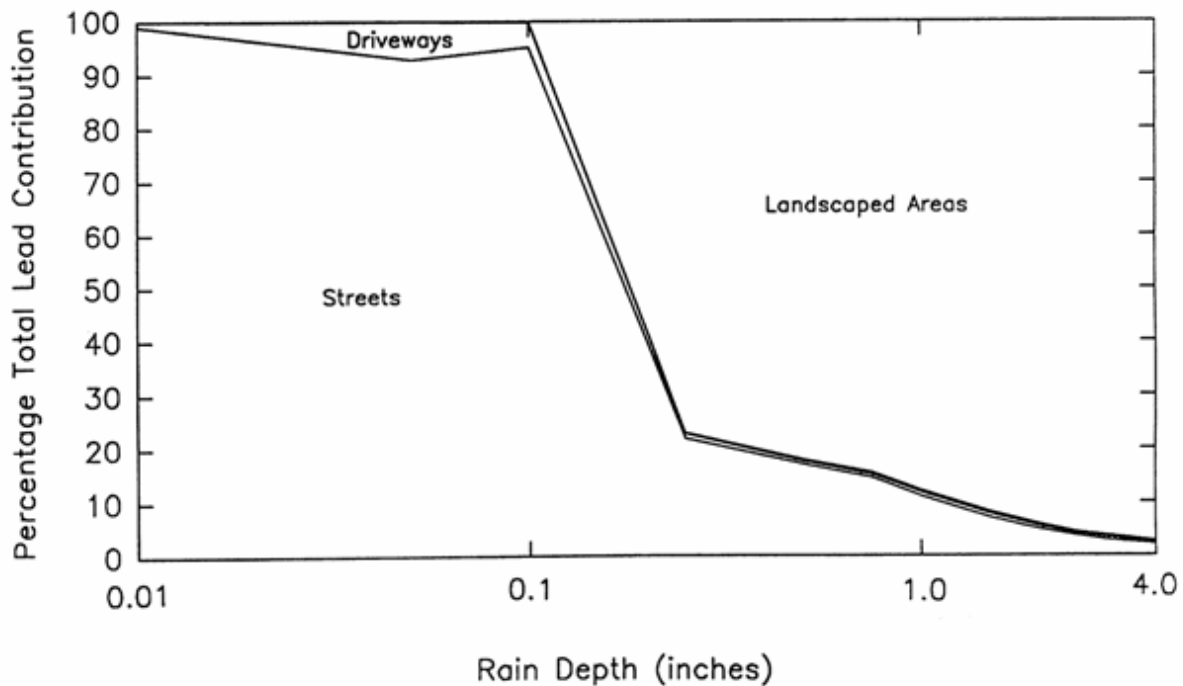

Figure 9-18 Total lead sources for example medium density residential area having clayey soils (Pitt and Voorhees 1995).
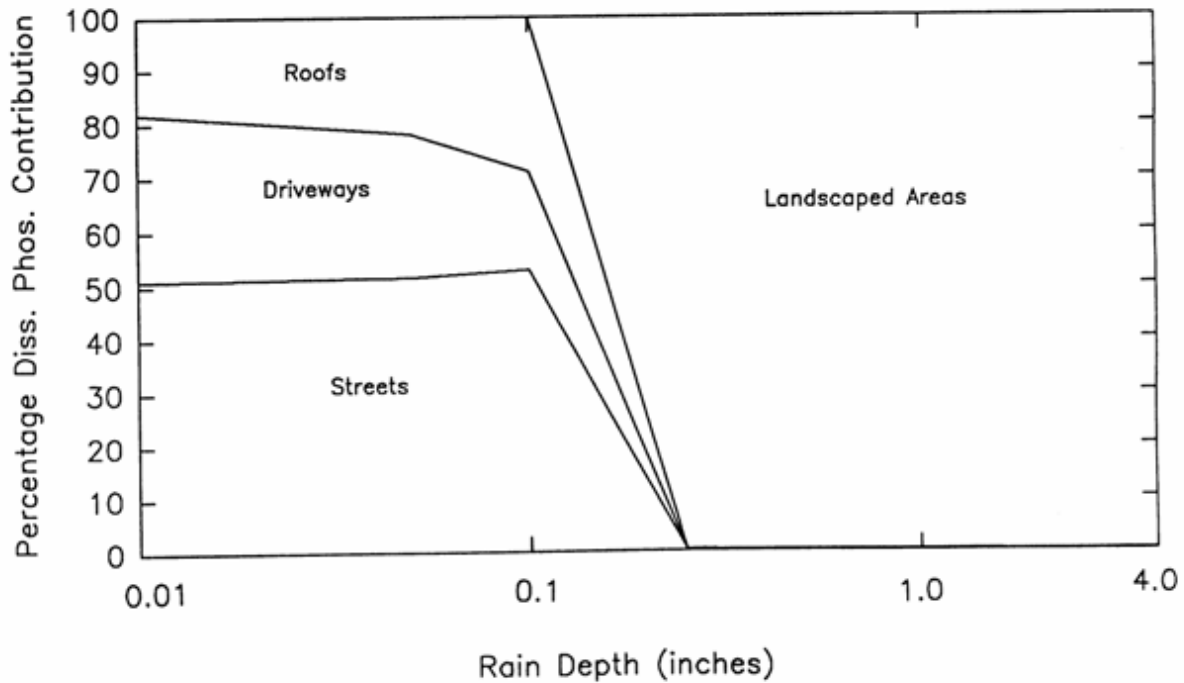
Figure 9-19 Dissolved phosphate sources for example medium density residential area having clayey soils (Pitt and Voorhees 1995).

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

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

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

areas and at outfalls. Besides those controls examined individually, catchbasin and street cleaning controls combined were also evaluated, in addition to the combination of disconnecting some of the rooftops and the use of grass swales. Finally, all of the controls together were also examined.

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

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

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

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

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

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

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

An outfall wet detention pond suitable for 100 acres of this medium density residential area would have a wet pond surface of 0.5% of drainage area to provide about 90% suspended solids control. It would need 3 ft. of dead storage and live storage equal to runoff from 1.25" rain. A 90° 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 9-6 summarizes the SLAMM results for runoff volume, suspended solids, filterable phosphate, and total lead for 100 acres of this medium density residential area. The only control practices evaluated that would reduce runoff volume are the grass swales and roof disconnections. All of the other control practices evaluated do not infiltrate stormwater. Table 9-6 also shows the total annual average volumetric runoff coefficient (Rv) for these different options. The base level of control has an annual flow-weighted Rv of about 0.3, while the use of swales would reduce the Rv to about 0.1. Only a small reduction of Rv (less than 10 percent) would be associated with complete roof disconnections compared to the existing situation because of the large amount of roof disconnections that already occur. The suspended solids analyses shows that catchbasin cleaning alone could result in about 14 percent suspended solids reductions. Street cleaning would have very little benefit, while the use of grass swales would

reduce the suspended solids discharges by about 60 percent. Grass swales would have minimal effect on the reduction of suspended solids concentrations at the outfall (they are primarily an infiltration device, having very little filtering benefits). Wet detention ponds would remove about 90 percent of the mass and concentrations of suspended solids. Similar observations can be made for filterable phosphates and lead.

Table 9-6 SLAMM Predicted Runoff and Pollutant Discharge Conditions for Example[1] (Pitt and Voorhees 1995)

Birmingham 1976 rains: (112 rains, 55 in. total 0.01-3.84 in. each)	Runoff Volume		CN range	Suspended Solids		Filterable Phosphate		Total Lead	
	annual ft3/acre	flow-wtg. Rv		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) ($85/acre/yr)	N/A				0.43		N/A		293
Street cleaning	59800	0.3	77-100	385	1430	157	0.58	543	2.0
reduction (lbs or ft3)	0				0		0		0.01
reduction (%)	0			0	0	0	0	0	0.49
cost ($/lb or $/ft3) ($30/acre/yr)	N/A				N/A		N/A		3000
Grass swales	23300	0.12	63-100	380	554	151	0.22	513	0.75
reduction (lbs or ft3)	36500				876		0.36		1.28
reduction (%)	61			1	61	4	62	6	63
cost ($/lb or $/ft3) ($minimal/acre/yr)	minimal				minimal		minimal		minimal
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) ($10/acre/yr)	0				N/A		333		21
Wet detention pond	59800	0.3	77-100	49	185	157	0.58	69	0.26
reduction (lbs or ft3)	0				1250		0		1.8
reduction (%)	0			87	87	0	0	87	87
cost ($/lb or $/ft3) ($130/acre/yr)	N/A				0.10		N/A		73
CB & street cleaning	59800	0.3	77-100	331	1230	157	0.58	468	1.7
reduction (lbs or ft3)	0				200		0		0.29
reduction (%)	0			14	14	0	0	14	14
cost ($/lb or $/ft3) ($115/acre/yr)	N/A				0.58		N/A		397
Roof dis. & swales	20900	0.1	63-100	403	526	139	0.18	352	0.46
reduction (lbs or ft3)	38900				904		0.40		1.6
reduction (%)	65			-5	63	11	69	35	77
cost ($/lb or $/ft3) ($10/acre/yr)	0.00026				0.01		25		6.4
All above controls	20900	0.1	63-100	42	55	139	0.18	36	0.05
reduction (lbs or ft3)	38900				1375		0.40		1.98
reduction (%)	65			89	96	11	69	93	97
cost ($/lb or $/ft3) ($255/acre/yr)	0.0066				0.19		638		129

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

Figures 9-20 through 9-23 show the maximum percentage reductions in runoff volume and pollutants, along with associated unit removal costs. As an example, Figure 9-20 shows that roof disconnections would have a very small potential maximum benefit for runoff volume reduction and at a very high unit cost compared to the other practices. The use of grass swales could have about a 60 percent reduction at minimal cost. The use of roof disconnection plus swales would slightly increase the maximum benefit to about 65 percent, at a small unit cost. Obviously, the use of roof disconnections alone, or all controlled practices combined, are very inefficient for this example. For suspended solids control, catchbasin cleaning and street cleaning would have minimal benefit at high cost, while the use of grass swales would produce a substantial benefit at very small cost. However, if additional control is necessary, the use of wet detention ponds may be necessary at a higher cost. If close to 95 percent reduction of suspended solids were required, then all of the controls investigated could be used together, but at substantial cost.
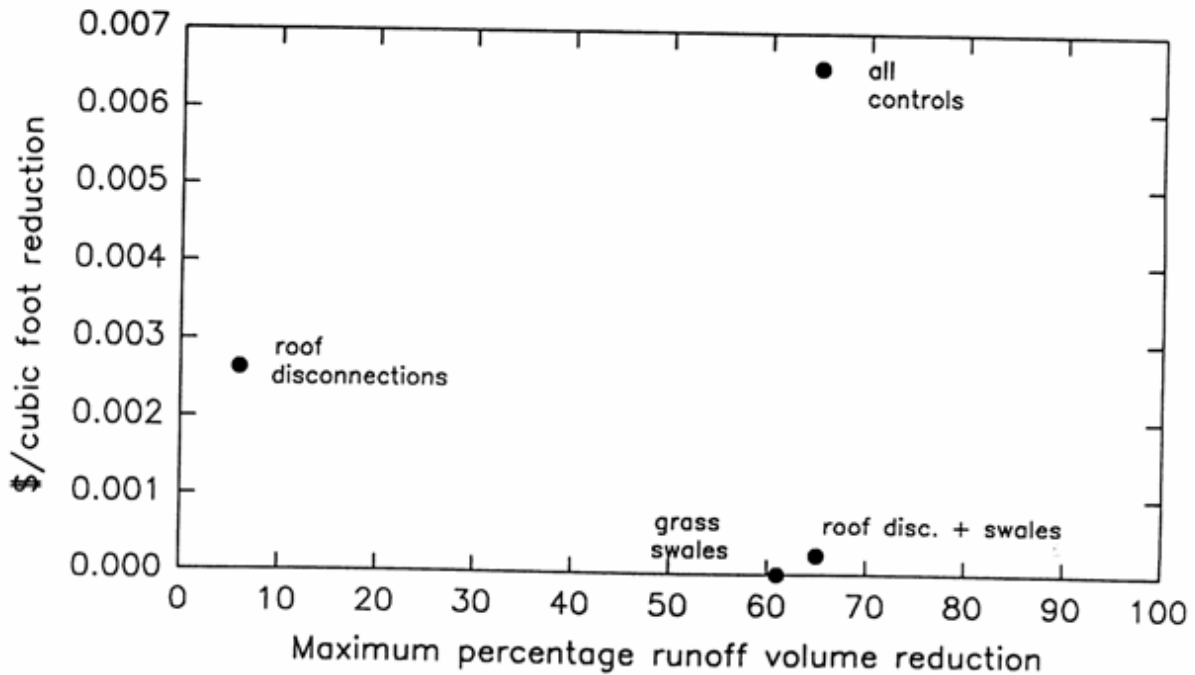

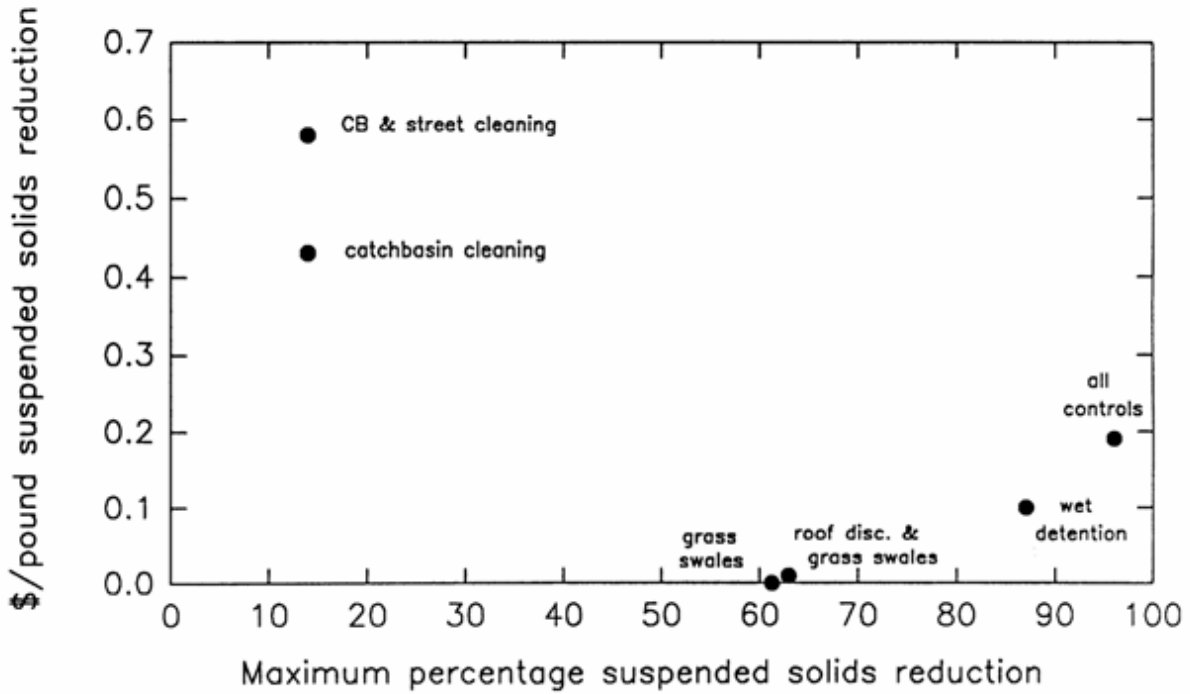**Figure 9-20. Cost-effectiveness data for runoff volume reduction benefits (Pitt and Voorhees 1995).**

Figure 9-21. Cost-effectiveness data for suspended solids reduction benefits (Pitt and Voorhees 1995).
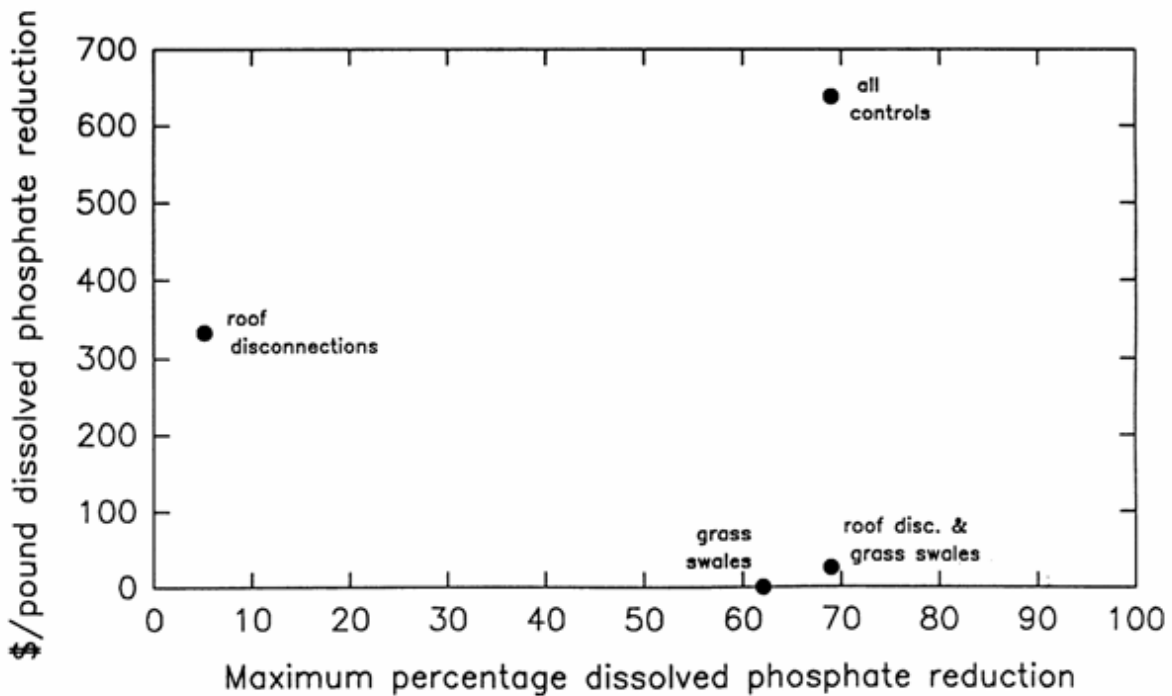

Figure 9-22. Cost-effectiveness data for dissolved phosphate reduction benefits (Pitt and Voorhees 1995).
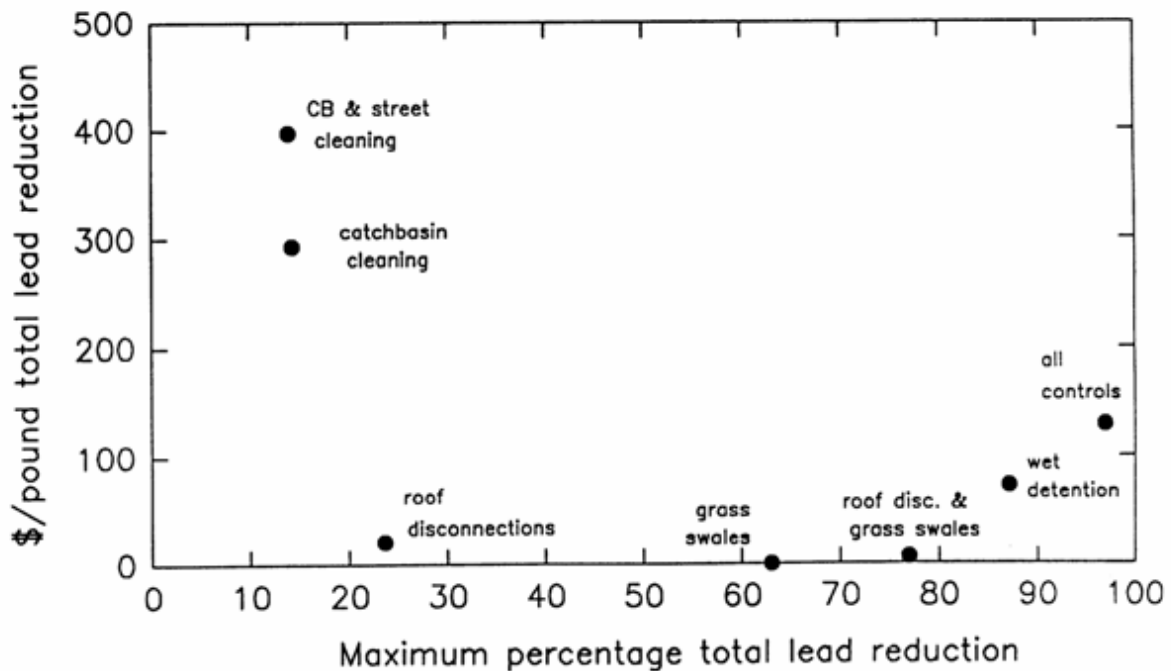
Figure 9-23. Cost-effectiveness data for total lead reduction benefits (Pitt and Voorhees 1995).

SLAMM/SWMM Interface Program
Introduction
The purpose of the SLAMM-SWMM Interface Program (SSIP) is to allow the user to replace SWMM's RUNOFF Block with SLAMM. This allows SLAMM to provide the runoff and pollutant loads for input into the TRANSPORT or EXTRAN Blocks of SWMM, instead of using results from the RUNOFF Block. Using SLAMM better accounts for small storm processes and adds greater flexibility in evaluating source area flow and pollutant controls. The interface program manipulates the output from SLAMM so that it is acceptable for SWMM. The principal manipulation is to convert the event volumes and loads into event hydrographs and pollutographs.

The version of the SLAMM-SWMM Interface Program presented here is Version 1. 1. This version has not reached the full potential envisioned for the program. This is discussed later. It is assumed that the reader is familiar with both SLAMM and SWMM and has the appropriate documentation.

SSIP Version 1.0
An early version of the SLAMM-SWMM Integration Program was developed to work with SWMM Windows provided by the US Environmental Protection Agency (based on SWMM Version 4.3, USEPA, 1995). This was used to create SSIP Version 1.1, which is deigned for use with all SWMM 4 sub-versions.

SSIP Version 1.1
SSIP Version 1.1 takes hydrographs and pollutographs from SLAMM and partially prepares input hydrographs for use in the SWMM EXTRAN Block and input hydrographs and pollutographs for the SWMM TRANSPORT Block. *However, at this time SSIP has only been tested in the preparation of hydrographs for SWMM EXTRAN.*

SLAMM currently has the option of producing source area hydrographs and pollutographs over continuous periods. Each location is produced as a separate file. The format for these files is as follows:

- First Line = subcatchment number (defined in SLAMM)
- Second Line = labels for each column in "quotation marks", separated by commas
- Third Line = Values separated by commas, no spaces (e.g., time,flow,pollutant,pollutant,)
- NOTE: The time increments used in each file must be identical (e.g., 1, 1.5, 2, … must be the same for each file).

These files are converted into files appropriate for SWMM. However, at this time, the user must manually manipulate some of these converted files for actual use in SWMM. The SLAMM/SWMM Interface Program Version 1.1 is Windows-based and is programmed in Visual Basic. A new version is currently being prepared that will further minimize the needed user manipulation.

How SSIP Works
1. SSIP goes through each SLAMM hydrograph/pollutograph file, one at a time, in the directory chosen by the user. These files have the extension *.hyd.

2. SSIP then creates the files for SWMM (*.hp1, *.hp2, and*.hp3 for TRANSPORT and *.hp4 for EXTRAN).

3. Next, it reads the second hydrograph/pollutograph file and appends the information to the first files that were created. This will be done for all files with the extension *.hyd. So it is important that only the files desired are located in the directory.

4. When there are no more SLAMM files left, the user gets a message that the file conversions are completed.

Interface Program Instructions
The instructions below are illustrated with a series of files provided with the disk that accompanies this report. These files are referred to throughout this section in order to illustrate the process for executing SSIP and creating useable hydrograph files for SWMM EXTRAN. (Recall that this is the only application of SSIP that has been tested to date.) All of the needed SLAMM and SSIE files are installed in a single directory when the files are installed (from the attached disks having zipped filed).

1 . The user begins by opening the file "Interface1.exe" provided on the disk. A series of dialog boxes will then appear. Instructions for each dialog box appear with that box. The dialog boxes are discussed below:

- A start-up box. This box starts the program.
- A file location box (to identify where the SLAMM files are and where the SWMM files are to be placed.) At this time, SSIP seems to work best if all file operations (including the execution of SIPP) are carried out under the same directory. Set the SLAMM file locator to the directory to which you placed the contents of the supplied disk (this is where the SLAMM files are located). For this application there are three files, associated with each of three locations for which SLAMM produced hydrographs and pollutographs. These three locations will be input to SWMM. Set the SWMM file locator to the same directory.
- A SWMM Block selection box (i.e. for which SWMM Block files are to be produced). The TRANSPORT option has not been tested. Use only the EXTRAN option at this time. Select the EXTRAN option.
- A "process complete" box informing the user that the SWMM files have been created.

2. Once the processing is complete, as many as four files (*.hp 1, *.hp2, and *.hp3 for TRANSPORT and *.hp4 for EXTRAN) will have been produced. These files need to be manually placed in a SWMM system input file produced by the user. (The term "system input file" is meant to describe the file that describes the drainage system.) An example system input file is included on the disk as "extrn001.run". This file is associated with

Example 1 in the SWMM EXTRAN Block users manual (Roesner, *et al*. 1988). Be sure it is on the directory you created on your hard drive.

The SWMM system input file will need to be modified before SWMM can be executed. For the most part, this requires the user to modify and then merge the file created by SSIP with the SWMM system input file. Open the file named "usehp001.hp4" with any text editor. (The "001" indicates that this is the first time a file was created. If you repeated this operation, a file called "usehp002.hp4" would be produced.) Then do the following:

- Remove the first line that simply says "3".
- On the line labeled "K2", replace the three alphanumeric labels (in quotes) with 82309, 80408, and 81009 (no quotes), respectively. These are the three locations in SWMM to which the SLAMM produced flows are being directed (see Example 1 in the SWMM EXTRAN users manual).
- Resave this file.

Open the example SWMM system input file "extrn001.run" with any text editor. Then do the following:

- Optional: change the value 1440 to some other appropriate value. This is the number of time steps. The number of time steps multiplied by the computational time step length (the value 20 to the right of the number of time steps), in seconds, must be equal to or shorter than the time represented by the flow history provided by SLAMM. In this case, the example SLAMM files covers 365 hours, or 1,314,000 seconds. The hydrograph time step is 2.5 minutes. (The computational time step and the flow time step do not have to be the same.)
- Replace the lines labeled "K3" with the file "usehp001.hp4". Be sure that the "$ENDPROGRAM" line is the last line in the resulting file. The K3 lines in EXTRAN are the hydrographs to input to the sewer system, with each line representing a different point in time.
- Resave this file.

3. Execute SWMM with the modified "extrn001.run" file. You can follow this process with any sub-version of SWMM Version 4.

Limitations and Caveats
SSIP takes all the SLAMM files from the directory chosen by the user and converts them. If there are SLAMM files (i.e., those with the extension *.HYD) in the directory chosen by the user that are not to be included in the conversion, it is suggested that the user delete or move these files before running the Interface Program.

SSIP does not run on Windows NT because of file permissions. It is designed to run under Windows 95 or Windows 98. SSIP may work under other operating systems, but these have not been tested or supported.

Future Versions
Work is continuing on making SSIP much more user friendly and efficient. In its present form, the user is far too involved in file manipulation. Future versions will also transfer information through the more efficient and automated interface mechanisms found in SWMM (see Section 2 of the SWMM user's manual, Huber, *et al*. 1988) rather than through the user-prepared system input files. Location matching will also be part of SSIP (as opposed to the manual matching done now). These changes will make the interface effort much more seamless for the user.

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