“Low Impact Development” Calculations using the Source Loading and Management Model (WinSLAMM)

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Introduction

WinSLAMM, the Source Loading and Management Model was developed starting in the mid-1970’s as part of early EPA street cleaning and receiving water projects in San Jose (Pitt 1979) and Coyote Creek (CA) (Pitt and Bozeman 1983). The primary purpose of the model is to identify sources of urban stormwater pollutants and to evaluate the efficiency of control practices. During the mid-1980s, the model was expanded to include more management options beyond street cleaning. The Nationwide Urban Runoff Program (NURP) projects (EPA 1983) provided a large data set for model, especially, Alameda Co. CA (Pitt and Shawley 1982); Bellevue, WA (Pitt and Bissonnette 1984); and Milwaukee, WI (Bannerman, et al 1983). Research funded by the Ontario Ministry of the Environment (Ottawa) (Pitt 1987) and the Toronto Area Watershed Management Strategy study in the Humber River (Pitt and McLean 1986) also provided much information on bacteria sources in urban areas. During the mid-1980s, the model started to be used by the Wis. Dept. of Natural Resources in their Priority Watershed Program (Pitt 1986). The first Windows version of the model was developed in 1995 and the current version is 9.4, with a major update (version 10) to be released in the near future. The model is continuously being updated based on user needs and new research (recent and current support from Stormwater Management Authority of Jefferson County, AL; the TVA, Economic Development group; WI DNR; the USGS; Contech Stormwater Solutions; and Hydro-International). The new version 10 currently being finalized will include drag and drop watershed elements and more complete flow and particle size routing components.

Over the years, WinSLAMM has been extensively revised and expanded and now includes a wide range of capabilities. The following lists several important model features:

- The model can evaluate a long-series of rain events, usually one to five years of typical rains are used, but several decades of rains can be evaluated
- The model is based on actual field data. Street dirt accumulation and washoff equations and direct runoff from paved surfaces during all rains are used, for example, based on many thousands of actual measurements.
- The effects of compacted urban soils are also considered
- Uncertainties of many modeling parameters are represented by built-in Monte Carlo components
- Costs of control practices can be directly calculated and considered in model runs
- Runoff flow-duration probability distributions and associated receiving water biological conditions are calculated based on site conditions and the control measures being used
- The model can be interfaced with several other models for more detailed drainage system and receiving water evaluations.

Prior descriptions of WinSLAMM have been presented during the earlier Engineering Foundation and in the Urban Water Modeling Conference series, and in other publications (Pitt 1986; 1997; 1999; Pitt and Voorhees 2002 for example). The model web site (http://www.winslamm.com/) also contains further model descriptions and references.

The effectiveness of the control practices in WinSLAMM are calculated based on the actual sizing and other attributes of the devices, the source area or outfall location characteristics, and the calculated runoff characteristics. The model does a complete mass balance and routing of water volume and particulate mass, considering the combined effects of all controls. Hydraulic and particle size routing occurs for each device individually, and serial effects of multiple devices are being expanded for these parameters in the new model 10 version. The effects of the sedimentation controls are calculated using modified Puls hydraulic routing with surface overflow rate particulate routing. The performance of wet ponds have been verified by extensive monitoring of several ponds (WI DNR and USGS, with extensive documentation at: http://unix.eng.ua.edu/~rpitt/SLAMMDETPOND/WinDetpond/WinDETPOND%20user%20guide%20and%20documentation.pdf). The infiltration and biofiltration devices use a combination of hydraulic routing with infiltration and evaporation losses, plus any pumped withdrawals, and have been verified using both small and large-scale field tests conducted by the USGS (Selbig, et al 2008 and 2010), and on-going Kansas City EPA demonstration projects (Pitt and Voorhees 2010 and Struck 2009), for example. Evapotranspiration losses are being added to the devices in the next model update. Underdrain filtering is based on extensive tests of media filtration (Pitt, et al. 2010, Silehsi, et al. 2010a and 2010b) . Grass swale performance is calculated based on extensive laboratory and outdoor testing of particulate trapping of shallow flowing water and infiltration losses (Kirby 2005; Johnson, et al. 2003; Nara and Pitt 2005). Porous pavement performance is calculated based on infiltration losses and clogging effects. Street cleaning and catchbasin benefits are based on extensive EPA research, and newer updated research that have examined modern equipment. Hydrodynamic devices are based on the basic sedimentation processes, but have been verified by tests conducted by the USGS and the DNR, plus continued tests at the University of Alabama.

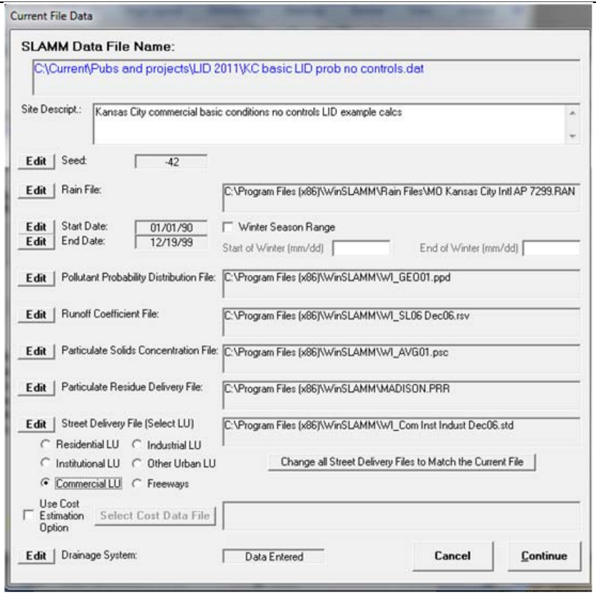
As noted, WinSLAMM conducts a continuous water mass balance for every storm in the study period. As an example, for rain barrels, water tanks or cisterns, capturing roof runoff, the model fills the available storage during rains. Between rains, the storage tank is drained according to the water demands for each month. If the tank is almost full from a preceding close rain (and not enough time was available to drain the storage tank), excess water from the event would be discharged to the drainage system after the tank fills. Curb-cut rain gardens/biofilters along a street are basically a cascading swale system where the site runoff is allowed to infiltrate. If the runoff volume is greater than the capacity of the rain gardens, the excessive water is discharged into the drainage system. When evaluated together, the cisterns treat the roof runoff first, but the excess water is discharged to the curb-cut rain gardens for infiltration. The continuous simulation drains the devices between events, depending on the interevent conditions.

Calculation Examples for Low Impact Development Components

The main purpose of this paper is to illustrate how WinSLAMM uses site information to examine the performance of various components commonly used in low impact developments, or in conservation design. Montalto and Lucas, in a parallel paper at this conference, describe the site conditions and stormwater controls being examined by a selection of different stormwater models. In this paper demonstrating WinSLAMM, site meteorological conditions appropriate for Kansas City, MO, were used

Basic Setup for Site Characteristics

The first step in setting up a WinSLAMM analysis is to identify the rain and the calibrated parameter files to be used, as shown in Figure 1. The rain file describes the series of rains to be considered in the analysis. In this example, the Kansas City rain file was selected. The 10 years of rains from 1990 through 1999 are selected from the complete series. During this period, 920 rains occurred that were 0.01 inches in depth, or larger. The largest rain observed in this period was 3.79 inches. WinSLAMM has an utility that assists in the creation of rain files from NOAA data sources. EarthInfo (Santa Monica, CA) CDs of these data are most convenient, for example, having many decades of rainfall records from throughout the US. Figure 1 also shows several other selections for the calibrated parameter files. These describe the rainfall-runoff relationships for the different source areas for the different land uses. These relationships are based on the small storm hydrology concepts described by Pitt (1987) and summarized in a chapter in the urban water systems modeling monograph series (Pitt 1999). The pollutant probability distribution files and the particulate solids concentration files are based on field data, also summarized by Pitt, et al (2005a and 2005b) in chapters published in the urban water systems modeling monograph series. These files contain probability distributions of the expected particulate bound pollutant concentrations and the filtered pollutant concentrations for the different source areas. Monte Carlo sampling methods can be optionally used to randomly vary these characteristics for different events, as observed during field monitoring. The street dirt accumulation and washoff mechanisms are specifically modeled, as described by Pitt (1987 and 2005c). Delivery functions are used to describe deposition and transport of the particulates through the storm drainage systems, and are again based on field observations. The set of files shown selected on Figure 2 are based mostly on observations obtained in Wisconsin and have been calibrated and verified by the USGS through their joint monitoring activities with the WI Dept. of Natural Resources. It is expected that these files are suitable for most of the US. A similar set of files is available based on monitoring in the Birmingham, AL area. These are likely most applicable for southeastern US conditions. It is possible to modify these files based on local observations. Verifications of the model output results are possible using information from regional stormwater permit monitoring, for example.



SLAMM Data File Name: C:\Current\Pubs and projects\LID 2011\KC basic LID prob no controls.dat

Site Descript.: Kansas City commercial basic conditions no controls LID example calcs

Seed: -42

Rain File: C:\Program Files (x86)\WinSLAMM\Rain Files\MO Kansas City Intl AP 7299.RAN

Start Date: 01/01/90

End Date: 12/19/99

☐ Winter Season Range

Start of Winter (mm/dd):

End of Winter (mm/dd):

Pollutant Probability Distribution File: C:\Program Files (x86)\WinSLAMM\WI_GEO01.ppd

Runoff Coefficient File: C:\Program Files (x86)\WinSLAMM\WI_SL06 Dec06.rsv

Particulate Solids Concentration File: C:\Program Files (x86)\WinSLAMM\WI_AVG01.psc

Particulate Residue Delivery File: C:\Program Files (x86)\WinSLAMM\MADISON.PRR

Street Delivery File (Select LU): C:\Program Files (x86)\WinSLAMM\WI_Com Inst Indust Dec06.std

○ Residential LU ○ Industrial LU

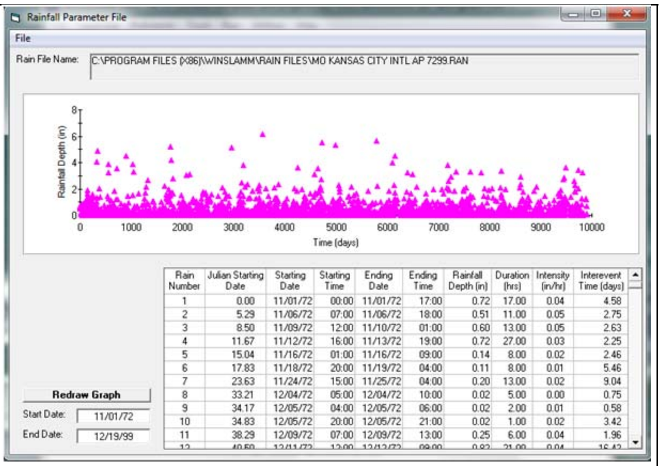
○ Institutional LU ○ Other Urban LU

● Commercial LU ○ Freeways

☐ Use Cost Estimation Option

Drainage System: Data Entered

Figure 1. Base parameter files selection.



Rain File Name: C:\PROGRAM FILES (X86)\WINSLAMM\RAIN FILES\MO KANSAS CITY INTL AP 7299.RAN

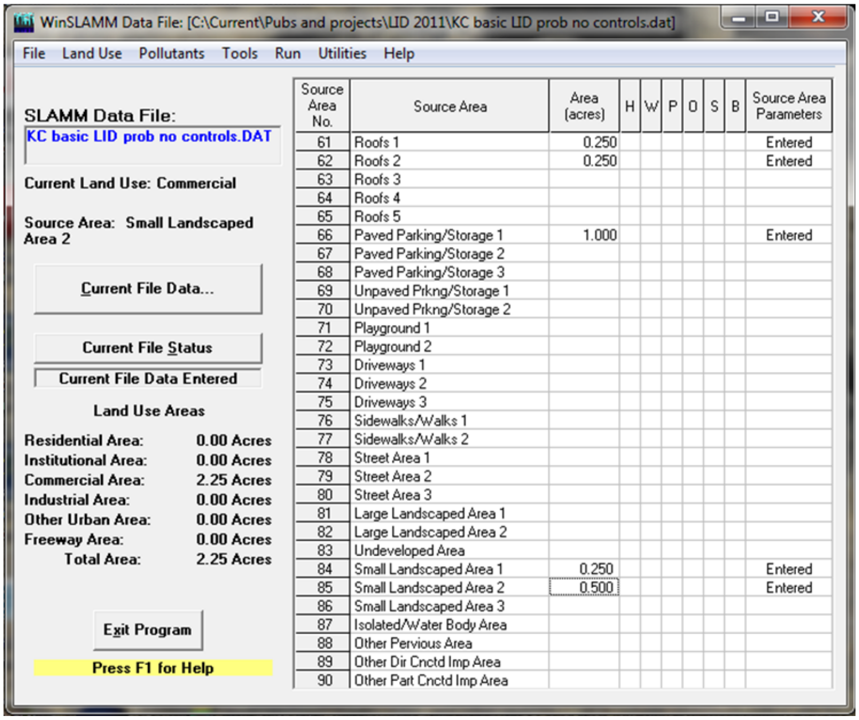
Start Date: 11/01/72

End Date: 12/19/99

Rain Number	Julian Starting Date	Starting Date	Starting Time	Ending Date	Ending Time	Rainfall Depth (in)	Duration (hrs)	Intensity (in/hr)	Interevent Time (days)
1	0.00	11/01/72	00:00	11/01/72	17:00	0.72	17.00	0.04	4.58
2	5.29	11/06/72	07:00	11/06/72	18:00	0.51	11.00	0.05	2.75
3	8.50	11/09/72	12:00	11/10/72	01:00	0.60	13.00	0.05	2.63
4	11.67	11/12/72	16:00	11/13/72	19:00	0.72	27.00	0.03	2.25
5	15.04	11/16/72	01:00	11/16/72	09:00	0.14	8.00	0.02	2.46
6	17.83	11/18/72	20:00	11/19/72	04:00	0.11	8.00	0.01	5.46
7	23.63	11/24/72	15:00	11/25/72	04:00	0.20	13.00	0.02	9.04
8	33.21	12/04/72	05:00	12/04/72	10:00	0.02	5.00	0.00	0.75
9	34.17	12/05/72	04:00	12/05/72	06:00	0.02	2.00	0.01	0.58
10	34.83	12/05/72	20:00	12/05/72	21:00	0.02	1.00	0.02	3.42
11	38.29	12/09/72	07:00	12/09/72	13:00	0.25	6.00	0.04	1.96

Figure 2. Scatterplot of Kansas City, MO, rain file.

Land development characteristics describing local site conditions of the study area are used by WinSLAMM to calculate expected runoff characteristics. Figure 3 is a screen shot for entered site conditions for the commercial example being used in this demonstration, while Figure 4 are screen shots describing the five source areas used in this example. There are two roof area types, one paved parking area, and two landscaped areas. The soils are described as silty in texture (corresponding to originally sandy soils that are typically compacted due to urban activities, or silt-loam soils that have been restored to their natural density conditions; Pitt, et al. 2009b). Bochis, et al (2008) has described land use patterns and development characteristics, including the procedures used to collect that needed information.



SLAMM Data File:
KC basic LID prob no controls.DAT

Current Land Use: Commercial

Source Area: Small Landscaped Area 2

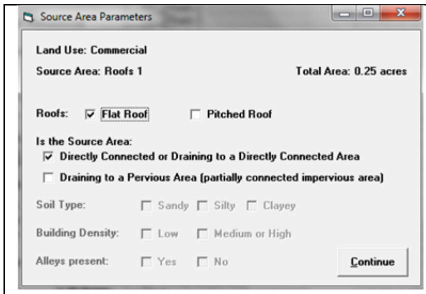
Current File Data Entered

Land Use Areas

Residential Area:	0.00 Acres
Institutional Area:	0.00 Acres
Commercial Area:	2.25 Acres
Industrial Area:	0.00 Acres
Other Urban Area:	0.00 Acres
Freeway Area:	0.00 Acres
Total Area:	2.25 Acres

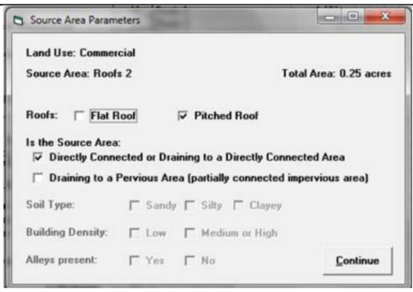
Source Area No.	Source Area	Area (acres)	H	W	P	O	S	B	Source Area Parameters
61	Roofs 1	0.250							Entered
62	Roofs 2	0.250							Entered
63	Roofs 3								
64	Roofs 4								
65	Roofs 5								
66	Paved Parking/Storage 1	1.000							Entered
67	Paved Parking/Storage 2								
68	Paved Parking/Storage 3								
69	Unpaved Prkng/Storage 1								
70	Unpaved Prkng/Storage 2								
71	Playground 1								
72	Playground 2								
73	Driveways 1								
74	Driveways 2								
75	Driveways 3								
76	Sidewalks/Walks 1								
77	Sidewalks/Walks 2								
78	Street Area 1								
79	Street Area 2								
80	Street Area 3								
81	Large Landscaped Area 1								
82	Large Landscaped Area 2								
83	Undeveloped Area								
84	Small Landscaped Area 1	0.250							Entered
85	Small Landscaped Area 2	0.500							Entered
86	Small Landscaped Area 3								
87	Isolated/Water Body Area								
88	Other Pervious Area								
89	Other Dir Cnctd Imp Area								
90	Other Part Cnctd Imp Area								

Figure 3. Base commercial conditions for examples.



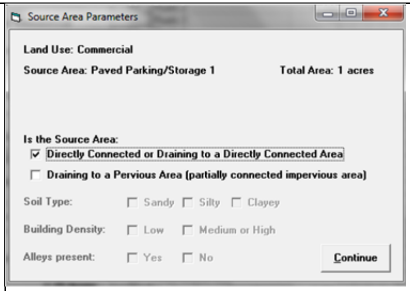
Land Use: Commercial
Source Area: Roofs 1 Total Area: 0.25 acres
Roofs: ☑ Flat Roof ☐ Pitched Roof
Is the Source Area:
☑ Directly Connected or Draining to a Directly Connected Area
☐ Draining to a Pervious Area (partially connected impervious area)
Soil Type: ☐ Sandy ☐ Silty ☐ Clayey
Building Density: ☐ Low ☐ Medium or High
Alleys present: ☐ Yes ☐ No

Roof 1 (directly connected flat roof)



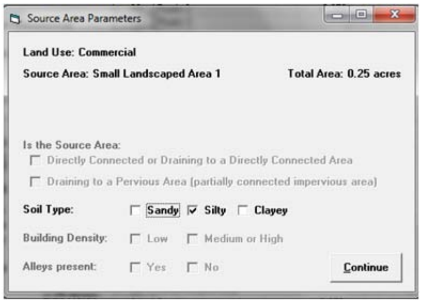
Land Use: Commercial
Source Area: Roofs 2 Total Area: 0.25 acres
Roofs: ☐ Flat Roof ☑ Pitched Roof
Is the Source Area:
☑ Directly Connected or Draining to a Directly Connected Area
☐ Draining to a Pervious Area (partially connected impervious area)
Soil Type: ☐ Sandy ☐ Silty ☐ Clayey
Building Density: ☐ Low ☐ Medium or High
Alleys present: ☐ Yes ☐ No

Roof 2 (directly connected pitched roof)



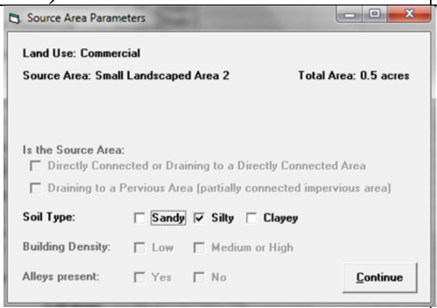
Land Use: Commercial
Source Area: Paved Parking/Storage 1 Total Area: 1 acres
Is the Source Area:
☑ Directly Connected or Draining to a Directly Connected Area
☐ Draining to a Pervious Area (partially connected impervious area)
Soil Type: ☐ Sandy ☐ Silty ☐ Clayey
Building Density: ☐ Low ☐ Medium or High
Alleys present: ☐ Yes ☐ No

Paved parking/storage area 1 (directly connected)



Land Use: Commercial
Source Area: Small Landscaped Area 1 Total Area: 0.25 acres
Is the Source Area:
☐ Directly Connected or Draining to a Directly Connected Area
☐ Draining to a Pervious Area (partially connected impervious area)
Soil Type: ☐ Sandy ☑ Silty ☐ Clayey
Building Density: ☐ Low ☐ Medium or High
Alleys present: ☐ Yes ☐ No

Small landscaped area 1 (filter strip area)



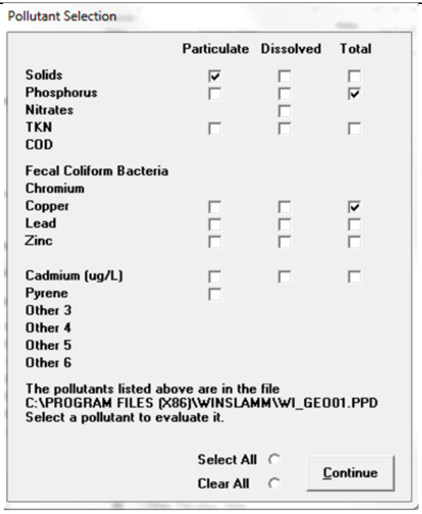
Land Use: Commercial
Source Area: Small Landscaped Area 2 Total Area: 0.5 acres
Is the Source Area:
☐ Directly Connected or Draining to a Directly Connected Area
☐ Draining to a Pervious Area (partially connected impervious area)
Soil Type: ☐ Sandy ☑ Silty ☐ Clayey
Building Density: ☐ Low ☐ Medium or High
Alleys present: ☐ Yes ☐ No

Small landscaped area 2 (other pervious areas)

Figure 4. Source area characteristics for example problem.

Figure 5 shows the pollutant selection form. The pollutants shown are a function of those that are included in the pollutant probability distribution file and are calibrated for the area of interest. In this example, particulate solids (SSC or TSS, depending on the laboratory method used in the monitoring activities; for this file, TSS are used), total phosphorus, and total copper have been selected as examples. As noted, it is possible to select the particulate-bound or dissolved forms of the pollutants separately, or the total concentrations. Special studies have focused on urban area bacteria and for PAHs, for example, and those constituents can be described in the pollutant probability distribution file and then selected in this form.

Figure 6 illustrates the form that can be used to select the main output formatting desired. If not selected, option 4 (selected here) is used, which gives a brief summary of the calculated results for the outfall (total study area). It is possible to also select more detailed output formats. However, for many years of rainfall data, some of these options can be very extensive. After the calculations and when viewing the output summary form, it is possible to view the other output forms by having the data reformatted, if desired, without having to rerun the model scenario.

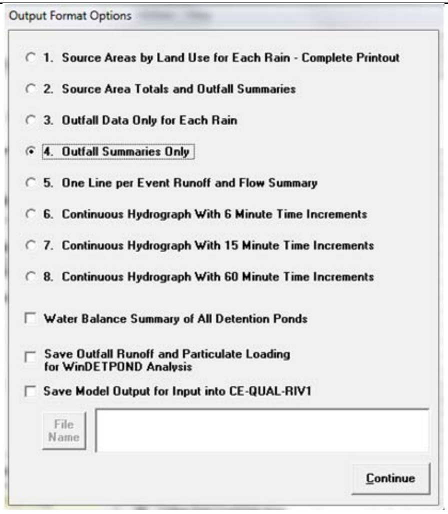


Pollutant Selection

	Particulate	Dissolved	Total
Solids	☑	☐	☐
Phosphorus	☐	☐	☑
Nitrates		☐	
TKN	☐	☐	☐
COD			
Fecal Coliform Bacteria			
Chromium			
Copper	☐	☐	☑
Lead	☐	☐	☐
Zinc	☐	☐	☐
Cadmium (ug/L)	☐	☐	☐
Pyrene	☐		
Other 3			
Other 4			
Other 5			
Other 6			

The pollutants listed above are in the file
C:\PROGRAM FILES (X86)\WINSLAMM\WI_GEO01.PPD
Select a pollutant to evaluate it.

Figure 5. Selection of pollutants to be evaluated.



Output Format Options

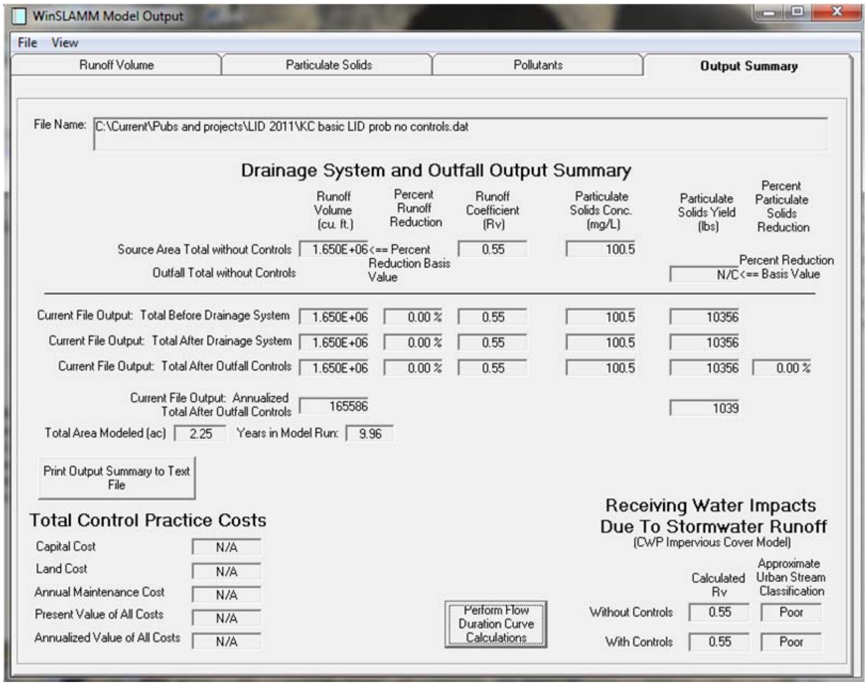
○ 1. Source Areas by Land Use for Each Rain - Complete Printout
○ 2. Source Area Totals and Outfall Summaries
○ 3. Outfall Data Only for Each Rain
● 4. Outfall Summaries Only
○ 5. One Line per Event Runoff and Flow Summary
○ 6. Continuous Hydrograph With 6 Minute Time Increments
○ 7. Continuous Hydrograph With 15 Minute Time Increments
○ 8. Continuous Hydrograph With 60 Minute Time Increments

☐ Water Balance Summary of All Detention Ponds
☐ Save Outfall Runoff and Particulate Loading for WinDETPOND Analysis
☐ Save Model Output for Input into CE-QUAL-RIV1

Figure 6. Selection of output formats.

Base Analyses with No Stormwater Controls

When this basic information is entered in the model, the model scenario is executed and the results presented in different forms. Figure 7 is the summary output screen that is displayed when the model run is completed. This screen shows runoff quantity and TSS conditions at different locations in the test area. If selected, different costs associated with described stormwater controls are also shown, along with expected receiving water habitat conditions (based on the Center for Watershed Protection's Impervious Cover Model). This form also has a selection to show the flow-duration curves for the base conditions and with the stormwater controls for the area, as shown in Figure 8. This base example has no stormwater controls, so the two plots are identical. It is also possible to see these data in much higher resolution by selecting another output option.



File Name: C:\Current\Pubs and projects\LID 2011\KC basic LID prob no controls.dat

Drainage System and Outfall Output Summary

	Runoff Volume (cu. ft.)	Percent Runoff Reduction	Runoff Coefficient (Rv)	Particulate Solids Conc. (mg/L)	Particulate Solids Yield (lbs)	Percent Particulate Solids Reduction
Source Area Total without Controls	1.650E+06 <== Percent Reduction Basis Value		0.55	100.5		
Outfall Total without Controls					N/C <== Percent Reduction Basis Value	
Current File Output: Total Before Drainage System	1.650E+06	0.00 %	0.55	100.5	10356	
Current File Output: Total After Drainage System	1.650E+06	0.00 %	0.55	100.5	10356	
Current File Output: Total After Outfall Controls	1.650E+06	0.00 %	0.55	100.5	10356	0.00 %
Current File Output: Annualized Total After Outfall Controls	165586				1039	

Total Area Modeled (ac) 2.25 Years in Model Run: 9.96

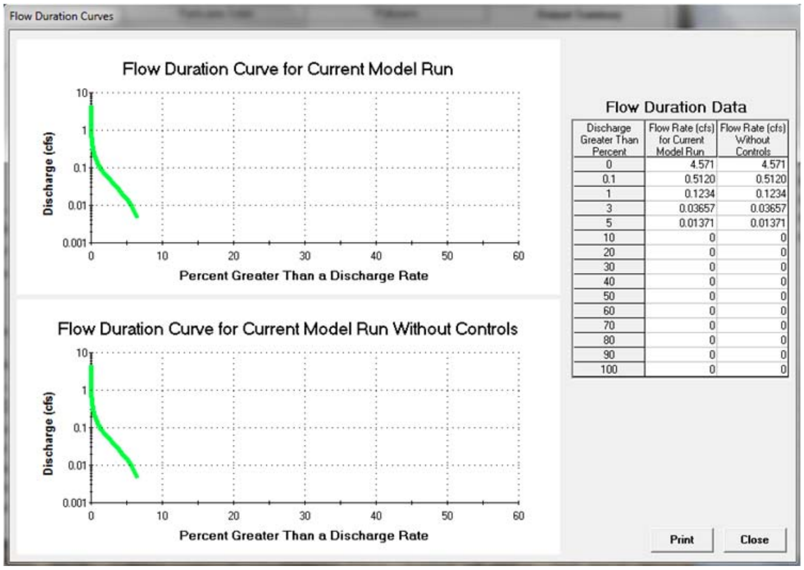
Total Control Practice Costs

Capital Cost	N/A
Land Cost	N/A
Annual Maintenance Cost	N/A
Present Value of All Costs	N/A
Annualized Value of All Costs	N/A

Receiving Water Impacts Due To Stormwater Runoff
(CWP Impervious Cover Model)

	Calculated Rv	Approximate Urban Stream Classification
Without Controls	0.55	Poor
With Controls	0.55	Poor

Figure 7. Basic Summary Screen.



Flow Duration Data

Discharge Greater Than Percent	Flow Rate (cfs) for Current Model Run	Flow Rate (cfs) Without Controls
0	4.571	4.571
0.1	0.5120	0.5120
1	0.1234	0.1234
3	0.03657	0.03657
5	0.01371	0.01371
10	0	0
20	0	0
30	0	0
40	0	0
50	0	0
60	0	0
70	0	0
80	0	0
90	0	0
100	0	0

Figure 8. Base flow duration plot.

Sources of Pollutants of Interest

One of the important features of WinSLAMM is to calculate the sources of the flows and pollutants of interest for the study area under different rain conditions. Figure 9 is a simple area plot created in Excel from imported values from WinSLAMM. The rain file used for this analysis only contains 12 events, ranging from 0.01 to 4.0 inches. This plot is for runoff volume sources and indicates that the large paved parking/storage area is the major runoff source for all events (from about 85% during the smallest rains to about 55% during the largest rains). The runoff contributions from the roofs combined range from about 15 to 35%, while the landscaped areas only start to contribute flows after about 0.25 inches and reach their maximum contributions after 2.0 inches, approaching about 10% of the total flows from the area. This type of plot can be created for each of the constituents selected in the model run and indicate locations for the most effective source controls, or if the sources are too diverse, if outfall or drainage system controls should be stressed. For this example, it is not surprising that the paved parking/storage areas should receive the most attention, followed by the directly connected roofs.

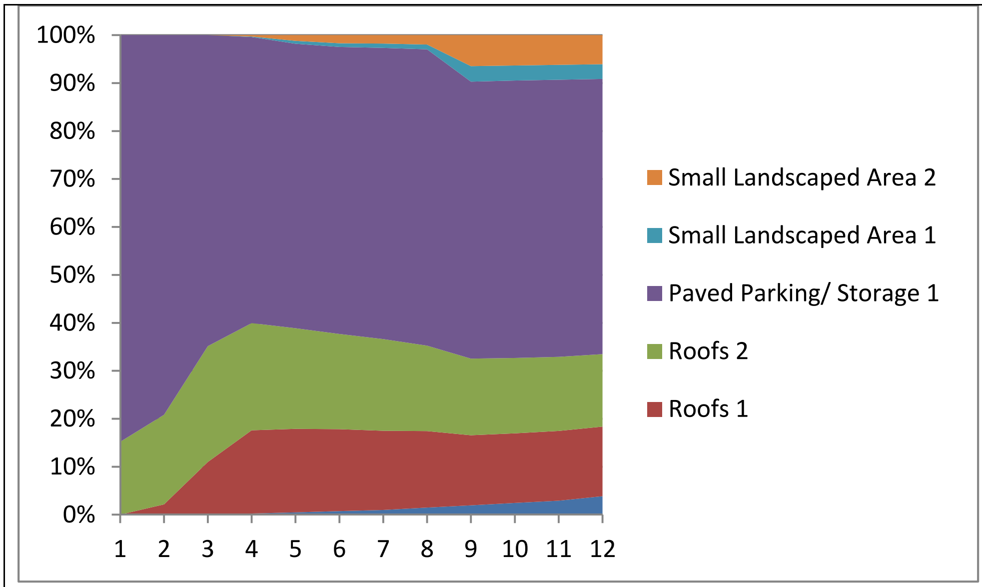


Figure 9. Flow sources for different rains.

Rain #	Rain depth (in)
1	0.01
2	0.05
3	0.10
4	0.25
5	0.50
6	0.75
7	1.0
8	1.5
9	2.0
10	2.5
11	3.0
12	4.0

Key for rain numbers on area contribution plot.

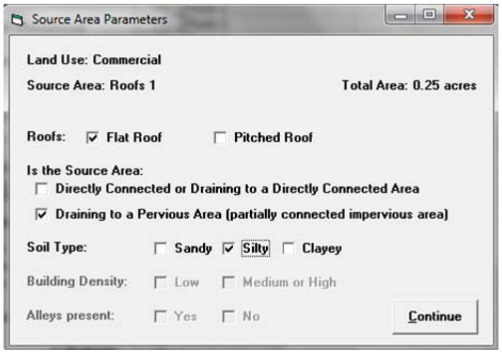
Disconnecting Directly Connected Impervious Areas

The first stormwater control to be examined is disconnecting the previously directly connected impervious areas. WinSLAMM can evaluate disconnections different ways. The most direct way to evaluate disconnections of impervious areas is by changing the source are parameter characteristic from directly connected (or draining to a directly connected area) to draining to a pervious area (partially connected impervious area), as shown in Figure 10. If the area has clayey soils, the building density is needed, and if a medium or high density area, the presence of alleys also needs to be known. This process is based on extensive monitoring of residential and commercial sites that ranged from completely connected to completed disconnected with varying density and soil conditions (Pitt 1987). Table 1 shows the results of these disconnections, showing excellent control when all areas are disconnected. As an example, in order to obtain good receiving habitat conditions, all of the roofs and the parking areas need to be disconnected. As expected from observing the flow source area plot (Figure 9), disconnecting only a portion of these impervious areas has limited benefits. It is noted that the concentrations of the pollutants increase with increasing roof disconnections because the better quality roof runoff is being infiltrated and not diluting the runoff from the paved parking/storage area. However, the mass discharges all decrease with increased disconnections.

Table 1. Effectiveness of Disconnecting Impervious Areas in 2.25 Acre Commercial Site over Ten Years

Description	Rv	Expected habitat conditions	TSS (mg/L)	solids yield (lbs/yr)	peak runoff rate (CFS)	TP (mg/L)	TP load (lbs)	Cu (mg/L)	Cu load (lbs)
base conditions, no controls	0.55	poor	100	1040	4.6	0.28	29	17	1.7
flat roof disconnections	0.47	poor	112	990	3.8	0.29	26	18	1.6
pitched roof disconnections	0.46	poor	115	980	3.7	0.29	25	18	1.6
both roof disconnections	0.38	poor	132	930	3.0	0.31	22	20	1.4
parking lot disconnections	0.25	poor	66	309	1.9	0.36	17	12	0.56

all roofs and parking area disconnections	0.08	good	140	200	0.72	0.67	9.8	15	0.21


Source Area Parameters

Land Use: Commercial

Source Area: Roofs 1 Total Area: 0.25 acres

Roofs: ☑ Flat Roof ☐ Pitched Roof

Is the Source Area:
☐ Directly Connected or Draining to a Directly Connected Area
☑ Draining to a Pervious Area (partially connected impervious area)

Soil Type: ☐ Sandy ☑ Silty ☐ Clayey

Building Density: ☐ Low ☐ Medium or High

Alleys present: ☐ Yes ☐ No

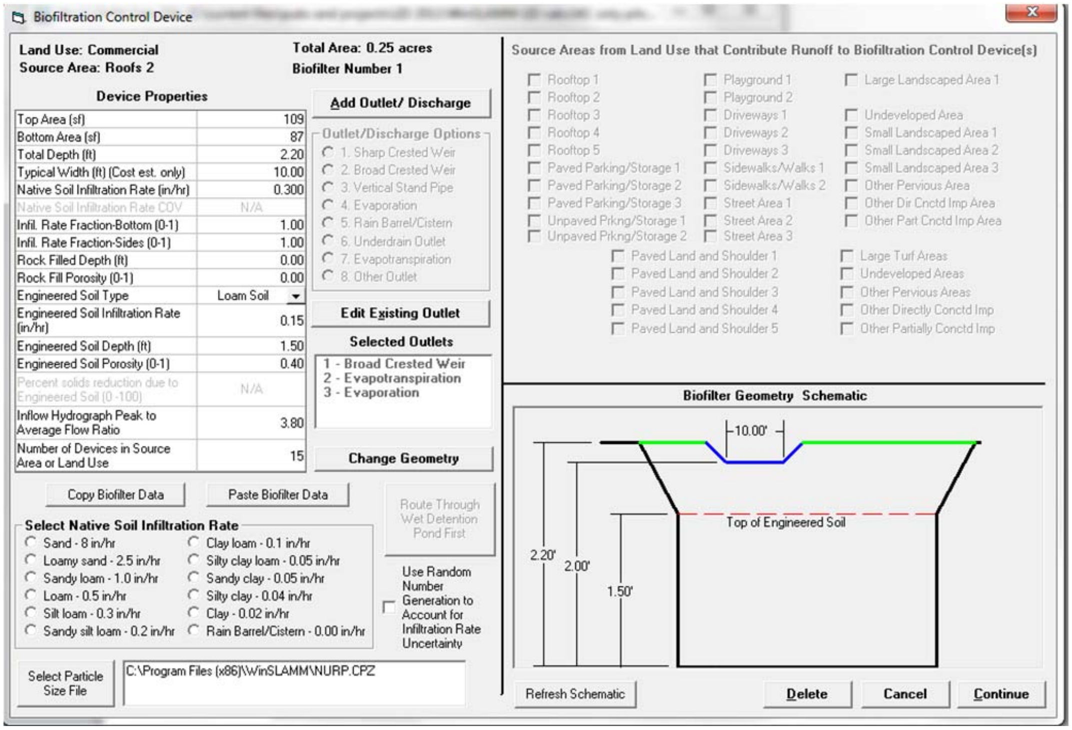
Figure 10. Disconnection of flat roof to silty soil.

Roof Runoff Rain Gardens

Rain gardens for controlling roof runoff are being used for residential areas in the Kansas City CSO green infrastructure demonstration project study area (Struck XXX). They are located on private property and receive the runoff from directly connected roofs. Their maximum benefit is dependent on the amount of runoff that is contributed from the source areas where they would be located. Obviously, rain gardens located to receive runoff from already disconnected roofs provide much less overall benefit than if they are located at directly connected roofs.

The performance of these devices is affected by several unit processes that are modeled in WinSLAMM. Modified puls hydraulic routing, with surface overflow calculations, are the basic processes modeled. However, several layers in the rain garden (or biofilter) must be considered. As runoff enters the device, water infiltrates through the engineered soil or media (or natural soil, as in a rain garden). If the entering rain cannot all be infiltrated through the surface layer, water will pond. If the ponding becomes deep, it may overflow through the broad-crested weir, or other surface outlet. The percolating water moves down through the device until it reaches the bottom and intercepts the native soil. If the native soil infiltration rate is less than the percolation water rate, then there is no subsurface ponding; if the native soil infiltration rate is slower that the percolation water rate, ponding will occur. This ponding may buildup to the surface of the device and add to the surface ponding. If an underdrain id present (usually with a subsurface storage layer), the subsurface ponding will be intercepted by the drain which is then discharged to the surface water, but later in the event. With the water percolating through the engineered soil, or other fill, particulates and particulate-bound pollutants are trapped by the media through filtering actions. Therefore, the underdrain water usually has a lower particulate solids content that the surface waters entering the device. The calculations are sensitive to the amount of the different media used as fill (or the native soil) and it characteristics (especially its porosity and percolation rate; and if evapotranspiration (ET) is used, the wilting point). The hydraulic routing uses the sum of the void volumes in the device to determine the effluent hydrograph, while the different infiltration/percolation rates affect the internal ponding. The stage-discharge relationships of the outlet devices are all modeled using conventional hydraulic processes. The ET loss calculations are based on the changing water content in the root zone at each time increment, and the ET adjustment factors for the mixture of plants in the device (Pitt 2008a).

Figure 11 is the main input screen used for rain gardens. This is a general format that is also used for other infiltration devices, including biofilters and bioinfiltration devices, along with rain water harvesting water tanks or rain barrels. This form includes the geometry of the device and material placed in the device. Most simple rain gardens do not have any special media, using only soils, nor do they have underdrains, so only some of the form is used. In this example, a loam soil is used in the rain garden and the native soil is assumed to be a silt loam having long-term infiltration rates of about 0.3 in/hr. As indicated, it is possible to also incorporate a Monte Carlo routine to better represent the variable infiltration rates that any individual unit has. All of the devices using this input screen requires a hydraulic overflow, describes as a broad crested weir. For these devices, evaporation of water from any pooled standing water above the soil, and evapotranspiration losses associated with plants installed in the rain garden are also added as outlet devices. The input screens for these outlets are shown in Figure 12.



Land Use: Commercial
Source Area: Roofs 2
Total Area: 0.25 acres
Biofilter Number 1

Device Properties

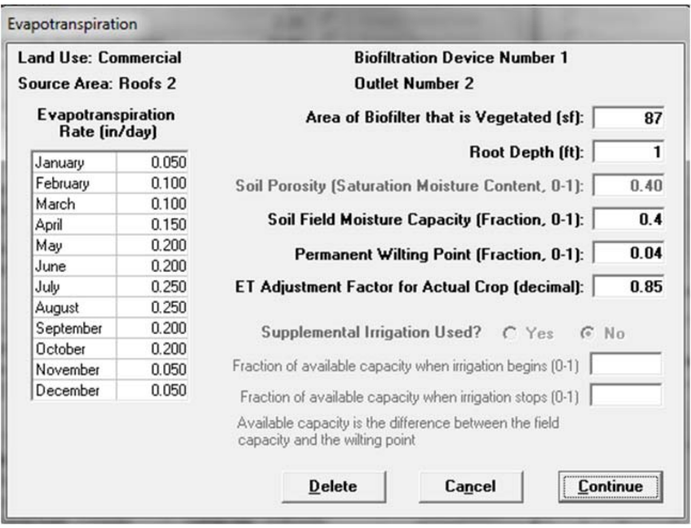
Top Area (sf)	109
Bottom Area (sf)	87
Total Depth (ft)	2.20
Typical Width (ft) (Cost est. only)	10.00
Native Soil Infiltration Rate (in/hr)	0.300
Native Soil Infiltration Rate COV	N/A
Infil. Rate Fraction-Bottom (0-1)	1.00
Infil. Rate Fraction-Sides (0-1)	1.00
Rock Filled Depth (ft)	0.00
Rock Fill Porosity (0-1)	0.00
Engineered Soil Type	Loam Soil
Engineered Soil Infiltration Rate (in/hr)	0.15
Engineered Soil Depth (ft)	1.50
Engineered Soil Porosity (0-1)	0.40
Percent solids reduction due to Engineered Soil (0 -100)	N/A
Inflow Hydrograph Peak to Average Flow Ratio	3.80
Number of Devices in Source Area or Land Use	15

Selected Outlets

1 - Broad Crested Weir
2 - Evapotranspiration
3 - Evaporation

C:\Program Files (x86)\WinSLAMM\NURP.CPZ

Figure 11. Rain garden input screen.



Land Use: Commercial
Source Area: Roofs 2
Biofiltration Device Number 1
Outlet Number 2

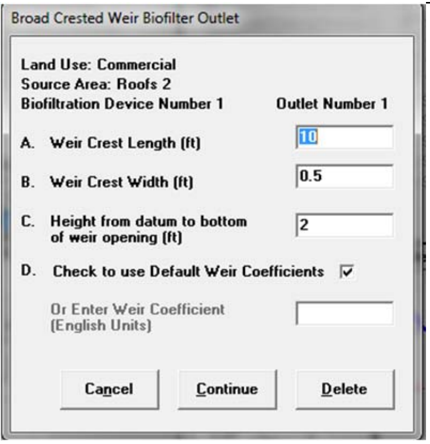
Evapotranspiration Rate (in/day)

January	0.050
February	0.100
March	0.100
April	0.150
May	0.200
June	0.200
July	0.250
August	0.250
September	0.200
October	0.200
November	0.050
December	0.050

Area of Biofilter that is Vegetated (sf): 87
Root Depth (ft): 1
Soil Porosity (Saturation Moisture Content, 0-1): 0.40
Soil Field Moisture Capacity (Fraction, 0-1): 0.4
Permanent Wilting Point (Fraction, 0-1): 0.04
ET Adjustment Factor for Actual Crop (decimal): 0.85

Supplemental Irrigation Used? ○ Yes ● No
Fraction of available capacity when irrigation begins (0-1)
Fraction of available capacity when irrigation stops (0-1)
Available capacity is the difference between the field capacity and the wilting point

Evapotranspiration input screen.


Broad Crested Weir Biofilter Outlet

Land Use: Commercial
Source Area: Roofs 2
Biofiltration Device Number 1 Outlet Number 1

A. Weir Crest Length (ft) 10

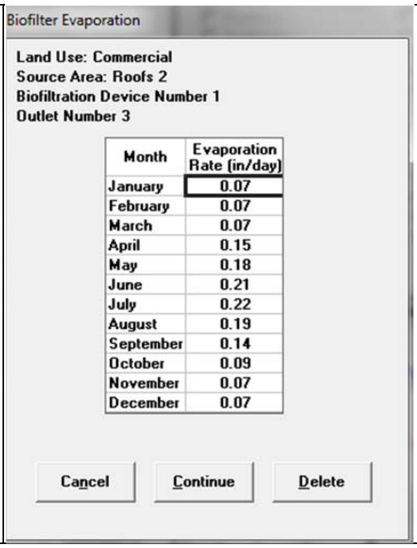
B. Weir Crest Width (ft) 0.5

C. Height from datum to bottom of weir opening (ft) 2

D. Check to use Default Weir Coefficients ☑

Or Enter Weir Coefficient (English Units)

Broad crested wier input screen.


Biofilter Evaporation

Land Use: Commercial
Source Area: Roofs 2
Biofiltration Device Number 1
Outlet Number 3

Month	Evaporation Rate (in/day)
January	0.07
February	0.07
March	0.07
April	0.15
May	0.18
June	0.21
July	0.22
August	0.19
September	0.14
October	0.09
November	0.07
December	0.07

Evaporation input screen.

Figure 12. Outlet device screens for rain gardens.

The performance of the rain garden for controlling runoff from the directly connected pitched roof is summarized in Table 2 and Figure 13. Obviously, as the rain garden increases in size in relationship to the roof area, less water is discharged to the collection system. About 80% of the long-term runoff would be infiltrated for a rain garden that is about 20% of the roof area for these conditions. The concentrations all remain the same, as there is no underdrain or subsurface collection of filtered water; the water quality of the water discharged through the surface overflow weir is the same as the incoming water. However, the mass discharges are decreased as the runoff volume decreases. The roof runoff has relatively low TSS concentrations and the life of the rain gardens shown here would be very long, with very little clogging potential (clogging of biofilters occur with accumulative solids loadings of about 10 to 25 kg/m^2). The peak flow rate reductions are also substantial, being about 2/3rds for the rain gardens being 20% of the roof area.

Table 2. Rain Garden Performance for Directly Connected Pitched Roofs

rain garden as a % of roof area	Estimated habitat conditions	TSS (mg/L)	peak runoff rate (CFS)	peak rate reduction (%)	TP (mg/L)	TP load (lbs)	Cu (ug/L)	Cu load (lbs)
	poor	33	0.87	0	0.22	4.2	11	0.21
2%	poor	33	0.78	10	0.22	3.4	11	0.17
5%	poor	33	0.67	23	0.22	2.6	11	0.13
10%	poor	33	0.47	46	0.22	1.6	11	0.08
15%	poor	33	0.34	61	0.22	1	11	0.05
20%	fair	33	0.31	64	0.22	0.59	11	0.029
25%	good	33	0.28	68	0.22	0.35	11	0.017
30%	good	33	0.22	75	0.22	0.19	11	0.0095
40%	good	33	0.15	83	0.22	0.039	11	0.0019
50%	good	33	0.079	91	0.22	0.01	11	0.00045

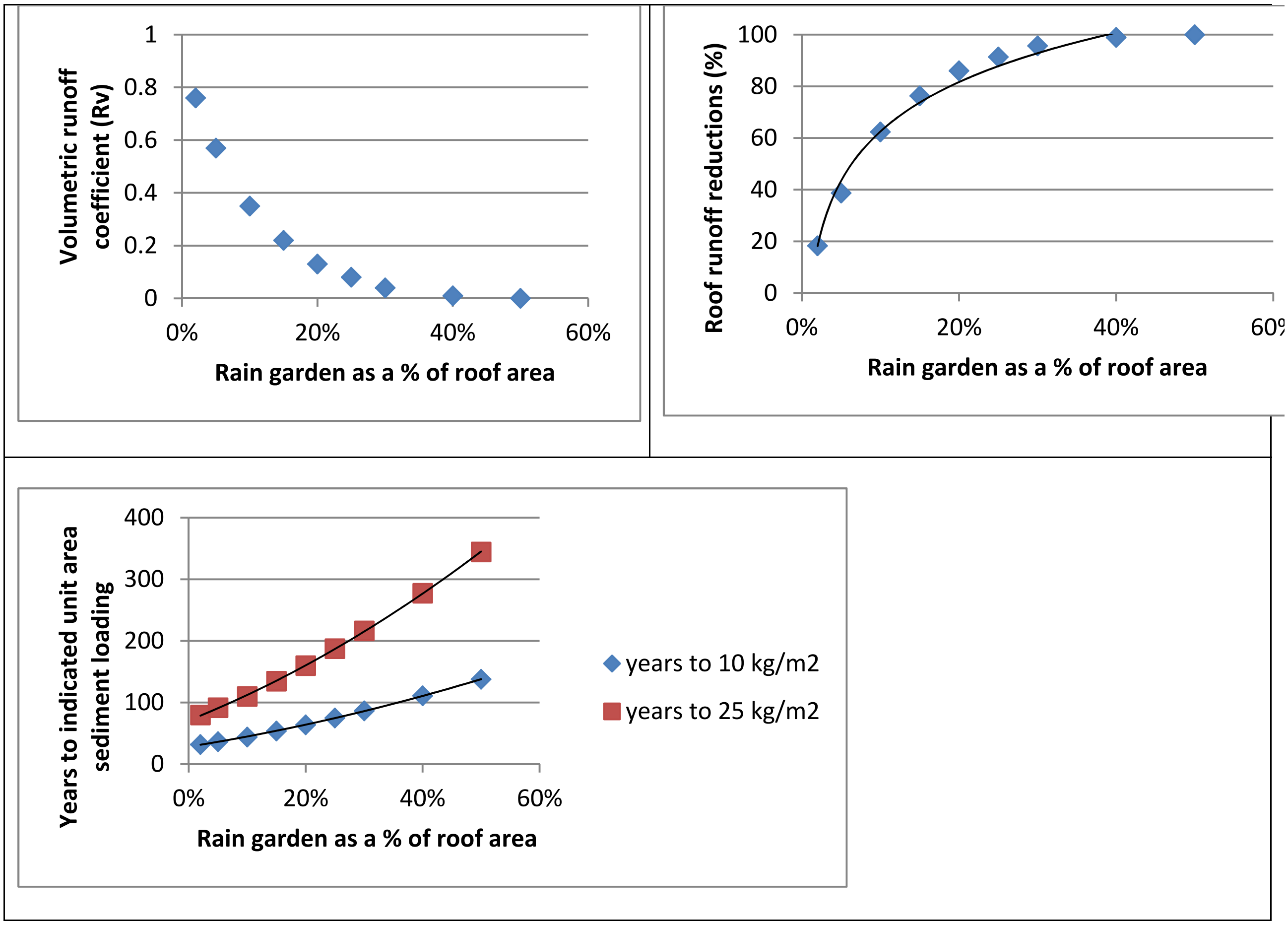


Figure 13. Calculated roof runoff rain garden performance as a function of size.

Grass Filters

Grass filters have broad, shallow flows. They can be modeled as a special case of grass swale in the current version of WinSLAMM. The model calculations are based on extensive pilot-scale and field measurements of grass swales and filters recently conducted for the Alabama Dept. of Transportation. This method determines the flow conditions for every calculation increment, especially flow velocity and depth. Special shallow Manning's n values are used based on shallow sheetflow tests that were conducted as part of this research. Sediment transport is calculated for each narrow particle size range, based on their sedimentation rate, depth of flow, and length of flow. Scour is also considered, along with equilibrium concentrations. The pilot-scale tests were confirmed during full scale tests during actual rains.

The grass swale control device allows the user to determine the pollutant reduction and runoff volume reduction due to grass swales. The model determines the runoff volume reduction by calculating the infiltration loss for each time step. The particulate reduction is based upon the settling frequency of the particles entering the swales and the height of the grass relative to the flow depth. The grass swale filters the runoff using the settling frequency and the length of the swale. The algorithms used to determine the Manning's n values were developed from the master's thesis work by Jason Kirby (Kirby, J.T., S.R. Durrans, R. Pitt, and P.D. Johnson. "Hydraulic resistance in grass swales designed for small flow conveyance." *Journal of Hydraulic Engineering*, Vol. 131, No. 1, Jan. 2005.) as part of a WERF-supported research project: Johnson, P.D., R. Pitt, S.R. Durrans, M. Urrutia, and S. Clark. Metals Removal Technologies for Urban Stormwater. *Water Environment Research Foundation*. WERF 97-IRM-2. ISBN: 1-94339-682-3. Alexandria, VA. 701 pgs. Oct. 2003. The particle trapping algorithms were based on the master's thesis research conducted by Yukio Nara (Nara, Y., R. Pitt, S.R. Durrans, and J. Kirby. "Sediment transport in grass swales." In: *Stormwater and Urban Water Systems Modeling*. Monograph 14. edited by W. James, K.N. Irvine, E.A. McBean, and R.E. Pitt. CHI. Guelph, Ontario, pp. 379 402. 2006.), supported by the University Transportation

Center for Alabama: "Alabama Highway Drainage Conservation Design Practices - Particulate Transport in Grass Swales and Grass Filters", by Yukio Nara and Robert Pitt, *University Transportation Center for Alabama*, University of Alabama, Tuscaloosa, Alabama, November, 2005.

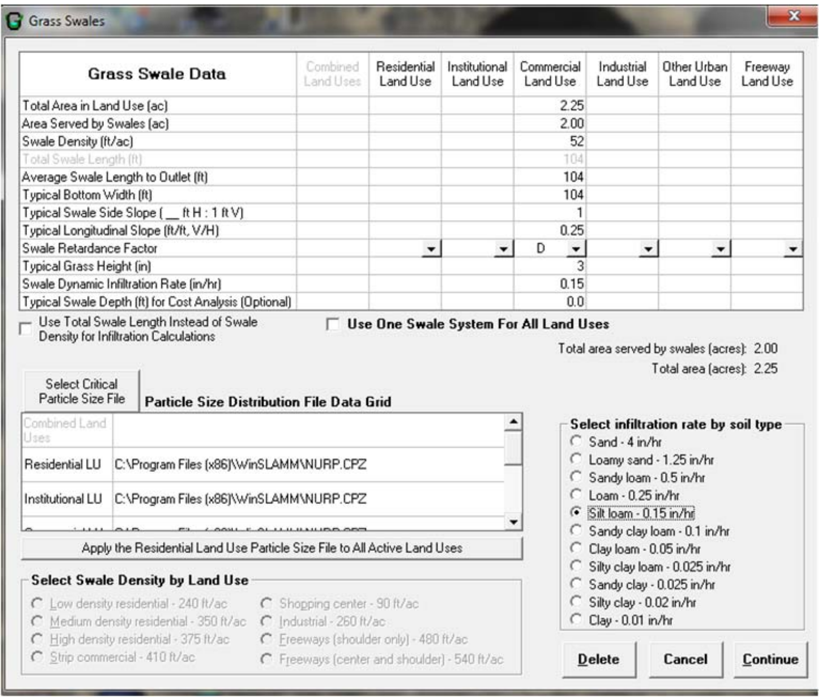
Grass swale performance is determined by routing a complex triangular hydrograph through the swales entered in the model by the user. Runoff volume reductions are determined by infiltration losses, and particulate losses are determined through particle trapping. Runoff volume is reduced by the dynamic infiltration rate of the swales for each six minute time step of the hydrograph. The flow and the swale geometry are used to determine the Manning's n to iteratively determine the depth of flow in the swale for each time step, using traditional VR-n curves that were extended by Kirby to cover the smaller flows found in roadside swales. Using the calculated depth of flow for each time increment, the model calculates the wetted perimeter (based on the swale cross-sectional shape) which is then multiplied by the total swale length to determine the area used to infiltrate the runoff. Details for these calculations are available by selecting the "Hydraulics Detailed Output File" checkbox from the "Detailed Output Options" listing under "Program Options." The event-by-event summary detailed output is available by selecting the "Hydraulics and Concentration by Event" checkbox from the Detailed Output Options listing. These comma-separated tabular files are created when the model is executed and can be reviewed using a spreadsheet after importing the files.

Particulate filtering is calculated for each time step using the average swale length to the outlet and the calculated depth of flow for each 6-minute time step of the hydrograph. The depth of flow and swale geometry are used to calculate the flow velocity, which in turn is used to determine the travel time, settling velocity, and settling frequency for the average swale length in the study area. This information is used to determine the flow depth to grass height ratio needed to calculate particulate trapping, adapted from the Nara and Pitt reference cited above. The settling frequency and resultant particulate trapping is calculated for each of the thirty-one particle size fractions in the selected particle size distribution file. The detailed output for these calculations is available by selecting the "Particulate Reduction Output File" checkbox from the "Detailed Output Options" listing. The resulting particulate concentrations are then combined into one of eight groups of particle sizes, where it is evaluated to determine if it is below the irreducible concentration values for each particle size group. No resulting concentration values are allowed to go below the irreducible concentration values unless the inflow value is already below that level. For grass swales, no particles smaller than 50 µm are trapped due to turbulent resuspensions of the small particles. The detailed output for these calculations is available by selecting the "Incremental Performance Output File" checkbox and the "Irreducible Concentration Detailed Output" checkbox from the "Detailed Output Options" listing.

Figure 14 is the basic input screen used for grass swales, with the data for this example grass filter shown. As noted above, the grass filters are a special case of the grass swales, with wide and very shallow flows. Table 3 summarizes the performance of the grass filters for controlling the runoff from the 2 acres of impervious areas. As the grass filters become steep, they lose some of their performance due to the faster flow water reducing the effective infiltration rates. These are somewhat conservative calculations as they include the restrictions that are used for the grass swales (especially the effects of turbulence). Version 10 has a more direct calculation of the grass filter strips which uses the same basic calculation approach, but without some of the turbulent induced restrictions, and it uses Muskingum channel routing to more effectively calculate the flow conditions in the filters. Figure 15 is the grass filter strip data entry screen used in version 10.

Table 3. Grass Filter Performance for Different Soils and Slopes

description	Rv	% runoff volume reduction	TSS (mg/L)	solids yield (lbs/yr)	% solids yield reduction	peak runoff rate (CFS)	% peak runoff rate reduction	TP (mg/L)	TP load (lbs)	Cu (mg/L)	Cu load (lbs)
base conditions, no controls	0.55		100	1040		4.6		0.28	29	17	1.7
grass filter 0.5% slope	0.17	69	91	300	71	2.6	43	0.27	8.7	16	0.52
grass filter 2 to 25% slopes	0.22	60	90	376	64	3.5	24	0.26	11	16	0.67



Grass Swale Data	Combined Land Uses	Residential Land Use	Institutional Land Use	Commercial Land Use	Industrial Land Use	Other Urban Land Use	Freeway Land Use
Total Area in Land Use (ac)				2.25			
Area Served by Swales (ac)				2.00			
Swale Density (ft/ac)				52			
Total Swale Length (ft)				104			
Average Swale Length to Outlet (ft)				104			
Typical Bottom Width (ft)				104			
Typical Swale Side Slope (__ ft H : 1 ft V)				1			
Typical Longitudinal Slope (ft/ft, V/H)				0.25			
Swale Retardance Factor				D			
Typical Grass Height (in)				3			
Swale Dynamic Infiltration Rate (in/hr)				0.15			
Typical Swale Depth (ft) for Cost Analysis (Optional)				0.0			

☐ Use Total Swale Length Instead of Swale Density for Infiltration Calculations

☐ Use One Swale System For All Land Uses

Total area served by swales (acres): 2.00

Total area (acres): 2.25

Particle Size Distribution File Data Grid

Combined Land Uses	
Residential LU	C:\Program Files (x86)\WinSLAMM\NURP.CPZ
Institutional LU	C:\Program Files (x86)\WinSLAMM\NURP.CPZ

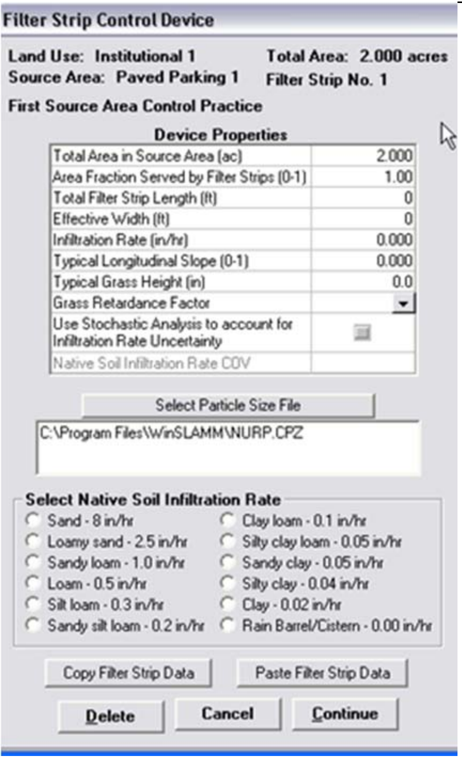
Select infiltration rate by soil type

○ Sand - 4 in/hr
○ Loamy sand - 1.25 in/hr
○ Sandy loam - 0.5 in/hr
○ Loam - 0.25 in/hr
● Silt loam - 0.15 in/hr
○ Sandy clay loam - 0.1 in/hr
○ Clay loam - 0.05 in/hr
○ Silty clay loam - 0.025 in/hr
○ Sandy clay - 0.025 in/hr
○ Silty clay - 0.02 in/hr
○ Clay - 0.01 in/hr

Select Swale Density by Land Use

○ Low density residential - 240 ft/ac
○ Medium density residential - 350 ft/ac
○ High density residential - 375 ft/ac
○ Strip commercial - 410 ft/ac
○ Shopping center - 90 ft/ac
○ Industrial - 260 ft/ac
○ Freeways (shoulder only) - 480 ft/ac
○ Freeways (center and shoulder) - 540 ft/ac

Figure 14. Grass filter input using the grass swale form.



Land Use: Institutional 1 **Total Area: 2.000 acres**
Source Area: Paved Parking 1 **Filter Strip No. 1**

First Source Area Control Practice

Device Properties

Total Area in Source Area (ac)	2.000
Area Fraction Served by Filter Strips (0-1)	1.00
Total Filter Strip Length (ft)	0
Effective Width (ft)	0
Infiltration Rate (in/hr)	0.000
Typical Longitudinal Slope (0-1)	0.000
Typical Grass Height (in)	0.0
Grass Retardance Factor	
Use Stochastic Analysis to account for Infiltration Rate Uncertainty	☐
Native Soil Infiltration Rate COV	

C:\Program Files\WinSLAMM\NURP.CPZ

Select Native Soil Infiltration Rate

○ Sand - 8 in/hr
○ Loamy sand - 2.5 in/hr
○ Sandy loam - 1.0 in/hr
○ Loam - 0.5 in/hr
○ Silt loam - 0.3 in/hr
○ Sandy silt loam - 0.2 in/hr
○ Clay loam - 0.1 in/hr
○ Silty clay loam - 0.05 in/hr
○ Sandy clay - 0.05 in/hr
○ Silty clay - 0.04 in/hr
○ Clay - 0.02 in/hr
○ Rain Barrel/Cistern - 0.00 in/hr

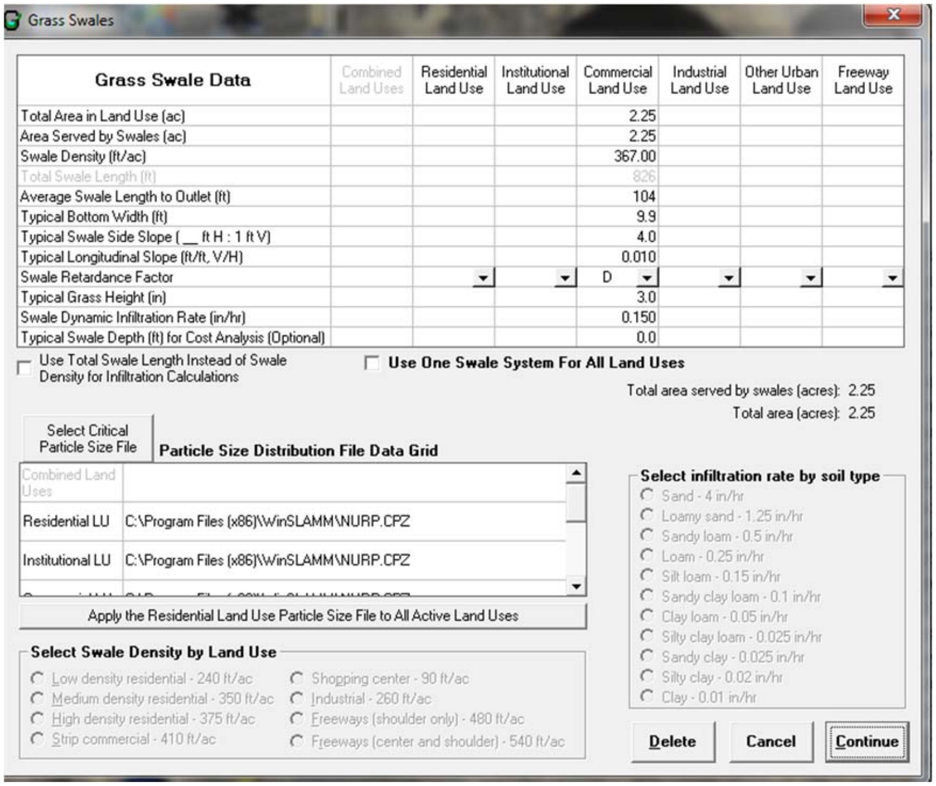
Figure 15. Grass filter strip form in Version 10.

Grass Swales

Grass swales are evaluated using the processes described above under grass filter strips. As indicated, these procedures are based on extensive laboratory and field tests and calculate swale performance through infiltration mechanisms and sedimentation of many discrete particles sizes. On the initial data entry form (Figure 3), a subform is used to describe how the drainage system is divided into different types of roadside systems. Figure 17 is used to enter the appropriate data for the swales that serve different land uses in the study area. Table 4 summarizes the performance of a swale in this area, for two different soil conditions. Obviously, the swale water volume and pollutant reduction performance is better for the loam soil than for the silty soil.

Table 4. Grass Swale Performance

Descscription	Rv	% runoff volume reduc.	Expected habitat conditions	TSS (mg/L)	% solids yield reduc.	solids yield (lbs/yr)	peak runoff rate (CFS)	% peak runoff rate reduc.	TP (mg/L)	TP load (lbs)	Cu (mg/L)	Cu load (lbs)
base conditions, no controls	0.55		poor	100		1040	4.6		0.28	29	17	1.7
silty soil	0.33	40	poor	86	92	535	4.4	4	0.25	16	16	0.98
loam soil	0.16	71	fair	87	92	263	2.9	37	0.26	7.8	16	0.47



Grass Swale Data	Combined Land Uses	Residential Land Use	Institutional Land Use	Commercial Land Use	Industrial Land Use	Other Urban Land Use	Freeway Land Use
Total Area in Land Use (ac)				2.25			
Area Served by Swales (ac)				2.25			
Swale Density (ft/ac)				367.00			
Total Swale Length (ft)				826			
Average Swale Length to Outlet (ft)				104			
Typical Bottom Width (ft)				9.9			
Typical Swale Side Slope (__ ft H : 1 ft V)				4.0			
Typical Longitudinal Slope (ft/ft, V/H)				0.010			
Swale Retardance Factor				D			
Typical Grass Height (in)				3.0			
Swale Dynamic Infiltration Rate (in/hr)				0.150			
Typical Swale Depth (ft) for Cost Analysis (Optional)				0.0			

☐ Use Total Swale Length Instead of Swale Density for Infiltration Calculations

☐ Use One Swale System For All Land Uses

Total area served by swales (acres): 2.25

Total area (acres): 2.25

Particle Size Distribution File Data Grid

Combined Land Uses	
Residential LU	C:\Program Files (x86)\WinSLAMM\NURP.CPZ
Institutional LU	C:\Program Files (x86)\WinSLAMM\NURP.CPZ

Figure 16. Grass swale information.

Biofilters

As indicated previously during the rain garden discussion, the biofiltration control option is a many-featured control device that uses full routing calculations associated with pond storage along with a variety of “discharge” and soil treatment options. The “outlet” devices include natural soil infiltration (the wide range of variability in infiltration rates in disturbed urban soils can be considered by selecting the built-in Monte Carlo option), evaporation and ET, surface discharges through overflows (a stand pipe or weirs), and subsurface discharges through underdrains. The device description can also be used to calculate the beneficial uses of stormwater by using rain barrels or water tanks/cisterns. This is a very flexible control device, and as such can be used to evaluate the following types of control practices, including: biofilters, rain gardens, infiltration basins and trenches, water tanks/cisterns and rain barrels, infiltration pits and dry wells, rock-filled trenches, and even green roofs. Biofiltration controls are usually numerous in an area and can be represented in the model individually or by specifying how many of each unit is treating the flow from an individual or combination of source areas.

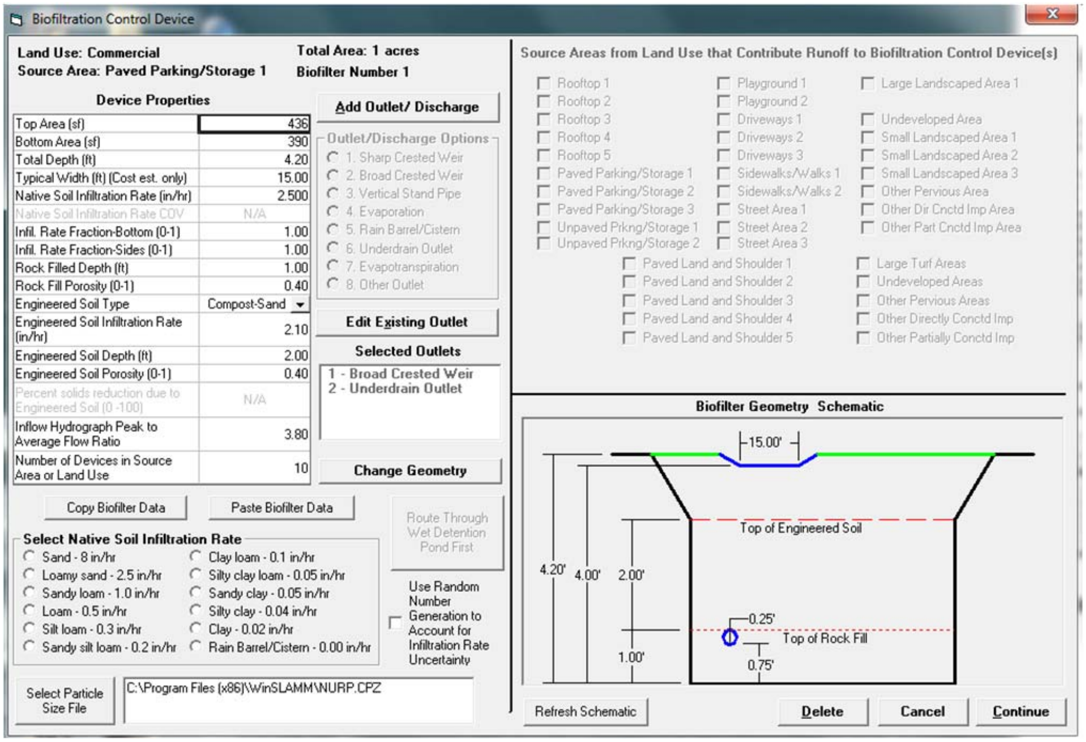
Biofilter performance is based upon the flow entering the device, the infiltration rate into the native soil, the filtering capacity and infiltration rate of the engineered soil fill, the amount of rock fill storage, the size of the device and the outlet structures for the device. Pollutant filtering by the engineered soil (usually containing amendments) is based upon the engineered soil type and the particle size distribution of the inflowing water.   If the engineered soil flow rate is lower than the flow rates entering the device, then the engineered soil will affect the device performance by forcing the excess water to bypass the device through surface discharge if the storage capacity above the engineered soil in inadequate.

The device operation is modeled using the Modified Puls Storage-Indication method, and is analyzed differently depending on the presence of rock and engineered soil layers present in the model. The model simulates the inflow and outflow hydrographs using a six minute time interval, although this interval is automatically reduced if the simulation becomes unstable. The inflow complex triangular hydrograph is divided into six minute time intervals, which are routed to the surface of the biofilter. The biofilter is evaluated in two basic sections: the above ground section (or above the engineered soil), and the below ground section (below the surface of the engineered soil). If there is a rock and engineered soil layer, the available surface outflow devices are the broad and sharp crested weirs, the vertical stand pipe, evaporation, evapotranspiration, and flow through the engineered soil.

As water enters the device, all flow is routed to the below ground section of the device, as long as the engineered soil infiltration rate is greater than the inflowing water rate. As the inflow rate increases, the above ground storage begins to fill up if the inflow rate exceeds the engineered soil infiltration rate. If the inflow rate is high enough and the excess volume exceeds the available storage, the water will begin to discharge from the device through the above ground surface outflow devices. As water enters the below ground section of the device, it discharges through the native soil and, as the bottom section fills, through the underdrain (if used). All water that flows through the underdrain is assumed to be filtered by the engineered soil based on the particle size distribution of the influent particulates and the media characteristics. If the water level in the below ground section of the device reaches the top of the engineered soil layer, then infiltration from the surface layer into the below ground layer is turned off until the water level in the below ground section is below the top of the engineered soil layer. If there are no rock and engineered soil layers, then flow into the native soil is considered to be an outflow, there is no below ground section, and all treatment by the device is assumed to be through volume loss by infiltration into the native soil.

Biofilters can be used as control devices in individual source areas, in land uses, as a part of the drainage system or at the outfall. If modeled as an outfall biofilter, the biofiltration control can be used with an upstream wet detention pond for pretreatment. To model biofilters in a source area, describe the geometry and other characteristics of a typical biofilter, then enter the number of biofilters in the source area. The model divides the total source area runoff volume by the number of biofilters in the source area, creates a complex triangular hydrograph for that representative flow fraction that is then routed through that biofilter, and then multiplies the resulting losses by the number of biofilters for the total source area.

Figure 17 is the basic biofilter input screen (the same as shown previously for the rain garden, but with more information used). As the depths and other features of the biofilter are entered, the drawing is recomposed to approximate the device, including labeling of the dimensions. If an underdrain is used (as in a biofilter; rain gardens and bioretention devices do not have underdrains), the model hydraulically models the described underdrain (form shown as Figure 18) to determine the stage-discharge relationship needed for the routing calculations.



Land Use: Commercial
Source Area: Paved Parking/Storage 1
Total Area: 1 acres
Biofilter Number 1

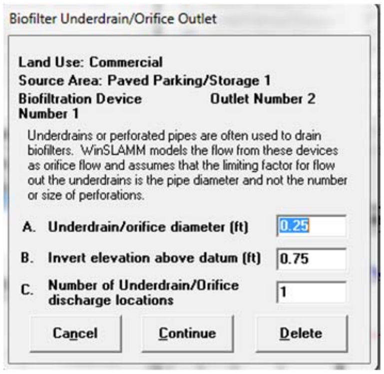
Device Properties

Top Area (sf)	436
Bottom Area (sf)	390
Total Depth (ft)	4.20
Typical Width (ft) (Cost est. only)	15.00
Native Soil Infiltration Rate (in/hr)	2.500
Native Soil Infiltration Rate COV	N/A
Infil. Rate Fraction-Bottom (0-1)	1.00
Infil. Rate Fraction-Sides (0-1)	1.00
Rock Filled Depth (ft)	1.00
Rock Fill Porosity (0-1)	0.40
Engineered Soil Type	Compost-Sand
Engineered Soil Infiltration Rate (in/hr)	2.10
Engineered Soil Depth (ft)	2.00
Engineered Soil Porosity (0-1)	0.40
Percent solids reduction due to Engineered Soil (0 -100)	N/A
Inflow Hydrograph Peak to Average Flow Ratio	3.80
Number of Devices in Source Area or Land Use	10

Selected Outlets
1 - Broad Crested Weir
2 - Underdrain Outlet

C:\Program Files (x86)\WinSLAMM\NURP.CPZ

Figure 17. Biofilter main input screen.



Land Use: Commercial
Source Area: Paved Parking/Storage 1
Biofiltration Device Number 1
Outlet Number 2

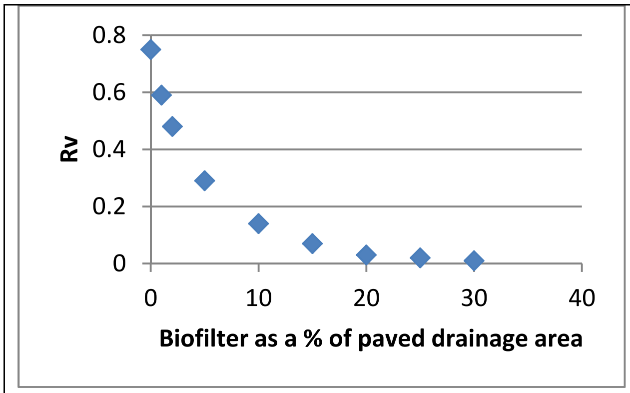
Underdrains or perforated pipes are often used to drain biofilters. WinSLAMM models the flow from these devices as orifice flow and assumes that the limiting factor for flow out the underdrains is the pipe diameter and not the number or size of perforations.

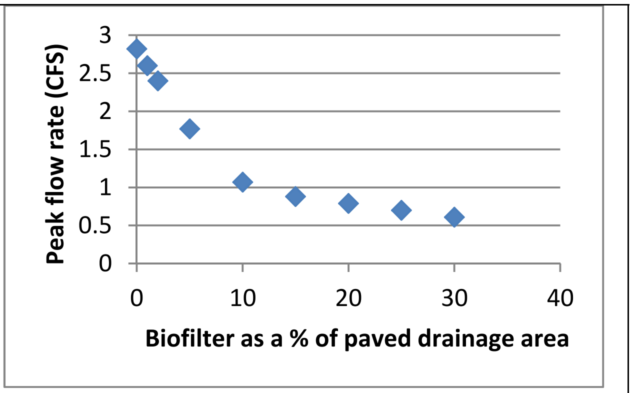
A. Underdrain/orifice diameter (ft) 0.25
B. Invert elevation above datum (ft) 0.75
C. Number of Underdrain/Orifice discharge locations 1

Figure 18. Underdrain input screen.

Figure 19 and Table 5 are summaries of the biofilter calculations. The paved parking/storage area was examined for a range of biofilter sizes, from 1 to 30% of the source drainage area. As indicated in the specifications, the native soil has infiltration characteristics similar to loamy sand. A conventional 3" perforated pipe underdrain system was also used in these calculations. Figure 19 indicates significant benefits with these biofilters when they are in the specified 10 to 20% size range. From 80 to more than 95% volume reductions are expected, along with about 60 to 75% peak flow rate reductions. Very large sediment reductions are also shown (>90%). Clogging may occur within 8 to 15 years for the 10% area biofilter. Biofilters smaller than this size are not recommended due to premature clogging potential.

Similar calculations (not shown) were also performed examining alternative underdrain systems. It is possible to not use any underdrain in these well-drained soils. If so, the volume and peak flow rate reductions would be even greater, as the underdrain allows short-circuiting of the subsurface water before it infiltrates into the natural soils. The use of a more restrictive underdrain (such as the SmartDrain^{TM}) also increases the biofilter performance, while still reducing surface ponding durations.





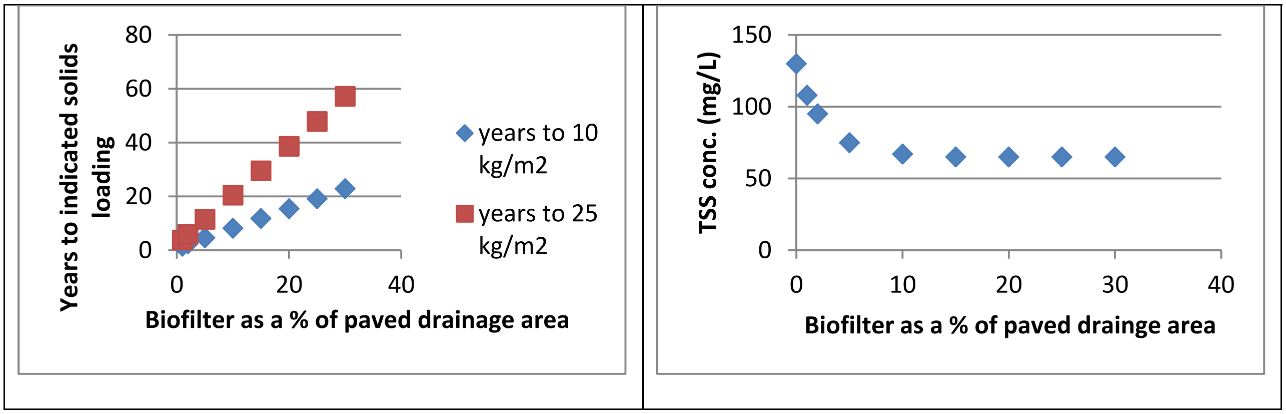


Figure 19. Biofilter performance for paved parking/storage area (using conventional 3" perforated underdrains and loamy sand soil).

Table 5. Calculated Performance of Biofilters Treating Paved Parking/Storage Area (loamy sand soil, 3" underdrains)

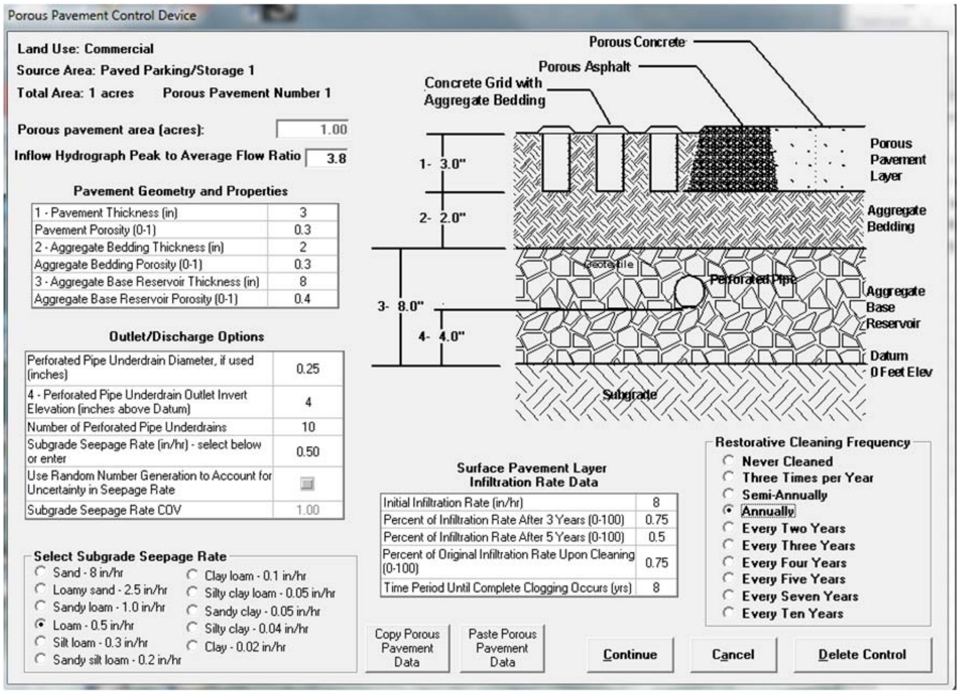
Biofilter as a percentage of source area	Rv	Volume reduc. (%)	Expected habitat conditions	TSS (mg/L)	solids discharged (lbs/yr)	peak runoff rate (CFS)	peak rate reduc. (%)	TP (mg/L)	TP load (lbs)	Cu (ug/L)	Cu load (lbs)
Base conditions	0.75	n/a	poor	130	812	2.82	n/a	0.21	13	21	1.3
1	0.59	21	poor	108	528	2.6	8	0.18	8.9	19	0.94
2	0.48	36	poor	95	380	2.4	15	0.16	6.5	18	0.73
5	0.29	61	poor	75	182	1.77	37	0.14	3.3	17	0.4
10	0.14	81	fair	67	78	1.07	62	0.12	1.4	16	0.18
15	0.07	91	good	65	37	0.88	69	0.12	0.68	16	0.088
20	0.03	96	good	65	19	0.79	72	0.12	0.35	16	0.045
25	0.02	97	good	65	9.2	0.7	75	0.12	0.17	16	0.022
30	0.01	99	good	65	4.6	0.61	78	0.12	0.086	16	0.011

Porous Pavement

The WinSLAMM porous pavement control option now has full routing calculations associated with pond storage in conjunction with other porous pavement features. The "outlet" options for porous pavement include subgrade seepage as well as an optional underdrain, which is modeled as an orifice. The porous pavement control device option has a surface seepage rate that limits the amount of runoff that can enter the storage system. The seepage rate is usually much larger than the rain intensity, so this would be unusual, except if it is significantly reduced by clogging. This surface seepage rate is reduced to account for clogging over time, and the surface seepage rate can be partially restored with cleaning at a stated cleaning frequency. The porous pavement control device infiltrates water originating from the rainfall hitting the pavement surface area only - it currently does not accept run-on from other surfaces. The runoff volume reaching the porous pavement surface is therefore equal to the rainfall volume directly falling on the porous pavement. The porous pavement surface area can be any material, including paver blocks, porous concrete, porous asphalt, or any other porous surface, including reinforced turf. Porous pavements are usually installed over a subsurface storage layer that can dramatically increase the infiltration performance of the device, while reinforced turf does not have subsurface storage.

The porous pavement control option can be used as a control device only in individual source areas. Porous pavements are usually located at paved parking and storage areas, paved playgrounds, paved driveways, or paved walkways. They should be used in relatively clean areas (walkways or driveways or other surfaces that receive little traffic, for example), to minimize groundwater contamination potential. Porous pavements direct the infiltrating water to subsurface soil layers, usually beneath much or the organic surface soils that tend to sorb many pollutants. Salts used for ice control in northern areas are also problematic when considering infiltrating stormwater. Therefore, only use porous pavements in areas needing minimal salt applications. Consider biofiltration devices to infiltrate water from more contaminated sites, as they can use amended soils to help trap contaminants before infiltration, or use other appropriate pre-treatment before infiltration. No common pretreatment device is suitable for the removal of salts, however, so minimal use of de-icing chemicals is the preferred control option in that case.

To model porous pavement in a suitable source area, describe the geometry and other characteristics of a typical porous pavement surface, as shown in Figure 20. The model computes the runoff volume, equal to the rainfall volume, and then creates a complex triangular hydrograph that is used to statistically describe a random rainfall pattern (the flow duration equals the rain duration) that it routes through that porous pavement system.



Land Use: Commercial
Source Area: Paved Parking/Storage 1
Total Area: 1 acres Porous Pavement Number 1

Porous pavement area (acres): 1.00
Inflow Hydrograph Peak to Average Flow Ratio 3.8

Pavement Geometry and Properties

1 - Pavement Thickness (in)	3
Pavement Porosity (0-1)	0.3
2 - Aggregate Bedding Thickness (in)	2
Aggregate Bedding Porosity (0-1)	0.3
3 - Aggregate Base Reservoir Thickness (in)	8
Aggregate Base Reservoir Porosity (0-1)	0.4

Outlet/Discharge Options

Perforated Pipe Underdrain Diameter, if used (inches)	0.25
4 - Perforated Pipe Underdrain Outlet Invert Elevation (inches above Datum)	4
Number of Perforated Pipe Underdrains	10
Subgrade Seepage Rate (in/hr) - select below or enter	0.50
Use Random Number Generation to Account for Uncertainty in Seepage Rate	☐
Subgrade Seepage Rate COV	1.00

Select Subgrade Seepage Rate
○ Sand - 8 in/hr
○ Loamy sand - 2.5 in/hr
○ Sandy loam - 1.0 in/hr
● Loam - 0.5 in/hr
○ Silt loam - 0.3 in/hr
○ Sandy silt loam - 0.2 in/hr
○ Clay loam - 0.1 in/hr
○ Silty clay loam - 0.05 in/hr
○ Sandy clay - 0.05 in/hr
○ Silty clay - 0.04 in/hr
○ Clay - 0.02 in/hr

Surface Pavement Layer Infiltration Rate Data

Initial Infiltration Rate (in/hr)	8
Percent of Infiltration Rate After 3 Years (0-100)	0.75
Percent of Infiltration Rate After 5 Years (0-100)	0.5
Percent of Original Infiltration Rate Upon Cleaning (0-100)	0.75
Time Period Until Complete Clogging Occurs (yrs)	8

Restorative Cleaning Frequency
○ Never Cleaned
○ Three Times per Year
○ Semi-Annually
● Annually
○ Every Two Years
○ Every Three Years
○ Every Four Years
○ Every Five Years
○ Every Seven Years
○ Every Ten Years

Figure 20. Porous pavement main input screen.

Table 6 summarizes the calculated performance of porous pavement located at the paved parking/storage area. The given underlying soil is similar to loam soil conditions which were used in these calculations. A conventional 3" perforated pipe underdrain was also used. The calculations for the porous pavement in areas less than the full area were conducted by reducing the storage and infiltration rates proportionally. As indicated, even the smallest area examined (25% of the area as porous pavement) had very good runoff volume reductions. The porous pavement was cleaned every year, restoring much of the lost surface infiltration rate capacity in this example. If the area was not cleaned, clogging would be expected in about 8 years, based on field experience.

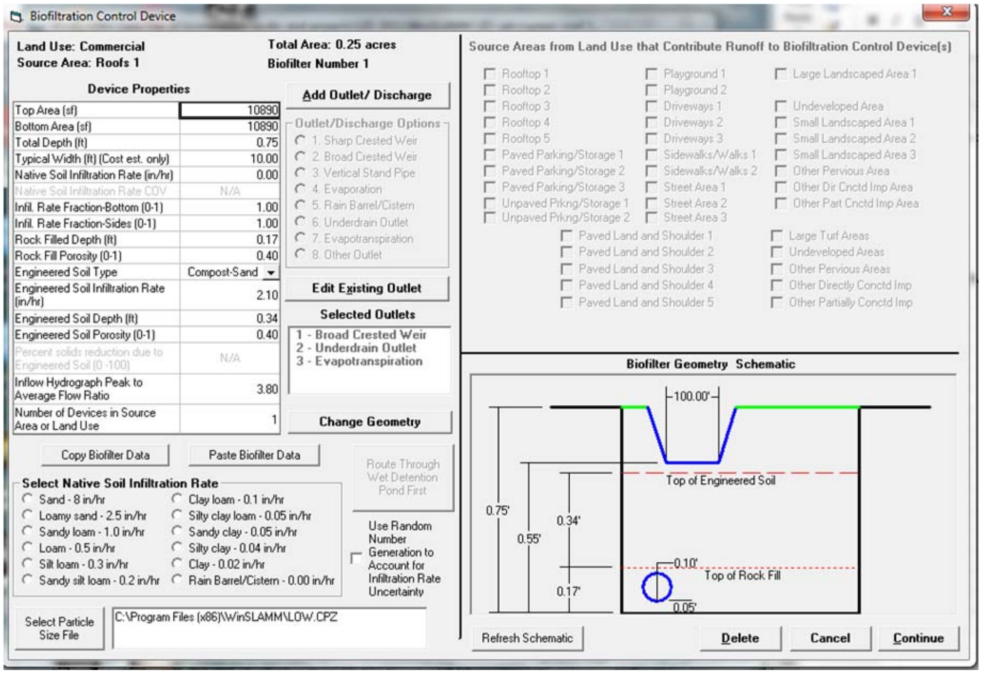
Table 6. Porous Pavement Performance (paved parking and storage area; loam soil; 3" underdrains every 20 ft.)

porous pvt as a % of paved parking area	Rv	Volume reduction (%)	Expected habitat conditions	TSS (mg/L)	solids discharged (lbs/yr)	TP (mg/L)	TP load (lbs)	Cu (ug/L)	Cu load (lbs)
none	0.75	n/a	poor	130	812	0.21	13	21	1.3
25%	0.06	92	good	130	60	0.21	0.98	21	0.098

50%	0.05	93	good	130	58	0.32	0.94	12	0.093
100%	0.05	93	good	130	58	0.21	0.94	21	0.093

Green Roofs

As noted above under the description of the biofilter calculations, the biofilter device can be configured to represent green roofs, as illustrated in Figure 21. In version 10, a separate screen is provided for these devices. Basically, the green roof area is used as the area of the biofilter, and no natural infiltration is obviously allowed. The only outlets include the required broad crested weir for surface overflows, underdrains, and ET. Partial roof coverage can be modeled by using a smaller area for the "biofilter" to represent the area dedicated to green roof processes.



Biofiltration Control Device

Land Use: Commercial
Source Area: Roofs 1
Total Area: 0.25 acres
Biofilter Number 1

Device Properties

Top Area (sf)	10890
Bottom Area (sf)	10890
Total Depth (ft)	0.75
Typical Width (ft) (Cost est. only)	10.00
Native Soil Infiltration Rate (in/hr)	0.00
Native Soil Infiltration Rate COV	N/A
Infil. Rate Fraction-Bottom (0-1)	1.00
Infil. Rate Fraction-Sides (0-1)	1.00
Rock Filled Depth (ft)	0.17
Rock Fill Porosity (0-1)	0.40
Engineered Soil Type	Compost-Sand
Engineered Soil Infiltration Rate (in/hr)	2.10
Engineered Soil Depth (ft)	0.34
Engineered Soil Porosity (0-1)	0.40
Percent solids reduction due to Engineered Soil (0 -100)	N/A
Inflow Hydrograph Peak to Average Flow Ratio	3.80
Number of Devices in Source Area or Land Use	1

Selected Outlets
1 - Broad Crested Weir
2 - Underdrain Outlet
3 - Evapotranspiration

Select Particle Size File: C:\Program Files (x86)\WinSLAMM\LOW.CPZ

Figure 21. Green roof main input screen.

Table 7 summarizes the calculated performance of the specified green roof system, for different roof coverages. The concentrations are similar for all scenarios because almost all of the water is filtered by the roof media, with little being discharged to the surface overflows. The available ET resulted in about 25% reductions in runoff volume reductions. If more surface storage was provided in the green roof design and if more efficient plants were used, it is likely that these runoff volume reductions could be about double the reductions shown in this example.

Table 7. Calculated Green Roof Performance.

green roof as a % of flat roof area (3" conventional underdrains every 20 ft)	Rv	volume reductions (%)	TSS (mg/L)	solids discharged (lbs/yr)	peak runoff rate (CFS)	peak rate reductions (%)	TP (mg/L)	TP load (lbs)	Cu (ug/L)	Cu load (lbs)
none	0.8	n/a	33	55	0.76	n/a	0.22	3.6	11	0.18
25%	0.71	11	24	35	0.57	25	0.17	2.4	9.8	0.14
50%	0.66	18	24	33	0.45	41	0.16	2.2	9.7	0.13
100%	0.6	25	24	29	0.38	50	0.16	2	9.7	0.12

Summary and Conclusions

Stormwater quality models can produce copious amounts of information for large numbers of alternative management programs that contain a wide variety of individual stormwater control practices, as described by Pitt and Clark (2008). In most cases, just a few of the values presented on the calculation summary screen are sufficient for quick comparisons. These include the overall percent runoff and particulate solids reductions, the final Rv and runoff volume, and the resulting particulate solids yields and concentrations. Recent enhancements to WinSLAMM also now enable the costs and the expected habitat conditions of the receiving waters to be compared, in addition to flow-duration information. Cost data were summarized from several studies, including those by APWA 1992, Brown and Schueler 1997, Frank 1989, Heaney, *et al*. 2002, Muthukrishnan, *et al*. 2006, Sample, *et al.* 2003, SEWRPC 1991, Wiegand, *et al*. 1986, and Wossink and Hunt 2003, as summarized by Naryanan and Pitt (2005). The use of decision analysis procedures, based on methods developed by Keeney and Raiffa (1976) with the WinSLAMM batch processor has also been demonstrated (Pitt and Voorhees 2007) and allows semi-automatic formal evaluations of alternative stormwater control programs considering multiple conflicting objectives.

WinSLAMM has been undergoing development and changes since the mid-1970s and now includes a wide range of options. Over the years, periodic major upgrades have occurred to take advantage of advancing computer capabilities and knowledge gained through stormwater research, and to respond to requests by users. Version 10 is scheduled to be released in the early spring of 2011 and is one such major upgrade. The examples shown in this paper are based on the prior available version of the model and do not include some of the improvements that will enhance the ability to model some of the stormwater control practices discussed. However, this paper does present the types of information used in these calculations and the general methods employed, along with some example sensitivity results and production functions that can be calculated by WinSLAMM model users to support designs and/or evaluations.

Acknowledgment

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