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February 16, 2013

WinSLAMM Basic Runoff and Pollutant Calculations

Runoff Volume, Total Suspended Solids and Other Pollutant Calculations

Regional Calibration Files

WinSLAMM uses the concept of small storm hydrology to calculate runoff volumes and pollutant loadings for urban drainage basins for all rainfall events over a defined time period. All rainfall events are used because, though large events contribute significant amounts of pollutants to urban runoff, many smaller events contribute more runoff volume and total pollutant load over the course of a year than the very few large events.

Drainage Basin Characterization.

Drainage basins in WinSLAMM are characterized by defining and describing the land uses that drain to an outfall. The study area could be the land draining to a storm sewer pipe's outfall that discharges to a river, stream or lake, or simply a location in the drainage system where runoff volumes and pollutant loads are defined by the user. A drainage basin can be defined as a single lot, a block, subdivision, industrial area, shopping center, school campus, military base, or subbasin draining a large portion of a community.

In WinSLAMM, drainage basins are composed of one or more land uses. These land uses are described as either residential, commercial, institutional, industrial, open space or freeway. These land uses are distinct because the pollutant loading calculated by WinSLAMM will vary depending upon the land use. Each land use is further described by the source areas within the land use. Source areas include rooftops, driveways, streets, parking areas, playgrounds, or landscaped areas (the complete list is included in the WinSLAMM Help File). The type of land use (for example, low density residential vs. high density residential) is characterized by the composition of the source areas within that land use. A low density residential land use will have significantly more landscaped pervious areas than a high density residential area. The high density residential area will have significantly more rooftop, street and paved parking areas than a low density residential area.

Finally, each source area type is characterized by a small group of source area parameters. For example, the source area parameters for roof areas include the slope of the roof – is it pitched or flat, if the source area is directly connected to the drainage system, or if it is disconnected, whether the runoff drains to sandy, silty or clayey soils. Other impervious areas (besides roofs and streets) ask if the source area is directly connected to the drainage system, or if disconnected, whether the runoff drains to sandy, silty or clayey soils. If the runoff drains to clayey soils, then two further characterizations are possible for the non-street impervious areas, wither the building density is low, medium or high, and if medium or high, if the source areas include alleys. These impervious area disconnection issues affect the amount of runoff (and associated pollutants) actually make it to the drainage system. The highest yields occur when the areas are directly connected, while the lowest yields occur when the areas are disconnected in low density land uses having sandy soils, as these would have the longest flow paths over pervious ground having high infiltration rates. The yield factors were determined through extensive monitoring at highly different drainage areas (initially in Milwaukee during the EPA's NURP project and also in Toronto as part of the TAWMS program conducted in the early 1980s). These have been verified in many other locations and conditions since then.

This list of source area parameters might seem detailed, but it typically is not for two reasons. The first is that these parameters are general. Rooftops are defined as either flat or pitched – it is not necessary to specify a roof pitch. A source area is directly connected if runoff from it flows directly to the drainage system without passing over a significant pervious area. This means that runoff from a rooftop that flows down a driveway to a curb and gutter drainage system before entering the storm sewer is directly connected. Sandy, silty or clayey soils are typically classified by SCS soil types A, B or C and D, respectively.

The second reason source areas need not be thought of as requiring excessive detail is because WinSLAMM provides users with a set of standard land uses (for example, downtown commercial or low density residential) that include specific lists of source areas for each standard land use. These standard land uses are easily accessed (see the Standard Land Use help topic) and can be modified or added to, if necessary, by the user. These were developed through extensive site surveys in Wisconsin in support of their priority watershed program. Supplemental literature describes similar standard land uses for other areas. There is relatively little difference across North America for the same land use in different areas. However, the "connectiveness" of the impervious area can be highly varied even in a small area. Therefore, these features should be verified locally.

Typically, WinSLAMM users who are evaluating more than a few drainage basins will divide drainage basins by land use, and then select specific standard land uses for each land use in the drainage basin. Users who are evaluating a small number of drainage basins often measure street areas and lengths, and rooftop, sidewalk, and driveway areas to accurately characterize the drainage area characteristics of the site they are modeling.

Runoff Volume Calculation

Runoff volumes in WinSLAMM are calculated from runoff coefficients (the ratio of runoff to rainfall as a function of rainfall depth) for each of the source areas described in the previous section. These runoff coefficients, which have been determined through extensive field monitoring, are multiplied by the rainfall depth and area of each source area to determine the runoff volume. For example, a drainage basin in a medium density residential area will be composed primarily of street, rooftop, driveway, sidewalk, and pervious source areas. To calculate the runoff volume for each rainfall event in a model run, the program first determines the runoff coefficient for each medium density residential source area, for each rainfall event. This coefficient is calculated from the runoff coefficient (R_v), or RSV file table the user has selected for the model run. Figures 1a and 1b below are examples of a runoff coefficient table from WinSLAMM, and a plot of the data from the table, respectively. The R_v values increase in magnitude as the rain depth increases, reflecting the increasing yield of rainfall to runoff as the runoff losses become satisfied.

Area Types (AT):

AT 1: Connected flat roofs
AT 2: Connected Pitched Roofs
AT 3: Directly connected impervious areas
AT 4: Directly connected unpaved areas
AT 5: Pervious areas - Sandy soils
AT 6: Pervious areas - Silty soils
AT 7: Pervious areas - Clayey soils
AT 8: Smooth textured streets
AT 9: Intermediate textured streets
AT 10: Rough textured streets
AT 11: High Traffic Urban Paved Areas
AT 12: High Traffic Urban Pervious Areas

(•) **Runoff Coefficient Data**
( ) **Drainage Efficiency Coefficient Data**

Volumetric Runoff Coefficients for Rains (in. and mm.)

Rain (in)	0.01	0.08	0.12	0.20	0.39	0.59	0.79	0.98	1.2	1.6	2.0	2.4	2.8	3.2	3.5	3.9	4.9
Rain (mm)	1	2	3	5	10	15	20	25	30	40	50	60	70	80	90	100	125
AT 1	0.00	0.00	0.30	0.54	0.72	0.79	0.83	0.84	0.86	0.88	0.90	0.91	0.93	0.94	0.94	0.95	0.96
AT 2	0.25	0.63	0.75	0.85	0.93	0.95	0.96	0.97	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99
AT 3	0.93	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99
AT 4	0.00	0.00	0.00	0.00	0.47	0.64	0.72	0.77	0.81	0.86	0.89	0.91	0.92	0.93	0.94	0.94	0.95
AT 5	0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.02	0.03	0.04	0.07	0.10	0.13	0.15	0.20	0.22	0.25
AT 6	0.00	0.00	0.00	0.05	0.08	0.10	0.11	0.12	0.13	0.14	0.16	0.19	0.22	0.24	0.28	0.30	0.35
AT 7	0.00	0.00	0.00	0.10	0.15	0.19	0.20	0.21	0.22	0.23	0.26	0.29	0.32	0.33	0.36	0.39	0.45
AT 8	0.35	0.49	0.54	0.59	0.65	0.69	0.72	0.76	0.80	0.85	0.88	0.90	0.91	0.93	0.93	0.94	0.95
AT 9	0.26	0.43	0.49	0.55	0.60	0.64	0.67	0.67	0.73	0.80	0.84	0.86	0.88	0.90	0.91	0.92	0.93
AT 10	0.18	0.39	0.47	0.53	0.60	0.64	0.67	0.70	0.73	0.80	0.84	0.86	0.88	0.90	0.91	0.92	0.93
AT 11	0.55	0.73	0.77	0.83	0.87	0.97	0.97	0.97	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.99	1.00
AT 12	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.33	0.40	0.50	0.55	0.60	0.62	0.65	0.65	0.65	0.65

Figure 1a – Runoff Coefficient Table (v10 Runoff.rsv)

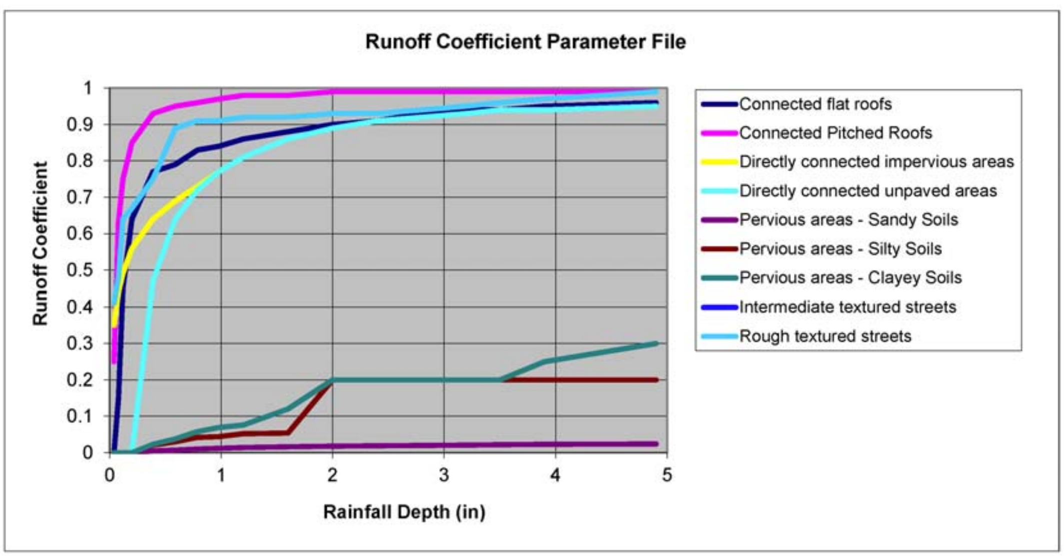


Figure 1b – Runoff Coefficient Plot (v10 Runoff.rsv)

Each runoff coefficient is interpolated from the RSV file for each source area and rainfall depth, and multiplied by the rainfall depth and appropriate source area to determine the runoff volume. Note that based upon monitored data, runoff volume coefficients do not vary by land use, but by surface cover at the source area and by rain depth. The runoff volume equation is:

Runoff Volume (ft^3) = Rainfall Depth (in) * Source Area (ac) * Runoff Coefficient * unit conversion

The graphic below (Figure 2) represents a small medium density residential drainage area with connected and disconnected (draining to a pervious area) rooftops, driveways, sidewalks, pervious areas and streets. The R_v value for the first rainfall event is listed with the source area label. Each of these source areas is listed in Table 2, below, along with the runoff coefficient and rainfall volume for each source area for three rainfall events. The main data grid in Table 2 lists the runoff coefficient and volume for each of the source areas, for each of the rainfall events on the table.

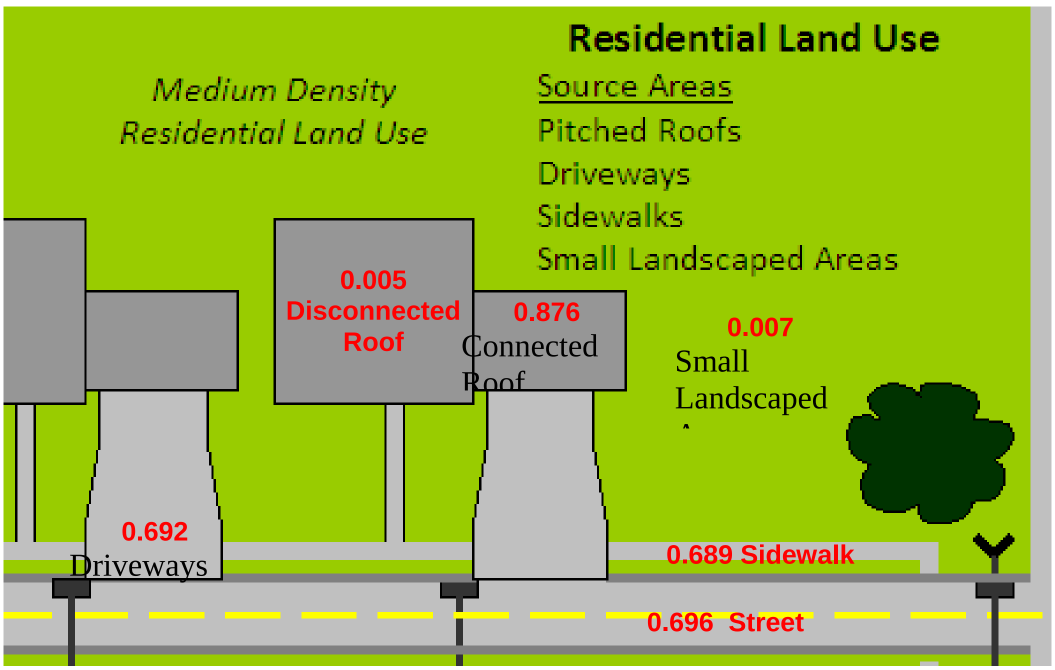


Figure 2 – Medium Density Residential Drainage Area with Runoff Coefficients for the First Rainfall Event Listed in Table 2

Table 2 – Medium Density Runoff Coefficient Example for Three Rainfall Events

Rainfall Depth (in) ==>		0.26		0.71		0.41	
Source Area	Area (ac)	Rv	Runoff (cf)	Rv	Runoff (cf)	Rv	Runoff (cf)
Residential Land Use							
Roof - Connected	0.15	0.876	124	0.957	370	0.932	208
Roof - Disconnected	0.20	0.005	1	0.037	19	0.020	6
Driveway	0.15	0.692	98	0.903	349	0.761	170
Sidewalk	0.04	0.689	26	0.902	93	0.756	45
Small Landscape Area	1.25	0.007	8	0.037	120	0.022	40
Street	0.30	0.696	197	0.903	698	0.761	340
Total	2.09		454		1649		809

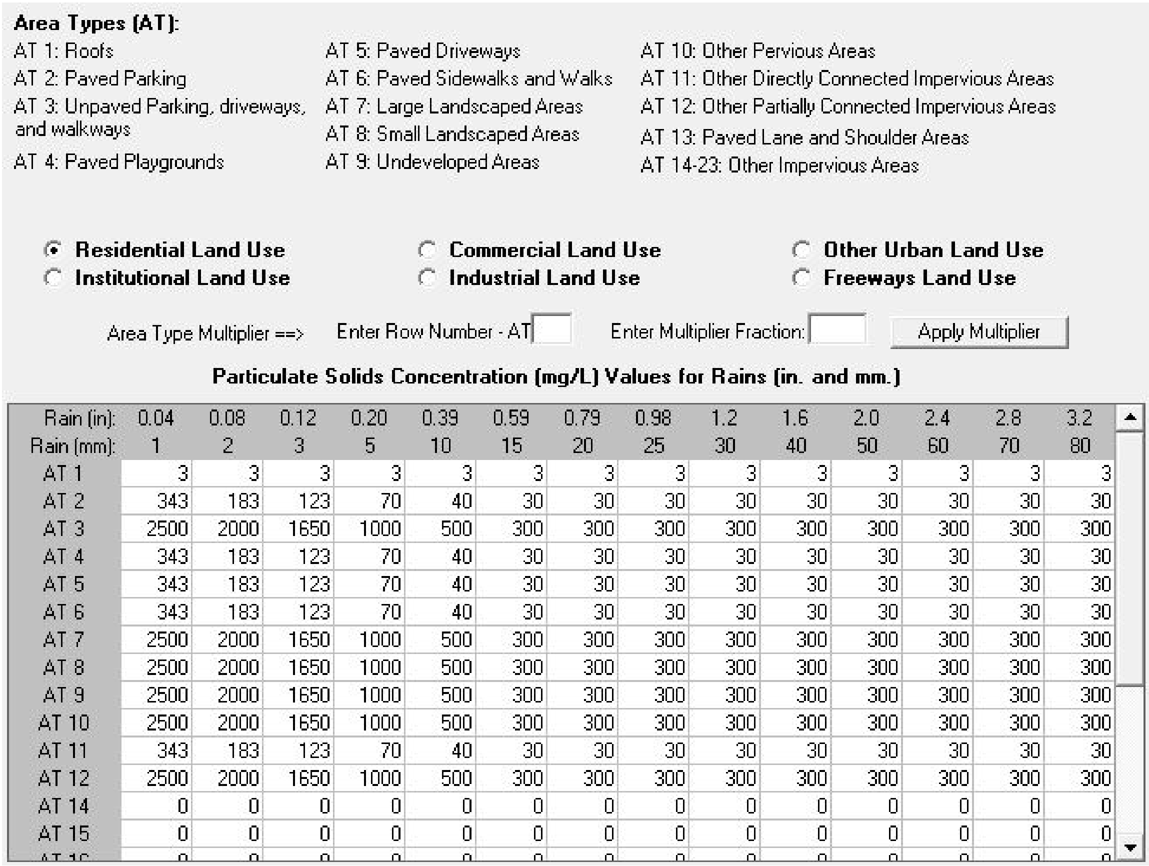
WinSLAMM calculates the runoff volume for each source area and for each rainfall event, in the model run as a base model condition. This is without stormwater control practices and is listed as the 'Base' condition on the WinSLAMM output summary. Stormwater control practices affecting runoff from source areas and/or the drainage system are added to the model run to evaluate the effectiveness of the control practices for comparison.

Total Suspended Solids Calculation

Total suspended solids pollutant values are determined in a similar manner. The program determines the particulate solids concentration for each source area in each land use, for each rainfall event. This coefficient is calculated from the particulate solids concentration, or PSC file (Figure 3) table you select for the model run. Each particulate solids concentration value is interpolated from the PSC file for each land use, source area and rainfall depth, and multiplied by the runoff volume to determine the particulate solids loading. The equation is:

Particulate Solids Loading (lbs) = Runoff Volume (ft^3) * Particulate Solids Concentration (mg/L) * unit conversion

The particulate solids concentration values in Table 3 are examples for residential land uses, and are calibrated from monitored data from the Birmingham, Alabama area. This file contains similar sets of data for the other land uses. The values are varied as a function of the rainfall depth.



Rain (in):	0.04	0.08	0.12	0.20	0.39	0.59	0.79	0.98	1.2	1.6	2.0	2.4	2.8	3.2
Rain (mm):	1	2	3	5	10	15	20	25	30	40	50	60	70	80
AT 1	3	3	3	3	3	3	3	3	3	3	3	3	3	3
AT 2	343	183	123	70	40	30	30	30	30	30	30	30	30	30
AT 3	2500	2000	1650	1000	500	300	300	300	300	300	300	300	300	300
AT 4	343	183	123	70	40	30	30	30	30	30	30	30	30	30
AT 5	343	183	123	70	40	30	30	30	30	30	30	30	30	30
AT 6	343	183	123	70	40	30	30	30	30	30	30	30	30	30
AT 7	2500	2000	1650	1000	500	300	300	300	300	300	300	300	300	300
AT 8	2500	2000	1650	1000	500	300	300	300	300	300	300	300	300	300
AT 9	2500	2000	1650	1000	500	300	300	300	300	300	300	300	300	300
AT 10	2500	2000	1650	1000	500	300	300	300	300	300	300	300	300	300
AT 11	343	183	123	70	40	30	30	30	30	30	30	30	30	30
AT 12	2500	2000	1650	1000	500	300	300	300	300	300	300	300	300	300
AT 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AT 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3 – Particulate Solids Concentration Table (BHAM_PPD_CALIB_June07.ppdx)

Other Pollutant Calculations

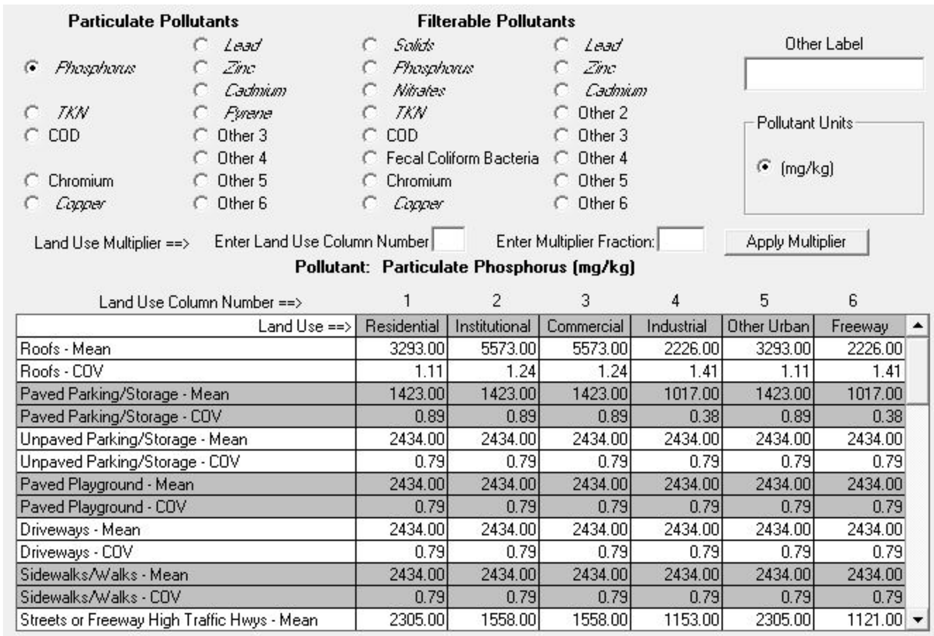
Particulate and filterable pollutants are determined in a similar manner. WinSLAMM has a set of pollutants available for analysis associated with each pollutant probability distribution (.PPDx) file. These files are calibrated based upon monitored data and are available for different areas of the country, as described below. Figure 4 shows an example set of available pollutants. Note that Cadmium and Pyrene are not standard pollutants, but have been added to the illustrated pollutant file as “Other” pollutants.

For each selected pollutant, the program determines the particulate pollutant concentration for each source area in each land use. The particulate pollutant strength units in the PPDx file are either milligrams or micrograms of pollutant per kilograms of the calculated particulate solids loading for each source area. Particulate pollutant strengths are multiplied by the calculated particulate solids loading for each source area in each land use to determine the particulate pollutant loading for that source area. The equation is:

Particulate Pollutant Loading (lbs) = Particulate Solids Loading (lbs) * Particulate Pollutant strength (mg/kg) * unit conversion

WinSLAMM determines the filterable pollutant concentration for each source area in each land use in a similar manner. The filterable pollutant concentration units are either milligrams, micrograms, or a Count (for bacteria) of pollutant per Liter of the calculated runoff volume. This coefficient is obtained from the table used in the model run for each land use and source area. Filterable pollutant concentrations are multiplied by the runoff volume to determine the filterable pollutant loading. The equation is:

Filterable Pollutant Loading (lbs) = Runoff Volume (ft^3) * Filterable Pollutant Concentration (mg/L) * unit conversion



Land Use Column Number ==>	1	2	3	4	5	6
Land Use ==>	Residential	Institutional	Commercial	Industrial	Other Urban	Freeway
Roofs - Mean	3293.00	5573.00	5573.00	2226.00	3293.00	2226.00
Roofs - COV	1.11	1.24	1.24	1.41	1.11	1.41
Paved Parking/Storage - Mean	1423.00	1423.00	1423.00	1017.00	1423.00	1017.00
Paved Parking/Storage - COV	0.89	0.89	0.89	0.38	0.89	0.38
Unpaved Parking/Storage - Mean	2434.00	2434.00	2434.00	2434.00	2434.00	2434.00
Unpaved Parking/Storage - COV	0.79	0.79	0.79	0.79	0.79	0.79
Paved Playground - Mean	2434.00	2434.00	2434.00	2434.00	2434.00	2434.00
Paved Playground - COV	0.79	0.79	0.79	0.79	0.79	0.79
Driveways - Mean	2434.00	2434.00	2434.00	2434.00	2434.00	2434.00
Driveways - COV	0.79	0.79	0.79	0.79	0.79	0.79
Sidewalks/Walks - Mean	2434.00	2434.00	2434.00	2434.00	2434.00	2434.00
Sidewalks/Walks - COV	0.79	0.79	0.79	0.79	0.79	0.79
Streets or Freeway High Traffic Hwys - Mean	2305.00	1558.00	1558.00	1153.00	2305.00	1121.00

Figure 4 – Particulate Solids Concentration Table (BHAM_PPD_CALIB_June07.ppdx)

Sets of Regional Calibration Files Distributed with WinSLAMM

Detailed land use characteristics and concurrent monitoring data are available from several older and current stormwater research projects. The projects and locations used in developing the regional calibration files include:

• Jefferson County, AL (high density residential; medium density residential <1960, 1960 to 1980 and >1980; low density residential; apartments; multi-family; offices; shopping center; schools; churches; light industrial; parks; cemeteries; golf courses; and vacant land). These areas were inventoried as part of regional stormwater research and included about 10 single land use neighborhoods for each land use category. Local NPDES data were available to calibrate WinSLAMM for regional conditions using the specific monitored areas. The sites are described in several publications, including:

- Bochis, C., R. Pitt, and P. Johnson. "Land development characteristics in Jefferson County, Alabama." In: *Stormwater and Urban Water Systems Modeling*, Monograph 16. (edited by W. James, E.A. McBean, R.E. Pitt and S.J. Wright). CHI. Guelph, Ontario, pp. 249 – 282. 2008.

• Bellevue, WA (medium density residential <1960). These data were from test and control watersheds that were extensively monitored as part of the Bellevue project of the EPA's

Nationwide Urban Runoff Program (NURP). Much monitoring data from these sites are available for calibration of WinSLAMM. These areas are described in:

- Pitt, R. and P. Bissonnette. *Bellevue Urban Runoff Program Summary Report*, U.S. Environmental Protection Agency, Water Planning Division. PB84 237213. Washington, D.C. 173 pgs. 1984.
- Pitt, R. *Characterizing and Controlling Urban Runoff through Street and Sewerage Cleaning*. U.S. Environmental Protection Agency, Storm and Combined Sewer Program, Risk Reduction Engineering Laboratory. EPA/600/S2-85/038. PB 85-186500. Cincinnati, Ohio. 467 pgs. June 1985.

• Kansas City, MO (medium density residential <1960). These descriptions are from the test watershed in the EPA green infrastructure demonstration project conducted in Kansas City. Detailed inventories were made of each of the approximately 600 homes in the area. These are summarized in the following:

- Pitt, R., J. Voorhees. "Modeling green infrastructure components in a combined sewer area." Monograph 19. ISBN 978-0-9808853-4-7. *Modeling Urban Water Systems*. *Cognitive Modeling of Urban Water Systems*. James, W., K.N. Irvine, James Y. Li, E.A. McBean, R.E. Pitt, and S.J. Wright (editors). Computational Hydraulics International. Guelph, Ontario. 2011. pp. 139 – 156.
- Pitt, R. and J. Voorhees. "Green infrastructure performance modeling with WinSLAMM." *2009 World Environmental and Water Resources Congress* Proceedings, Kansas City, MO, May 18 - 22, 2009.

• Downtown Central Business Districts (Atlanta, GA; Chicago, IL; Los Angeles, CA; New York, NY; and San Francisco, CA). These were not monitored locations, but were selected to represent a land use category for land development characteristics that are not well represented in the available research projects. Five example areas in the high density downtown areas of each of these five cities were examined in detail using Google maps. The areas associated with each land cover in a several block area were manually measured and described. No runoff quality or quantity data are available for these areas.

• Millburn, NJ (medium density residential 1961-80). Nine homes were monitored during this EPA research project investigating the effects of dry-well disposal of stormwater from individual homes, and the potential for irrigation use of this water. Google map aerial photographs and site surveys were conducted at each home to determine the land covers and characteristics. Data were presented at the following technical conferences:

- Talebi, L. and R. Pitt. "Stormwater Non-potable Beneficial Uses: Modeling Groundwater Recharge at a Stormwater Drywell Installation." ASCE/EWRI World Environment and Water Resources Congress. Palm Springs, CA, May 22-26, 2011.
- Talebi, L. and R. Pitt. "Stormwater Non-potable Beneficial Uses and Effects on Urban Infrastructure." 84th Annual Water Environment Federation Technical Exhibition and Conference (WEFTEC), Los Angeles, CA, October 15–19, 2011.

• San Jose, CA (medium density residential 1961-80; downtown central business district). Two residential and one downtown area were characterized as part of this early stormwater research project. Stormwater characterization data are available for these areas. These are described in the following report:

- Pitt, R. *Demonstration of Nonpoint Pollution Abatement Through Improved Street Cleaning Practices*, EPA-600/2-79-161, U.S. Environmental Protection Agency, Cincinnati, Ohio. 270 pgs. 1979.

• Toronto, Ontario (medium density residential 1961-80; medium industrial). These two areas were characterized and monitored as part of a research project conducted for the Toronto Area Wastewater Management Strategy Study (TAWMS). Stormwater characterization data are also available for these areas. These are described in the following reports:

- Pitt, R. and J. McLean. *Humber River Pilot Watershed Project*, Ontario Ministry of the Environment, Toronto, Canada. 483 pgs. June 1986.
- Pitt, R. *Small Storm Urban Flow and Particulate Washoff Contributions to Outfall Discharges*, Ph.D. Dissertation, Civil and Environmental Engineering Department, University of Wisconsin, Madison, WI, November 1987.

• Tuscaloosa, AL (parking lots at city park and at the city hall). These two sites were characterized and monitored as part of the pilot-scale and full-scale monitoring projects of the Up-Flo™ filter. The pilot-scale tests were conducted as part of an EPA SBIR project and were conducted at the Tuscaloosa City Hall. The full-scale tests were conducted at the Riverwalk parking lot. Stormwater quality and quantity data are available from both of these sites for model calibration. These sites are described in the following reports:

- Pitt, R. and U. Khambhammettu. *Field Verification Tests of the UpFlow™ Filter. Small Business Innovative Research, Phase 2 (SBIR2) Report*. U.S. Environmental Protection Agency, Edison, NJ. 275 pages. March 2006.
- Khambhammettu. U., R. Pitt, R. Andoh, and S. Clark "UpFlow filtration for the treatment of stormwater at critical source areas." Chapter 9 in: *Contemporary Modeling of Urban Water Systems*, ISBN 0-9736716-3-7, Monograph 15. (edited by W. James, E.A. McBean, R.E. Pitt, and S.J. Wright). CHI. Guelph, Ontario. pp 185 – 204. 2007.
- Togawa, N., R. Pitt. R. Andoh, and K. Osei. "Field Performance Results of UpFlow Stormwater Treatment Device." ASCE/EWRI World Environment and Water Resources Congress. Palm Springs, CA, May 22-26, 2011. Conference CD.

• Wisconsin (downtown central business district; duplex residential; high density residential with alleys; high density residential without alleys; high rise residential; hospital; fairgrounds; light industry; low density residential; medium density residential; medium industry; mobile homes; multi-family residential; open space; schools; shopping center; strip commercial; and suburban residential). These areas are the standard land use areas studied and described by the Wisconsin Department of Natural Resources and the USGS to support WinSLAMM modeling in the state. These area descriptions are based on locations studied throughout the main urban areas in Wisconsin, including Milwaukee, Madison, Green Bay, etc. Generally, about 10 homogeneous areas representing each land use category were examined in each study area to develop these characteristic descriptions. Much stormwater characterization data are available for these areas and calibrated versions of the WinSLAMM parameter files are maintained by the USGS for use by state stormwater managers and regulators. Descriptions of these projects and the source water quality data are summarized in the following:

- Pitt, R., R. Bannerman, S. Clark, and D. Williamson. "Sources of pollutants in urban areas (Part 1) – Older monitoring projects." In: *Effective Modeling of Urban Water Systems*, Monograph 13. (edited by W. James, K.N. Irvine, E.A. McBean, and R.E. Pitt). CHI. Guelph, Ontario, pp. 465 – 484 and 507 – 530. 2005.

- Pitt, R., R. Bannerman, S. Clark, and D. Williamson. “Sources of pollutants in urban areas (Part 2) – Recent sheetflow monitoring results.” In: *Effective Modeling of Urban Water Systems*, Monograph 13. (edited by W. James, K.N. Irvine, E.A. McBean, and R.E. Pitt). CHI. Guelph, Ontario, pp. 485 – 530. 2005.
- Pitt, R., D. Williamson, and J. Voorhees. “Review of historical street dust and dirt accumulation and washoff data.” *Effective Modeling of Urban Water Systems*, Monograph 13. (edited by W. James, K.N. Irvine, E.A. McBean, and R.E. Pitt). CHI. Guelph, Ontario, pp 203 – 246. 2005.

• Lincoln, NE (low density residential; medium density residential <1960; 1960-80; >1980; light industry; strip malls; shopping centers; schools; churches; hospitals). These site descriptions are for a stormwater management project in Lincoln, NE that examined pollutant sources and controls. About ten homogeneous examples representing each land use were studied to develop these land use descriptions. Regional NPDES stormwater data are available for this area.

There are many land uses described from many locations throughout the country. The Wisconsin standard land use files represent the broadest range of land uses and the most observations. The Birmingham, AL and Lincoln, NE areas also have data representing a broad range of land uses. Several other study areas are also available that represent other geographical areas of the county. The individual data were initially grouped into six major land use categories: commercial, industrial, institutional, open space, residential, and freeway/highway land uses. Table 3 summarizes the breakdown of these categories into directly connected impervious areas (DCIA), partially connected impervious areas, and pervious areas.

Table 3. Summary of Major Land Use Characteristics (average and COV)

Land Use Category (# of example areas)	Total directly connected impervious areas (DCIA)	total partially connected impervious areas	Total pervious areas
Commercial (16)	79.5 (0.3)	1.8 (2.8)	18.6 (1.0)
Industrial (5)	54.3 (0.3)	21.4 (0.4)	24.3 (0.5)
Institutional (8)	50.0 (0.4)	9.1 (0.9)	40.8 (0.3)
Open Space (5)	10.2 (1.2)	10.6 (1.3)	79.1 (0.3)
Residential (25)	24.0 (0.6)	12.1 (0.5)	63.8 (0.2)
Freeway and Highway (4)	31.9 (1.2)	27.4 (1.2)	40.7 (0.3)

The directly connected impervious areas are most closely related to the runoff quantities. The partially connected impervious areas contribute runoff at later portions of larger rains, while the pervious areas may only contribute flows after substantial rain has occurred. As expected, most of the data represent residential areas, with commercial areas next, and the other areas having fewer than 10 detailed area descriptions each.

In order to examine geographical variations in stormwater characteristics, these land uses were sorted into six areas: Northwest; Southwest; Central; Southeast; Great Lakes; and East Coast. Model calibration was performed in each of these six geographical areas for all of the land uses in each area. If a land use was not represented in an area, the overall average land use characteristics were used. Stormwater quality data from the National Stormwater Quality

Database (NSQD) was sorted into groups representing major land use and geographical categories. Figure 5 shows the EPA Rain Zones (not to be confused with the EPA administrative regions), the locations for the NSQD stormwater data, and the general calibration set regions. The modeled concentrations were compared to the observed concentrations, as described in the following section.

The parameter files for each of these regions are listed in the table below.

Region	Runoff Coefficient	Particulate Solids Concentration	Pollutant Probability Distribution	Street Dirt Coefficient
Northwest	v10 Northwest.rsv	Northwest.pscx	Northwest.pdpx	Northwest street Com Inst Indust.std Northwest street Res and Other Urban.std Northwest Freeway.std
Southwest	v10 Southwest.rsv	Southwest.pscx	Southwest.pdpx	Southwest street Com Inst Indust.std Southwest street Res and Other Urban.std Southwest Freeway.std
Central	v10 Central.rsv	Central.pscx	Central.pdpx	Central street Com Inst Indust.std Central street Res and Other Urban.std Central Freeway.std
Southeast	v10 Southeast.rsv	Southeast.pscx	Southeast.pdpx	Southeast street Com Inst Indust.std Southeast street Res and Other Urban.std Southeast Freeway.std
Great Lakes	v10 GreatLakes.rsv	GreatLakes.pscx	GreatLakes.pdpx	GreatLakes street Com Inst Indust.std GreatLakes street Res and Other Urban.std GreatLakes Freeway.std
East Coast	v10 EastCoast.rsv	EastCoast.pscx	EastCoast.pdpx	EastCoast street Com Inst Indust.std EastCoast street Res and Other Urban.std EastCoast Freeway.std

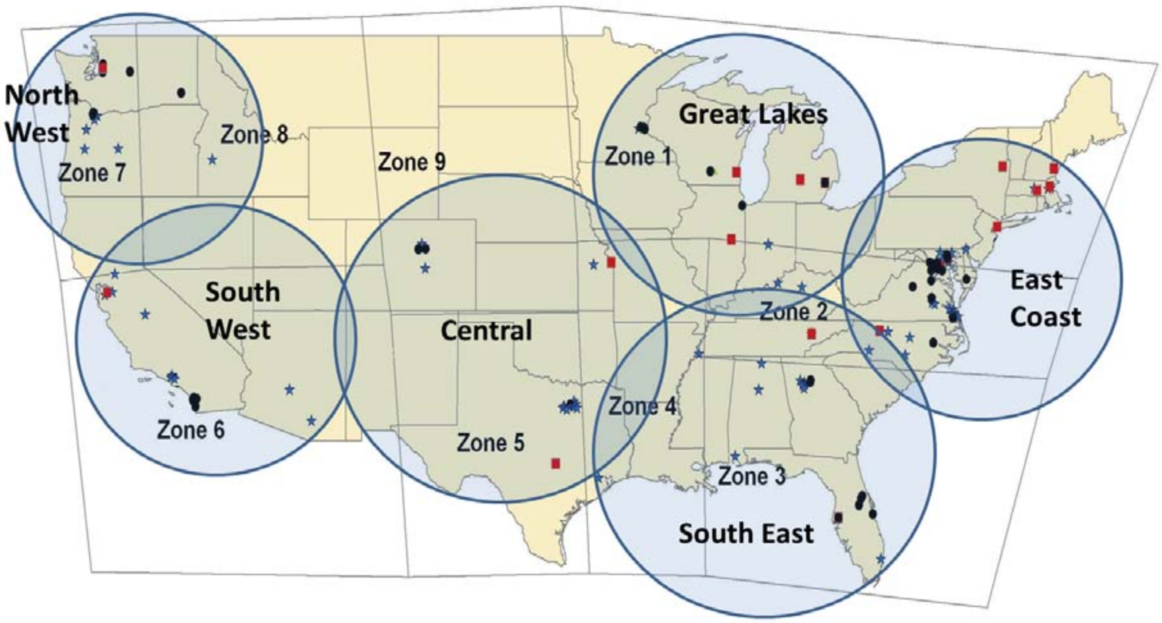


Figure 5. Sampling locations for data contained in the National Stormwater Quality Database (NSQD), version 3, showing EPA Rain Zones and general calibration set regions.

Modeled Stormwater Characteristics Compared to Observed Data
As noted above, the land use characteristics were used to create a range of standard land use files for evaluation with WinSLAMM. Six geographical areas with six major land use categories in each geographical area were examined. Many of the locations where the site characteristics were available also had stormwater monitoring data available that were used for regional calibration. If sites did not have site-specific data, NSQD regional data were used instead.

The first task was to sort all of the land use files into these six major land use categories. Table 4 lists the number of sites that were available for each group. As noted, most of the data were available for residential, then commercial areas, with less data available for institutional, industrial, open space, and highway/freeway areas. Overall site characteristics (averaged) were determined for each of these six categories. These six overall averaged files were then used in each of the six geographical areas, to complement available data for each location and land use data set. Some of the area and land use combinations only had this one file available, if no areas were monitored. A total of 114 files were used, with most in the residential and commercial areas, as previously noted, and with most of the files located in the Great Lakes region (due to the large number of Wisconsin observations) and in the Southeast (due to the large number of Birmingham, AL area observations).

Table 4. Number of Land Use Files Used for Each Category

	Commercial	Industrial	Institutional	Open Space	Residential	Freeways/ Highways	Total by Location
Central	4	2	4	1	5	3	19
East Coast	3	1	1	1	2	3	11
Great Lakes	6	4	4	2	11	4	31
Northwest	2	1	1	1	3	3	11
Southeast	7	2	3	5	8	4	29
Southwest	5	1	1	1	2	3	13
Total by Land Use	27	11	14	11	31	20	114

Each of these 114 files was associated with stormwater characteristic data, with preference given to site-specific monitoring data. If local observations were not available, then NSQD data was used. As noted in the earlier NSQD project memo, those observations were separated into land use and regional EPA rain zone categories. The NSQD data associated with the land use-area category were used if at least 30 events were monitored; if not, then the overall land use values for the constituent were used. Infrequently, the overall land use data did not have at least 30 event observations, so the overall average concentration was used.

The characteristics and constituents examined and calibrated included: Rv (the volumetric runoff coefficient, the ratio of runoff depth to rain depth), TSS, TDS, COD, TP, filtered P, TKN, NO_3+NO_2, Cu, Pb, Zn, and fecal coliforms. The bacteria data was not available for the WI locations, so the NSQD was used for the Great Lakes locations. In addition, calculated peak flow (CFS/100 acres) was also examined.

Initially, each of the 114 standard land use files were used in WinSLAMM using the original calibrated parameter files. The source area concentration data used in these files are described and summarized in the following publications (previously listed as the sources of the WI data, but these also include data from most of the source areas examined):
- Pitt, R., R. Bannerman, S. Clark, and D. Williamson. "Sources of pollutants in urban areas (Part 1) – Older monitoring projects." In: Effective Modeling of Urban Water Systems, Monograph 13. (edited by W. James, K.N. Irvine, E.A. McBean, and R.E. Pitt). CHI. Guelph, Ontario, pp. 465 – 484 and 507 – 530. 2005.
- Pitt, R., R. Bannerman, S. Clark, and D. Williamson. "Sources of pollutants in urban areas (Part 2) – Recent sheetflow monitoring results." In: Effective Modeling of Urban Water Systems, Monograph 13. (edited by W. James, K.N. Irvine, E.A. McBean, and R.E. Pitt). CHI. Guelph, Ontario, pp. 485 – 530. 2005.
- Pitt, R., D. Williamson, and J. Voorhees. "Review of historical street dust and dirt accumulation and washoff data." Effective Modeling of Urban Water Systems, Monograph 13. (edited by W. James, K.N. Irvine, E.A. McBean, and R.E. Pitt). CHI. Guelph, Ontario, pp 203 – 246. 2005.

Area rain files were selected for each of the regions. The averaged land use files were evaluated using the following rain data for 4 or 5 years (1995 through 1999, except for Lincoln, NE that started in 1996 due to missing rain records): Great Lakes: Madison, WI; East Coast: Newark, NJ; Central: Lincoln, NE; Northwest: Seattle, WA; Southeast: Birmingham, AL; and Southwest: Los Angeles, CA. The sites having site-specific observations used the rain records associated with the sites and for the period of record. The Great Lakes region recognized a winter period (Dec 3 to March 12) as did the Central region (Dec 20 to Feb 10). During these winter periods, no stormwater calculations were made.

The calculated long-term averaged modeled concentrations were compared to the monitored concentrations for each site and for the land use category combined. Factors were applied uniformly to each land use-area pollutant parameter file to adjust the long-term modeled concentrations to best match the monitored/observed values. The WI and AL location files were not changed as they were associated with previously calibrated conditions (except for the constituents that were not measured locally). In addition, the runoff parameter files were not modified as they have been shown to compare well to observed conditions under a wide range of situations throughout the country.

Table 5 summarizes the results of the comparisons of the modeled to the observed values for all of the 114 files (91 for Rv, as some areas did not have suitable comparison flow data) for each constituent. As noted in this summary table, the regression statistics were all excellent (the P-values of the regression equations and for the slope terms were all highly significant), and the regression slope terms were all close to 1.0, with a few exceptions. The residual behaviors were all very good, except for total and filtered phosphorus that showed a strong bias, with modeled concentrations being too high for small observed concentrations. All of the other constituents had random variations about the best fit lines with small variabilities.

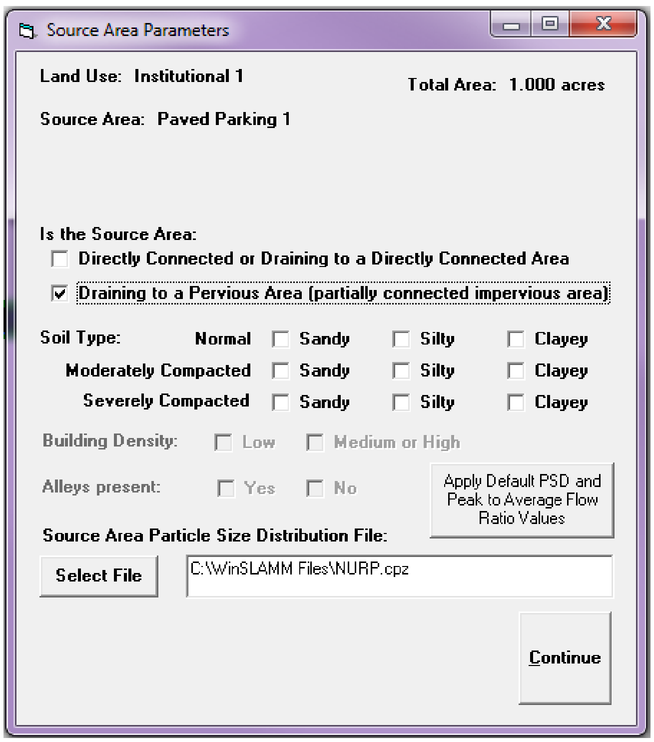
Table 5. Summary of Observed vs. Modeled Concentrations

	Regression Slope (intercept = 0) and 95% CI	P-value of slope term	P-value of regression	Adjusted R^2	Number of Observations	Residual Behavior Comments
Volumetric Runoff Coefficients	0.93 (0.87, 0.99)	<0.0001	<0.0001	0.90	91	Some modeled values high for small observed RV
Total Suspended Solids	0.90 (0.83, 0.97)	<0.0001	<0.0001	0.85	114	Good
Total Dissolved Solids	0.62 (0.53, 0.70)	<0.0001	<0.0001	0.63	114	Good
Chemical Oxygen Demand	1.00 (0.92, 1.04)	<0.0001	<0.0001	0.93	114	Good
Total Phosphorus	0.88 (0.68, 1.08)	<0.0001	<0.0001	0.40	114	Most modeled values high for small observed TP concentrations
Filterable Phosphorus	0.95 (0.81, 1.09)	<0.0001	<0.0001	0.61	114	Most modeled values high for small observed filterable P concentrations
Total Kjeldahl Nitrogen	1.06 (0.96, 1.15)	<0.0001	<0.0001	0.80	114	Good
Nitrites plus Nitrates	0.70 (0.62, 0.78)	<0.0001	<0.0001	0.71	114	Good
Total Copper	0.59 (0.50, 0.67)	<0.0001	<0.0001	0.60	114	Good
Total Lead	0.99 (0.93, 1.05)	<0.0001	<0.0001	0.90	114	Good
Total Zinc	0.96 (0.92, 1.00)	<0.0001	<0.0001	0.95	114	Good
Fecal Coliform Bacteria	0.74 (0.65, 0.83)	<0.0001	<0.0001	0.68	114	Good

Soil Compaction Effects on Infiltration Rates, as used in WinSLAMM

Destruction of soil structure (specifically compaction) has been identified as a major cause of decreased infiltration rates in urban areas. All soils suffer when compacted, although compacted sandy soils still retain significant infiltration after compaction (but much less than if not compacted), while soils with substantial fines (especially clays) are more easily compacted to almost impervious conditions.

WinSLAMM therefore allows a selection of the compaction conditions for sandy, silty, and clayey soils. The model then uses the user defined infiltration rate reduction factor to represent the decreased infiltration rate of the soils. This option is only available for source area soil and landscaped conditions (and areas that receive runoff from disconnected impervious areas). Biofilter media compaction conditions should be reflected in the infiltration rates selected (the built-in biofilter infiltration rate values are based on measured values and already reflect typical conditions, but can be changed as warranted). The compaction option is selected as a Source



Area Parameter, as shown below in Figure 1.

Figure 1 – Entering Soil Compaction in a WinSLAMM Source Area

Field Tests of Infiltration Rates in Disturbed Urban Soils

A series of 153 double ring infiltrometer tests were conducted in disturbed urban soils in the Birmingham, and Mobile, Alabama, US, areas as part of an EPA project that investigated disturbed urban soils and soil amendments (Pitt, R., J. Lantrip, R. Harrison, C. Henry, and D. Hue. *Infiltration through Disturbed Urban Soils and Compost-Amended Soil Effects on Runoff Quality and Quantity*. U.S. Environmental Protection Agency, Water Supply and Water Resources Division, National Risk Management Research Laboratory. EPA 600/R-00/016. Cincinnati, Ohio. 231 pgs. December 1999, available at: http://www.unix.eng.ua.edu/~rpitt/Publications/BooksandReports/Compacted%20and%20compost%20amended%20soil%20EPA%20report.pdf). The tests were organized in a complete 2^3 factorial design to examine the effects of soil-water, soil texture, and soil density (compaction) on water infiltration through historically disturbed urban soils. Ten sites were selected representing a variety of desired conditions (compaction and texture) and numerous tests were conducted at each test site area. Soil-water content and soil texture conditions were determined by standard laboratory soil analyses. Compaction was measured in the field using a cone penetrometer and confirmed by the site history. During more recent tests, compaction is directly measured by obtaining samples from the field from a known volume (digging a small hole and retrieving all of the soil into sealed bags that are brought to the lab for moisture and weight analyses. The hole that is carefully cleaned of all loose soil is then filled with free-flowing sand from a graduated cylinder to determine the volume. The laboratory dry weight of the excavated soil is divided by the volume of the hole to obtain the density). From 12 to 27 replicate tests were conducted in each of the eight experimental categories in order to measure the variations within each category for comparison to the variation between the categories.

Soil infiltration capacity was expected to be related to the time since the soil was disturbed by construction or grading operations (turf age). In most new developments, compacted soils are expected to be dominant, with reduced infiltration compared to pre-construction conditions. In older areas, the soil may have recovered some of its infiltration capacity due to root structure development and from soil insects and other digging animals. Soils having a variety of times since development, ranging from current developments to those about 50 years old, were included in the sampling program. These test sites did not adequately represent a wide range of age conditions for each test condition, so the effects of age could not be directly determined. Other analyses have indicated that several decades may be necessary before compacted loam soils recover to conditions similar to pre-development conditions, if not continually compacted by site activities (such as parked cars on turf, unpaved walkways and parking lots, unpaved storage areas, or playing fields).

Figures 2 and 3 are 3D plots of this field infiltration data, illustrating the effects of soil-water content and compaction, for both sands and clays. Four general conditions were observed to be statistically unique. Compaction has the greatest effect on infiltration rates in sandy soils, with little detrimental effects associated with higher soil-water content conditions (the factor usually considered by most rainfall-runoff models). Clay soils, however, are affected by both compaction and soil-water content. Compaction was seen to have about the same effect as saturation on clayey soils, with saturated and compacted clayey soils having very little effective infiltration.

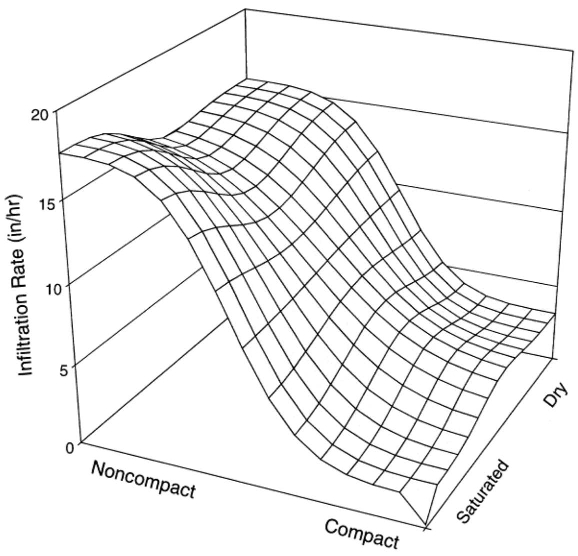


Figure 2. Three dimensional plot of infiltration rates for sandy soil conditions.

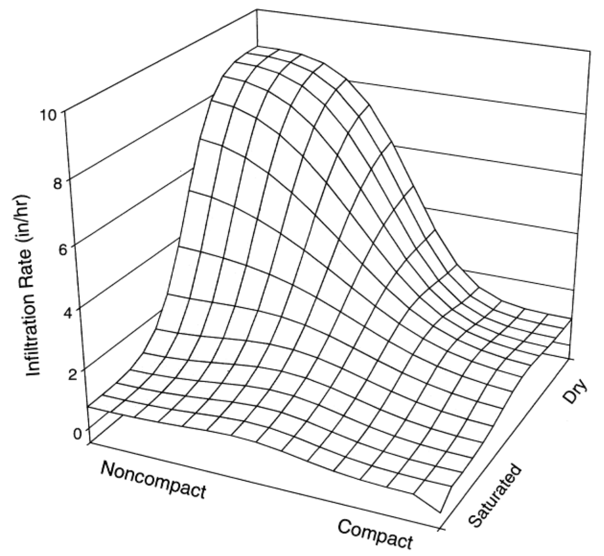


Figure 3. Three dimensional plot of infiltration rates for clayey soil conditions.

Laboratory Controlled Compaction Infiltration Tests

We use three levels of compaction to modify the density of soil samples during controlled laboratory tests: hand compaction, Standard Proctor Compaction, and Modified Proctor Compaction. Both Standard and Modified Proctor Compactions follow ASTM standard (D 1140-54). The Standard Proctor compaction hammer is 24.4 kN and has a drop height of 300 mm. The Modified Proctor hammer is 44.5 kN and has a drop height of 460 mm. For the Standard Proctor setup, the hammer is dropped on the test soil 25 times on each of three soil layers, while for the Modified Proctor test, the heavier hammer was also dropped 25 times, but on each of five soil layers. The Modified Proctor test therefore results in much more compacted soil, and usually reflects the most compacted soil usually observed in the field. The hand compaction is done by gentle hand pressing to force the soil into the test cylinder with as little compaction as possible. A minimal compaction effort is needed to keep the soil in contact with the mold walls and to prevent short-circuiting during the tests. The hand compacted soil specimens therefore have the least amount of compaction.

A series of controlled laboratory tests were conducted for comparison with the double-ring infiltration tests and to represent a wide range of soil conditions, as shown in Table 1. Six soil samples were tested, each at three different compaction levels described previously. Small depths of standing water on top of the soil test mixtures (4.3 inches, or 11.4 cm, maximum head) was also used. Most of these tests were completed within 3 hours, but some were continued for more than 150 hours. Only one to three observation intervals were used during these tests, so they did not have sufficient resolution or enough data points to attempt to fit to standard infiltration equations. However, these longer-term averaged values may be more suitable for infiltration rate predictions due to the high natural variability observed during the field tests. As shown, there was very little variation between the different time periods for these tests, compared to the differences between the compaction or texture groupings. The sandy soils can provide substantial infiltration capacities, even when compacted greatly, in contrast to the soils having clays that are very susceptible to compaction, resulting in near zero infiltration rates if compacted.

Table 1. Low-Head Laboratory Infiltration Tests for Various Soil Textures and Densities (densities and observed infiltration rates)

	Hand Compaction	Standard Compaction	Modified Compaction
Sand (100% sand)	Density: 1.36 g/cm^3 (ideal for roots) 0 to 0.48 hrs: 9.35 in/h 0.48 to 1.05 hrs: 7.87 in/h 1.05 to 1.58 hrs: 8.46 in/h	Density: 1.71 g/cm^3 (may affect roots) 0 to 1.33 hrs: 3.37 in/h 1.33 to 2.71 hrs: 3.26 in/h	Density: 1.70 g/cm^3 (may affect roots) 0 to 0.90 hrs: 4.98 in/h 0.90 to 1.83 hrs: 4.86 in/h 1.83 to 2.7 hrs: 5.16 in/h
Silt (100% silt)	Density: 1.36 g/cm^3 (close to ideal for roots) 0 to 8.33 hrs: 0.26 in/h 8.3 to 17.8 hrs: 0.24 in/h 17.8 to 35.1 hrs: 0.25 in/h	Density: 1.52 g/cm^3 (may affect roots) 0 to 24.2 hrs: 0.015 in/h 24.2 to 48.1: 0.015 in/h	Density: 1.75 g/cm^3 (will likely restrict roots) 0 to 24.2 hrs: 0.0098 in/h 24.2 to 48.1: 0.0099 in/h
Clay (100% clay)	Density: 1.45 g/cm^3 (may affect roots) 0 to 22.6 hrs: 0.019 in/h 22.6 to 47.5 hrs: 0.016 in/h	Density: 1.62 g/cm^3 (will likely restrict roots) 0 to 100 hrs: <2X10-3 in/h	Density: 1.88 g/cm^3 (will likely restrict roots) 0 to 100 hrs: <2X10-3 in/h
Sandy Loam (70% sand, 20% silt, 10% clay)	Density: 1.44 g/cm^3 (close to ideal for roots) 0 to 1.17 hrs: 1.08 in/h 1.17 to 4.37 hrs: 1.40 in/h 4.37 to 7.45 hrs: 1.45 in/h	Density: 1.88 g/cm^3 (will likely restrict roots) 0 to 3.82 hrs: 0.41 in/h 3.82 to 24.3 hrs: 0.22 in/h	Density: 2.04 g/cm^3 (will likely restrict roots) 0 to 23.5 hrs: 0.013 in/h 23.5 to 175 hrs: 0.011 in/h
Silty Loam (70% silt, 20% sand, 10% clay)	Density: 1.40 g/cm^3 (may affect roots) 0 to 7.22 hrs: 0.17 in/h 7.22 to 24.8 hrs: 0.12 in/h 24.8 to 47.1 hrs: 0.11 in/h	Density: 1.64 g/cm^3 (will likely restrict roots) 0 to 24.6 hrs: 0.014 in/h 24.6 to 144 hrs: 0.0046 in/h	Density: 1.98 g/cm^3 (will likely restrict roots) 0 to 24.6 hrs: 0.013 in/h 24.6 to 144 hrs: 0.0030 in/h
Clay Loam (40% silt, 30% sand, 30% clay)	Density: 1.48 g/cm^3 (may affect roots) 0 to 2.33 hrs: 0.61 in/h 2.33 to 6.13 hrs: 0.39 in/h	Density: 1.66 g/cm^3 (will likely restrict roots) 0 to 20.8 hrs: 0.016 in/h 20.8 to 92.8 hrs: 0.0066 in/h	Density: 1.95 g/cm^3 (will likely restrict roots) 0 to 20.8 hrs: <0.0095 in/h 20.8 to 92.8 hrs: 0.0038 in/h

Comparing Field and Laboratory Measurement Methods

A soil infiltration study was recently conducted by Redahegn Sileshi, a PhD student in the Department of Civil, Construction, and Environmental Engineering at the University of Alabama, in July 2011 at four test sites located in areas that were affected by the April 27, 2011 Tornado that devastated the city of Tuscaloosa, AL. Double-ring infiltration measurements (using three Turf-Tec infiltrometers at each location) were conducted to determine the infiltration characteristics of the soils in typical areas where reconstruction with stormwater infiltration controls is planned. The small field double-ring (4 inch, 10 cm, diameter) test results were compared to large (24 inch, 60 cm, diameter, 3 to 4 ft, 1 to 1.2 m, deep) pilot-scale borehole tests to identify if the small test methods can be accurately used for rapid field evaluations. The borehole tests required drilling a hole and placing a Sonotube cardboard concrete form into the hole to protect the sides of the hole. The borehole was 2 to 4 ft deep (depending on subsoil conditions). The bare soil at the bottom of the tube was roughened to break up any smeared soil and back-filled with a few inches of coarse gravel to prevent erosion during water filling. The tubes were filled with water from adjacent fire hydrants and the water elevation drop was monitored using a recording depth gage (a simple pressure transducer with a data logger).

In addition, controlled laboratory column tests were also conducted on surface and subsurface soil samples under the three different compaction conditions to see if depth of the test (and response to compaction) affected the infiltration results. The test sites were all located adjacent to fire hydrants (for water supply for the large borehole tests) and are located in the City's right-of way next to roads. Figure 4 shows some of the features of these tests.

Figure 4. Photographs showing borehole drilling, Sonotube infiltration tube installation, double-ring infiltration measurements, and laboratory column tests.

The soil densities of the surface soils averaged 1.7 g/cc (ranged from 1.6 to 1.9 g/cc). The median soil particle sizes averaged 0.4 mm (ranging from 0.3 to 0.7), and the soil had a clay content of about 20%. Figure 5 shows the saturated infiltration rates for the different locations and test methods.

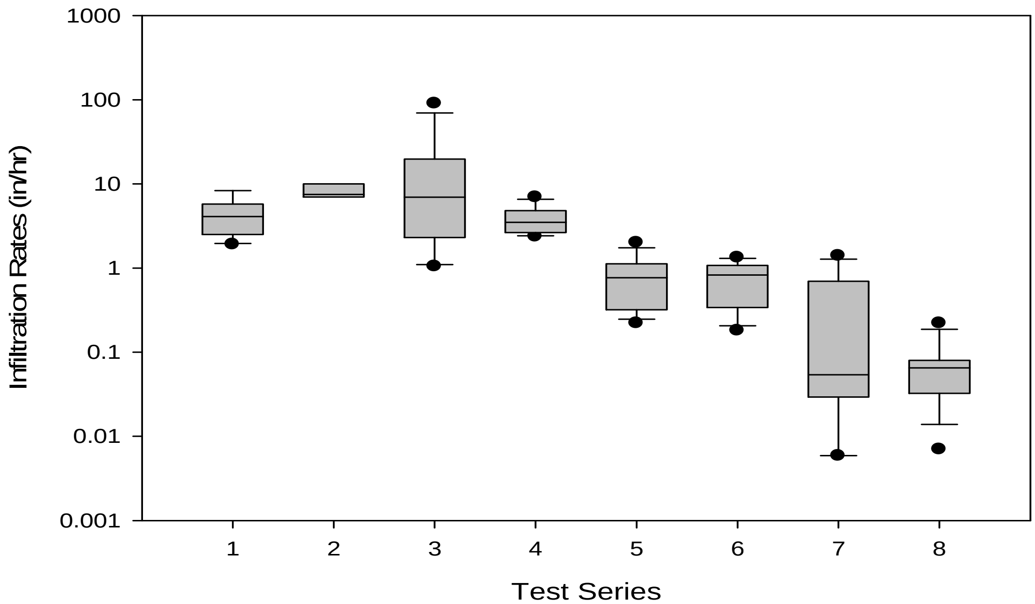


Figure 5. Box and whisker plots comparing saturated soil infiltration rates (in/hr). Test series descriptions (12 replicates in each test series except for the borehole tests which only included 3 observations):

1) Turf-Tec small double ring infiltrometer
2) Pilot-scale borehole infiltration tests
3) Surface soil composite sample with hand compaction (1.4 g/cc density)
4) Subsurface soil composite sample with hand compaction (1.4 g/cc density)
5) Surface soil composite sample with standard proctor compaction (1.6 g/cc density)
6) Subsurface soil composite sample with standard proctor compaction (1.6 g/cc density)
7) Surface soil composite sample with modified proctor compaction (1.7 g/cc density)
8) Subsurface soil composite sample with modified proctor compaction (1.7 g/cc density)

Using the double ring infiltrometers, the final saturated infiltration rates (of most significance when designing bioinfiltration stormwater controls) for all the test locations was found to average about 4.4 in/hr (11 cm/hr) for the 12 measurements and ranged from 1.9 to 8.3 in/hr (4.8 to 21 cm/hr). The borehole test results were about twice these values. The laboratory column tests indicated that surface and subsurface measurements were similar for all cases, but that compaction dramatically decreased the infiltration rates, as expected. The slightly (hand) compacted test results were similar to the Turf-Tec and the borehole test results, indicating that these sites, even in the road rights-of-ways, were minimally compacted. These areas were all originally developed more than 20 years ago and had standard turf grass covering. They were all isolated from surface disturbances, beyond standard landscaping maintenance. It is not likely that the tornado affected the soils. The soil profile (surface soils vs subsurface soils from about 4 ft, 1.2 m) did not affect the infiltration rates at these locations. Due to the relatively high clay content, the compaction tests indicated similarly severe losses in infiltration rates as found in prior studies, of one to two orders of magnitude reductions, from about 25, to 2, to 0.1 cm/hr, usually far more than the differences found between different soil textures.

Summary of Compaction Effects on Infiltration Tests

These recent tests indicated that the three soil infiltration test methods resulted in similar results, although the small –scale Turf-Tec infiltrometers indicated reduced rates compared to the borehole tests. Another study, summarized below, however indicated that the Turf-Tec infiltrometers resulted in substantially greater infiltration rates than observed in a failing bioinfiltration device, compared to actual infiltration rates during rain events. Therefore, if surface characteristics are of the greatest interest (such as infiltration through surface landscaped soils, as in turf areas, grass swales or in grass filters), the small-scale infiltrometers work well. These allow a cluster of measurements to be made in a small area to better indicate variability. Larger, conventional double-ring infiltrometers are not very practical in urban areas due to the excessive force needed to seat the units in most urban soils (usually requiring jacking from a heavy duty truck) and the length of time and large quantities of water needed for the tests. In addition, they also only measure surface soil conditions. More suitable large-scale (deep) infiltration tests would be appropriate when subsurface conditions are of importance (as in bioinfiltration systems and deep rain gardens). The borehole and Sonotube test used above is relatively easy and fast to conduct, if a large borehole drill rig is available along with large volumes of water (such as from a close-by fire hydrant). For infiltration facilities already in place, simple stage recording devices (small pressure transducers with data loggers) are very useful for monitoring during actual rain conditions.

In many cases, disturbed urban soils have dramatically reduced infiltration rates, usually associated with compaction of the surface soils. The saturated infiltration rates can be one to two orders of magnitude less than assumed, based on undisturbed/uncompacted conditions. Local measurements of the actual infiltration rates, as described above, can be a very useful tool in identifying problem areas and the need for more careful construction methods. Having accurate infiltration rates are also needed for proper design of stormwater bioinfiltration controls. In situations of adverse infiltration rates, several strategies can be used to improve the existing conditions, as noted below.

Summary of Compacted Soil Restoration Methods

Mechanical restoration of compacted clayey soils must be carefully done to prevent the development of a hardpan and further problems. Spading implements are the safest methods for large scale improvements. However, if large fractions of clay are present in the soil, the addition of sand and possibly also organic amendments may be needed. The use of periodic rain gardens in a large compacted area allows deeper soil profile remediation in a relatively small area and may be suitable to enhance drainage in problem locations.

To address water quality concerns and numeric effluent limits, water and soil chemistry information is needed in order to select the best amendments for a soil or biofilter media. As summarized by Clark and Pitt (Clark, S. and R. Pitt. "Filtered Metals Control in Stormwater using Engineered Media." *ASCE/EWRI World Environment and Water Resources Congress*. Palm Springs, CA, May 22-26, 2011. Conference CD.), the removal of "dissolved" metals from stormwater by soils and amendments will need to be based on the ratio of valence states to determine the proportion of ion exchange resins versus organic-based media in the final media mixture. As more of the metal concentrations have either a 0 or +1 valence charge (as ions), or as more are associated with organic complexes, the smaller the fraction of an ion exchange resin, such as a zeolite, is needed. For metals such as thallium, where few inorganic and organic complexes are formed and where the predominant valence state is +2, increasing the amount of zeolite in the final media mixture is important for improving removal. Therefore, the final media mixture will be based on the pollutants of interest and their water chemistry. The capacity for pollutant removal by soils is directly related to OM and CEC content for many metals. Organic media provides a wide range of treatment sites besides increasing the CEC. Activating an organic media, such as granular activated carbon, will increase the number of surface active sites for treatment, but this media will not sustain plant growth by itself. As an example, copper removal capacity is related to soil carbon content, and CEC, plus, soil Mg content relates to the ability of the media to participate in ion exchange reactions.

Therefore, at least one component in an amendment media mixture should provide excellent ion exchange, such as would be found with a good zeolite. This media should be able to participate in reactions with the +2 metals and a portion of the +1 metals, although the +1 metals may not be as strongly bound and may be displaced if a more preferable exchangeable ion approaches the media's removal site. Soil OM, soil C, and soil N all relate to the organic matter content and indicate that these are sites that may participate in a variety of reactions and may be able to remove pollutants that do not carry a valence charge. Therefore, mixtures of amendments may be needed for effective removal of a range of pollutants: an organic component should be incorporated, along with a GAC. In most cases, sand may also be needed for structural support (to minimize compaction) and for controlling the flow rate to a level that allows for sufficient contact time.

Use of Compacted Soil Factors in WinSLAMM

WinSLAMM considers decreased infiltration rates associated with compaction when calculating runoff values for disturbed urban soils. For all pervious surfaces (landscaped areas, undeveloped areas, and for areas receiving flows from disconnected impervious area), the model user selects the level of compaction (normal, moderately, or severely compacted). The model uses the urban soil volumetric runoff ratio (from the calibrated *.rsv file) for normal soils. However, the example factors shown in Table 2 (suggested values based on the field and laboratory research) are used to modify these values for compacted soil conditions.

Table 2. Example Infiltration Rate Factors Associated with Various Levels of Soil Compaction

	sandy	silty	clayey
Normal urban soils (a slight amount of compaction expected due to urbanization, especially with well-established and healthy vegetation)	1.00	1.00	1.00
Moderately compacted (near buildings or other structures associated with construction, or compacted with use)	0.50	0.20	0.10
Severely compacted (the highest level of compaction possible associated with extreme use)	0.20	0.10	0.00

The factors shown in Table 2 are user accessible as part of the tools/program options/default model options (see Figure 6 below) and are saved in the *.ini file. As an example, if the normal Rv (the ratio of runoff volume to rainfall volume) for a silty soil was 0.35 for a specific rain condition, the modified value associated with moderately compacted conditions increases due to the compacted conditions, using the following relationships:

> Normal amount of infiltration (plus evapotranspiration) with Rv of 0.35: 1 - 0.35 = 0.65
>
> With a compaction factor of 0.20, only 1/5 of the normal amount of infiltration would actually infiltrate: 0.2*0.65 = 0.13
>
> And the new adjusted Rv associated with moderately compacted silty soils for that rain would therefore be: 1-0.13 = 0.87
>
> Therefore: adjusted Rv = 1-((1- normal Rv)*factor), or: 1-((1-0.35)*0.2) = 0.87

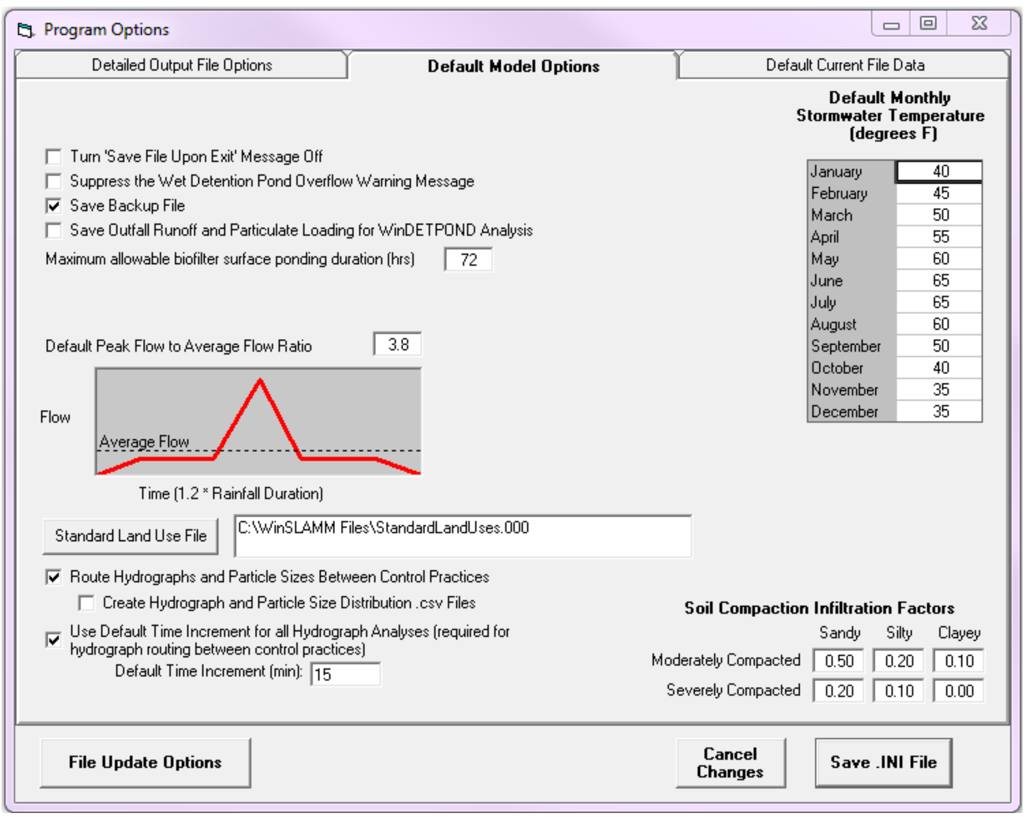


Figure 6 – WinSLAMM Program Options Window for Soil Compaction Infiltration Factors

Grass Swale Infiltration and Filtering Functions

General Description

Grass swale performance is determined by directing the hydrograph developed by the program through the swales described in the model. Runoff volume reductions are determined by infiltration losses, particulate pollutant losses are determined through particle trapping and infiltration, and dissolved pollutant losses are determined by the infiltration losses.

The runoff volume is reduced using the area affected by the wetted perimeter and the dynamic infiltration rate of the swales for each time step of the hydrograph. The calculated flow and the swale geometry are used to iteratively determine the Manning's n and the depth of flow in the swale for each time step, using traditional VR-n curves based upon retardance measurements that were extended 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) 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. The dynamic infiltration rate is taken to be about one-half the static infiltration rate as measured using double ring infiltration devices. For relatively flat swale gradients (<0.5%), the static infiltration is used without modification. The dynamic infiltration rate is used for steeper swales based on field mass balance measurements of swale infiltration during swale research by Bell and Wanielista (Bell, J.H., and Wanielista, M.P., *Use of Overland Flow in Stormwater Management on Interstate Highways*, Transportation Research Record 736, National Academy of Sciences, Washington, D.C., 1979.) in Florida, as described later.

Particulate trapping is based on the settling frequency: how many times would a particle be able to completely settle during the length of the swale. Particles that may settle many times in the swale (the large particles) are much more likely to remain trapped in the swale, while particles that settle less frequently have a greater probability of moving through the swale. Taller grass is also more effective in trapping the particles than shorter grass. Particulate capture is calculated for each time step using the average swale length to the outlet and the calculated depth of flow for each time step of the hydrograph. The depth of grass, compared to the water depth, affects the particulate trapping in the swale. The depth of flow and swale geometry are used to calculate the flow velocity, which in turn is used to determine the travel time and particulate settling frequency for the average swale length in the study area, for each particle size increment.

The flow, particulate, and swale geometry information is used to determine the flow depth to grass height ratio and the settling frequency that are needed to calculate particulate trapping, as described by Nara, *et al.* (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). 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 resulting particulate concentrations are then combined into eight broader groups of particle sizes, where they are evaluated to determine if the concentrations are below the irreducible concentration values for each particle size group. Concentrations are not allowed to go below the irreducible concentration values unless the inflow value is already below that level. Also, no particles smaller than 50 microns are trapped in grass swales due to turbulent resuspension of these small particles during typical swale flow conditions.

The outline of the swale infiltration and sediment trapping functions is as follows:

1. **Swale Properties**. The average swale length is the length of the typical swale in the drainage area before it discharges into the drainage system (either inlet or outfall). For a

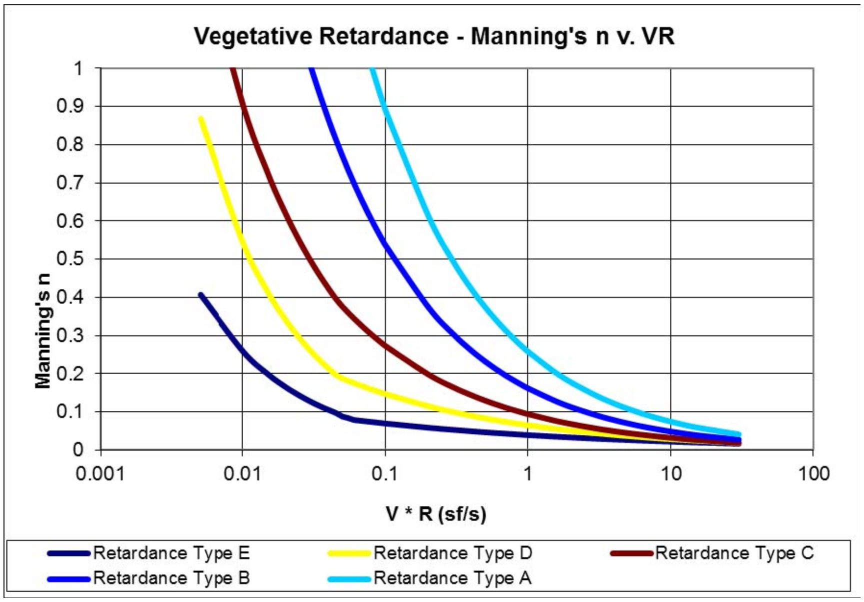
square drainage area, this average length is assumed to be the height of the area, plus one-half the width of the area, corresponding to a swale going thru the center and draining to a corner of the area. The user can enter their own average swale length of the modeled area. This would be important if a specific site is being examined and the actual swale lengths are known and are different from the above calculated value, for example. Determine the swale system properties.

a. For Infiltration: The entire swale length, as represented by the product of the swale density (ft of swale per acre of study area), times the area served by the swales, times the wetted perimeter, is used in the infiltration calculation.
b. For Particulate Trapping: The average grass swale length is reduced by 25 feet times the number of acres of impervious surface in the area served by the swales to account for the initial turbulent zone as the water enters the swale.
The average swale length (either entered by the user or 1.5 times the square root of the area served by swales, as described above) is further reduced based upon either or both of the following criteria. This is needed to ensure that a minimum swale length is used for all calculations:

Flow Velocity (inches/sec)		Longitudinal Slope	Swale Length Reduction (ft)
< 0.5	And	< 0.02	3
< 1	Or	> 0.02 and <= 0.05	6
>= 1	Or	> 0.05	10

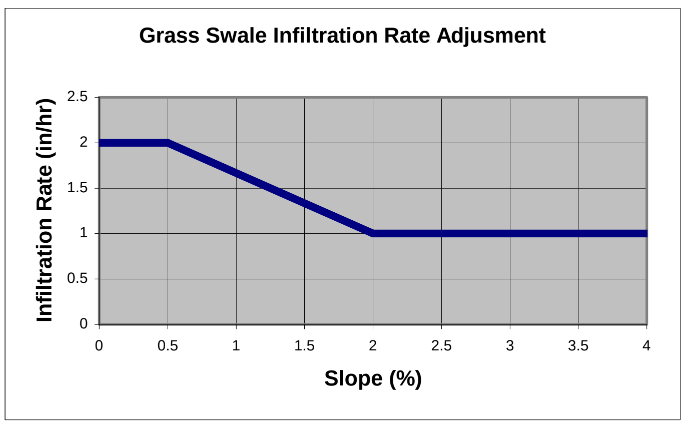
2. **Swale Hydraulic Properties**. After the swale length is determined, the program will calculate the incremental flow rate for each time steps. The flow in the swale system at each time step is half the flow from the time step, assumed to be the average flow. This is an iterative process, where

a. Assume a depth of flow in the swale
b. Calculate the VR (Velocity times Hydraulic Radius) using that depth
c. Estimate the Manning's n value from the VR value using the plot shown below (based upon the Stillwater, OK, USDA data for the large VR values and Kirby's data for the smaller VR values typical of urban drainage systems).
d. Calculate the flow rate based on the Manning's n and assumed depth
e. Determine the difference between the calculated flow and the modeled incremental flow entering the swale. If the difference between the two flows is greater than 0.0001 cfs, re-estimate the flow depth, and begin the iterative process again.



The Stillwater data and the vegetative retardance D value from the Kirby data were used to extrapolate the remaining VR-n retardance lines. However, the maximum allowable Manning's n value is 1.0.

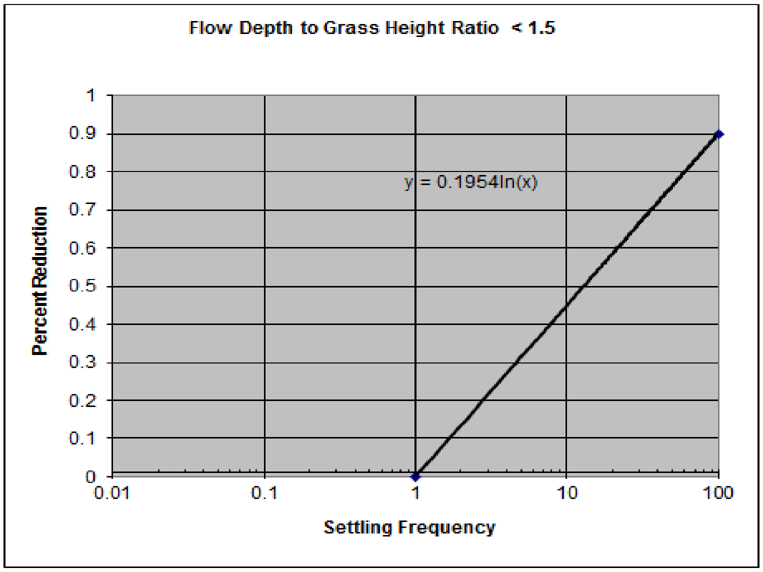
3. **Swale Filtering Process**. After determining the flow properties of the swale for each time step -



   a. Adjust the infiltration rate based upon the swale slope, as illustrated in the adjacent plot where the measured double ring static infiltration rate was determined to be 2 in/hr..
   b. Calculate the runoff volume infiltrated by the swale using the adjusted infiltration rate and the calculated wetted area for each time step.
   c. Adjust the average swale length as described above in 1b., Average Swale Properties.
   d. Determine the average travel time (swale length/flow velocity) for the average swale length
   e. Determine the flow depth to grass height ratio
   f. For each particle size increment, determine the
      i. Average settling velocity for the particles in each of the 31 narrow particle size increments
      ii. Settling duration (depth of flow/settling velocity)
      iii. Setting frequency (travel time/settling duration)
      iv. Determine the percent particulate reduction based upon the settling frequency and the flow depth to grass height ratio for each particle size increment, as shown on the example plot below for a flow depth to grass

height ratio < 1.5. Other graphs are used for flow depth to grass height ratios of 1.5 to 4.5 and >4.5, based on the research by Nara and Pitt (2006).

v. If the particle size is less than 50 microns, the settling frequency is assumed to be zero as no permanent trapping of these small particles is expected.



g. Combine the results from the 31 narrow particle size classes into 8 coarser particle size distribution groups.

i. Calculate the effluent particulate solids concentrations for each particle size group.

ii. Check to make sure the effluent treated particulate solids concentrations for each group are not less than the irreducible concentration for each group (unless the influent concentration is less than these values). The groups and irreducible concentrations are listed below.

Particle Size Range Number	Particle Size Range	Irreducible Conc. for Size Range (mg/L)
1	0.45 to 2 µm	5
2	2 to 5 µm	4
3	5 to 10 µm	3
4	10 to 30 µm	2
5	30 to 60 µm	1
6	60 to 106 µm	0
7	106 to 425 µm	0
8	> 425 µm	0

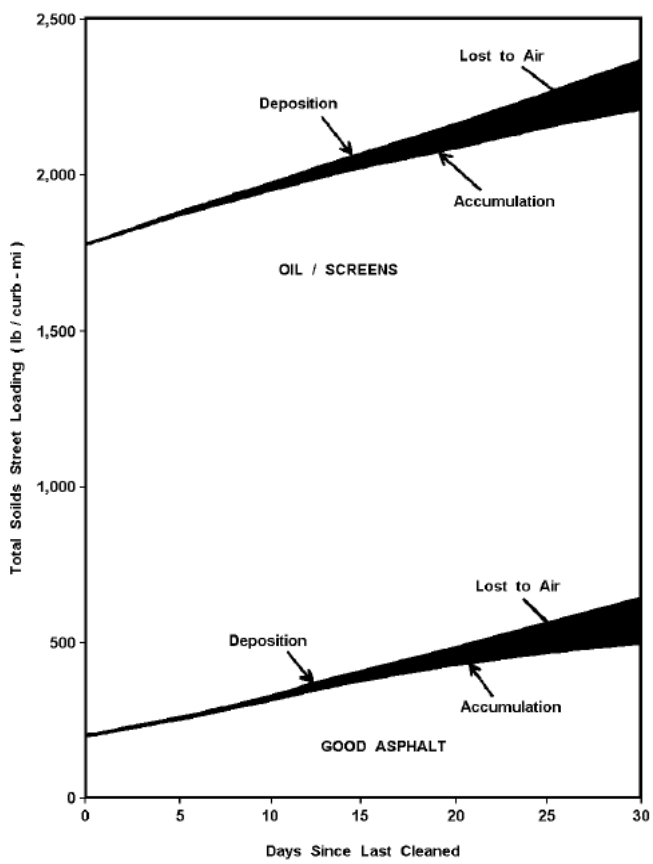
h. Sum the concentration values for each particle size group to determine the final concentration in the effluent discharged from the swale system.

Street Dirt Accumulation, Washoff and Street Cleaning Functions

Street Dirt Accumulation

Street dirt accumulation is expressed in WinSLAMM as a function of the initial deposition rate, time since the time series started (after a rain event or street cleaning event), and a decrease function. The street dirt loading equation uses a higher initial street dirt loading rate immediately after a rainfall or street cleaning event (the deposition rate); the rate of accumulation of material on the street decreases over time, until the maximum street dirt loading is reached.

The following figure from EPA-sponsored research conducted in San Jose, CA (Pitt 1979) shows the relationship between the deposition rate, the accumulation rate, and the amount of street dirt lost to the air as fugitive dust (determined by the decrease function) for two different streets in the same study area: the only difference is the street texture. Very rough streets have a larger initial load after an event compared to smooth streets, but the accumulation rate of street dirt is the same, resulting in much greater street dirt loadings for rough textured streets. The amount of street dirt lost as fugitive dust (due to traffic turbulence or high winds) increases with time, as the amount of material increases on the street (more exposed to these fugitive dust losses compared to the street dirt being protected in the street texture). Eventually, the street dirt loading levels off, reaching a steady load (after an extended period).



Source: Pitt 1979

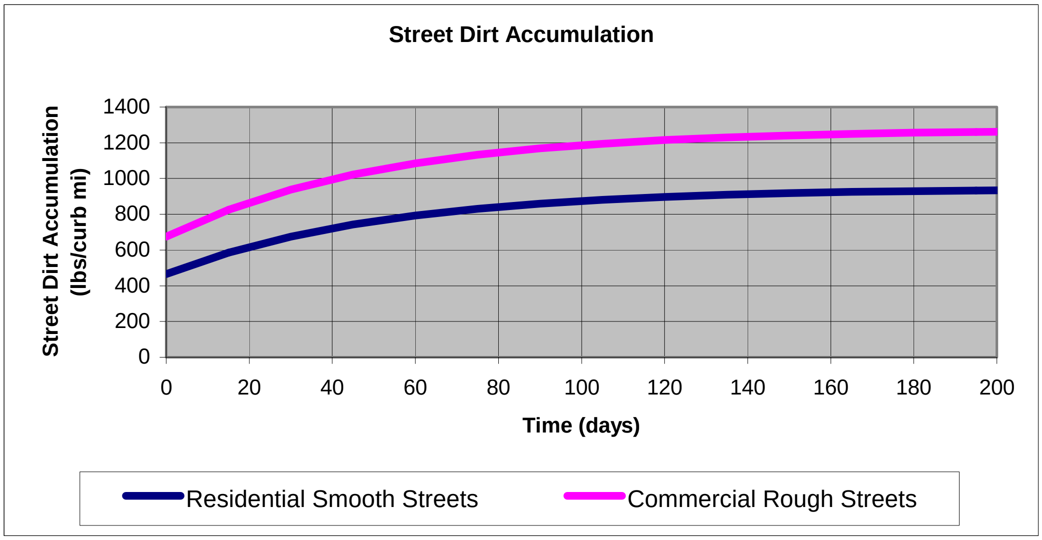
The following equation is used in WinSLAMM to calculate the street dirt load at any time.

$SDLoad_i = SDLoad_{i-1} + SDDepRate * AccRateReducFrac^{(i-1)} * (PerNum-1) * NumDays$

Where

$SDLoad_i$ = Street dirt load at the end of a given time period (lbs/curb-mi)
$SDLoad_{i-1}$ = Street dirt load at the end of the previous time period (lbs/curb-mi)
i = The time period number that a given street dirt accumulation rate is applied
SDDepRate = Street dirt deposition rate (lbs/curb-mi/day)
DepRateReducFrac = The fraction that the deposition rate is reduced by, for each time period due to fugitive dust losses
PerNum = The time period number
NumDays = The number of days per time period

To determine the street dirt loading at a given time period after the end of a washoff or street cleaning event, the program divides the accumulation curve into even time periods. The accumulation rate is progressively reduced for each time period by the accumulation rate reduction fraction, and this fraction is multiplied by the accumulation rate for each time period. The street dirt load from this time period is added to the load from the previous time period. The Street Dirt Accumulation plot illustrates two curves – one for smooth residential streets, and one for rough commercial streets.



Street Land Use and Texture	Accumulation Rate Reduction Period (days)	Street Dirt Base Load (lbs/curb-mi)	Street Dirt Deposition Rate (lbs/curb-mi/day)
Residential Smooth	15	225	8
Commercial Rough	5	375	10

The accumulation rate reduction periods, accumulation rate reduction fractions and deposition rates used in SLAMM are listed in the tables below. The minimum available load for street cleaning or washoff is B/(1-M)

Accumulation Rate Reduction Fraction

Land Use	Street Texture: Smooth and Intermediate	Street Texture: Rough and Very Rough
Residential and Other Urban	0.75	0.5
Commercial, Institutional and Industrial	0.75	0.5

Accumulation Rate Reduction Period (days)

Land Use	Street Texture: Smooth and Intermediate	Street Texture: Rough and Very Rough
Residential and Other Urban	15	15
Commercial, Institutional and Industrial	5	5

Street Dirt Base Load and Maximum Accumulation Load

Street Texture	Base Load (lbs/curb-mi)	Maximum Accumulation Load (lbs/curb-mi)
Smooth and Intermediate	225	1500
Rough	375	1750
Very Rough	375	2000

Deposition Rate (lbs/curb-mi/day)

Residential Land Use	8
Institutional Land Use	10
Commercial Land Use	10
Industrial Land Use	25
Other Urban Land Use	10

Washoff

Street dirt washoff is based upon modified relationships and equations that were initially developed by Sarter and Boyd (1972). Sartor and Boyd fitted their data to an exponential curve, assuming that the rate of particle removal of a given size is proportional to the street dirt loading and the constant rain intensity:

$$dN/dt = k\ r\ N$$

where:

- dN/dt = the change in street dirt loading per unit time
- k = proportionality constant
- r = rain intensity (in/h)
- N = street dirt loading (lb/curb-mile)

This equation, upon integration, becomes:

$$N = N_o\ e^{-krt}$$

where:

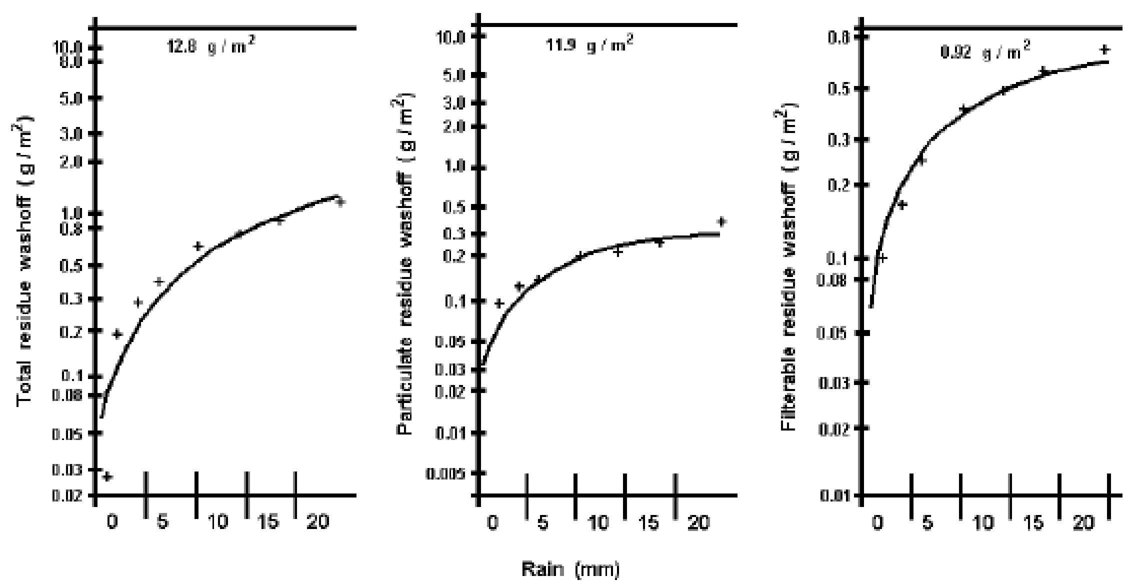
- N = residual street dirt load (after the rain)
- N_o = initial street dirt load
- t = rain duration

Street dirt washoff is therefore equal to N_o - N. The variable combination rt, or rain intensity times rain duration, is equal to total rain volume (R). This equation therefore further reduces to:

$$N = N_o e^{-kR}$$

Therefore, this equation is only sensitive to total rain, and not rain intensity. The proportionality constant, k, was found by Sartor and Boyd to be slightly dependent on street texture and condition, but was independent of rain intensity and particle size. The N_o factor is only the portion of the total street load available for washoff (the maximum asymptotic washoff load observed during the washoff tests). It is not the total initial street loading assumed by many models. WinSLAMM uses an availability factor for total solids on the street based on extensive field monitoring to reduce the washoff quantity to what is available for washoff. WinSLAMM also uses a street delivery fraction as an additional calibration tool to adjust the initial calculated washoff fraction to determine the final washoff load.

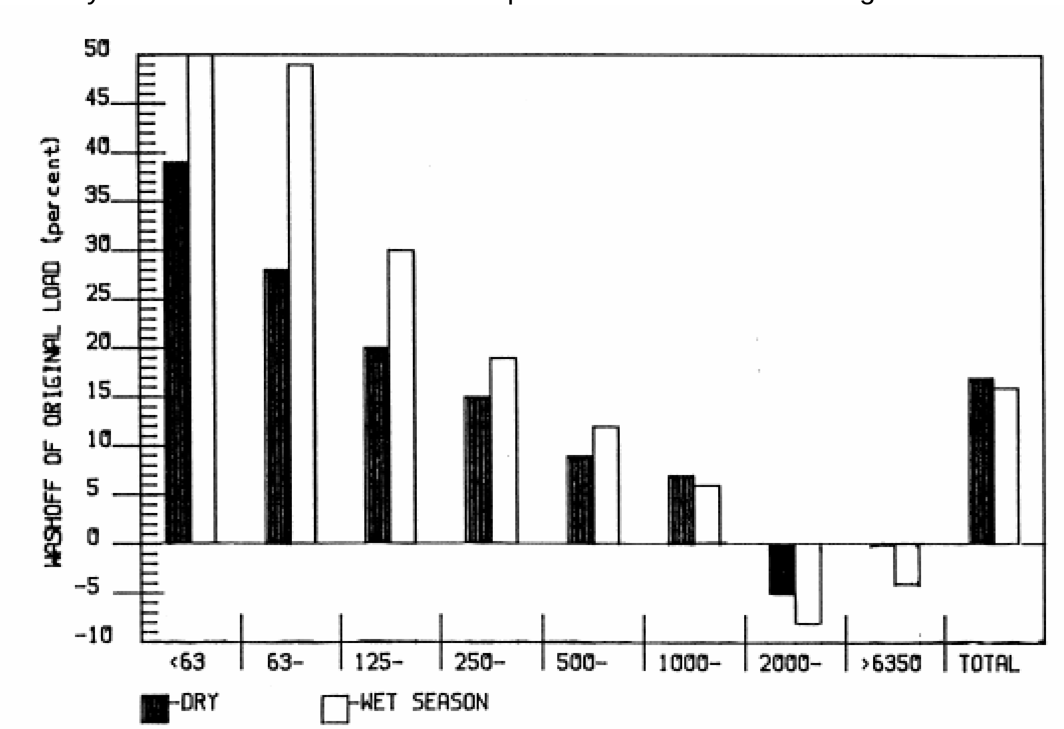
The following washoff plots are from field research conducted by Pitt (1987) and shows the accumulative washoff as a function of rain depth for particulates <0.45 µm (TDS), >0.45 µm (SS) and for total solids. The maximum washoff for the SS data is about 0.3 g/m^2, while the total loading on the street was about 12 g/m^2, an availability factor of about 1/35 for this test. Many controlled washoff tests were conducted to obtain these parameters.



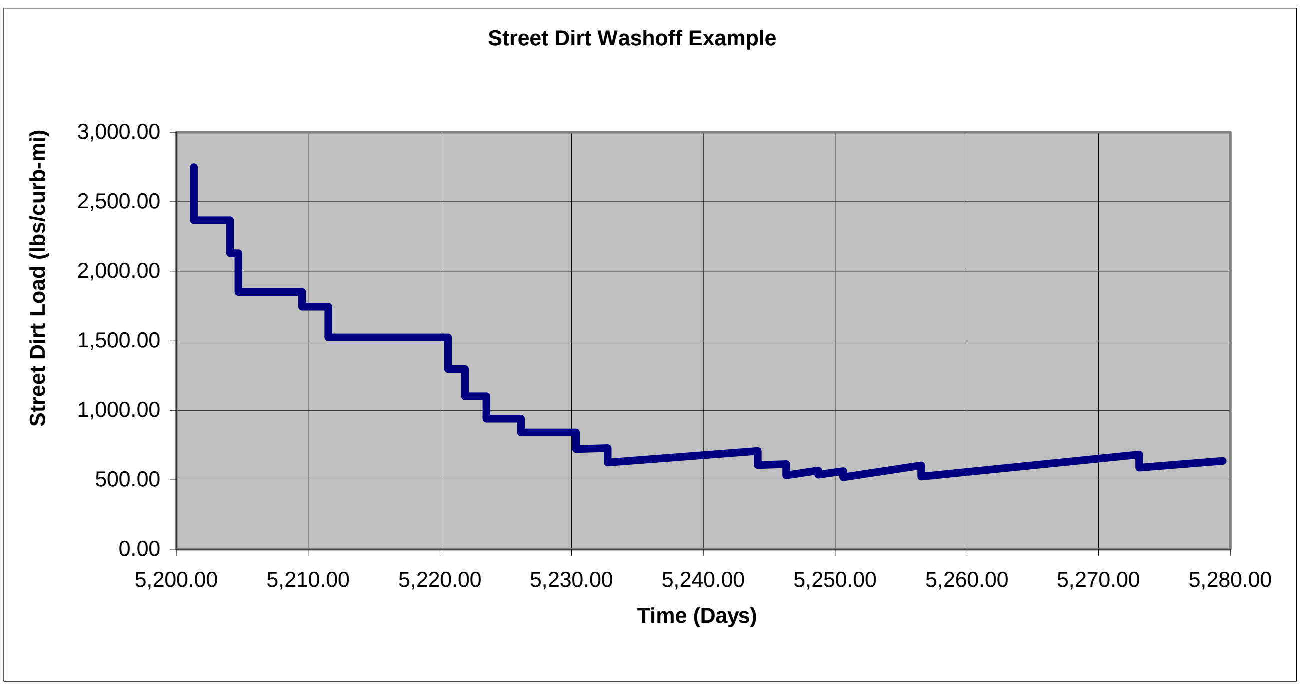
Washoff plots for HDR test (high rain intensity, dirty, and rough street) (Pitt 1987).

Both the availability factor and the proportionality constant, k, in WinSLAMM are a function of street texture, the before event load and rainfall intensity. The value of k varies from 0.12 to 0.92, and the availability factor varies from 0.09 to 0.18. To view these values for each event, select the detailed output option 'Washoff or Street Cleaning Detail File'.

The following plot shows the washoff amounts for different particle sizes during many rains in Bellevue, WA, obtained during another EPA project (Pitt 1985). Note that the rains more effectively remove the smaller particles than the larger particles. In fact, large particles may actually increase in loading during a rain due to large particulates not being able to be transported along the gutter during the rain. WinSLAMM therefore also includes a street dirt delivery function that addresses this deposition of street dirt in the gutters.



Observed washoff of street dirt during tests in Bellevue, WA (Pitt 1985).



The above example plot shows how washoff decreases with each rainfall event after the end of the winter season. The initial load of 2750 lbs/curb-mi is the street dirt load at the end of the winter season. The load decreases with each washoff event until the load after the washoff event plus the load accumulated before the next event is less than the load from the street dirt accumulation curve. Once the load reaches this level (in the above example, at about 720 lb/curb-mile), the street dirt load will begin to increase until the next washoff event.

Street Cleaning

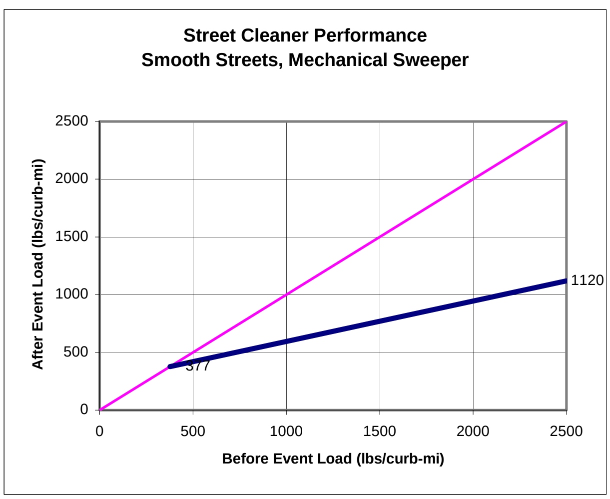
The street cleaning equation is a linear function with a slope and a constant term. Both terms are a function of the type of cleaning equipment (mechanical broom or vacuum assisted cleaner), the street texture, the parking density and whether or not parking controls are imposed. The slope must be less than one and the intercept must be greater than one. Note that the program will not calculate an AfterEventLoad that is greater than the BeforeEventLoad. The street cleaning equation is:

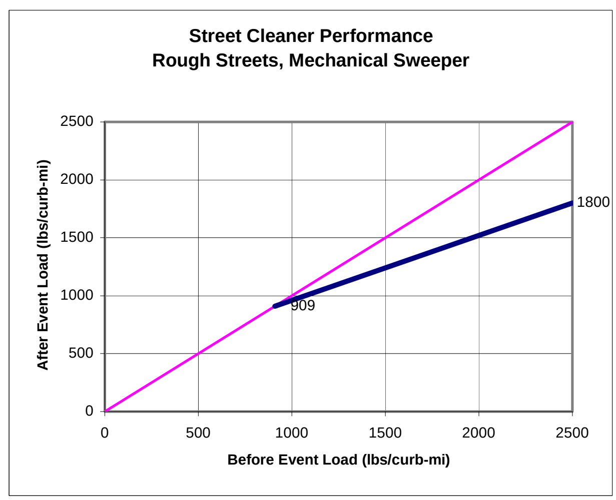
AfterEventLoad = M * BeforeEventLoad + B

where

AfterEventLoad = Street dirt load after the cleaning event
M = Maximum cleaner efficiency (less than 1.0, no units)
BeforeEventLoad = Street dirt load before the cleaning event (lbs/curb-mile)
B = Slope intercept term, (greater than 1, lbs/curb-mile)

Below is an example of how a mechanical sweeper will perform on smooth and rough streets if there is no parking allowed on the streets (Parking Density = None). The table below the plot lists the equation coefficients for these two conditions.





Street Cleaning Coefficients for the above Plots

	Slope Coefficient, M	Intercept Coefficient, B
Smooth Streets	0.35	245 lbs/curb-mi
Rough Streets	0.56	400 lbs/curb-mi

Parking Interferences to Street Cleaning Operations

Modified from: Demonstration of Nonpoint Pollution Abatement Through Improved Street Cleaning Practices; Robert Pitt, Woodward-Clyde Consultants, San Francisco, CA, EPA Report EPA-600/2-79-161, August 1979, pages 62-65. The entire report (with relevant figures) is included with the WinSLAMM model documentation.

Vehicles parked along a street cleaning route reduce the length of curb that may be cleaned. Since most of the street surface pollutants are found close to the curb on smooth streets with little parking, parked vehicles can drastically reduce the cleaning effectiveness of normal cleaning programs on these streets. The following discussion attempts to quantify this relationship.

Field work associated with this demonstration project has shown that street cleaners can be partially effective when cleaning around cars. Extensively parked cars block the migration of particulates toward the curb, resulting in higher “middle-of -the-street" loading values than for streets with little or no parking.

For example, consider several possible configurations for two cars: two closely parked cars, two parked cars with little space between them, two parked cars with enough space between them for the street cleaner to just get back to the curb and leave again, and two parked cars quite a distance from each other. The length of curb not cleaned because of parked cars may be determined geometrically by knowing the turning radius of a street cleaner and the parking layout along the street. The percentage of curb length occupied by parked vehicles is close to the percentage of parking spaces occupied, but is usually smaller due to parking restrictions such as driveways and fire hydrants. As the number of parked cars increases, the percentage of' curb left uncleaned increases proportionally. The turning radius has a small effect (less than 5 percent) on the percentage of curb left uncleaned.

If a smooth street has extensive on-street parking 24 hours a day (such as in a high-density residential neighborhood), most of the street surface particulates would not be within the 8 ft. strip next to the curb that is usually cleaned by street cleaning equipment. If the percentage of curb length occupied by parked cars exceeds about 80 percent for extensive 24-hour parking conditions, it would be best if the parked cars remained and the street cleaner swept around the cars (in the 8 to 16 ft. strip from the curb). Of course, all of the cars should be removed periodically to allow the street cleaner to operate next to the curb to remove litter caught under the cars. In an area with extensive daytime parking only (such as in downtown commercial areas), the parked cars should remain parked during cleaning (daytime cleaning) if the percentage of curb length occupied exceeds about 95 percent. The oil and screens surfaced streets are less critical to parked cars because of the naturally flatter distribution of solids across the street. Parking controls would be effective on those streets if the typical parking conditions involved less than about 95 percent curb length occupancy. Under most conditions, removal of parked cars during street cleaning operations can significantly improve the street cleaning effectiveness. Local monitoring of "across-the-street" loadings for various parking conditions should be conducted for other cities to determine their specific relationship.

Freeway Accumulation and Washoff

Freeway Accumulation

Freeway accumulation is expressed in WinSLAMM as available particulate residue, which is a function of average daily traffic, freeway length and the accumulation duration, which can be no greater than twenty days.

The following equation is used in WinSLAMM to calculate the available total residue at any time.

AvailTtlRes = 0.007 * ADT^0.89 * FreewayLength * AccumDur + CurLoad

Where

AvailTtlRes = Available Total Residue (lbs)
ADT = Average Daily Traffic (vehicles/day)
FreewayLength = Freeway Length (miles)
AccumDur = Length of time from the last washoff event (days)
CurLoad = The freeway load after the end of the washoff event (lbs)

Washoff

Freeway washoff is based upon modified relationships and equations that were initially developed by Sarter and Boyd (1972). Rexnord, Inc. (1985) conducted a series of monitoring projects for the USDOT in the early 1980s to measure the discharge of pollutants from limited access roads. They monitored several freeways in different cities throughout the country. They related runoff quality to traffic loads, and rain factors, and directly calibrated the Sartor and Boyd washoff equations. Sartor and Boyd fitted their data to an exponential curve, assuming that the rate of particle removal of a given size is proportional to the freeway loading and the constant rain intensity:

$$dN/dt = k\, r\, N$$

where:

dN/dt = the change in freeway loading per unit time
k = proportionality constant
r = rain intensity (in/h)
N = freeway loading (lb/curb-mile)

This equation, upon integration, becomes:

$$N = N_o\, e^{-krt}$$

where:

N = residual freeway load (after the rain)
N_o = initial freeway load
t = rain duration

Freeway washoff is therefore equal to N_o - N. The variable combination rt, or rain intensity times rain duration, is equal to total rain volume (R). This equation therefore further reduces to:

$$N = N_o e^{-kR}$$

Therefore, this equation is only sensitive to total rain, and not rain intensity. The proportionality constant, k, was adjusted to reflect freeway conditions, based upon the Rexnord data [1985], but was independent of rain intensity and particle size. The N_o factor is only the portion of the total freeway load available for washoff (the maximum asymptotic washoff load observed during the washoff tests). Because the Rexnord only monitored actual runoff (and not street dirt loads), WinSLAMM uses a lumped approach for highway runoff, directly predicting runoff from traffic volumes and the rain characteristics. As such, the benefits of street cleaning cannot be directly determined, as street cleaning affects the total street dirt load, which is much larger than the "available" street dirt loading. WinSLAMM also uses a freeway delivery fraction, which is a function of drainage system type and rainfall depth, as an additional calibration tool to adjust the initial calculated washoff fraction to determine the final washoff load to account for limiting effects of rain energy.

Rexnord, Inc. Effects of Highway Runoff on Receiving Waters. Volume 4. Procedural Guidelines for Environmental Assessments. PB86-228228/XAB. Federal Highway Administration. July 1985.

Biofiltration Infiltration and Filtering Functions

General Description

The biofiltration control option is a multi-featured control device that uses full routing calculations associated with pond storage along with a variety of outlet(s) and soil treatment options. The “outlet” devices include:

- natural soil infiltration (you can consider the wide range of variability in infiltration rates in disturbed urban soils by selecting the built-in Monte Carlo option),
- evaporation,
- surface discharges through overflows (a stand pipe or weirs),
- subsurface discharges through underdrains, or
- to set up the device as a rain barrel or a cistern with controlled withdrawals for beneficial uses of the captured stormwater.

This is a very flexible control device, and as such can be used to evaluate the following types of control practices:

- Biofilters
- Rain Gardens
- Infiltration Basins
- Infiltration Trenches
- Cisterns and Rain Barrels
- Infiltration Pits
- Rock-filled Trenches
- Percolation Ponds
- Perforated Pipes
- Bottomless Inlets

Biofiltration controls are usually numerous in an area and can be represented in the model individually or in multiples (by specifying how many of each unit is treating the flow from an individual or combination of source areas).

Hydraulic Algorithm

The device operation is modeled using the Modified Puls Storage-Indication method, and is analyzed differently depending upon the use of rock and/or engineered soil layers. The complex triangular inflow hydrograph is divided into six-minute time steps that are routed to the surface of the biofilter. The biofilter is evaluated in two sections, or cells: the above ground section (or above the engineered soil) and the below ground section (including the engineered soil and/or other fill material). The series of graphics below illustrates a number of different flow configurations.

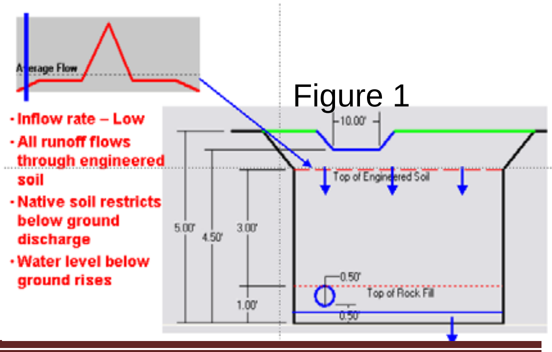


Figure 1

As water enters the device, all flow is routed from the surface to the below ground section of the device. This continues to occur as long as the engineered soil infiltration rate for the biofilter area is greater than the water inflow rate, and, if the antecedent soil conditions allow for infiltration. All runoff flows through the engineered soil and is infiltrated into the native soil. The runoff that is infiltrated into the native soil is considered completely (100 %) treated. See Figure 1.

As the inflow rate increases, the below ground water level increases to the point where water begins to flow out the orifice. At this point all runoff is treated by the engineered soil. But since some runoff flows through the orifice/drain tile, some treated runoff is discharged from the system. (Figure 2)

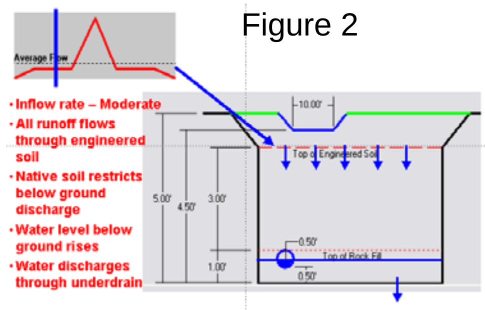


Figure 2

The above ground storage begins to fill up once the inflow rate exceeds the engineered soil infiltration rate. Water levels in the below ground cell continue to rise. This will occur as long as the inflow rate to the below ground cell is greater than the outflow rate from the orifice/drain tile plus the infiltration into the native soil. Some treated runoff is discharged from the system. (Figure 3)

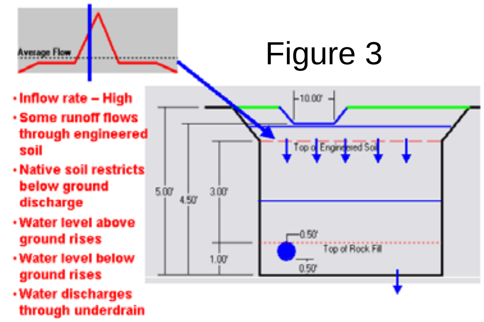


Figure 3

In Figure 4, the above ground storage exceeds the elevation of the overflow weir. At this point, untreated runoff is discharged into the system. Water levels in the below ground cell continue to rise as the inflow rate to the below ground cell is greater than the outflow rate from the drain tile plus the infiltration into the native soil. Some treated runoff is also discharged from the system. 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. Infiltration 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.

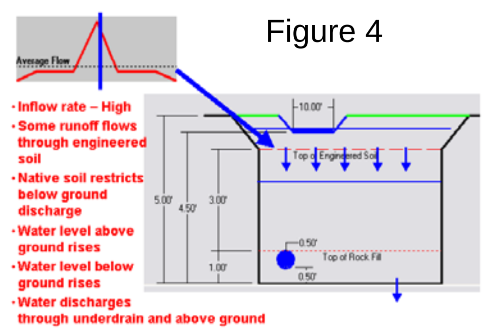


Figure 4

As the inflow rate decreases, the surface water level also decreases. No more untreated water is discharged, but treated water, which flowed through the engineered soil, is still discharged through the orifice/drain tile. (Figure 5)

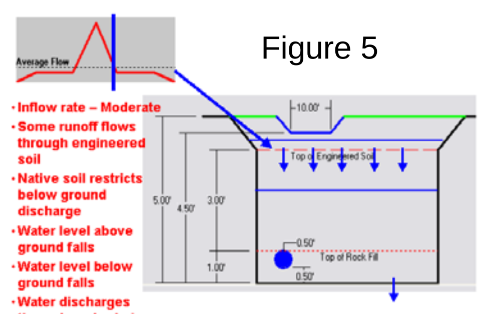


Figure 5

As the inflow rate continues to decrease, surface water vanishes and the water level below ground decreases. This will occur because the inflow rate through the engineered soil is less than the sum of the discharge rate through the orifice/drain tile and infiltration into the native soil. At this point all runoff is treated by the engineered soil, but since some runoff flows through the orifice, some treated runoff is discharged from the system. (Figure 6)

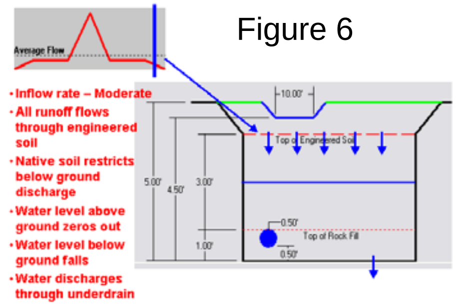


Figure 6

As the inflow rate approaches zero, the water level below ground continues to decrease. Once the water level is below the orifice/drain tile, then all water is treated because all water is infiltrated into native soil. (Figure 7)

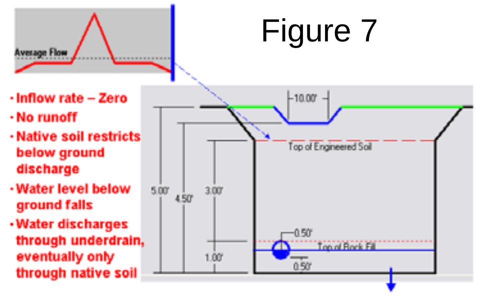


Figure 7

If there are no rock and engineered soil layers, then:

- o flow into the native soil is considered to be an outflow,
- o there is no below ground section, and
- o all treatment by the device is assumed to be through volume loss by infiltration into the native soil.

Pollutant Removal

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. The user can also directly enter the percent reduction due to filtering that is allowed by a regulatory agency.

Scenarios include:

1. Biofilter with Engineered Soil. Particulate solids (and associated particulate-bound pollutants) are removed based upon the influent particle size distribution and the engineered soil type, as described in Table 1. The fractional removal rate for each particle size range is applied to the influent concentration, for each event. For example, 18% of the particles in the NURP.CPZ particle size distribution fall within the range of 12 to 30 microns. If the engineered soil media were peat and sand, then eighteen percent of the influent concentration for each event would be reduced by 85% for that particle size range. This reduction is applied to all runoff that flows through the engineered soil. 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. This bypass water is considered, in the model, to be untreated. There is also an "irreducible" concentration that is considered below which the filtration media cannot remove the particulate solids concentration.

2. Biofilter with User-Defined Engineered Soil. The particulate solids reduction of all runoff that flows through the engineered soil will be reduced by the user-defined reduction value. The overall effluent concentration reduction for each event will be proportional to the runoff that bypasses the device. For example, if 75% of the runoff from a rainfall event flows through a device that is to get a 50% reduction, as defined by the user, then the total percent reduction for that event would be 37.5%.
3. Biofilter with No Engineered Soil. The particulate solids reduction is calculated by the volume of runoff that infiltrates into the native soil. If, for a given event, 40% of the runoff is infiltrated into the native soil, then there will be a 40% reduction in particulate solids.

Table 1 - Particulate Treatment in Stormwater Infiltration and Filter Control Devices

Fractional Removal of Stormwater Particulates

Media	Applicable Stormwater Controls	0.45 to 3µm	3 to 12µm	12 to 30µm	30 to 60µm	60 to 120µm	120 to 250µm	>250µm	Minimum Effluent TSS Concentration
Porous pavement surface (asphalt or concrete)	Porous pavement	0.00	0.00	0.00	0.00	0.25	0.50	1.00	n/a
Coarse gravel	Porous pavement and biofilter underdrain and storage layer	0.00	0.00	0.00	0.00	0.00	0.00	0.10	n/a
Sand	Porous pavement, biofilter, and filter	0.10	0.33	0.85	0.90	1.00	1.00	1.00	10 mg/L
Loam soil	Engineered soil/biofilter	0.10	0.33	0.85	0.90	1.00	1.00	1.00	25 mg/L
Peat – sand	Filter	0.10	0.33	0.85	1.00	1.00	1.00	1.00	5 mg/L
Compost – sand	Filter	0.10	0.33	0.85	0.90	1.00	1.00	1.00	10 mg/L
Peat	Filter	0.10	0.33	0.80	1.00	1.00	1.00	1.00	5 mg/L
Compost	Filter	0.00	0.10	0.20	0.50	0.75	1.00	1.00	10 mg/L

Notes:

1. If the calculated effluent concentration is greater than the allowable minimum concentration, then the model reports the calculated effluent concentration.
2. If the calculated effluent concentration is less that the allowable minimum concentration, then the model reports that value, but only if it is greater than the influent concentration.
3. If the minimum concentration is greater than the influent concentration, then the model reports the influent concentration (can't create a larger concentration!), but only if the calculated effluent concentration is less than the minimum allowable concentration.

Table 2 below lists, for each biofilter configuration, which biofilter outlet devices are applicable. There are either one or two cells for any biofilter configuration. The above ground cell is the cell where water initially enters the biofilter, and is the storage space above the ground surface/engineered soil. If there is no engineered soil or rock fill, then there is only the one cell, which is the above ground cell. If there is engineered soil and/or rock fill, then the second cell is the below ground cell containing the engineered soil and/or rock fill. For example, for a biofilter with rock fill (Biofilter Configuration 2), the underdrain is the only hydraulic outlet possible for the below ground cell.

Table 2 - Biofilter Outlet Device Operation Criteria

Biofilter Configuration	Cell Location	Broad Crested Weir	Sharp Crested Weir	Under-drain	Vertical Stand Pipe	Evapora-tion	Evapotrans-piration	Native Soil Infiltration	Engineered Soil Infiltration
1 - No Fill	Above Ground	Yes	Yes	Yes	Yes	Yes	Yes	Yes	N/A
2 - Rock Fill	Above Ground	Yes	Yes	Yes	Yes	Yes	No	No	N/A
	Below Ground	No	No	Yes	No	No	No	Yes	N/A
3 - Engineered Soil Fill	Above Ground	Yes	Yes	Yes	Yes	Yes	No	No	Yes
	Below Ground	No	No	Yes	No	No	Yes	Yes	No
4 - Rock and Engineered Soil Fill	Above Ground	Yes	Yes	Yes	Yes	Yes	No	No	Yes
	Below Ground	No	No	Yes	No	No	Yes	Yes	No

Output Options

There are six different output options available to view the performance of the biofilter. The output summary, which appears after an individual model run, will display the biofilter's performance on the entire modeled system. The user can also select detailed output. The detailed output options include:

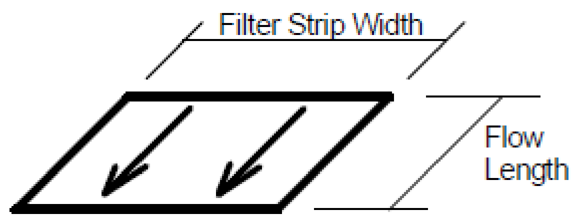
- Stage-Outflow File
- Detailed Biofilter Output File
- Stochastic Seepage Rate Detail File
- Water Balance File
- Particulate Reduction Output File
- Irreducible Concentration Detailed Output

The description of each of these files can be found elsewhere in the Help File.

Filter Strip Infiltration and Filtering Functions

General Description

Filter strip performance is determined by directing the hydrograph developed by the program through a sloped grass area via sheet flow. The resulting runoff volume reductions are determined by infiltration losses; particulate losses are determined through particle trapping due to sedimentation and infiltration, and dissolved pollutant losses are determined through infiltration. The runoff is assumed to be evenly distributed across the width of the filter strip (such as through the use of a level spreader) and to not form concentrated flow channels or rills as it flows across the strip. Below is a conceptual drawing of the filter strip. The program purposefully does not define a maximum flow length for the filter strip. This user must supply this by describing an appropriate length using engineering judgment.

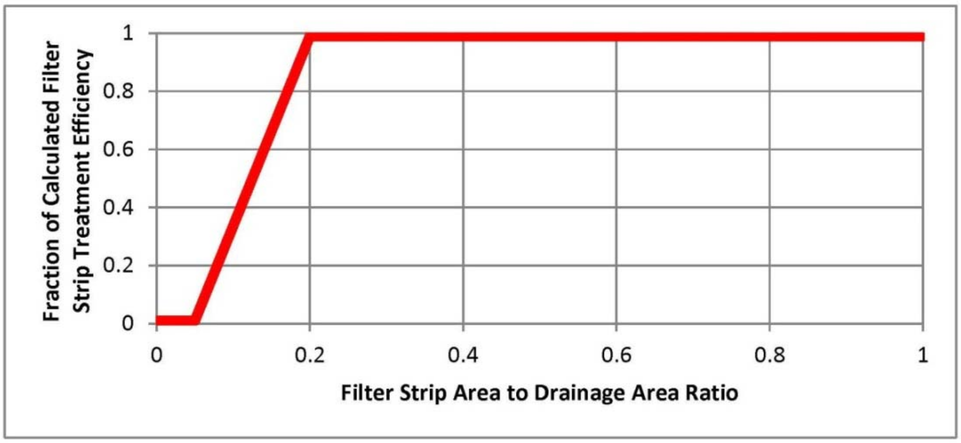


In order to calculate the infiltration and settling characteristics of the filter strip, the water flow rate and the water depth need to be determined for each calculation time step and each distance increment across the filter strip. The flow and the filter strip geometry are used to determine Mannings n, which is used to iteratively determine the depth of flow and water velocity in the strip for each time step. The traditional VR-n curve approach that was extended by Kirby was used for this purpose. This approach considers the much lower VR values encountered in small urban drainage systems, including grass swales and grass filter strips (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).

The process begins for each time step, using the flow rate from the hydrograph that enters the top edge of the filter strip. The stormwater infiltration is determined using the calculated depth of flow and the incremental infiltration area of the filter strip for each time increment, based on the width of the filter strip, which is the wetted perimeter, and the incremental length of flow. The water in that time step and that incremental area is infiltrated into the filter strip according to the infiltration rate (ponded conditions). The remaining water then moves downslope to the next calculated incremental area in the next time step, where this water is infiltrated to the extent possible based upon the infiltration rate and any available water. Any water that has not been infiltrated as it traverses the last calculation segment of the filter strip is discharged as runoff.

Particulate trapping in the filter strip is calculated for each time step using the calculated depth of flow and Manning's n for the corresponding time steps of the hydrograph. The Manning's n is used to calculate the flow velocity, which in turn is used to determine the travel distance, travel time, depth of flow, and the settling time for each particulate size category for each time step. The sediment capture is determined based on the flow depth to grass height ratio and the settling frequency (how many times the particles of a specific size could settle along the length of the grass filter), adapted from Nara, *et al*. (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). The particulate trapping is calculated for each of the thirty-one particle size fractions in the influent particle size distribution. The resulting effluent particulate concentrations for each of these size increments are then combined into eight coarser groups of particle sizes where they are evaluated to determine if they are below the irreducible concentration values for each particle size group. No resulting effluent concentration values are allowed to go below the irreducible concentration values unless the inflow value is already below that level.

Very small filter strips in relation to the impervious contributing area do not function effectively. Therefore, a scaling factor, the total suspended solids removal efficiency ratio, is used to discount the performance of grass filters for small filter strips. If the filter strip area is less than 5 percent, or 1/20th, of the contributing area the filter strip is assumed to provide no stormwater control benefits. Full benefits (as calculated by the model) are assumed to occur only for grass filters that are at least 20 percent, or 1/5th, of the contributing area. Intermediate filter strip to contributing area ratios receive interpolated performance levels. The figure below illustrates how the total suspended solids removal efficiency ratio is determined. The removal efficiency ratio is applied to both the infiltration rate and to the final effluent concentration calculation. Additional performance discounts are also applied for very short filter strips, as described in the following calculation step descriptions.



The following is an outline of the filter strip infiltration and particulate trapping calculation steps:

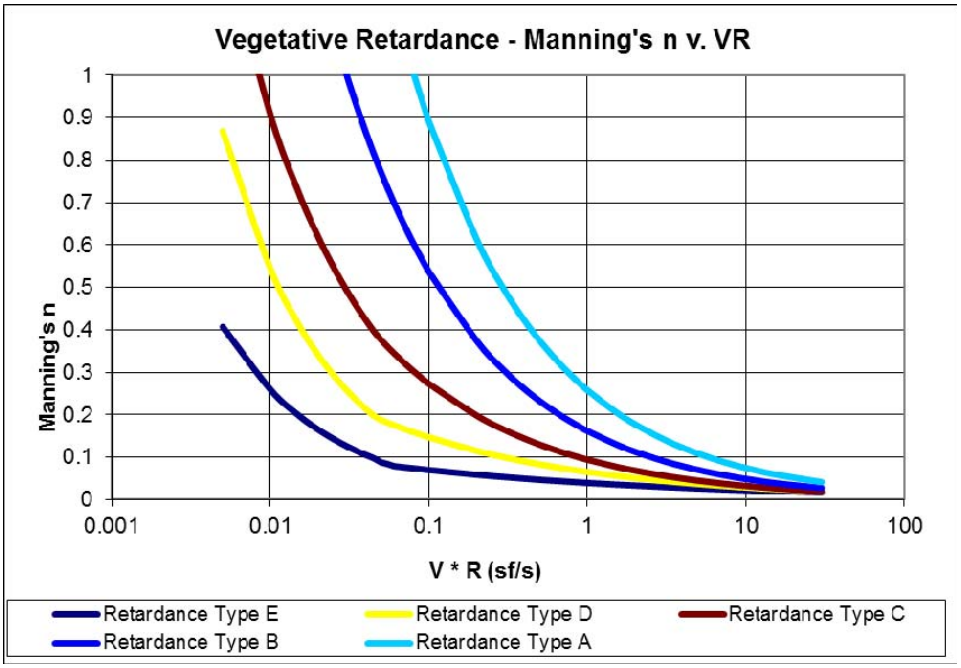
1. **Filter Strip Infiltration Properties**.
   a. The entire filter strip area, as represented by the sums of the products of each incremental flow distance times the filter strip width, is used to infiltrate runoff.
   b. The infiltration rate is reduced over time depending upon the amount of clogging that occurs in the system. The infiltration rate clogging adjustment factor, which is calculated after each rainfall event, equals the trapped mass of sediment divided by the clogging load. If the filter strip does not clog after 10 years, the program assumes that it will not clog and that it will maintain the infiltration rate calculated after 10 years of the model run.
   c. The infiltration rate is adjusted based upon the depth of water in the filter strip in each incremental flow step, for each time step, according to the following table.

Depth of Water in Filter Strip (ft)	Infiltration Rate (in/hr)
<= 0.015	Entered Rate x 2 (Static Infiltration Rate)
> 0.015 and < 0.03	Interpolated Between the Two Rates
>= 0.03	Entered Rate (Dynamic Infiltration Rate)

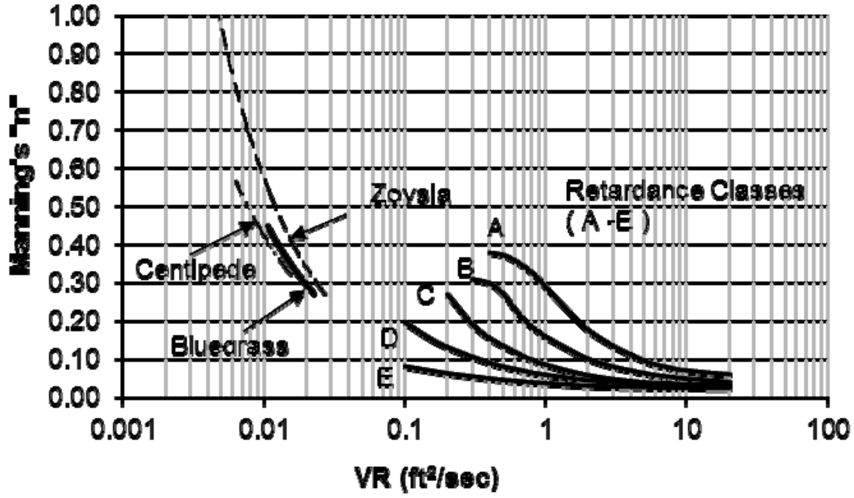
   d. The effective treatment length of the filter strip is reduced based the following criteria:

Longitudinal Slope	Swale Length Reduction (ft)
< 0.02	3
> 0.02 and <= 0.05	6
> 0.05	10

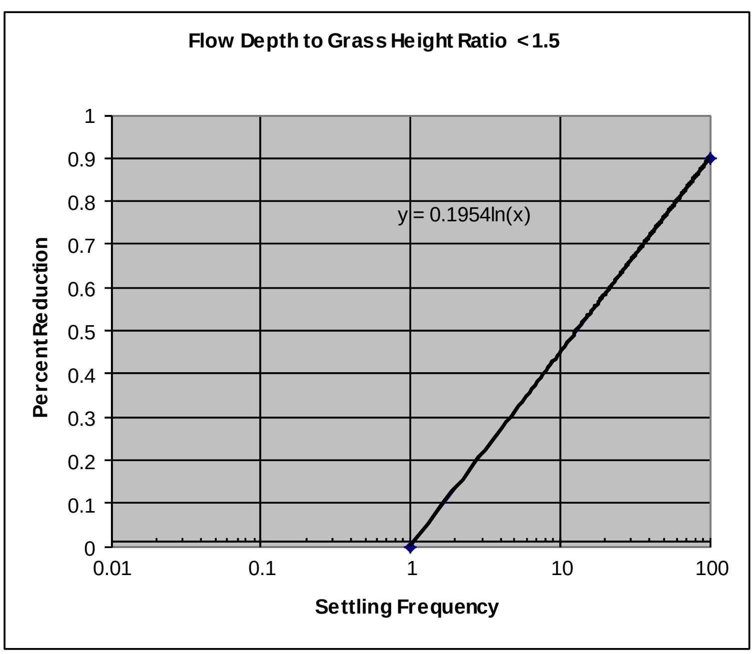
2. **Filter Strip Hydraulic Properties**. After the filter strip length is adjusted, depending upon the slope, the program calculates the incremental flow rate for each time step using the model default time increment set by the user. Using this flow rate, the program will calculate the depth of flow and the distance the flow will travel during each time increment. This is an iterative process, where the program:
   a. Assumes a depth of flow in the filter strip segment
   b. Calculates the VR (Velocity times Hydraulic Radius) based upon that depth
   c. Determines the Manning's n value using the calculated VR value from the plot shown below, based upon the Stillwater OK, USDA data and Kirby's data.
   d. Calculates the flow based upon the Mannings n and assumed depth
   e. Determines the difference between the calculated flow and the modeled incremental flow entering the filter strip segment. If the difference between the two flows is greater than 0.0001 cfs, the program re-estimates the flow depth and begins the iterative process again.



This Manning's n v. RV plot is based upon Observed VR-n curves for small urban drainage systems (Kirby, J. *Determination of Vegetal Retardance in Grass Swales used for the Remediation of Urban Runoff*, MSCE thesis. The University of Alabama, Tuscaloosa, AL 2003).compared to the Stillwater, OK, USDA curves (USDA. 1954. *Handbook of Channel Design for Soil and Water Conservation*. Washington D.C. USDA, Technical Paper TP-61) illustrated below. The Stillwater data shown in the curve below and the D values from Kirby were used to extrapolate the remaining VR-n retardance lines on the above plot. However, a value of 1.0 is the maximum allowable Manning's n.



3. **Filter Strip Analysis Process**. After determining the flow properties of the filter strip segment, for each time step, the program will:
    a. Adjust the infiltration rate based upon both the clogging factor and total suspended solids removal efficiency ratio described above.
    b. Calculate the volume infiltrated by the filter strip using the adjusted infiltration rate and the calculated infiltration area.
    c. Determine the travel time down the filter strip segment
    d. Determine the flow depth to grass height ratio
    e. For each particle size category, determine the
        i. Settling velocity
        ii. Settling duration (depth of flow/settling velocity)
        iii. Setting frequency (travel time/settling duration)
        iv. Determine the percent particulate reduction based upon the settling frequency and the flow depth to grass height ratio, as shown on the example plot below for a flow depth to grass height ratio < 1.5.



f. Divide the particle size distribution into eight groups.
    i. Calculate the effluent concentration for each group.
    ii. Check to make sure the effluent (treated) particulate solids concentration for each group is not less than the irreducible concentration for that group, as shown below:

Particle Size Range Number	Particle Size Range	Irreducible Conc. for Size Range (mg/L)
1	0.45 to 2 µm	5
2	2 to 5 µm	4
3	5 to 10 µm	3
4	10 to 30 µm	2
5	30 to 60 µm	1
6	60 to 106 µm	0
7	106 to 425 µm	0
8	> 425 µm	0

g. Sum the concentration values for each particle size group to determine the final concentration in the effluent discharged from the swale system.

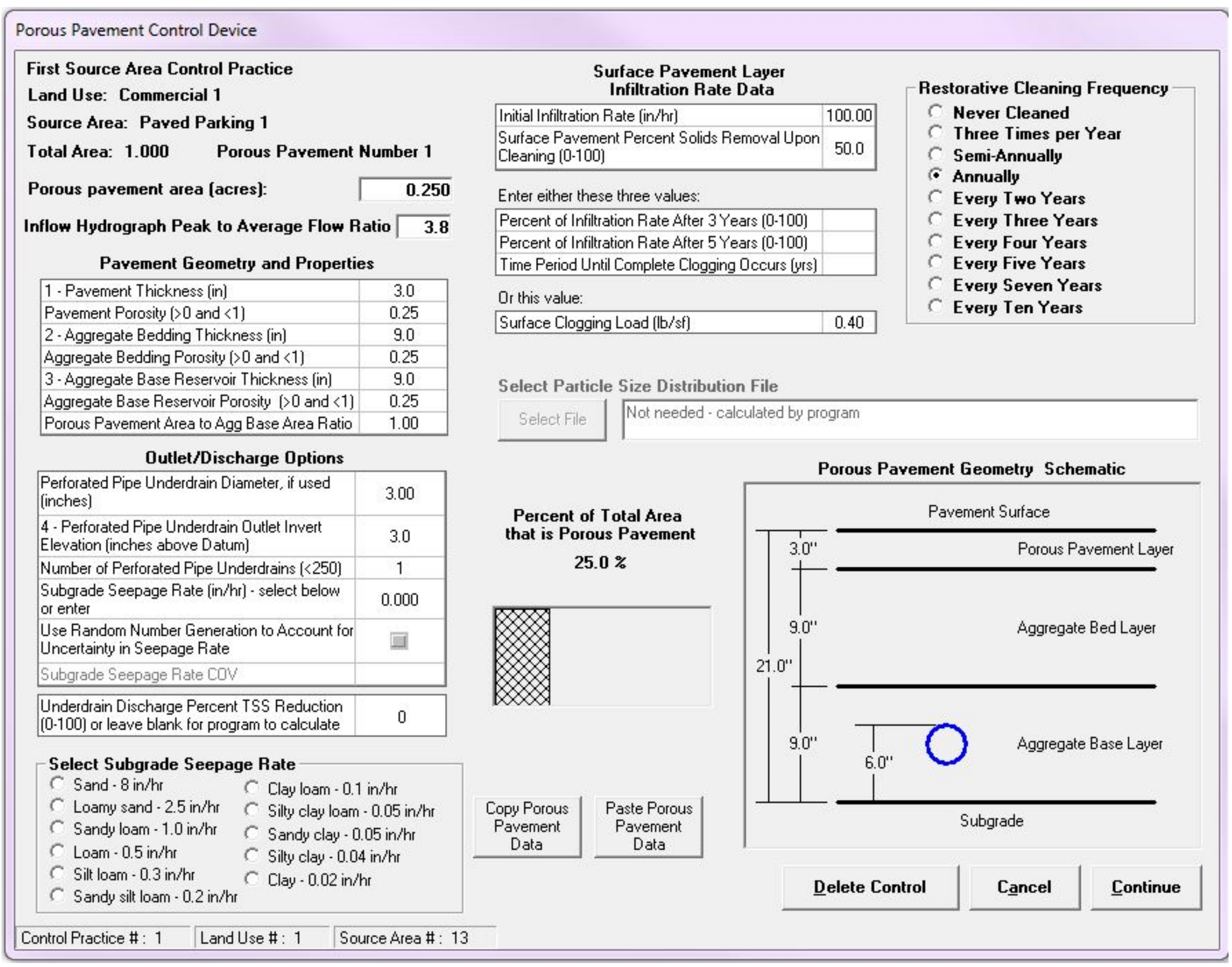
h. Adjust the final effluent concentration based upon the total suspended solids removal efficiency ratio. This ratio will prevent the program from reducing the effluent concentration if the filter strip area to drainage area ratio is small.

Porous Pavement

General Description

The porous pavement control option has particle trapping by particle size along with full water routing calculations associated with pond storage in conjunction with other porous pavement features. This allows the program to calculate both pollutant removal and water infiltration capability according to specific design characteristics and rain conditions. 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 also has a surface seepage rate that limits the amount of runoff that can enter the storage/infiltration system. This surface seepage rate is reduced due to partial to complete clogging over time. The surface seepage rate can be partially restored with cleaning according to the selected cleaning frequency.

The typical porous pavement structure has three components: 1) a surface pavement layer, 2) aggregate bedding, and 3) a base reservoir for water storage. The data entry form for porous pavement is shown below.



Porous Pavement Hydraulic Algorithm

The device operation is modeled using the Modified Puls Storage-Indication method, and is analyzed depending upon the use of bedding and rock (aggregate base reservoir) layers. The complex triangular inflow hydrograph is divided into time steps that are used when determining the flow rates for the runoff routed to the surface of the device from the drainage area and for the direct rainfall onto the porous pavement. As water enters the device, all flow is routed from the surface to the below ground section of the device as long as surface clogging has not reduced the surface infiltration rate to a level below the rate of the inflow hydrograph. In addition, water will also not enter the pavement surface if the water level within the device reaches the surface because of complete saturation of all internal pore volumes.

Once water enters the porous pavement, it flows to the bottom of the device and leaves either through infiltration into the native soil, at a rate determined by the user but modified by the program as the bottom of the device fills with sediment, or through optional underdrains. The program determines the water surface within the device at each time step using the Modified Puls Storage-Indication method. The storage volume is adjusted using the average porosity of the pavement-aggregate bed-aggregate base system.

Pollutant Removal

The program models porous pavement system pollutant removal as three separate processes. Pollutant removal initially occurs through filtering in the upper layer of the pavement. This clogging process removes larger particles beginning at about 60 micrometers in size. The remaining pollutants flow through the system. Any storage volume below the spring line (the maximum horizontal dimension) of an underdrain will allow setting to occur in the storage layer, which acts as the second removal process. These two processes are discussed in detail below. In addition, all runoff that is infiltrated is assumed to receive complete treatment, including all contaminants.

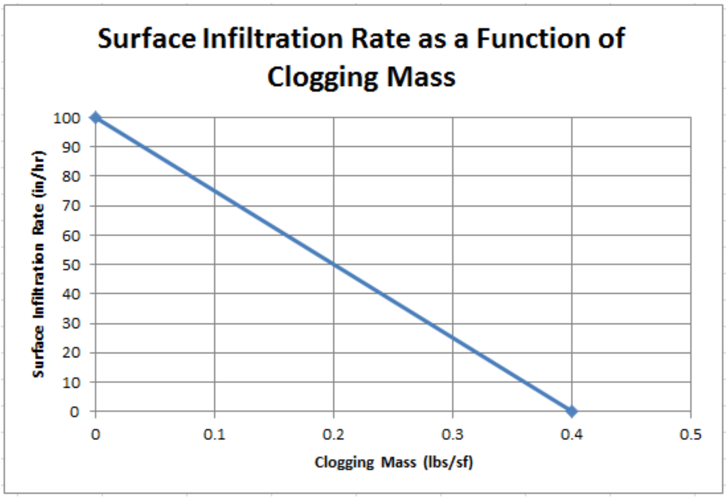
Pollutant removal through surface layer filtering.

Pollutant filtering in the porous pavement layer is based upon research performed by Dr. Robert Pitt's research group at the University of Alabama (Sileshi, Redahegn. Ph.D. *Soil Physical Characteristics Related to Failure of Stormwater Bioinfiltration Devices*. 2013), which determined the percent removal of various particle sizes as particulates flow through selected media. Table 1 below describes the reduction fraction for particle size groups through a surface porous pavement layer. Based upon this data, it is apparent that increased removal occurs as the particle size distribution entering the pavement gets coarser.

Table 1 - Particulate Treatment in Porous Pavement Devices
Fractional Removal of Stormwater Particulates

Media	0.45 to 3µm	3 to 12µm	12 to 30µm	30 to 60µm	60 to 120µm	120 to 250µm	>250µm
Porous pavement surface (asphalt or concrete)	0.00	0.00	0.00	0.00	0.25	0.50	1.00

As particulates are trapped in the pavement layer, the effect is to reduce the ability of the pavement to convey runoff into the lower part of the porous pavement system. This clogging is modeled as a linear surface pavement infiltration rate reduction, illustrated in the graph below. The initial surface infiltration rate and the mass that that causes complete surface clogging (100 in/hr and 0.4 lb/ft^2 in this example) are both entered by the user in the Porous Pavement data entry form.

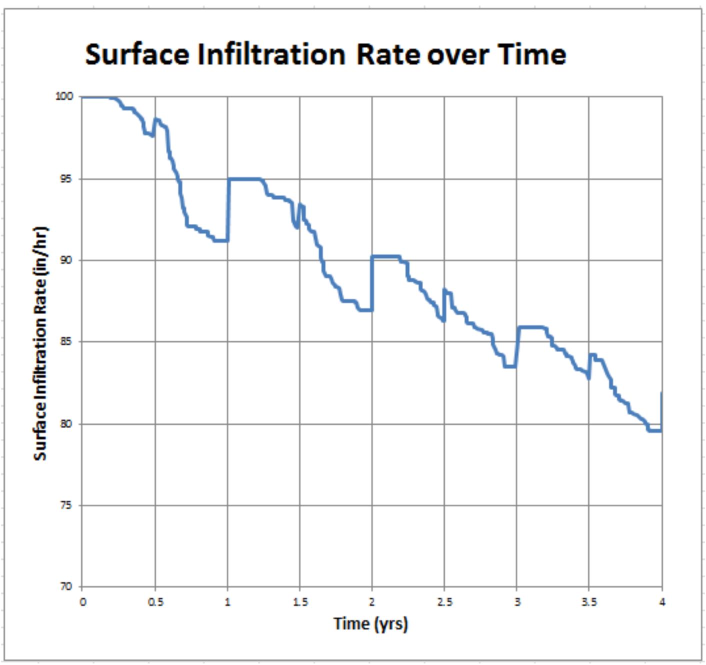


The slope of the line – the surface infiltration rate/clogging mass – is used in the linear equation that adjusts the pavement infiltration rate. This equation, for any rainfall event in the rainfall series, is:

Pavement Infiltration Rate$_i$ = Initial Surface Infiltration Rate – Initial Surface Infiltration Rate/Clogging Mass x Cumulative Clogged Mass$_i$

Note that a consequence of this approach to adjusting the pavement infiltration rate is that the time it takes to reach a zero infiltration rate will vary as a function of the clogging mass, and not the initial infiltration rate.

The adjustment in the surface infiltration rate, and the change associated with surface cleaning, are illustrated in the example model output in the figure below. The initial assumed surface infiltration rate of 100 in/hr is adjusted to reflect the clogging mass in the pavement. When pavement cleaning occurs, the infiltration rate is adjusted.



It is important to note that the critical clogging loading value is calculated based on the accumulative amount of sediment material actually trapped in the surface layer of the porous pavement. This value is substantially smaller than the total sediment load applied to the porous pavement, which is the typically available value used from field monitoring of clogging of porous pavements.

Pollutant Removal through Subsurface Settling

The porous pavement performance algorithms use the Modified Puls Storage-Indication method in conjunction with the surface overflow rate to determine the amount of particle settling that occurs in the porous pavement subsurface, by particle size. The settling area is the pavement surface area modified by the base material porosity and the porous pavement area to aggregate base area ratio. This later value, which must be equal to or greater than 1, accounts for any open graded areas such as a base course beneath impervious pavement adjacent to a porous pavement system. The settling performance is calculated by assuming flow through the quiescent settling area of the porous pavement aggregate base layer. The particulate removal in this settling area is assumed to occur due to ideal settling as described by Stokes Law (for laminar flow which is likely for the slow flowing water through the coarse media of the storage layer), or Newton's law (for turbulent flow that may occur for large particulates and unusual storage layer designs). The path of a settling particle is the vector sum of the particle velocity through the base aggregate and the settling velocity of the particle. It is assumed that particles settling to the bottom of the pavement before the outlet zone is reached are captured in the pores of the storage layer. Therefore, if the water velocity is slow, slowly falling very small particles can be retained in the water and removed by the underdrain. If the water velocity is fast, then only the heaviest (fastest falling) particles are likely to be retained.

The program determines the accumulated depth of the sediment in the pores of the storage layer after each rainfall event. If the depth of settled particles becomes greater than either the top of the aggregate bed layer or to the elevation of the invert of the underdrain pipe plus one-half the diameter, then the settling process is stopped, and no further settling is allowed. Infiltration into the native soil is assumed to stop once the sediment depth reaches 0.25 inches, and is reduced linearly as a function of the depth of the sediment up to 0.25 inches. There are no cleaning options to remove sediment from the below-ground system.