WinSLAMM Model Algorithms

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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)

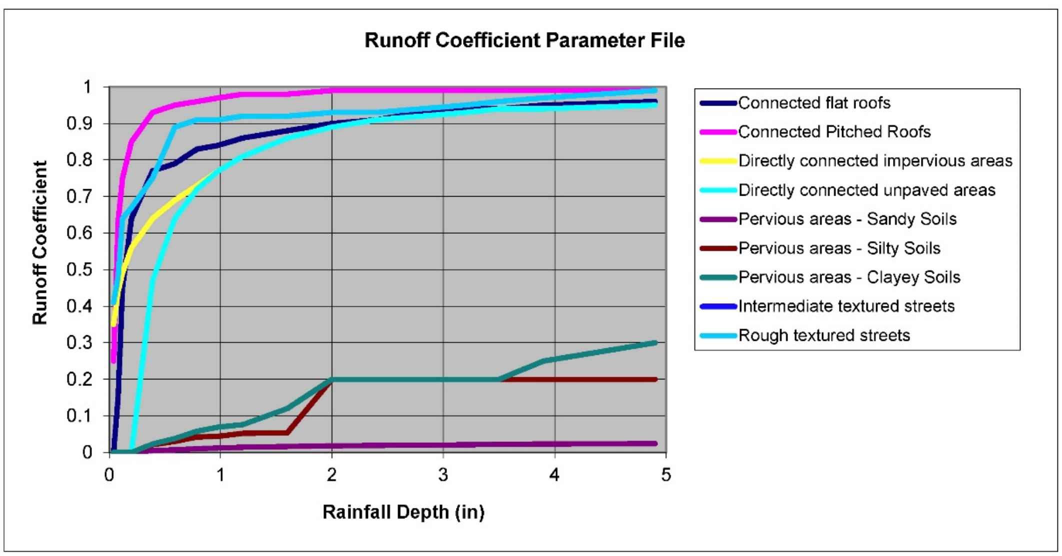


Figure 1b – Runoff Coefficient Plot (v10 Runoff.rsv)

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.

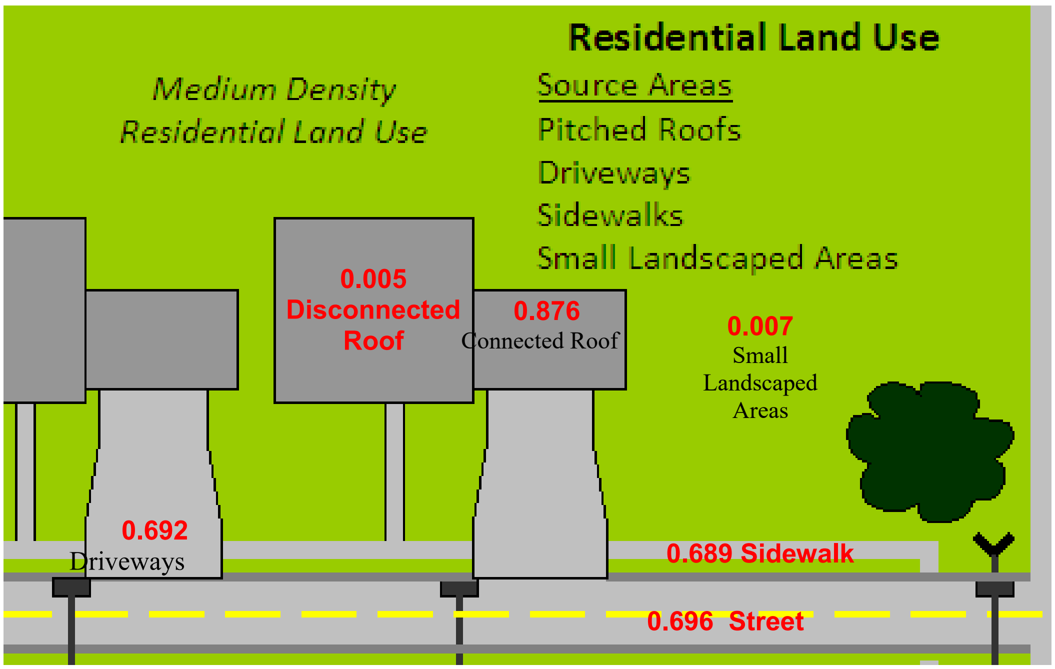


Figure 2 – Medium Density Residential Drainage Area with Runoff Coefficients for the First Rainfall Event Listed in Table 2

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

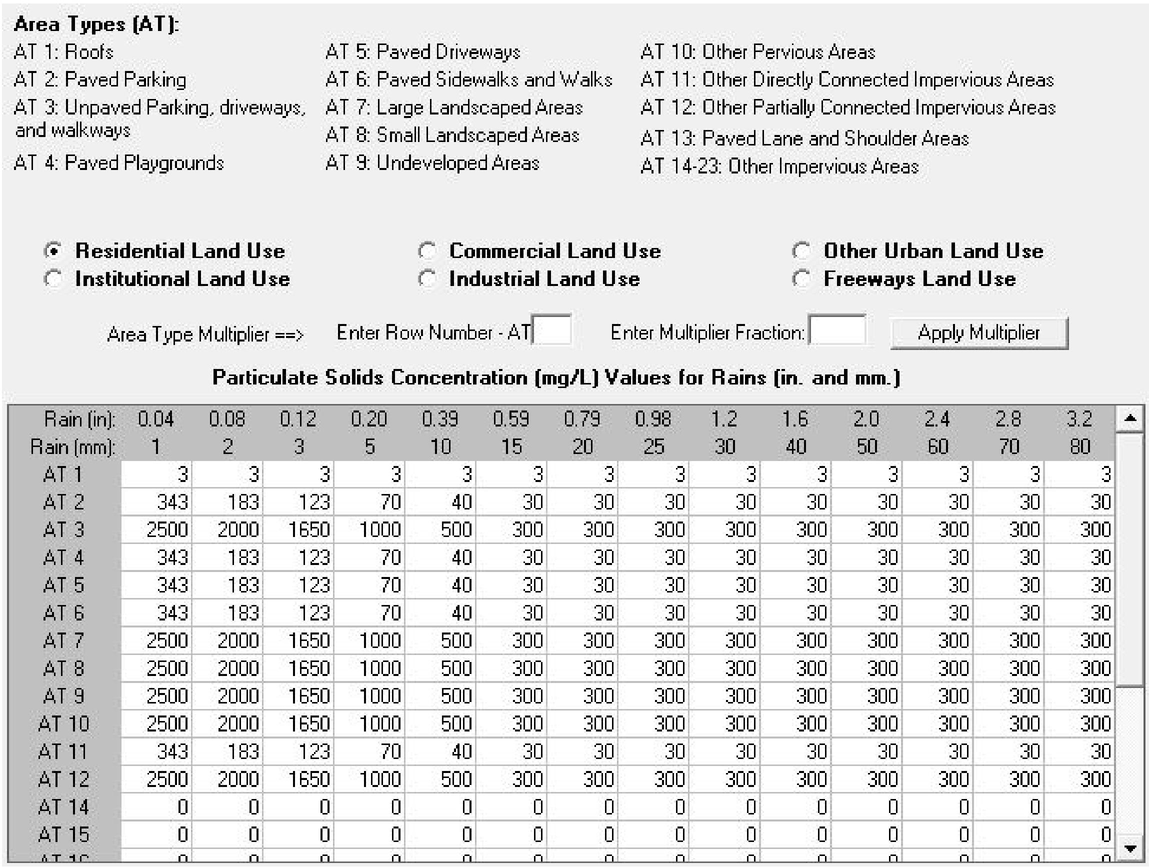
WinSLAMM calculates the runoff volume for each source area and for each rainfall event, in the model run as a base model condition. This is without stormwater control practices and is listed as the 'Base' condition on the WinSLAMM output summary. Stormwater control practices affecting runoff from source 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 except for streets, high traffic urban areas or freeways. These source areas are addressed in the Street Dirt Accumulation, Washoff and Street Cleaning section of this documentation. 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

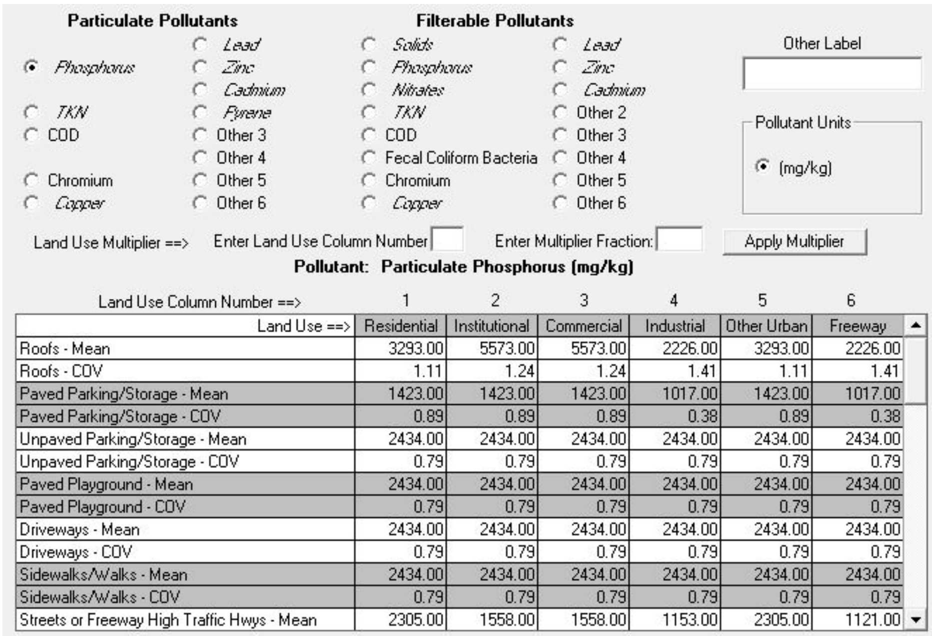
Particulate and filterable pollutants are determined in a similar manner. WinSLAMM has a set of pollutants available for analysis associated with each pollutant probability distribution (.PPDx) file. These files are calibrated based upon monitored data and are available for different areas of the country, 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 ==>	Residential (1)	Institutional (2)	Commercial (3)	Industrial (4)	Other Urban (5)	Freeway (6)
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

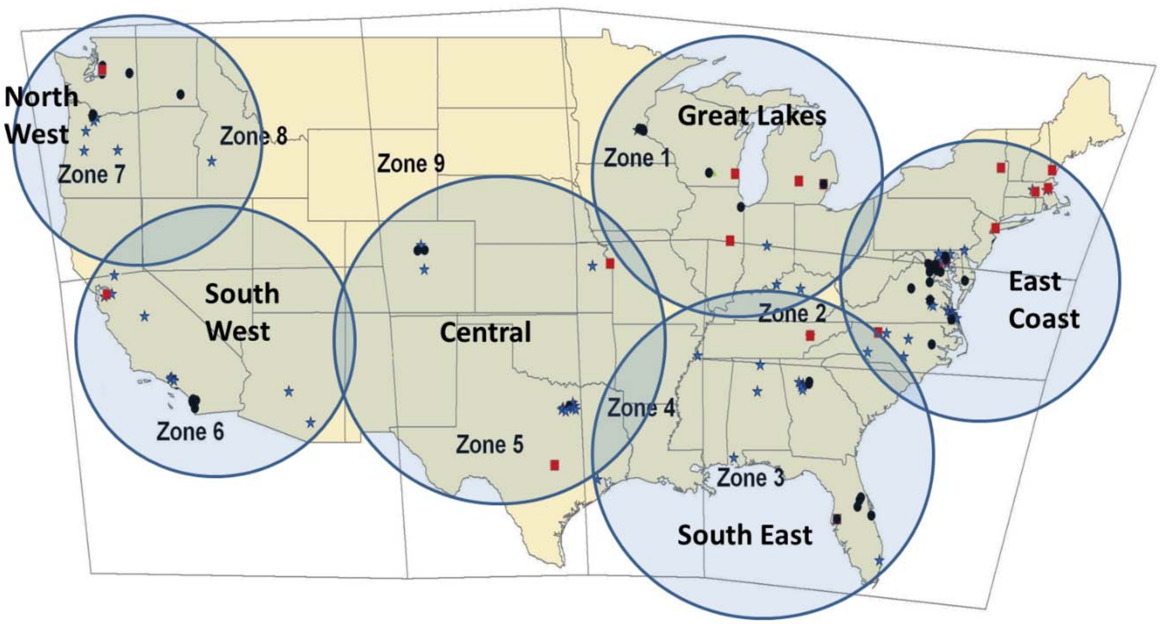


Figure 5. Sampling locations for data contained in the National Stormwater Quality Database (NSQD), version 3, showing EPA Rain Zones and general calibration set regions.

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.

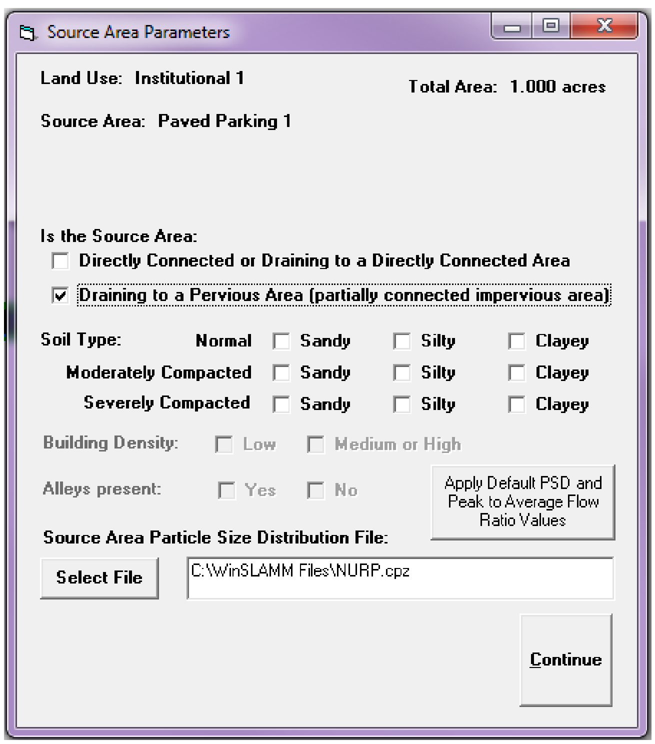
Table 5. Summary of Observed vs. Modeled Concentrations

	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.

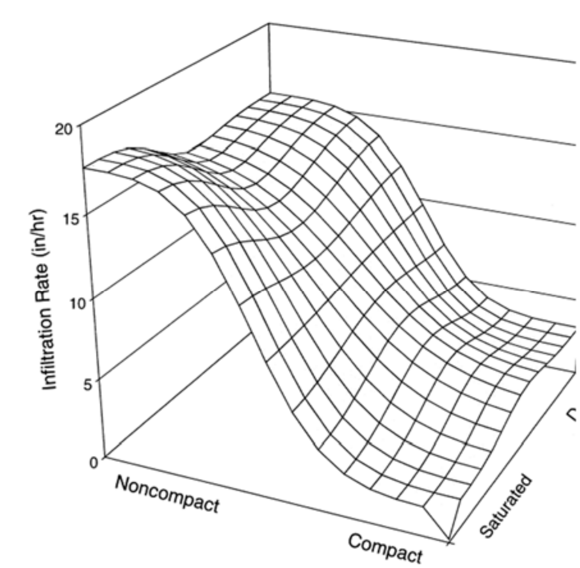


Figure 2. Three dimensional plot of infiltration rates for sandy soil conditions.

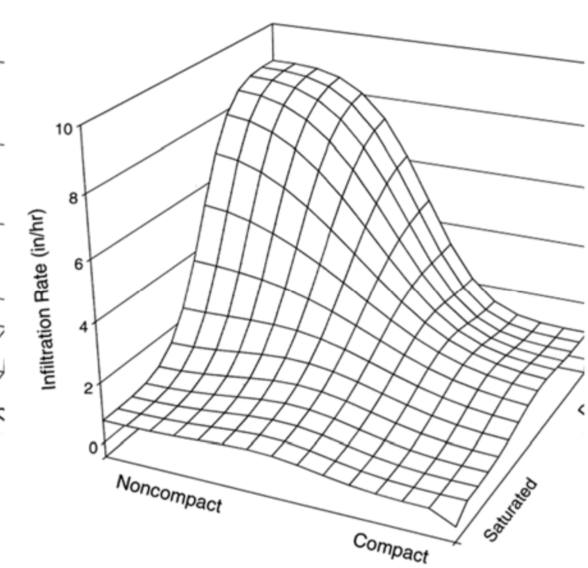


Figure 3. Three dimensional plot of infiltration rates for clayey soil conditions.

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.

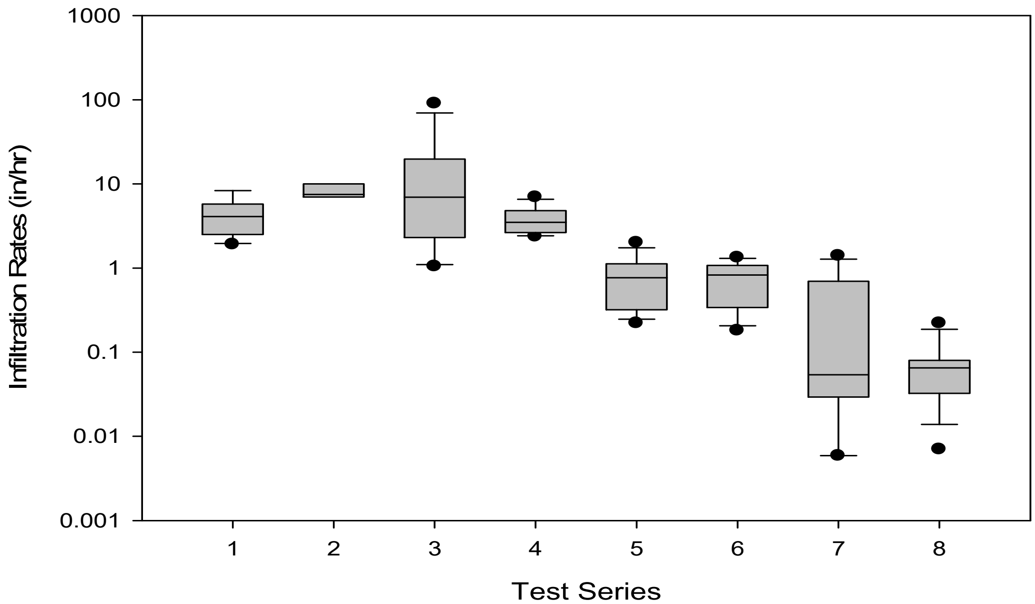


Figure 5. Box and whisker plots comparing saturated soil infiltration rates (in/hr). Test series descriptions (12 replicates in each test series except for the borehole tests which only included 3 observations):

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

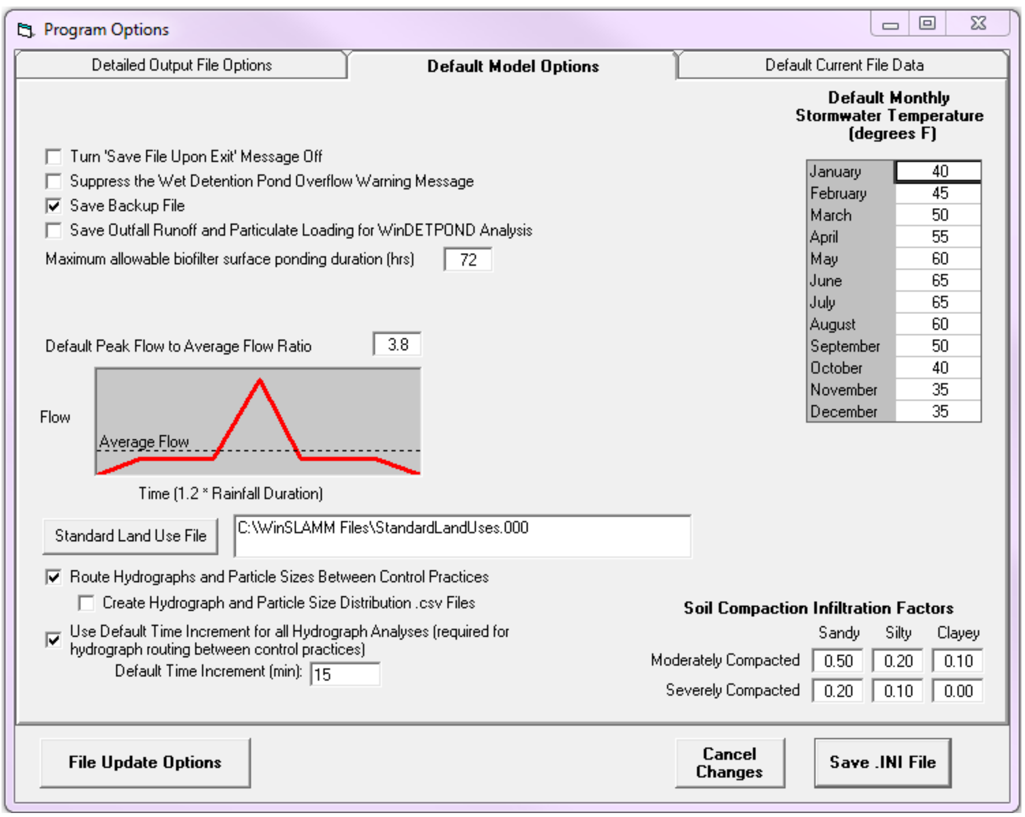


Figure 6 – WinSLAMM Program Options Window for Soil Compaction Infiltration Factors

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), and is used to calculate the filtering properties of the swale system. 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 also 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.

   The swale system properties.

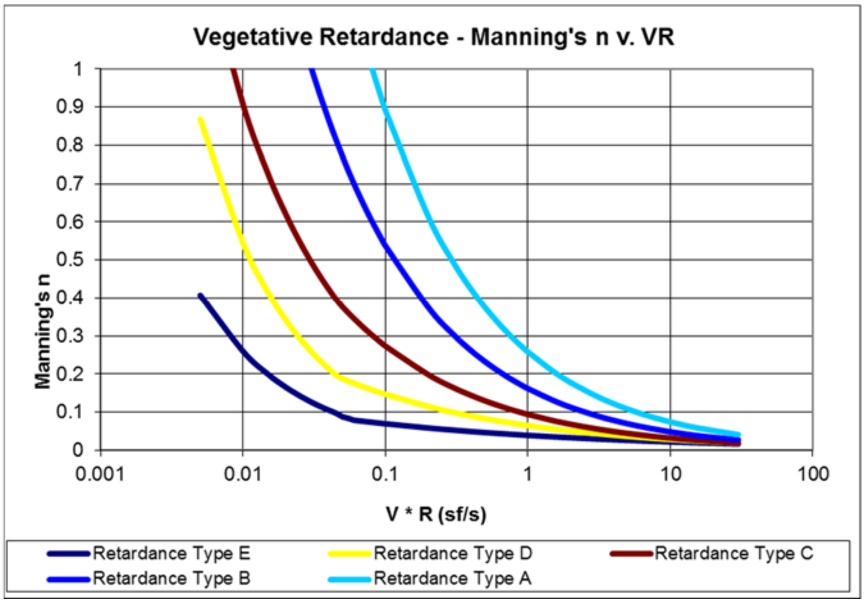
   a. For Infiltration: The entire swale length, as represented by the product of the swale density (ft of swale per acre of study area), times the area served by the swales, times the wetted perimeter, is used in the infiltration calculation.
   b. For Particulate Trapping: The average grass swale length 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

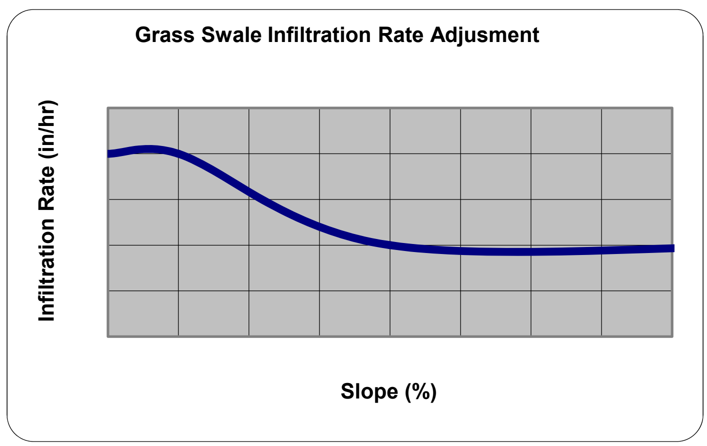
2. **Swale Hydraulic Properties**. After the swale length is determined, the program will calculate the incremental flow rate for each time steps. The flow in the swale system at each time step is half the flow from the time step, assumed to be the average flow. This is an iterative process, where the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

   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.

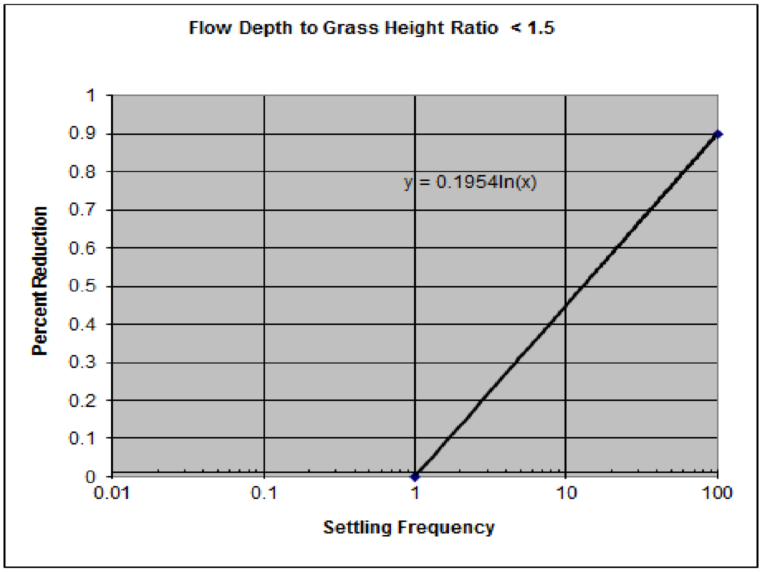
3. **Swale Filtering Process**. After determining the flow properties of the swale for each time step -



   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

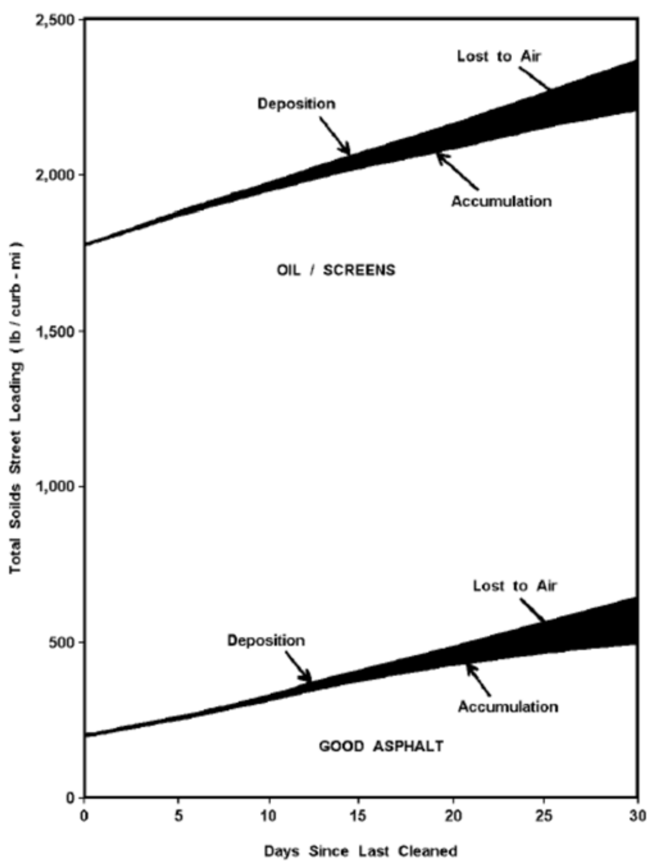
h. Sum the concentration values for each particle size group to determine the final concentration in the effluent discharged from the swale system.

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

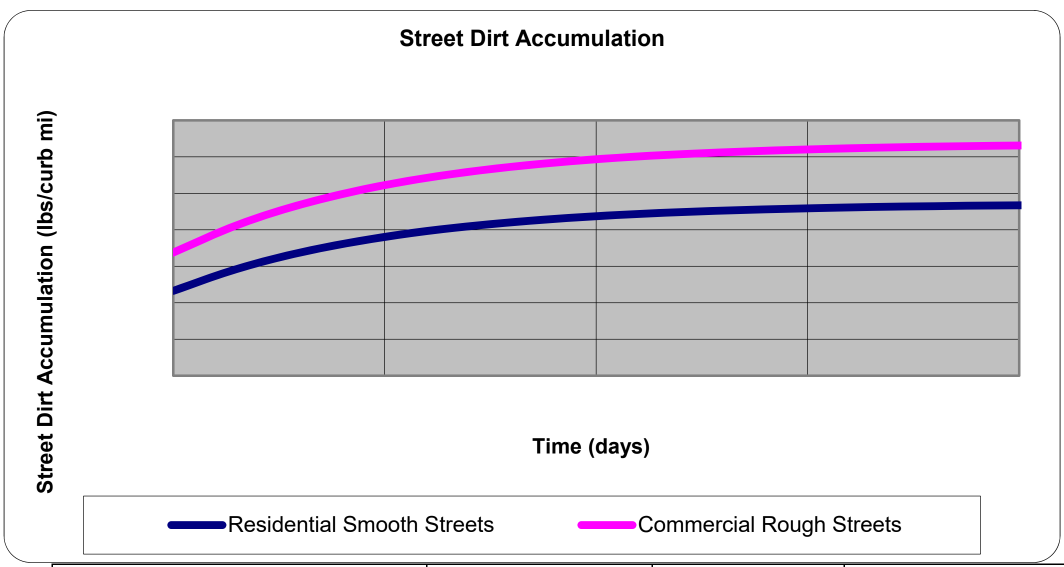
The following equation is used in WinSLAMM to calculate the street dirt load at any time.

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

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	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	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:

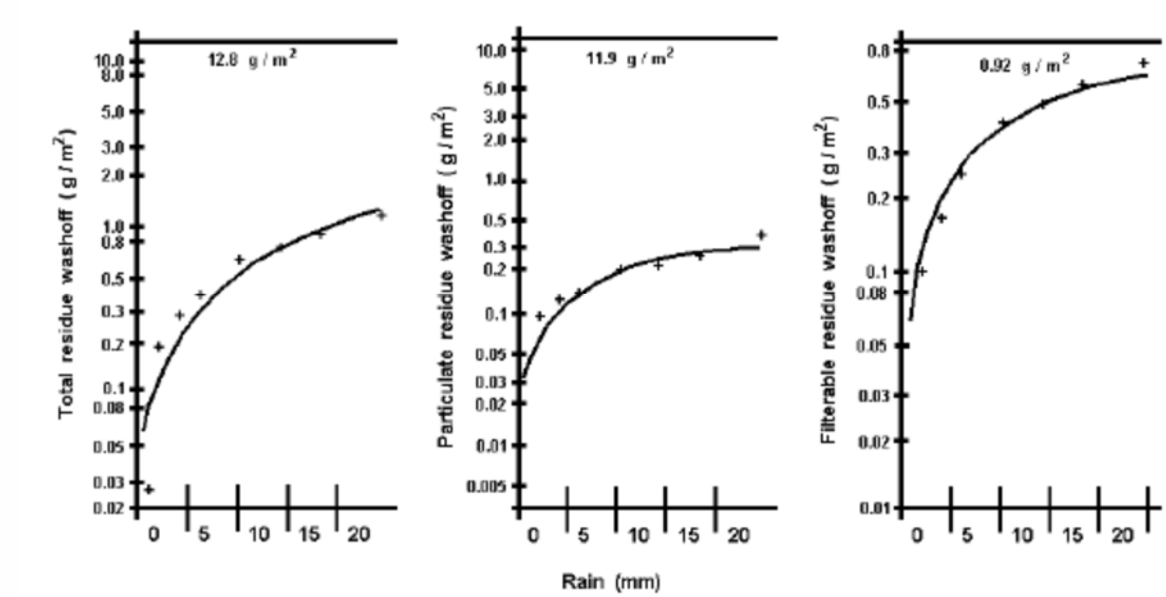
N = residual street dirt load (after the rain)
N_o = initial street dirt load
t = rain duration

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.

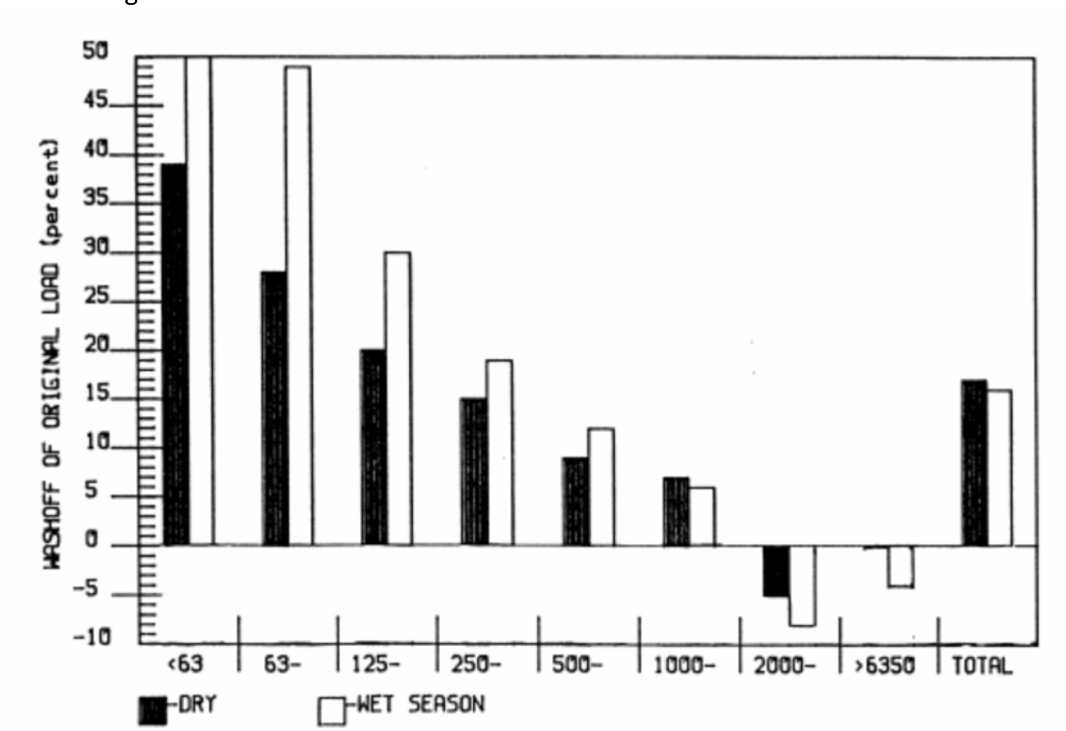
The following washoff plots are from field research conducted by Pitt (1987) and shows the accumulative washoff as a function of rain depth for particulates <0.45 µm (TDS), >0.45 µm (SS) and for total solids. The maximum washoff for the SS data is about 0.3 g/m^2, while the total loading on the street 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.



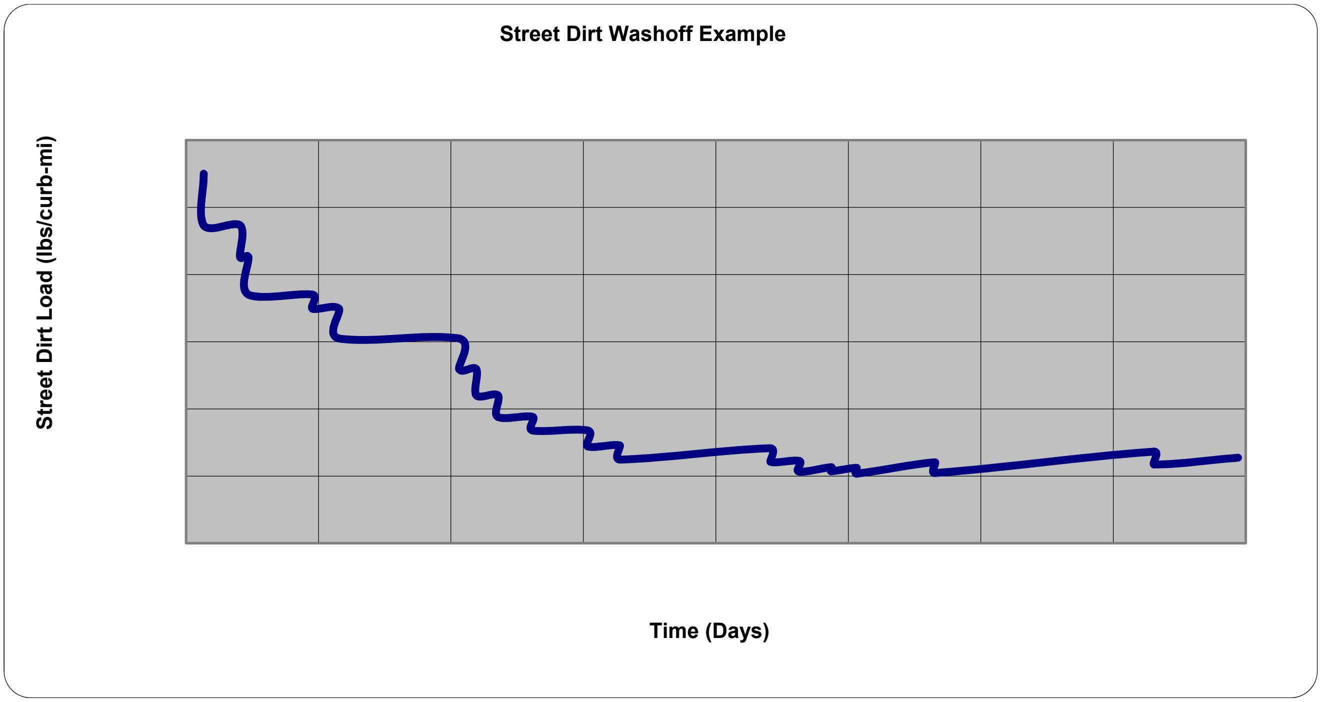
Washoff plots for HDR test (high rain intensity, dirty, and rough street) (Pitt 1987).

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

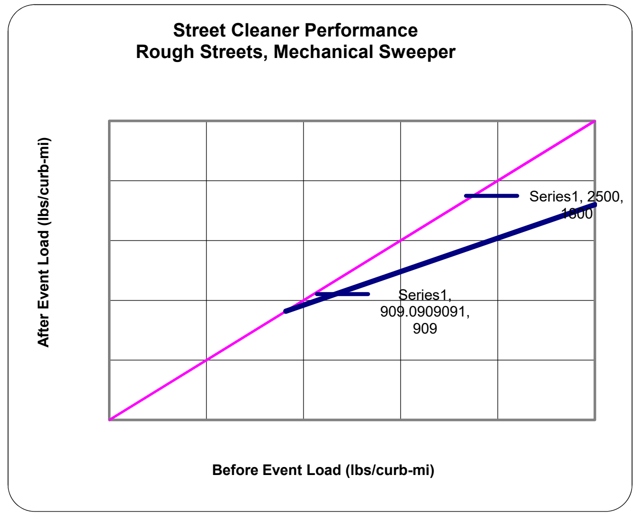
The street cleaning equation is a linear function with a slope and a constant term. Both terms are a function of the type of cleaning equipment (mechanical broom or vacuum assisted cleaner), the street texture, the parking density and whether or not parking controls are imposed. The slope must be less 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:

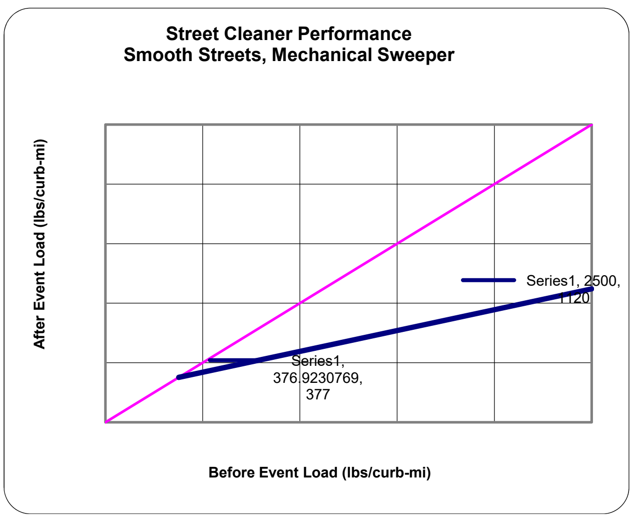
AfterEventLoad = M * BeforeEventLoad + B

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 for the Paved Lane and Shoulder source area in the Freeway land use 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.

Biofilter and Bioinfiltration Runoff Reduction and Pollutant Capturing 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 from standing water and evapotranspiration through drying soils in the vegetated root zone,
- surface discharges through overflows (through standpipes or weirs),
- subsurface discharges after media treatment through underdrains that discharge to surface flows.

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
- Infiltration Pits
- Rock-filled Trenches
- Percolation Ponds
- Perforated Pipes
- Bottomless Inlets

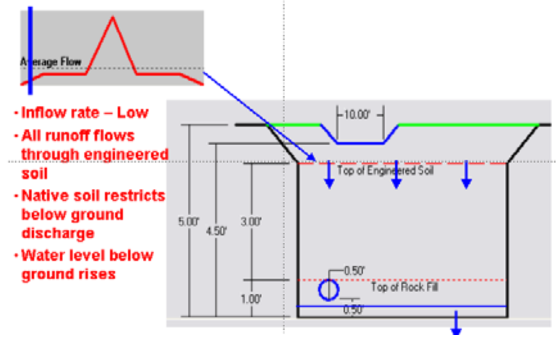
Biofiltration controls are usually numerous in an area and can be represented in the model individually or in multiples by specifying how many of each unit is treating the flow from an individual or combination of source areas. The structure of these calculations and the data included in WinSLAMM are based on many research studies that are summarized in the associated documentation report by Pitt, et al, 2022.

Hydraulic Algorithm

The device hydraulic operation is modeled using the standard Modified Puls Storage-Indication method, and is analyzed differently depending upon the use of rock and/or engineered soil (treatment media) layers. The complex triangular inflow hydrograph is divided into time steps that are routed to the surface of the biofilter. The time step can be selected by the user; the default value is six minutes. 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 the different flow phases for a biofilter having a surface water storage layer, an engineered soil/media and gravel storage, an underdrain discharging to the surface drainage system, and infiltration into the underlying soil.

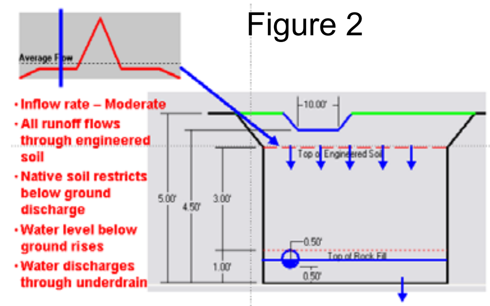
As water enters the device, all flow is routed from the surface to the below ground section of the device. This continues to occur as long as the sum of the engineered soil infiltration rate and the orifice/underdrain discharge rate for the biofilter area is greater than the water inflow rate, and if the antecedent moisture conditions allow for infiltration (not saturated). 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%) removed from any surface discharges. See Figure 1.

Figure 1



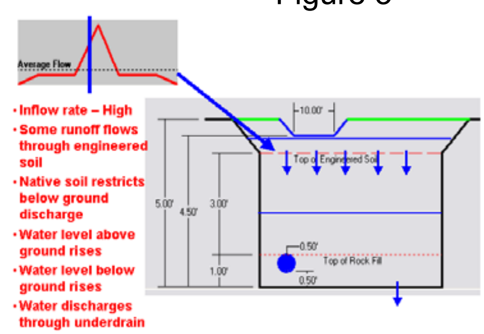
As the inflow rate increases, the below ground water level increases to the point where water begins to flow out the underdrain (if used). At this point all runoff is treated by the engineered soil. But since some runoff flows through the orifice/underdrain, some treated runoff is discharged through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

Figure 2



The above ground storage begins to fill 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/underdrain plus the infiltration into the native soil. Some treated runoff is discharged through the orifice/underdrain back to the surface drainage system. (Figure 3)

Figure 3



In Figure 4, the above ground storage exceeds the elevation of the overflow weir, which bypasses untreated water from the treatment device and is discharged back to the surface drainage 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 underdrain plus the infiltration into the native soil. Some treated runoff is also discharged from the system through the underdrain back to the surface drainage 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.

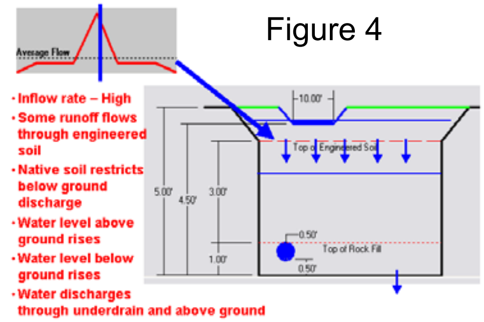


Figure 4

As the inflow rate decreases, the surface water level also decreases. No more untreated water is bypassed, but treated water, which flowed through the engineered soil, is still discharged through the orifice/underdrain back to the surface drainage system. (Figure 5)

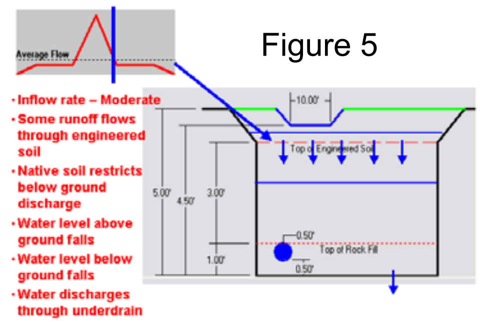


Figure 5

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

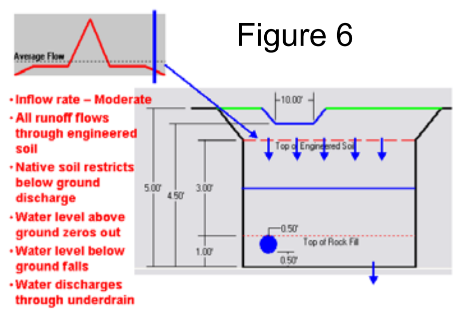


Figure 6

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

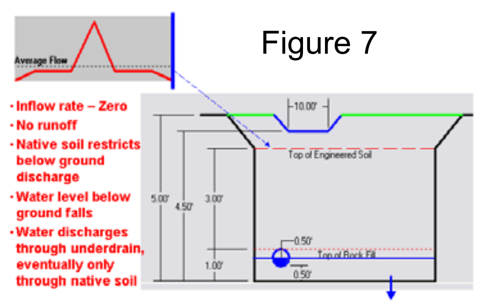


Figure 7

If there are no rock and engineered soil layers, such as in most rain gardens, then:

- infiltration into the native soil is considered to be an outflow pathway along with surface overflows to bypass water during periods of high inflowing water rates,
- there is no below ground section (no media, engineered soil, or rock storage layers), and
- all runoff treatment by the device is assumed to be through runoff volume loss by infiltration into the native soil.

Pollutant Removal

Biofilter pollutant removal performance is calculated considering the:

- stormwater flow rate entering the device and the water mass balance as described above for the various flow phases,
- the infiltration rate into the native soil,
- the amount of rock fill storage,
- the size of the device,
- the outlet structures for the device,
- the particulate filtering capacity and infiltration rate of the engineered media fill
- filterable pollutant sorption and ion exchange capture by the media, and
- treatment media clogging.

Media sorption capacity and contact time considerations will be incorporated in the model in the future.

Particulate filtering by the engineered media mixture containing different types of amendments is based upon the engineered media type and the particle size distribution of the particulates in the inflowing water. The user can also directly enter the percent reduction due to filtering that is allowed by a regulatory agency. The options and features available for calculating biofilter pollutant and runoff volume reductions include:

1. If required or allowed by a regulatory agency, entering a specific percent reduction for TSS. This option allows users to enter a percent reduction for TSS on the main Biofilter data entry form, which forces WinSLAMM to reduce the particulate solids concentration of the runoff flowing through the media by the user-defined percent reduction value, bypassing the WinSLAMM particulate removal calculations. 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 TSS reduction for that event would be 37.5%. Note that surface bypass discharges will not be treated. WinSLAMM will determine the appropriate media clogging rate to apply to the model run by matching the media infiltration rate with the closest soil infiltration rate and using that soil type to determine the clogging rate.
2. Calculating the TSS and other pollutant capture rates and determining the media clogging times by using the properties of the selected soils, amendments or media mixtures shown on the Media Data Table. This feature is only available if the biofilter is modeled with a second cell below the surface storage volume that contains media specified by the user.

3. Determining if the clogging rate is low enough for the biofilter infiltration rate to stabilize so long as the biofilter is vegetated. Sediment entering the biofilter over time will eventually clog the media unless vegetation, which assists in breaking up the clogging layers, is present in the biofilter and the rate of sediment entering the biofilter is low enough to not exceed one-tenth the maximum accumulation of sediment before a media will clog over one year. The accumulation rate for each media type is listed in Master Table 2, R. Pitt, et al, 2022.
4. Creating user-defined media amendments such as for a specific type of biochar or a proprietary phosphorus removal amendment using the same information and equation formats as those applied in WinSLAMM using the properties of the Media Data Table soils, amendments or media mixtures to determine TSS and other pollutant treatment rates and to determine media clogging times. This information is applied to WinSLAMM through a Biofilter User-Defined Media file that is described in the Help File topic 'Biofilter User Defined Media Amendment'.
5. Analyzing a biofilter with no added treatment media, such as for most rain gardens. The particulate solids reduction is calculated using the volume of runoff that infiltrates into the native soil. As an example, if for a given event, 40% of the runoff is infiltrated into the native soil, then there will be a 40% reduction in runoff volume, particulate solids, and pollutants discharged to the surface drainage system.

Biofilter with Engineered Media. Particulate solids (and associated particulate-bound pollutants) are removed based upon the TSS particle size removal equations, and the filterable pollutant removals are a function of the influent filterable pollutant concentrations and influent vs effluent relationships, as described in Attachment 1 and in more detail in R. Pitt, et al, 2022. Attachment 1 is a summary table listing pollutant removal equation tables in R. Pitt, et al, 2022 for the standard WinSLAMM pollutant. T10 is an abbreviation for Table 10 in that document.

TSS removal through biofilter media is a function of influent particle size and media type. Table 10 in R. Pitt, et al, 2022, shown below as Table 1 in this document, is used to determine the effluent TSS concentration for each of the seven ranges of influent particle sizes on the table. Due to the variation in the effluent concentration data by particle size, if an effluent concentration for a particle size range is greater than the calculated influent concentration for that range, the effluent concentration is set equal to the influent concentration, except for the smallest particle sizes where media washout of fines is common and can add fine particles to the treated runoff. Tables 10 to 12 in R. Pitt, et al, 2022 are used in WinSLAMM to calculate TSS and SSC removals for soils ranging from clays to gravel and Tables 13 to 23 in R. Pitt, et al, 2022 describe TSS and SSC removal equations through other media.

Table 1 - TSS Removal Table 10 from R. Pitt, et al, 2022

Table 10. Low to High Particulate Concentrations (100 to 800 SSC mg/L), fine media (about 300 um) (data from Sileshi 2013)

>1000 um	300 to 1000 um	100 to 300 um	30 to 100 um	10 to 30 um	3 to 10 um	1 to 3 um	total
no significant regression	no significant regression	no significant regression	significant intercept	significant intercept	significant intercept	no likely removal	significant intercept
Mean effluent = 0	Mean effluent = 0	Mean effluent = 0.06	mean effluent = 0.30	Mean effluent = 1.55	Mean effluent = 2.43		Mean effluent = 4.5
COV n/a	COV n/a	COV = 1.33	COV = 0.5	COV = 0.66	COV = 0.3		COV = 0.39

The fractional removal rate for each particle size range is applied to the influent concentration, for each event. For example, 22% of the particles in the NURP.CPZ particle size distribution fall within the range of 10 to 30 microns. If the engineered soil media was sand and loam, then the effluent concentration of twenty-two percent of the influent concentration for each event would be 1.55 mg/L for that particle size range. The coefficient of variation (COV) value can be used to introduce typical variability in the effluent concentrations if the Monte Carlo option is selected. The effluent concentration for this example 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.

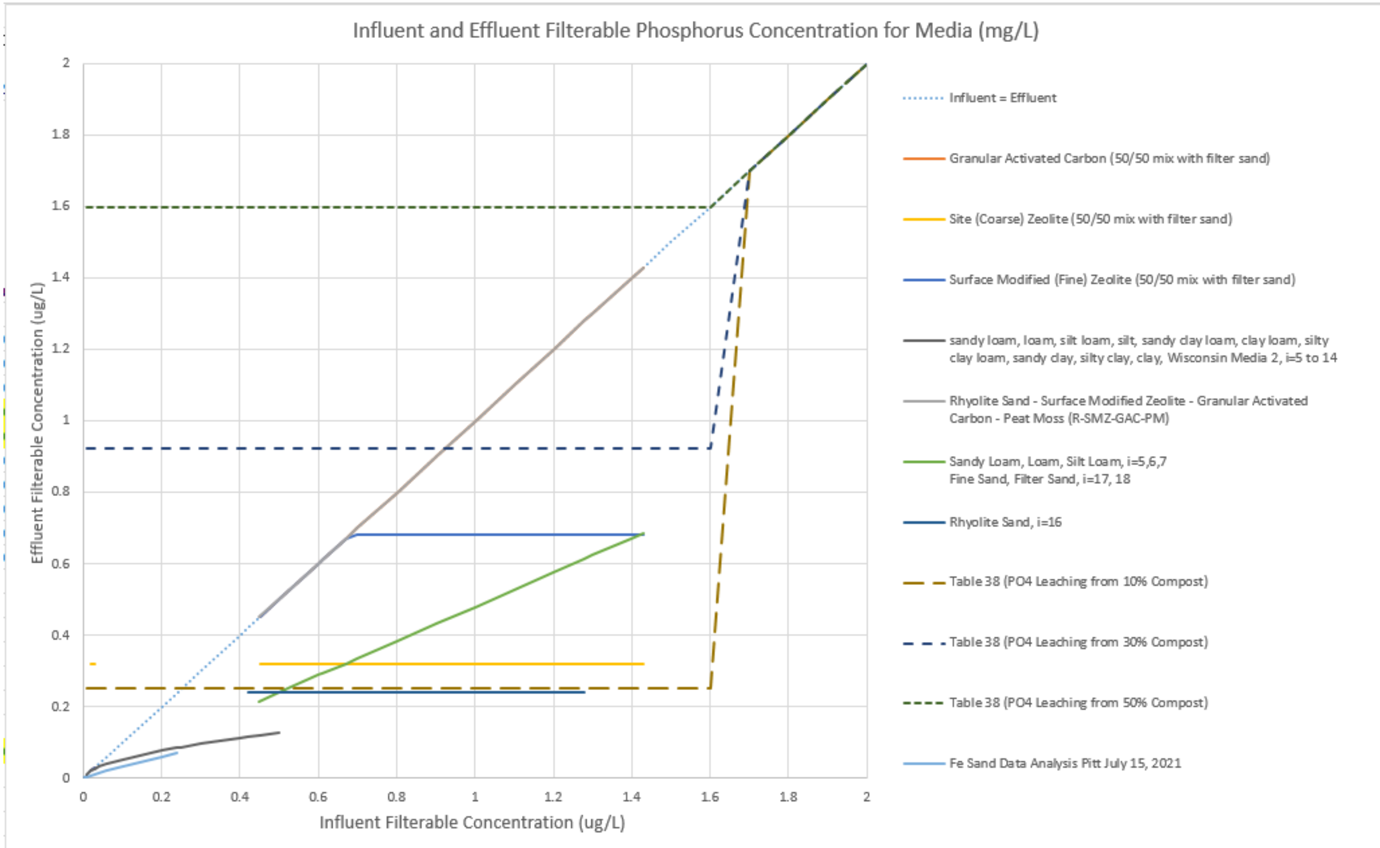
The removal of other filterable pollutants through the biofilter media is described in R. Pitt, et al, 2022 Tables 28 to 37. The complete pollutant table reference is in Table 2 at the end of this section. There is a filterable pollutant removal table in the report for each media included in WinSLAMM, as noted below.

Table 25 - SSFL granular activated carbon (GAC)
Table 26 - SSFL peat moss (PM)
Table 27 - SSFL Rhyolite sand (R-sand)
Table 28 - SSFL site sand
Table 29 - SSFL site zeolite
Table 30 - SSFL surface modified zeolite (SMZ)
Table 31 - SSFL R-SMZ
Table 32 - SSFL R-SMZ-GAC
Table 33 - SSFL R-SMZ-GAC-PM
Table 34 - Clark dissertation bacteria removal for all soils, compost-sand, peat-sand and other sand-based media
Table 35 - Clark dissertation for laboratory scale pollutant removals
Table 36 - Millburn NJ
Table 37 - Neenah media and Kansas City media

The tables include removal equations or effluent concentrations for some of the standard WinSLAMM pollutants (highlighted in yellow on the tables) as well as other pollutants, depending upon the available monitoring data. They also include the observed influent concentration data range of the data used to develop the equations. WinSLAMM tabulates the number of model run events with influent concentrations outside of the data range listed in the table. The tabulations are listed in the Biofilter Constants detailed output table available to users by selecting the biofilter Water Balance detailed file output option from the Program Options menu.

The equation for the removal of filterable Phosphorus through the use of iron-enhanced sand is documented in R. Pitt, "Univ. of Minnesota Iron Enhanced Sand Filters for the Removal of Filtered Phosphorus from Stormwater". The phosphorus removal equation was developed from extensive field monitoring data provided by the University of Minnesota's Saint Anthony Falls Laboratory.

Peat and compost provide significant pollutant removal benefits. However, compost can also leach phosphorus during stormwater events. The chart below illustrates the Influent and Effluent Filterable Phosphorus Concentrations for various media from the data analysis for each media. Note that the media with compost shows that phosphorus leaching occurs even with relatively small amounts (10%) of compost in the media mixture. These increased phosphorus concentrations are assigned to the treated effluent and are not reduced if greater than the influent concentrations.



Clogging. Clogging occurs when an excessive amount of particulates (sediment) become trapped within the media. The sediment accumulation rate is calculated based on the cumulative sediment captured by the media (influent concentration minus effluent concentration times the treated runoff (runoff flowing through the media) volume, for each event. If the media is vegetated (as in a biofilter), the plant roots assist in disturbing the sediment by providing micro-flow channels in the media and also help break up surface sediment layers. Therefore, planted biofilters can have a longer useful life compared to unplanted devices. If no plants are in the device, if the inflowing stormwater has unusually large sediment concentrations or if the device is small relative to the tributary drainage area, WinSLAMM assumes that the biofilter will fail through clogging and calculates the time until the failure of the device.

If the user elects to apply the User-Defined option to enter a user-defined percent TSS reduction for all treated runoff, WinSLAMM will determine the assumed soil type by matching the soil infiltration rate defined by the user with the standard soil infiltration rates listed in the media table. The program will use the standard clogging rate for that assumed soil type. WinSLAMM will then calculate the treated mass retained in the media by multiplying the influent concentration with the treated runoff volume and compare that retained mass with the assumed soil type clogging rate to determine the clogging load and time to failure. Note that this is a conservative calculation that will not vary regardless of the user-entered percent TSS reduction value because the clogging mass is determined from the influent concentration only, not the difference between the media influent and effluent concentrations as noted in the previous paragraph. This constant clogging load regardless of the value of the percent TSS reduction is an obvious incongruity that is necessary to determine clogging loads for user-defined TSS reductions. The alternative would be to calculate clogging loads based upon the percent reduction value, but this would make no sense because, for example, the extreme condition of 0% TSS reduction would provide no clogging, which physically is not at all likely to occur.

Outlet Devices. Table 2 below lists, for each biofilter configuration, which biofilter outlet devices are available and used to control the device hydraulics and water mass balance calculations. There are either one or two cells for any biofilter configuration. The above ground cell is where water initially enters the biofilter, and is the storage space above the ground surface/engineered soil (treatment media). If there is no engineered media or rock fill, then there is only the one cell, which is the above ground cell. If there is engineered media and/or rock fill, then the second cell is the below ground cell containing the engineered media 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 besides the native soil infiltration.

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 (only if planted)	Native Soil Infiltration
1 - No Fill	Above Ground	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2 - Rock Fill	Above Ground	Yes	Yes	Yes	Yes	Yes	No	No
	Below Ground	No	No	Yes	No	No	No	Yes
3 - Engineered Soil Fill	Above Ground	Yes	Yes	Yes	Yes	Yes	No	No
	Below Ground	No	No	Yes	No	No	Yes	Yes
4 - Rock and Engineered Soil Fill	Above Ground	Yes	Yes	Yes	Yes	Yes	No	No
	Below Ground	No	No	Yes	No	No	Yes	Yes

Output Options

There are eleven different output options available to view the performance details of the biofilter. These are selected from the Detailed Output File Options tab in the “Tools/Program Options” drop down menu on the main WinSLAMM screen. The output summary, which appears after an individual model run, will display the biofilter’s summary performance for the entire modeled system. The detailed output file options include:

1. Event and Summary Files selected using the Water Balance checkbox –
    - Biofilter Constants (File 90)
    - Event Water Balance Summary (File 91)
    - Event Performance Summary (File 92)
2. Stochastic Seepage Rate Detail File (File 93)
3. Particulate Reduction Output File (File 94)
4. Evapotranspiration Detail (File 95)
5. Stage-Elevation Files selected using the Stage-Outflow checkbox –
    - Stage-Outflow (File 96
    - Stage-Volume (File 97)

6. Time Step Detail (File 98)
7. TSS Concentration Detail (File 99)
8. Media Pollutant Detail (File 201)

The description of each of these files can be found in the Help File with the WinSLAMM program. All files are comma-separated-value files.

References

R. Pitt, J. Voorhees, S. Clark, R. Sileshi, "Biofilter Media Performance Updates for WinSLAMM", White paper summarizing biofilter data and analyses used in WinSLAMM. Posted on WinSLAMM website (http://www.winslamm.com/Select_documentation.html), April 2022.

R. Pitt, "Univ. of Minnesota Iron Enhanced Sand Filters for the Removal of Filtered Phosphorus from Stormwater", Posted on WinSLAMM website (http://www.winslamm.com/Select_documentation.html). 6 Sept 2021

Table 2 - Table References to Pollutants Analyzed in R. Pitt, J. Voorhees, S. Clark, R. Sileshi, "Biofilter Media Performance Updates for WinSLAMM"

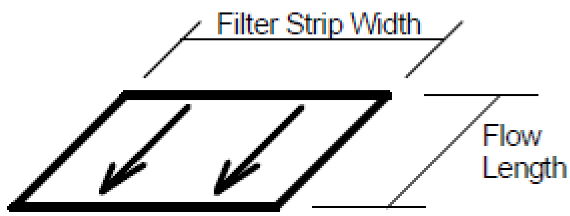
		Soil												Other Media						Chemically active amendments					Pre-defined media mixtures				Biofilter media mixtures		
Media Type Index No ==>		3	4	5	6	7	8	9	10	11	12	13	14	16	17	18	19	20	21	23	24	25	26	27	32	33	34	35	38	40	41
Index	Pollutant	Well graded sand	loamy sand	sandy loam	loam	silt loam	silt	sandy clay loam	clay loam	silty clay loam	sandy clay	silty clay	clay	fine Rhyolite sand	fine sand	filter sand	coarse sand	gravel	light media for green roofs	activated carbon	fine zeolite (SMZ)	coarse zeolite	compost	peat moss	Rhyolite sand - SMZ	Rhyolite Sand - SMZ - GAC	Rhyolite Sand - SMZ - GAC - PM	Iron fillings (5%) / sand	Kansas City	Wisconsin 2	North Carolina
	Total Suspended Solids (TSS)	T10 (2)	T10	T10	T10	T10	T10	T10	T10	T10	T10	T10	T10	T15	T10	T11	T11	T12	T12	T13	T18	T17	T14	T14	T19	T20	T21	T10	T22	T23	T23
2	Total Dissolved Solids (TDS)																												T37	T37	T37
5	Filtered Phosphorus	T34	T34	T37	T37	T37	T37	T37	T37	T37	T37	T37	T37	T27	T28	T28	T36			T25	T30	T29	T38				T33	FeRpt (1)	T38	T37	T37
8	Nitrate + Nitrite	T36	T36				T37	T37	T37	T37	T37	T37	T37				T36			T25						T32			T38	T38	T38
11	Filtered TKN	T36	T36														T36														
14	COD	T36	T36														T36														
17	Fecal Coliforms	T34	T34	T28	T28	T28	T37	T37	T37	T37	T37	T37	T37	T27	T28	T28					T34	T34	T34	T34				T28	T37	T37	T37
20	Chromium (Cr)																			T25	T30	T29	T26	T26	T31	T32	T33				
23	Copper (Cu)	T36	T36				T37	T37	T37	T37	T37	T37	T37				T36			T25		T29	T26	T26		T32	T33		T26	T37	T37
26	Lead (Pb)	T36	T36														T36														
29	Zinc (Zn)	T36	T36				T37	T37	T37	T37	T37	T37	T37				T36												T37	T37	T37

(1) Fe Sand Data Analysis Pitt September 6 2021.docx
(2) T## references the pollutant tables found in R. Pitt, J. Voorhees, S. Clark, R. Sileshi, "Biofilter Media Performance Updates for WinSLAMM"

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. The user must supply this by describing an appropriate length using engineering judgment.

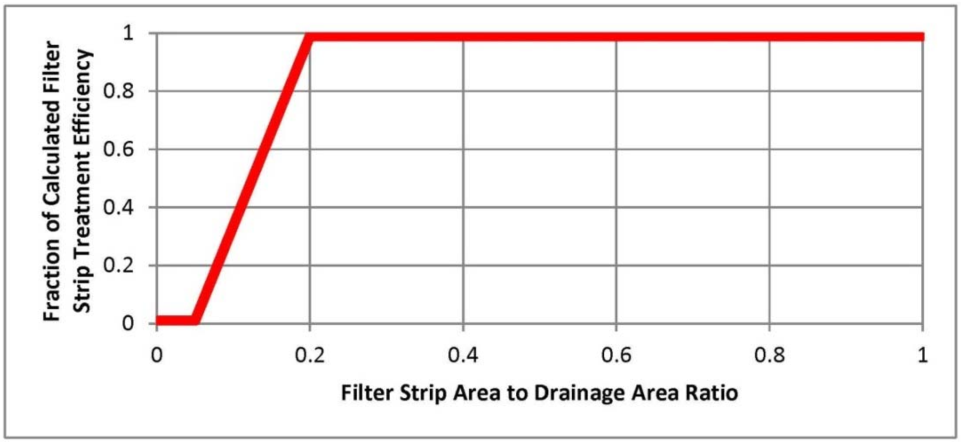


In order to calculate the infiltration and settling characteristics of the filter strip, the water flow rate and the water depth need to be determined for each calculation time step and each distance increment across the filter strip. The flow and the filter strip geometry are used to determine Mannings 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:

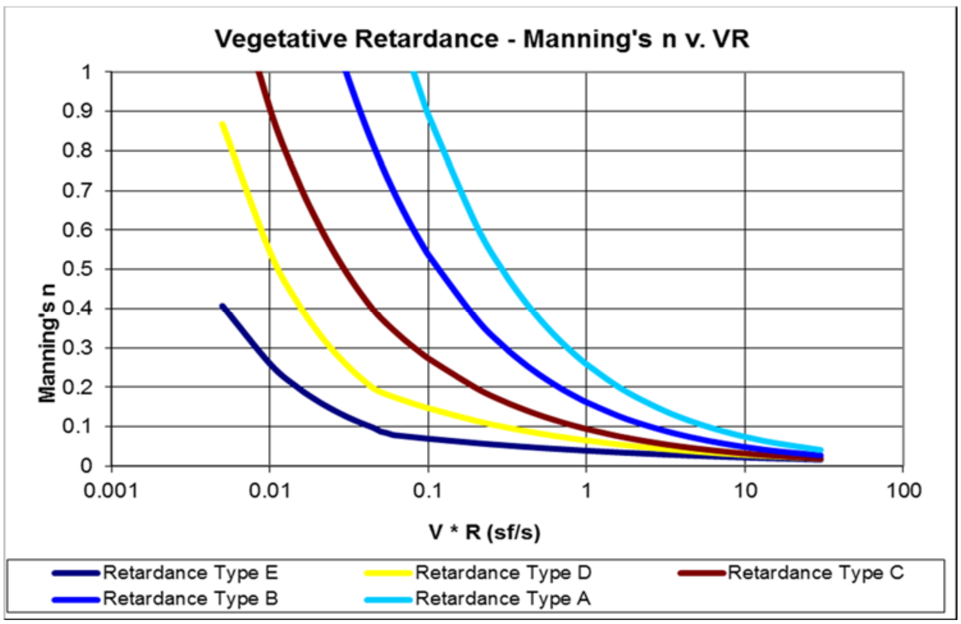
1. **Filter Strip Infiltration Properties**.
   a. The entire filter strip area, as represented by the sums of the products of each incremental flow distance times the filter strip width, is used to infiltrate runoff.
   b. The infiltration rate is reduced over time depending upon the amount of clogging 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)

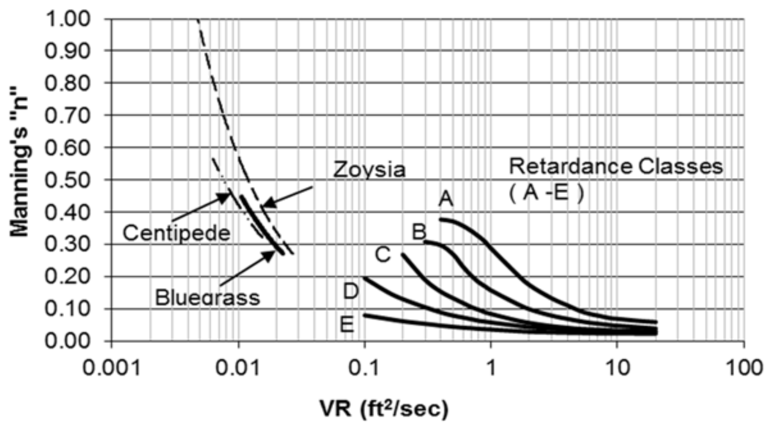
   d. The effective treatment length of the filter strip is reduced based the following criteria:

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

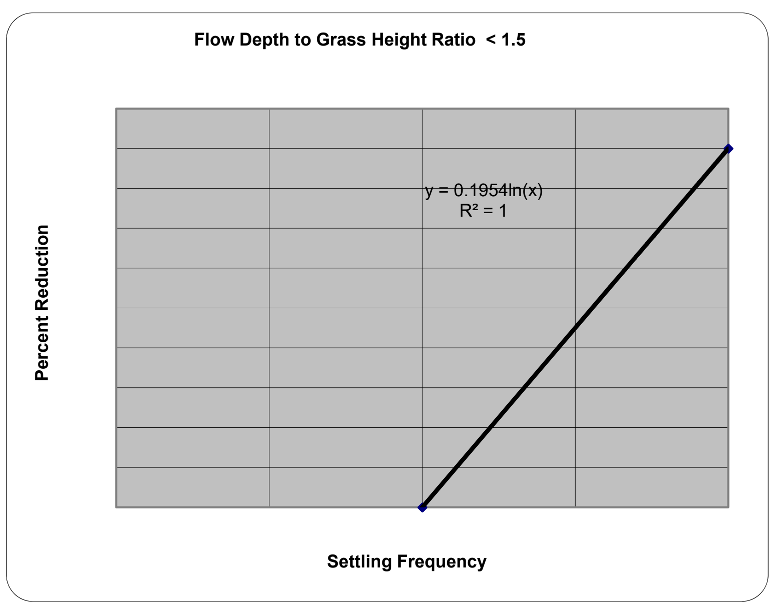
2. **Filter Strip Hydraulic Properties**. After the filter strip length is adjusted, depending upon the slope, the program calculates the incremental flow rate for each time step using the model default time increment set by the user. Using this flow rate, the program will calculate the depth of flow 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.

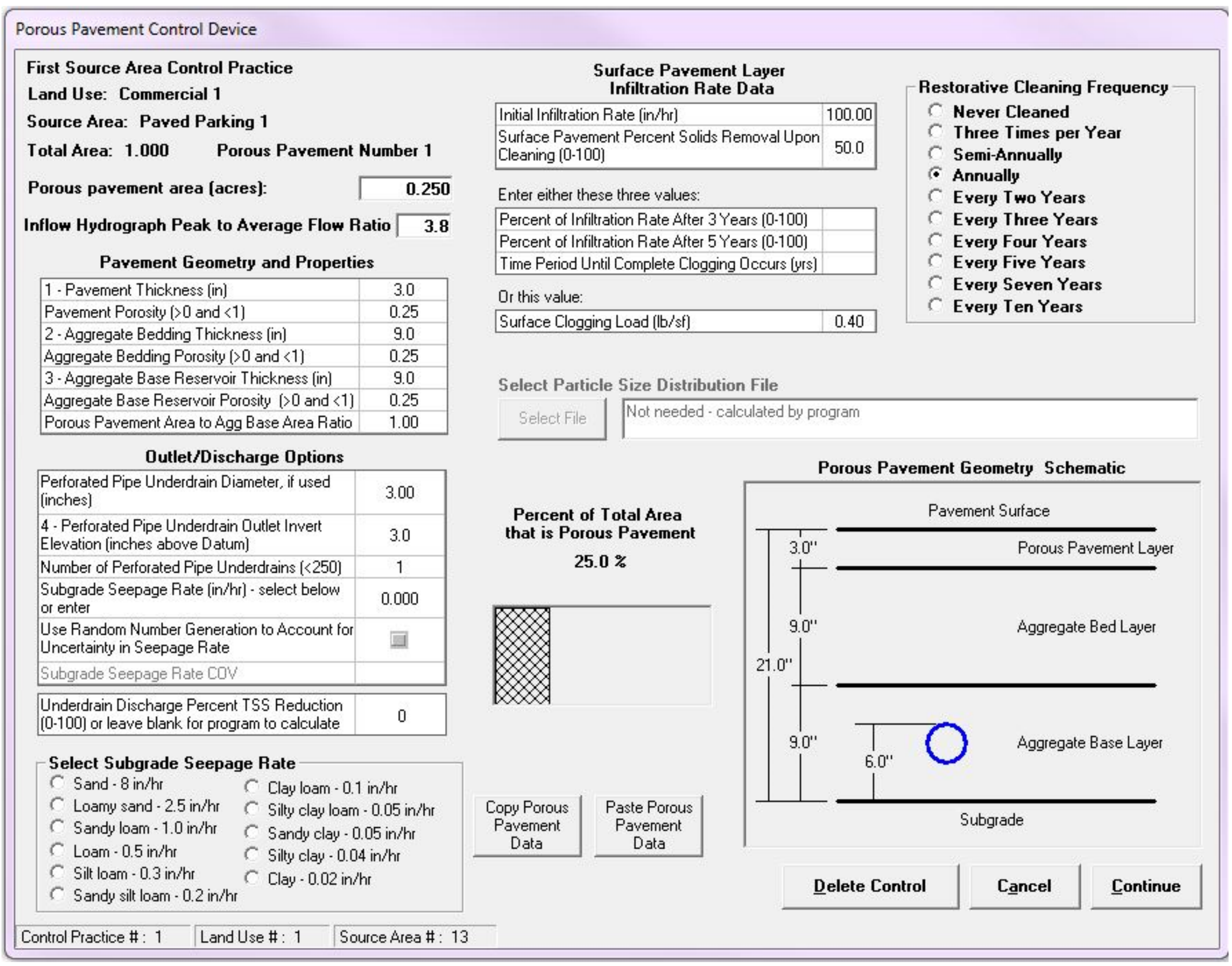
h. Adjust the final effluent concentration based upon the total suspended solids removal efficiency ratio. This ratio will prevent the program from reducing the effluent concentration if the filter strip area to drainage area ratio is small.

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, which is termed a surface overflow bypass.

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.

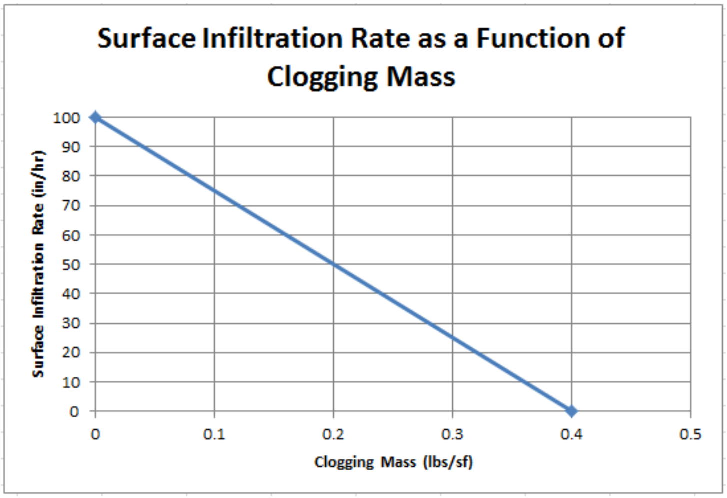
<u>Pollutant removal through surface layer filtering.</u>

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.

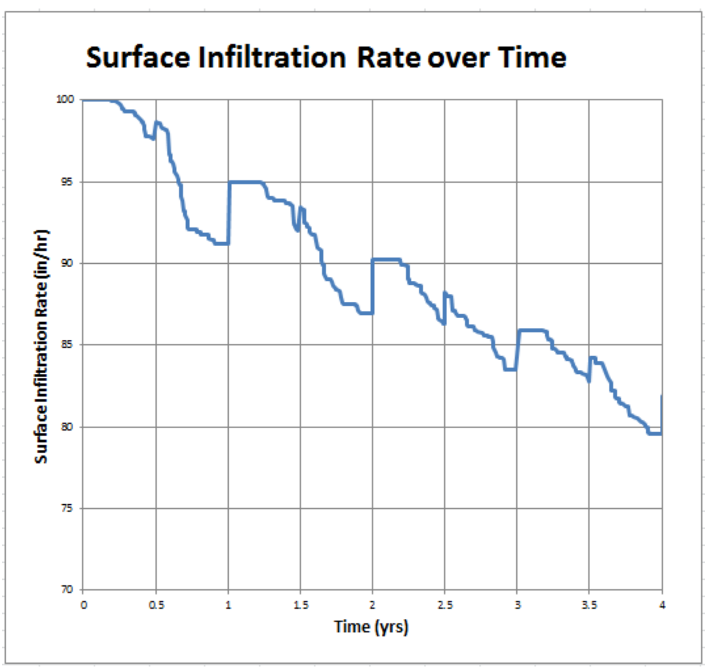


The slope of the line – the surface infiltration rate/clogging mass – is used in the linear equation that adjusts the pavement infiltration rate. This equation, for any rainfall event in the rainfall series, is:

$$\text{Pavement Infiltration Rate}_i = \text{Initial Surface Infiltration Rate} - \text{Initial Surface Infiltration Rate/Clogging Mass} \times \text{Cumulative Clogged Mass}_i$$

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.

User Defined Percent TSS Reduction

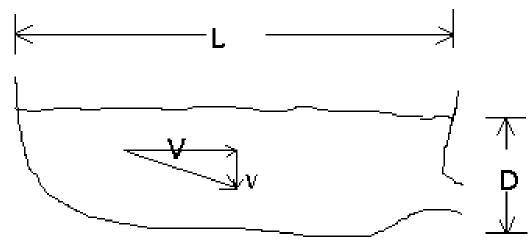
If you enter the "Underdrain discharge percent TSS reduction", which is a value ranging from 0 - 100, then you are setting a discharge concentration reduction for any effluent discharged from the underdrain rather than following the processes described above. However, the final calculated concentration from the drain tile will be less than the fraction reduction applied to the surface influent concentration because the entered value is applied to the effluent concentration from the surface pavement system. As discussed above, the surface pavement layer acts as a filter, which lowers the concentration of the effluent from the surface pavement layer. The percent reduction is applied to this surface layer effluent concentration. The overall effluent concentration could also be increased if there is surface overflow effluent or surface effluent due to clogging. The use of this option should be approved by the appropriate regulatory authority.

Wet Detention Pond Performance

General Description

Wet detention pond performance is calculated by assuming flow through a quiescent settling area. 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 most common for stormwater ponds), or Newton's law (for turbulent flow that may occur for very large particulates). The path of the settling particles is the vector sum of the particle velocity through the pond and the settling velocity of the particle. It is assumed (and verified by field monitoring) that particles settling to the pond bottom before the outlet zone is reached are captured in the pond. Therefore, if the water velocity is slow, slowly falling particles can be retained. If the water velocity is fast, then only the heaviest (fastest falling) particles are likely to be retained. The critical ratio of water velocity to particle settling velocity must therefore be equal to the ratio of the sedimentation pond length (L) to depth to the bottom of the outlet (D), as shown in equation (1) and the illustration below.

(1) $$\frac{V}{\nu} = \frac{L}{D}$$



The water velocity is equal to the water volume discharge rate (Q, such as measured by cubic feet per second) divided by the pond cross-sectional area (a = depth times width: DW, in equation (2):

(2) $$V = \frac{Q}{a}$$ or $$V = \frac{Q_{out}}{DW}$$

The pond outflow rate equals the pond inflow rate under steady state conditions. The critical time period for steady state conditions is the time of travel from the inlet to the outlet. During critical portions of a storm, the inflow rate (Q_{in}) will be greater than the outflow rate (Q_{out}) due to freeboard storage. Therefore, the outflow rate controls the water velocity through the pond. Substituting this definition of water velocity into the critical ratio to results in equation (3):

(3) $$\frac{Q_{out}}{DW\nu} = \frac{L}{D}$$

- L = Pond Length
- D = Outlet Depth
- V = Water Velocity through Pond
- v = Settling Velocity
- Q_{out} = Outflow from Pond
- *a* = Pond Cross Sectional Area

and cancel D to get:

(4) $$\frac{Q_{out}}{W\nu} = L$$ or $$\frac{Q_{out}}{\nu} = LW$$

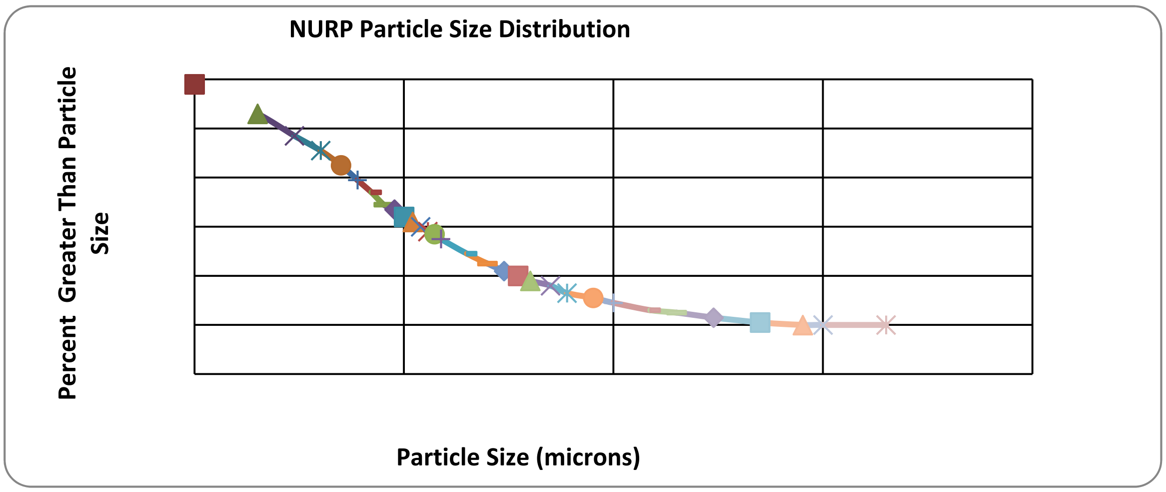
However, pond length (L) times pond width (W) equals pond surface area (A). Substituting leaves:

(5) $$\frac{Q_{out}}{v} = A$$

Solving for the settling velocity results in the conventional surface overflow rate (SOR) equation:

(6) $$v = \frac{Q_{out}}{A}$$

- L = Pond Length
- D = Outlet Depth
- V = Water Velocity through Pond
- v = Settling Velocity
- Q_{out} = Outflow from Pond
- *a* = Pond Cross Sectional Area



Therefore, for an ideal sedimentation pond, particles having settling velocities greater than this settling velocity will be removed. Only increasing the surface area or decreasing the pond outflow rate will increase pond settling efficiency. Increasing the pond depth lessens the possibility of bottom scour, decreases the amount of attached aquatic plants, and decreases the chance of a winter fish kill. Additional depth is also needed to provide sacrificial storage volumes for sediment between pond cleaning operations.

Since the settling velocity increases as particle size increases (using Stokes or Newton's law and appropriate shape factors, specific gravity and viscosity values), the pond water quality performance (or percent removal) is determined from the particle size distribution of the solids in the runoff entering the pond. This is done by determining the settling velocity and then calculating the particle size associated with that settling velocity, which is referred to as the critical particle size. The percent of the particles that will settle is then determined from the particle size distribution of the total suspended solids (TSS) concentration of the sediment in the stormwater runoff. An example particle size distribution is shown below (NURP, National Urban Runoff Program, particle size distribution) which is, used for stormwater runoff evaluations in Wisconsin.

By inspection of this NURP particle size distribution, all particles greater than about two or three microns would need to be trapped to achieve 80% particulate solids control of the stormwater particulates entering a pond.

For wet ponds, for each time step (typically 6 minutes, but the user can change that) the program determines the upflow velocity of the pond, which is a function of the pond area (which varies by stage) and the outflow rate (which also varies by stage). The program then calculates the particle size that would settle, based upon Stokes (or Newton's) Law, for the calculated upflow velocity. It then uses the particle size distribution to map the percent of the particles that are equal to and greater than that calculated particle size to determine the percent removal for that time step. For each storm event, the model calculates the flow weighted percent reduction for each time step to determine the overall percent reduction for that storm event

Calculation Process

The calculation flow chart for wet ponds is illustrated below, where:

V_{inf} = Influent Volume

M_{inf} = Influent Mass

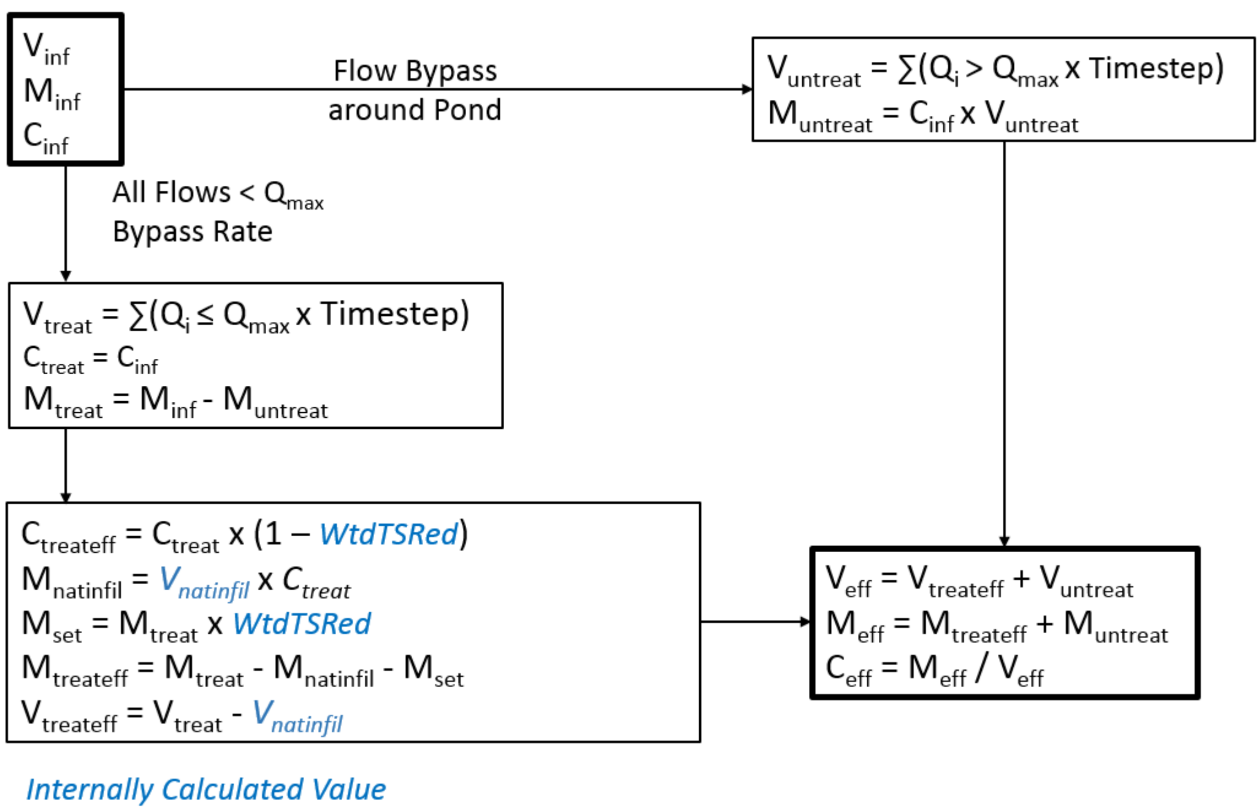
C_{inf} = Influent Concentration

WtdTSRed = Weighted Total Solids Reduction due to Settling

$V_{natinfil}$ = Volume Lost through Natural Infiltration

M_{set} = Mass Settled in Pond

Wet Pond Calculation Flow Chart



Pond Scour

WinSLAMM calculates sediment capture using standard modified Puls reservoir routing and incorporates Stokes (and Newton's) Law settling. This method has been shown to work well for typical wet sediment ponds, as reflected during actual performance monitoring. However, sediment capture assumes that there is at least 3 ft of standing water over the top of the sediment to prevent turbulence-induced scour. For dry detention ponds, monitoring has provided highly variable results, with some events capturing significant amounts of sediment, but other events showing large "negative" sediment capture. Long-term and complete monitoring of dry detention ponds typically results in close to zero sediment capture. The most robust detention pond design for capturing stormwater particulates requires several feet of standing water to minimize scour.

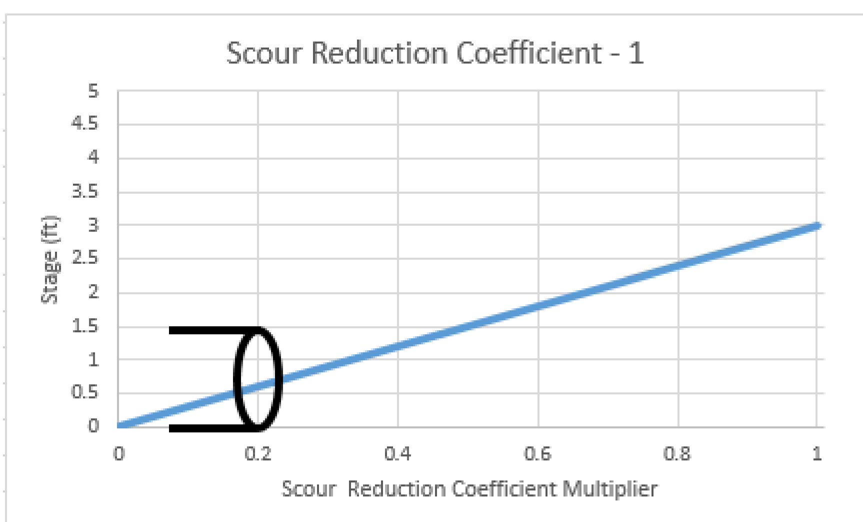
WinSLAMM addresses scour by modifying the sediment deposition rates for any pond volume below the elevation of the lowest outlet invert to the pond or sediment bottom that is less than three feet in depth (storage above scour depth). The deposition rate is not modified if the depth from the top of the sediment to the lowest outlet invert is greater than three feet (storage below scour depth). The scour depth is assumed to be three feet below the invert elevation of the lowest outlet structure. The dead storage volume is the volume of the pond between the lowest outlet invert and the bottom of the pond, or the top of the sediment.

Sediment storage reduction to account for scour, which can also be used to model a dry or extended wet detention pond, uses the Scour Reduction Coefficient Multiplier. The program calculates the Multiplier for each time step; the value is a function of the water surface elevation above the pond bottom and the invert elevation of the lowest outlet of the pond.

The scour reduction coefficient multiplier is a fraction between zero and one that lowers the wet detention pond TSS reduction for any time step when the water surface elevation is less than three feet but above the lowest outlet invert elevation. The three figures below illustrate the value of the multiplier for three different outlet elevation examples. The multiplier is calculated according to the water surface stage elevation for each time step. The product of the multiplier value and the initial calculated percent particulate solids controlled by the pond for that time step is the final percent particulate solids controlled by the pond for the time step. This final value will either be the same (multiplier = 1) or less than the initial value that is calculated assuming no scour losses.

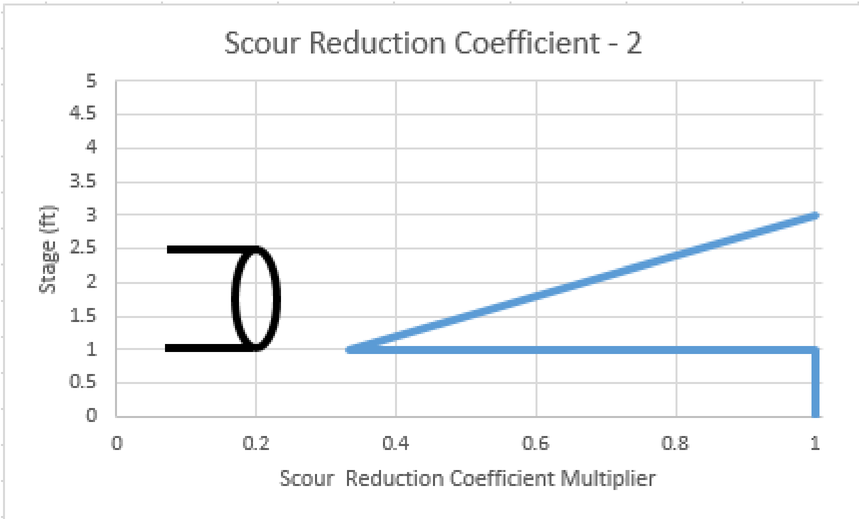
The elevation of the bottom of the pond will increase over time as the pond fills with sediment. This means that the performance of the pond will decrease over time because the multiplier value will decrease as the pond fills with sediment and effectively lowers the outlets.

Scour Reduction Coefficient Example 1. The lowest outlet invert is at the bottom of the pond. The scour reduction coefficient multiplier is determined for each time step, based on the water surface elevation stage in the pond for

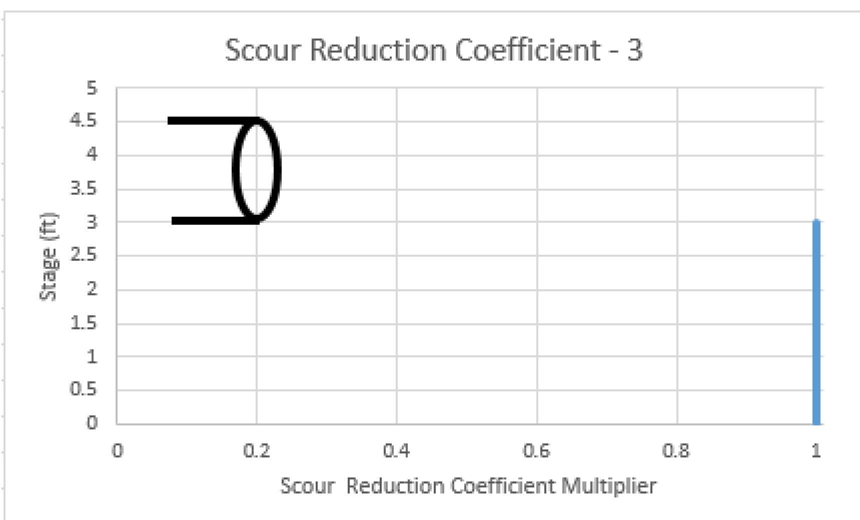


that time step. The range of the multiplier is from zero, at the pond bottom, to one, at three feet above the pond bottom (and for greater depths).

Scour Reduction Coefficient Example 2. The lowest outlet invert is one foot above the bottom of the pond. The scour reduction coefficient multiplier is determined for each time step, based upon the water surface elevation stage in the pond for that time step. The multiplier is 1, if the water surface is between zero and one foot, and then ranges from 0.333 to 1 as the water surface elevation changes for each time step from one foot to three feet above the pond bottom.



Scour Reduction Coefficient Example 3. The lowest outlet invert is three feet above the bottom of the pond. The scour reduction coefficient multiplier is determined for each time step, based upon the water surface elevation stage in the pond for that time step. The multiplier is 1 regardless of the elevation of the water surface because the lowest invert elevation is three feet above the pond bottom, preventing any scour.



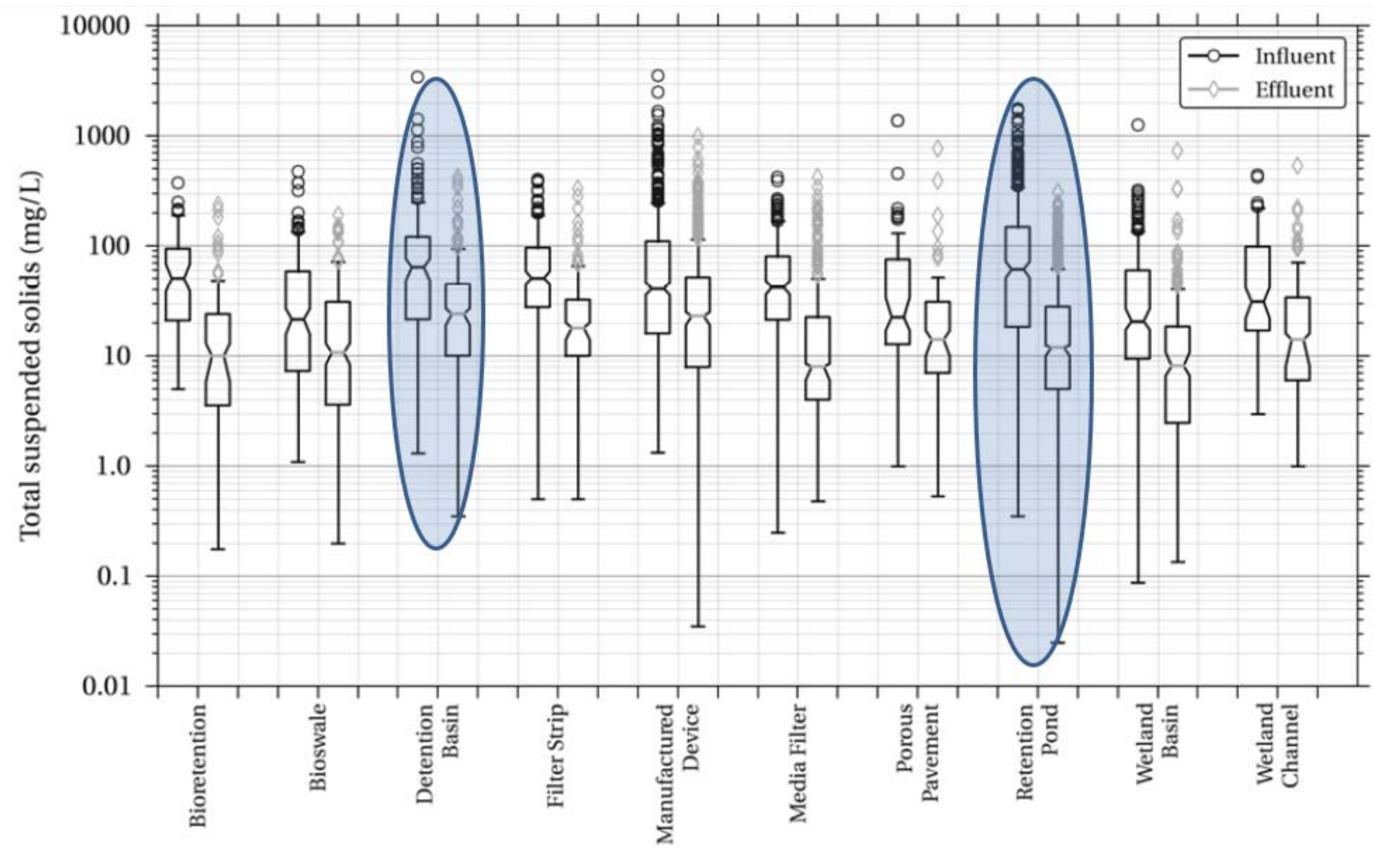
Dry Stormwater Pond Performance

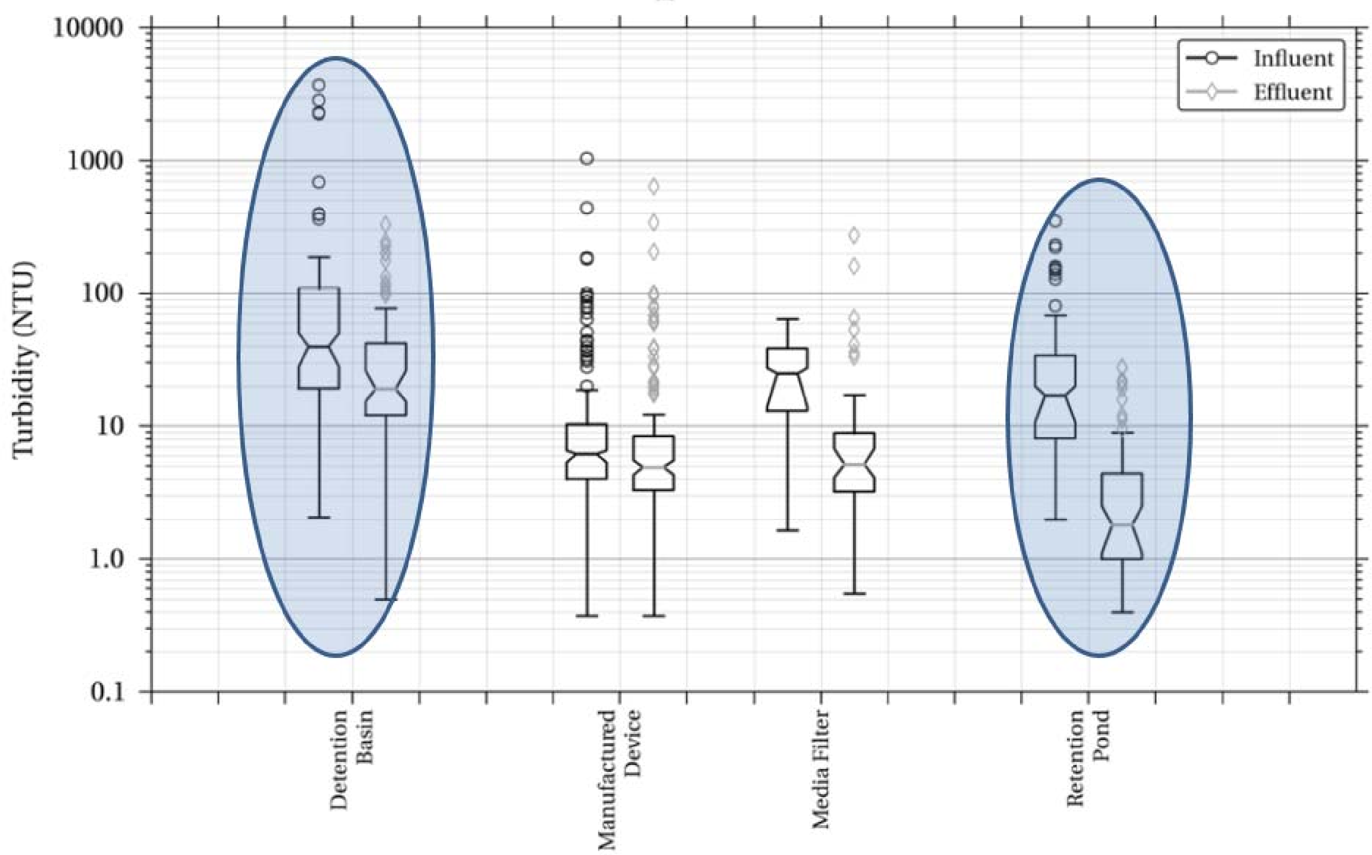
Dry stormwater ponds have been extensively used throughout the country. These ponds usually have been constructed to reduce peak runoff rates (peak shaving), with typically little consideration given to stormwater quality improvements. Their main purpose has therefore been in flood control by reducing flows and water elevations in the receiving waters. These flow reductions can also improve the aquatic habitat by reducing scour of stream beds and banks and by reducing flushing of fish and other organisms from urban creeks. The use of many dry ponds in a watershed, without regard to their accumulative effect, can increase downstream flooding or channel scour problems (McCuen, *et al.* 1984), as the delayed discharge of a mass of water from a downstream dry pond may be superimposed on an upstream hydrograph.

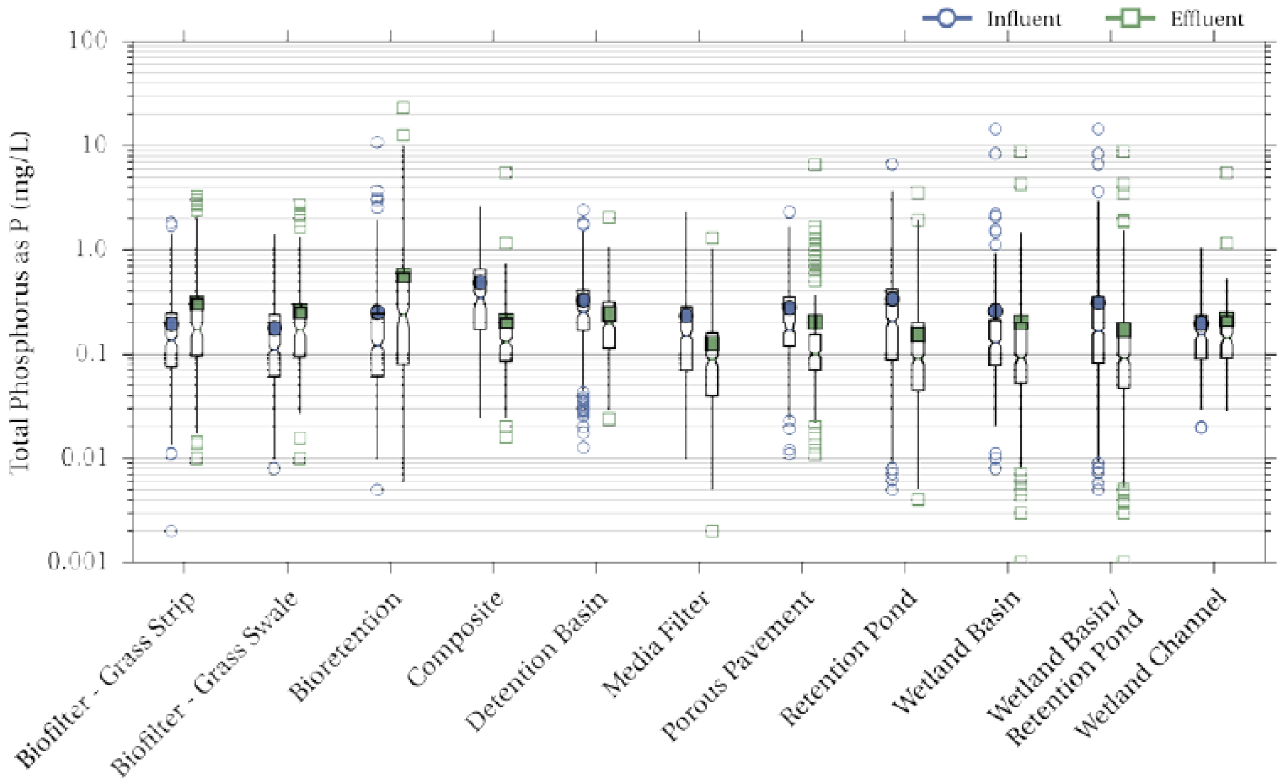
Some of the earliest comprehensive water quality monitoring of dry detention ponds occurred as part of the Nationwide Urban Runoff Program (NURP). Observed long-term monitored pollutant removals ranged from insignificant to quite poor (EPA 1983). Sedimentation may occur in dry ponds, but only during the major storms when flows are retained in the pond. Adler (1981) found that new sediment deposits have little cohesion and without removal as part of a maintenance program, or without several feet of overlaying water, bottom scour is probable. The deposited material should therefore be removed after each treated rain, or it can easily be resuspended by later rains and washed into the receiving waters, especially if the pond is paved for other uses, or contains a paved pilot channel.

The most comprehensive compilation of stormwater control performance is the International BMP Database (http://bmpdatabase.org/) which contains data and descriptions for more than 500 control practice installations from throughout the US. The International BMP Database website also contains several reports analyzing the performance of stormwater controls, in addition to containing the actual database. Users can download the database focusing on specific criteria, such as constituents of interest and location.

The following grouped box plots compare the range of influent and effluent concentrations for many stormwater controls for suspended solids, turbidity, and phosphorus, as examples. Dry ponds are labeled as detention ponds and wet ponds are labeled as retention ponds in the Database. These two sets of controls are high-lighted in these performance figures.


Total suspended solids (mg/L)
Influent
Effluent
Bioretention
Bioswale
Detention Basin
Filter Strip
Manufactured Device
Media Filter
Porous Pavement
Retention Pond
Wetland Basin
Wetland Channel


Turbidity (NTU)
Influent
Effluent
Detention Basin
Manufactured Device
Media Filter
Retention Pond



The influent TSS and TP concentrations are similar for the detention and retention pond categories, while the turbidity influent values are less for the retention ponds compared to the detention ponds. The detention ponds indicate some stormwater quality improvements, but the retention ponds have much greater percentage removals and better effluent quality. The main reason for the decreased performance of the detention ponds is due to scour of previously settled material, or from rapid flow rates through the ponds from less restrictive outlets that in turn decrease the surface overflow rates and so provide less sedimentation. Generally, at least three feet is needed to protect previously captured silt in ponds.

When modeling dry or extended detention ponds in WinSLAMM, consider the following guidelines.

Pavement/concrete lined ponds or ponds with smooth paved pilot channel and fast release rates:
Because these ponds are normally dry and only contain water for relatively short periods of time, they can be constructed as part of parking lots, athletic fields, tennis courts and other multi-use areas. Their outlets are designed to transmit all flows up to a specific design flow rate, after which excess flows are temporarily backed-up. In many cases, they only contain water during a few rains each year. These ponds have little direct water quality benefits. In the next version, new button will be added to the detention pond form in WinSLAMM to select ponds in this category. In this case, WinSLAMM will not calculate any water quality benefits (for outlets at the pond bottom), but does route the flows through the ponds, moderating the effluent hydrograph based on any retention of flows occurring. This in turn can provide enhanced treatment of downstream controls due to the decreased flow rates. However, ponds with small pilot channels compared to the detention area and designed to spill over to adjacent non-paved areas frequently would provide greater benefits compared to completely lined ponds, especially with check dams along the pilot channel. For this condition, it may be reasonable not to select this option on the form. The following are photographs of these example ponds.

East Lake Festival Center, Birmingham, AL, dry pond

Madison, WI, golf course dry pond with concrete pilot channel (frequent overflows of pilot channel)

Typical small dry pond (WI DNR photo) (infrequent channel overflows)

Los Angeles River, CA, stormwater pumping station forebay

Example dry ponds with paved linings or concrete pilot channels.

Extended detention ponds having relatively slow release rates:

These ponds have restricted outlets and are intended to retain the water in a pond for extended periods with a slow release. These are the dry detention ponds that are most common in the International BMP Database under the detention ponds category. These ponds may include paved lining or pilot channels, but the slow release rate provides enhanced particulate retention compared to similar ponds with less restricted release rates. In most cases, these ponds are vegetated which enhances retention of previously settled particulates. Micropools and check dams along the flow path also enhance retention of the settled particulates compared to smooth flow paths. The following are photographs of typical extended detention ponds:

Madison, WI, dry pond at apartment area play field

Austin, TX, dry pond prior to horizontal flow sand filter (lined pond with slow release rate through filter)

Extended detention pond at an industrial site in Mississippi with micropools and check dams

Extended detention pond in Cheasapeake Bay drainage area with small pool (and algae!)

Extended detention ponds with relatively slow release rates.

Although WinSLAMM reduces pollutant removal efficiency due to resuspension for a basin with less than three feet of permanent pool, the basin still needs to be designed to dissipate energy at inlets and to prevent channelized flow. Although a standard riprap outlet may be adequate to prevent scour at the outlet, a more robust energy dissipation feature (e.g. stone berm or gabion) may be needed to prevent energy from entering the basin during high flow events.

Particle Size Distribution Calculations

General Description

Urban stormwater runoff is characterized by highly variable particle size distributions. For example, the particle size distribution from a street in a commercial land use will be very different than the distribution from roof runoff in the same area. Further, particle size distributions from urban source areas are very different than those measured at urban drainage system outfalls as much of the larger particles are trapped in the drainage system pipes. WinSLAMM was developed to address these issues by providing users with the tools to evaluate particle size distributions at various locations, and using stormwater control practices, in the urban drainage system.

Particle size distributions (PSDs) are applied at each source area, for all land uses, in a WinSLAMM model. The particle size distributions can be entered in each source area by the user or defined for each land use, by source area category, in a comma-separated-value file. The program then applies the source area PSD to any source area controls. The effluent PSDs (based on preferential particle size removals in the treatment device) are then combined, on a mass-weighted basis, with any other source area PSDs from the land use, saved as a land use PSD and passed onto the junction immediately downstream of the land use. This process of combining particle size distributions continues downstream to the outfall and is affected by different stormwater controls along with the PSDs of tributary source areas and land uses.

Particle Size Distribution Characterizations in WinSLAMM

A particle size distribution is characterized in WinSLAMM by 31 distinct particle sizes, as shown in Table 1. Each of these particle sizes is characterized by a "Percent Greater Than" value, where 100% of the particles in a given distribution are greater than 0 microns (micrometers). Usually 0% of the particles are greater than 2,000 microns, or two millimeters, but the upper limit may be more indicating some particles larger than 2,000 microns. These are percentage particle size distributions, which total approximately 100% of the solids in the sample. The model uses this information in conjunction with the particulate solids concentrations to calculate the mass in each particle size range.

The particle size distribution illustrated in Table 1 is plotted in the figure below. This plot, which is a screen shot from the particle size file editor in WinSLAMM, characterizes the particle sizes on the X axis and the percent-greater-than-values on the Y axis.

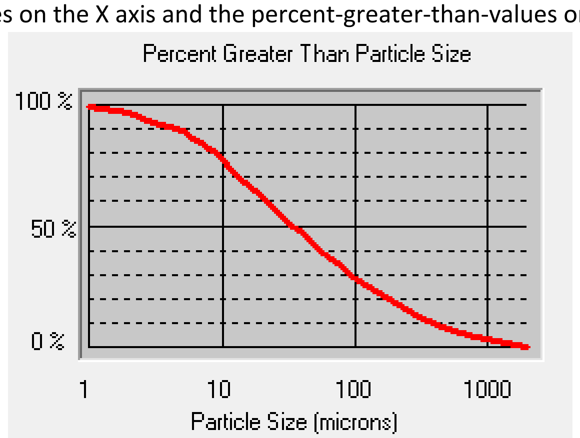


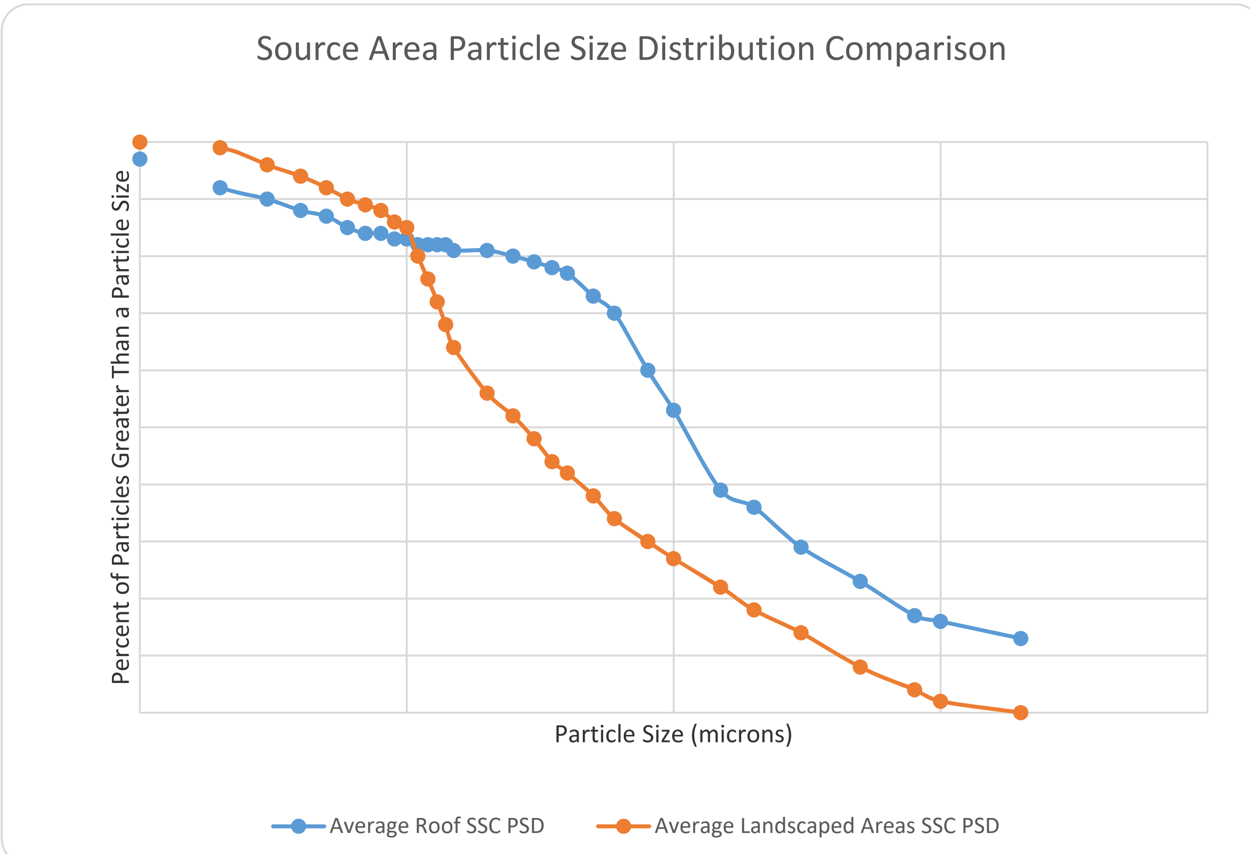
Table 1. Example PSD

Entry Number	Critical Size (microns)	Percent > Critical Size
1	1	99.
2	2	97.
3	3	93.
4	4	91.
5	5	89.
6	6	86.
7	7	84.
8	8	82.
9	9	80.
10	10	78.
11	11	75.
12	12	73.
13	13	71.
14	14	69.
15	15	68.
16	20	62.
17	25	57.
18	30	53.
19	35	49.
20	40	47.
21	50	42.
22	60	38.
23	80	33.
24	100	28.
25	150	22.
26	200	18.
27	300	12.
28	500	7.0
29	800	4.0
30	1000	3.0
31	2000	0.0

Each particle size distribution is defined by a text file that can be edited and viewed with the WinSLAMM CPZ (for Critical Particle siZe) file editor found in the Utilities/Parameter Files menu in WinSLAMM. The text file has the extension *.CPZ. The help file describes how to use this editor.

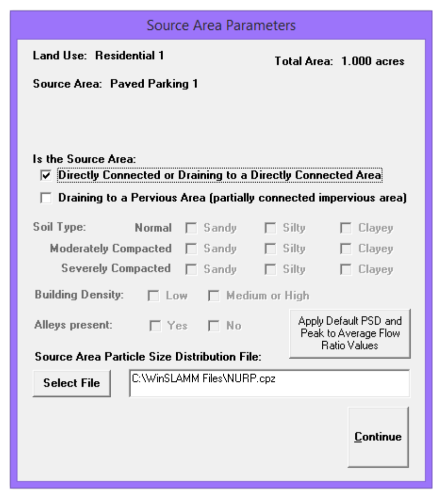
Assigning Particle Size Distributions in WinSLAMM

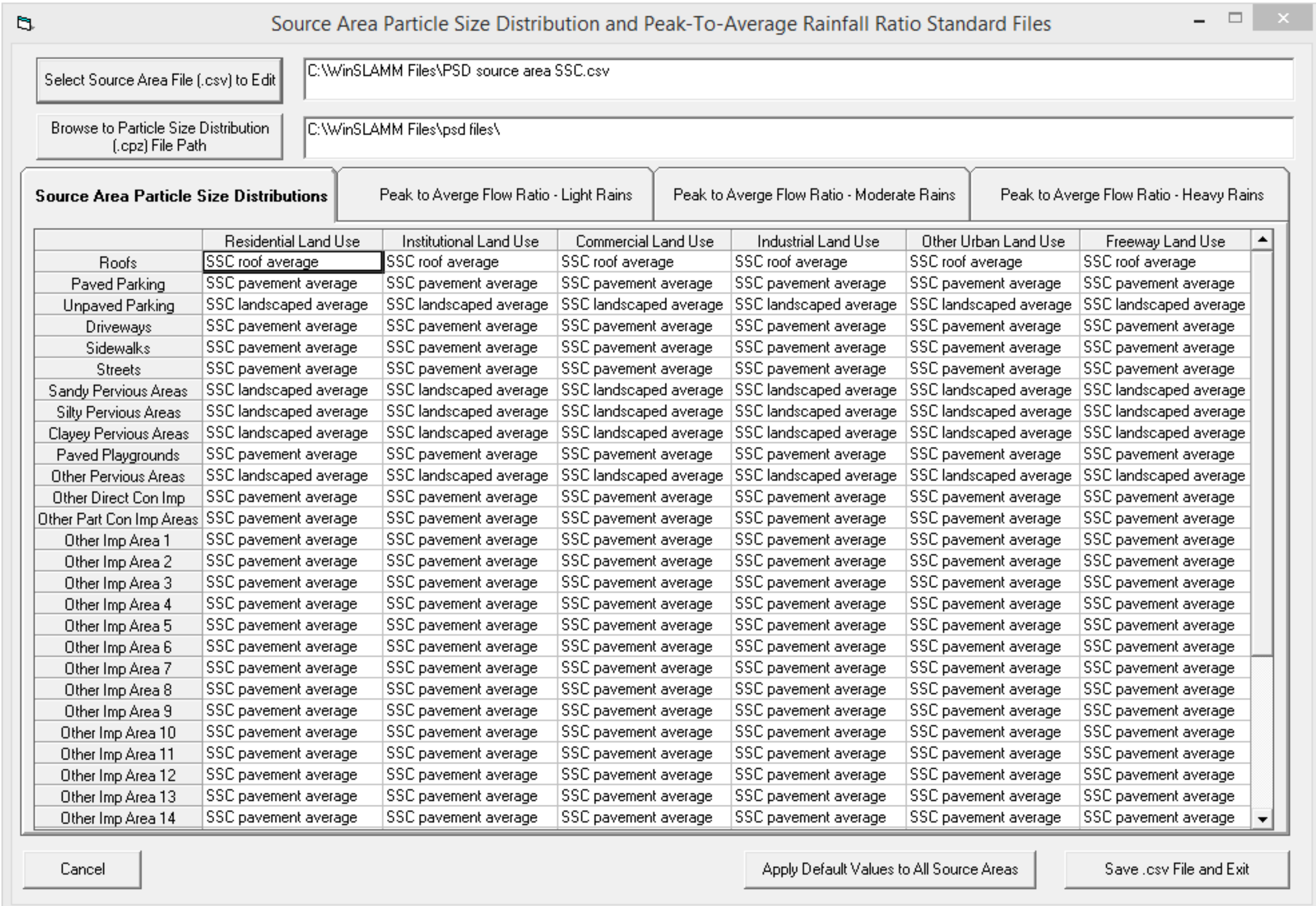
Particle size distributions are always assigned at the source area level in WinSLAMM. This means that users can accurately describe the differences in particle sizes from various source areas and land uses. For example, the particle size distribution for rooftop runoff will be different than for runoff from landscaped areas, as illustrated on the following plot.



There are two ways to assign a particle size distribution in WinSLAMM. The first is for the user to enter the particle size distribution for each source when entering source area parameter information. Source area parameters are entered by double-clicking on the appropriate row in the source area parameters column of the source area data grid. If the area is newly entered, then the Source Area Parameter cell for the data will be blank. If the source area data has already been entered, double-click on the word "Entered". Once you are in the form (as shown on the right), press the "Select File" button and browse to the desired particle size distribution file.

You can also use a Source Area PSD and Peak-to-Average Flow Ratio file, which allows you to assign a particle size distribution to each source area, for each land use. The program will apply the assigned PSD files listed in this comma separated value file to each active source area. WinSLAMM also has an editor that will allow you to either edit the current file or create a new one. The help file has a complete set of instructions describing how to either create or edit one of these files. An example of a file shown in the file editor is illustrated below. The particle size distribution determines if the model is calculating SSC or TSS. The particulate solids calibration file must also correspond to the desired SSC or TSS values. The SSC files have more larger particles than the corresponding TSS files, for example.





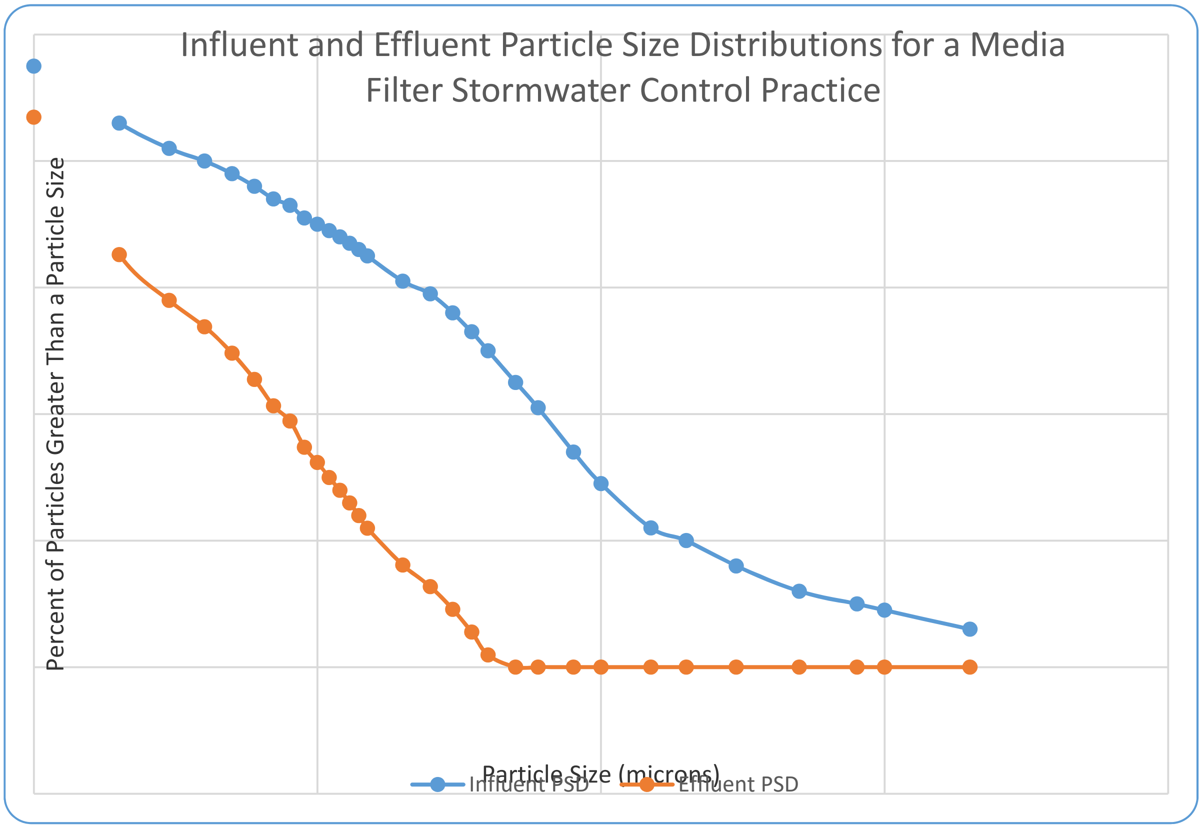
	Residential Land Use	Institutional Land Use	Commercial Land Use	Industrial Land Use	Other Urban Land Use	Freeway Land Use
Roofs	SSC roof average	SSC roof average	SSC roof average	SSC roof average	SSC roof average	SSC roof average
Paved Parking	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Unpaved Parking	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average
Driveways	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Sidewalks	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Streets	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Sandy Pervious Areas	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average
Silty Pervious Areas	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average
Clayey Pervious Areas	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average
Paved Playgrounds	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Pervious Areas	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average	SSC landscaped average
Other Direct Con Imp	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Part Con Imp Areas	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 1	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 2	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 3	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 4	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 5	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 6	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 7	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 8	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 9	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 10	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 11	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 12	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 13	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average
Other Imp Area 14	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average	SSC pavement average

Tracking Particle Size Distributions

To have WinSLAMM track particle size distributions as runoff flows through a drainage system and entered stormwater controls, go to the Tools menu item and select Program Options. On the Default Model Options tab, check the box "Create Hydrographs and Particle Size Distribution .csv Files." This action will cause the program to print a file of the particle size distribution for each land use, junction and control practice. Each land use file will have a particle size distribution of the particulates in the runoff from the land use, for each rainfall event. The junctions and control practice files will have a column for the influent and for the effluent particle size distribution for each rainfall event. The two columns will be identical for junctions because only the combined distributions are included in this output format. The two columns will vary for those control practices that affect particle sizes, such as wet detention ponds and media filters. These files can be imported into a spreadsheet and plotted, as shown below. The file naming conventions are as follows:

Junction PSD Files: <file name> PSD For JuncNum #.csv
Land Use Files: <file name> PSD For LUNum #.csv
Control Practices: <file name> PSD For CPNum #.csv

An example of a particle size distribution plot developed from one rainfall event for a media filter showing the influent and effluent particle size distributions is illustrated below.



Merging Particle Size Distributions

For land uses and junctions, particle size distributions from active source areas (for land uses) or from land uses and control practices (for junctions) are combined by mass-weighting the particle size distribution for each rainfall event. Specifically, each percent greater than a particle size value for a rainfall event is multiplied by the total suspended solids mass calculated for the event for each contributing source area or, for a junction, each land use and control practice entering the junction. The resulting products are summed and divided by the total mass from the land use, or entering the junction, for each rainfall event for each particle size increment. These values represent the merged mass-weighted particle size distribution.

The table below illustrates this process. There are three source areas in this land use example – roofs, paved parking and streets. For each particle size, the total mass from the event is multiplied by the % > (percent greater than) value for that particle size. For roofs, each value in column 7 is multiplied by the total roof mass of 2.366 lbs, to get the result in column 8. The same is done for paved parking and streets. The products for each of these source area particle sizes is summed and then divided by the sum of the masses from the three source areas. The resulting calculations, in column 13, represent the mass-weighted particle size distribution for the rainfall event. These values are shown in the .csv file created for this example in column 6. Note that the percent greater than a particle size of 0 microns is always considered to be 100%.

Example Source Area to Land Use Particle Size Distribution Merging Calculations

Land Use PSD Output for Rainfall Event # 22							Mass Weighted PSD Calculation Example						
							Roofs		Paved Parking		Streets		
1	2	3	4	5	6		7	8	9	10	11	12	13
Feature	Feature Number	Rain No.	Part. Size No.	Particle Size (microns)	Eff. % > Particle Size	Mass for Event #22 ==>		2.366		0.5253		38.26	Mass Weighted PSD
							% >	Mass x % >	% >	Mass x % >	% >	Mass x % >	
LU	3	22	0	0	100		0	0	0	0	0	0	
LU	3	22	1	1	95.11498		97	229.502	95	49.9035	95	3634.7	95.11499
LU	3	22	2	2	86.34493		92	217.672	86	45.1758	86	3290.36	86.344971
LU	3	22	3	3	82.45991		90	212.94	82	43.0746	82	3137.32	82.459961
LU	3	22	4	4	80.4599		88	208.208	80	42.024	80	3060.8	80.459961
LU	3	22	5	5	78.5174		87	205.842	78	40.9734	78	2984.28	78.517456
LU	3	22	6	6	76.51739		85	201.11	76	39.9228	76	2907.76	76.517456
LU	3	22	7	7	74.57488		84	198.744	74	38.8722	74	2831.24	74.574951
LU	3	22	8	8	73.63237		84	198.744	73	38.3469	73	2792.98	73.632447
LU	3	22	9	9	71.68986		83	196.378	71	37.2963	71	2716.46	71.689942
LU	3	22	10	10	70.74734		83	196.378	70	36.771	70	2678.2	70.747437
LU	3	22	11	11	69.74734		82	194.012	69	36.2457	69	2639.94	69.747437
LU	3	22	12	12	68.80483		82	194.012	68	35.7204	68	2601.68	68.804932
LU	3	22	13	13	67.86232		82	194.012	67	35.1951	67	2563.42	67.862427
LU	3	22	14	14	66.91981		82	194.012	66	34.6698	66	2525.16	66.919922
LU	3	22	15	15	65.91981		81	191.646	65	34.1445	65	2486.9	65.919922
LU	3	22	16	20	62.14976		81	191.646	61	32.0433	61	2333.86	62.149903
LU	3	22	17	25	60.20724		80	189.28	59	30.9927	59	2257.34	60.207398
LU	3	22	18	30	57.32222		79	186.914	56	29.4168	56	2142.56	57.322388
LU	3	22	19	35	54.43719		78	184.548	53	27.8409	53	2027.78	54.437379
LU	3	22	20	40	51.55217		77	182.182	50	26.265	50	1913	51.552369
LU	3	22	21	50	46.60966		73	172.718	45	23.6385	45	1721.7	46.609864
LU	3	22	22	60	42.66715		70	165.62	41	21.5373	41	1568.66	42.667359
LU	3	22	23	80	35.49468		60	141.96	34	17.8602	34	1300.84	35.494874
LU	3	22	24	100	30.37971		53	125.398	29	15.2337	29	1109.54	30.379884
LU	3	22	25	150	22.97729		39	92.274	22	11.5566	22	841.72	22.977417
LU	3	22	26	200	20.91981		36	85.176	20	10.506	20	765.2	20.919922
LU	3	22	27	300	16.74734		29	68.614	16	8.4048	16	612.16	16.747437
LU	3	22	28	500	12.63237		23	54.418	12	6.3036	12	459.12	12.632447
LU	3	22	29	800	10.40242		17	40.222	10	5.253	10	382.6	10.402466
LU	3	22	30	1000	9.402415		16	37.856	9	4.7277	9	344.34	9.402466
LU	3	22	31	2000	6.402415		13	30.758	6	3.1518	6	229.56	6.402466

The table below provides a similar demonstration of how WinSLAMM merges particle size distributions for two land uses and a control practice merging at a junction. The mass-weighted calculations, in column 15, represent the mass-weighted particle size distribution for the rainfall event. These values are found in the .csv file created for this example, as shown in column 7.

Example Junction Particle Size Distribution Merging Calculations

Junction PSD Output for Rainfall Event # 22								Mass Weighted PSD Calculation Example							
								LU# 3 - Institutional 2		LU# 4 - Commercial 1		CP# 1 - CB			
1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
Feature	Feature Number	Rain No.	Part. Size No.	Particle Size (microns)	Eff. % > Particle Size		Mass for Event #22 ==>		41.16		15.22	10.64	4.138		Mass Weighted PSD
								% >	Mass x % >	% >	Mass x % >	% >	Mass x % >		
Junc	2	22	0	0	100	100		100	4116	100	1522	100	100	413.8	100
Junc	2	22	1	1	94.75294	94.75294		95.11498	3914.932577	95.46638	1452.998304	95.5371	88.52806	366.3291	94.752966
Junc	2	22	2	2	85.36619	85.36619		86.34493	3553.957319	87.39912	1330.214606	87.61131	68.15471	282.0242	85.366273
Junc	2	22	3	3	81.22652	81.22652		82.45991	3394.049896	83.8655	1276.43291	84.14842	59.2533	245.1902	81.226626
Junc	2	22	4	4	79.01172	79.01172		80.4599	3311.729484	81.86549	1245.992758	82.14842	54.11227	223.9166	79.011845
Junc	2	22	5	5	76.94188	76.94188		78.5174	3231.776184	80.09868	1219.10191	80.41697	49.66155	205.4995	76.942027
Junc	2	22	6	6	74.7271	74.7271		76.51739	3149.455772	78.09869	1188.662062	78.41697	44.52052	184.2259	74.727251
Junc	2	22	7	7	72.65726	72.65726		74.57488	3069.502061	76.33186	1161.770909	76.68552	40.0698	165.8088	72.657421
Junc	2	22	8	8	71.69482	71.69482		73.63237	3030.708349	75.56506	1150.100213	75.95407	38.18961	158.0286	71.694986
Junc	2	22	9	9	69.62497	69.62497		71.68986	2950.754638	73.79824	1123.209213	74.22263	33.73891	139.6116	69.62516
Junc	2	22	10	10	68.66253	68.66253		70.74734	2911.960514	73.03143	1111.538365	73.49118	31.85872	131.8314	68.662716
Junc	2	22	11	11	67.55513	67.55513		69.74734	2870.800514	72.03143	1096.318365	72.49118	29.2882	121.1946	67.55533
Junc	2	22	12	12	66.59269	66.59269		68.80483	2832.006803	71.26461	1084.647364	71.75974	27.40801	113.4143	66.59289
Junc	2	22	13	13	65.63025	65.63025		67.86232	2793.213091	70.4978	1072.976516	71.02828	25.5278	105.634	65.630451
Junc	2	22	14	14	64.6678	64.6678		66.91981	2754.41938	69.73099	1061.305668	70.29684	23.64761	97.85381	64.668014
Junc	2	22	15	15	63.56041	63.56041		65.91981	2713.25938	68.73099	1046.085668	69.29684	21.0771	87.21704	63.560628
Junc	2	22	16	20	59.71064	59.71064		62.14976	2558.084122	65.66373	999.4019706	66.37105	13.55632	56.09605	59.710865
Junc	2	22	17	25	57.6408	57.6408		60.20724	2478.129998	63.89692	972.5111224	64.6396	9.105613	37.67903	57.641035
Junc	2	22	18	30	54.60851	54.60851		57.32222	2359.382575	61.3633	933.949426	62.1767	2.774698	11.4817	54.608773
Junc	2	22	19	35	51.81941	51.81941		54.43719	2240.63474	58.82967	895.3875774	59.71381	0	0	51.819662
Junc	2	22	20	40	49.22005	49.22005		51.55217	2121.887317	56.29604	856.8257288	57.25092	0	0	49.220282
Junc	2	22	21	50	44.6597	44.6597		46.60966	1918.453606	51.52922	784.2747284	52.51947	0	0	44.659908
Junc	2	22	22	60	41.03098	41.03098		42.66715	1756.179894	47.76242	726.9440324	48.78802	0	0	41.031163
Junc	2	22	23	80	34.21641	34.21641		35.49468	1460.961029	40.06285	609.756577	40.98236	0	0	34.216557
Junc	2	22	24	100	29.36283	29.36283		30.37971	1250.428864	34.59648	526.5584256	35.44526	0	0	29.362955
Junc	2	22	25	150	22.15728	22.15728		22.97729	945.7452564	25.96417	395.1746674	26.56539	0	0	22.157373
Junc	2	22	26	200	20.1963	20.1963		20.91981	861.0593796	23.73099	361.1856678	24.29684	0	0	20.196389
Junc	2	22	27	300	16.17659	16.17659		16.74734	689.3205144	19.03143	289.6583646	19.49118	0	0	16.176656
Junc	2	22	28	500	12.25462	12.25462		12.63237	519.9483492	14.56505	221.680061	14.95408	0	0	12.254675
Junc	2	22	29	800	10.0004	10.0004		10.40242	428.1636072	11.63231	177.0437582	11.87987	0	0	10.000452
Junc	2	22	30	1000	9.068785	9.068785		9.402415	387.0034014	10.63231	161.8237582	10.87987	0	0	9.0688251
Junc	2	22	31	2000	6.27393	6.27393		6.402415	263.5234014	7.632307	116.1637125	7.879867	0	0	6.2739534

Stormwater Control Effects on Particle Size Distributions

Stormwater control practices in WinSLAMM use different calculation procedures to determine changes to the influent particle size distributions to produce the effluent particle size distribution, depending upon the control practices used. The table below shows how each of the current control practices in WinSLAMM removes particulates from stormwater runoff. Below the table is a brief discussion of each of the particulate removal processes and how they modify the particle size distribution. See the model documentation and help files for further descriptions and examples of these treatment unit processes, as the discussions below are only summaries of the particle size distribution calculation processes used.

Stormwater Control Practice Particle Size Distribution Calculation Processes

Control Practice	Settling	Media Filtering	Particulate Trapping	Mechanical Removal	Infiltration	Other
Wet Detention	X				X	
Catchbasins	X				X	
Hydrodynamic Devices	X					
Porous Pavement	X		X		X	
Street Cleaning				X		
Grass Swales			X		X	
Grass Filter Strips			X		X	
Biofiltration		X			X	
Upflo Filter	X	X				
StormFilter	X	X				
Other Device						X
Green Roofs		X				

1. Settling. WinSLAMM calculates settling by determining the settling velocity using the surface area of the device and the device discharge rate for each rainfall event time increment (the surface overflow rate, or upflow velocity, as used in water and wastewater treatment systems). This settling velocity is used to determine the particle sizes from the influent distribution that will settle and be captured for each time increment. The smallest particle trapped is called the critical particle size. The percent-greater-than value that corresponds to this particle size in the influent particle size distribution represents the percent of particulates removed by the stormwater control practice for that time increment. This value is outflow-weighted for each time increment to determine the flow-weighted percent particulate control for each rainfall event. This percent reduction is used to determine the mass of particulate solids removed by the control device for each rainfall event, and the resulting particulate solids concentrations.

   The effluent particle size distributions for each event are calculated by setting the percent-greater-than-values of all particle size increments greater than the critical particle size for that event to zero. The influent percent-greater-than-values that are less than the critical particle size are reduced by the ratio of the difference between the percent-greater-than-values of each influent particle size and the next largest influent particle size, divided by the difference between 100 and the percent-greater-than-value of the critical particle size.

2. Media Filtering. Concentration and mass reductions for selected particle size ranges are developed from stormwater quality research and applied to influent particle size distributions for each rainfall event. These reductions, which vary depending upon the filter media type, are in the form of linear, logarithmic, or exponential equations that reduce the influent concentrations for each particle size range.

   The effluent particle size distribution for each event is calculated by subtracting the ratio of the incremental effluent particle size concentration by the event effluent concentration from the previous incremental effluent particle size.

3. Particulate Trapping. Particulate trapping is based on the settling frequency: how many times would a particle be able to completely settle as the particle flows through vegetation down a grass swale or filter strip. Particles that may settle many times in the vegetation (the large particles) are much more likely to remain trapped in the vegetation, while particles that settle less frequently (the smaller particles) have a greater probability of moving through the vegetation.
4. Mechanical Removal. The program assumes that the percent of particulate solids removed by the control practice equates to the percent-greater-than value of the influent particle size distribution. This value has a corresponding particle size, which is considered to be the critical particle size. All particles greater than the size of this value are removed from the particle size distribution.
5. Infiltration. The influent percent-greater-than-values that are less than the critical particle size are reduced by the ratio of the difference between the percent-greater-than-values of each influent particle size and the next largest influent particle size, divided by the difference between 100 and the percent-greater-than-value of the critical particle size. Infiltration. Infiltration losses remove total mass from the drainage system and do not differentiate between particle sizes, so the effluent particle size distribution is the same as the influent particle size distribution.
6. Other. The other control device assumes that the effluent particle size distribution is the same as the influent particle size distribution because the mass is assumed to be removed equally from each particle size.

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9 December 2022

Urban Tree Canopy Rainfall Interception in WinSLAMM

General Description

Tree canopy runoff interception is a source area feature in WinSLAMM. Unlike typical WinSLAMM stormwater control practices, you can only compare the results of a model run with and without tree canopy interception by running two separate models – one with and one without tree canopy interception.

Please note that there is also a possibility for double counting some of these benefits. For example, calibrated stormwater models rely on monitored outfall flow measurements of existing areas that have mature vegetation appropriate to the land use. These areas have varying amounts of trees through their landscapes. Adding additional interception to these calibrated models can result in improper estimates of runoff. However, if new trees are planted in an area, interception benefits may increase. The following figures are examples of monitored medium density residential areas used in WinSLAMM calibrations showing the contrast of mature trees in older areas and the few young trees in new developments. These residential areas were separated based on age of development to account for the differences in vegetation during the model calibration process. However, the outfall monitored runoff characteristics did not indicate any significant differences between the old and new developments, beyond which was explained by differences in directly connected impervious area types and other land surface areas.


Residential area with few isolated trees


Older medium density residential area with more mature trees

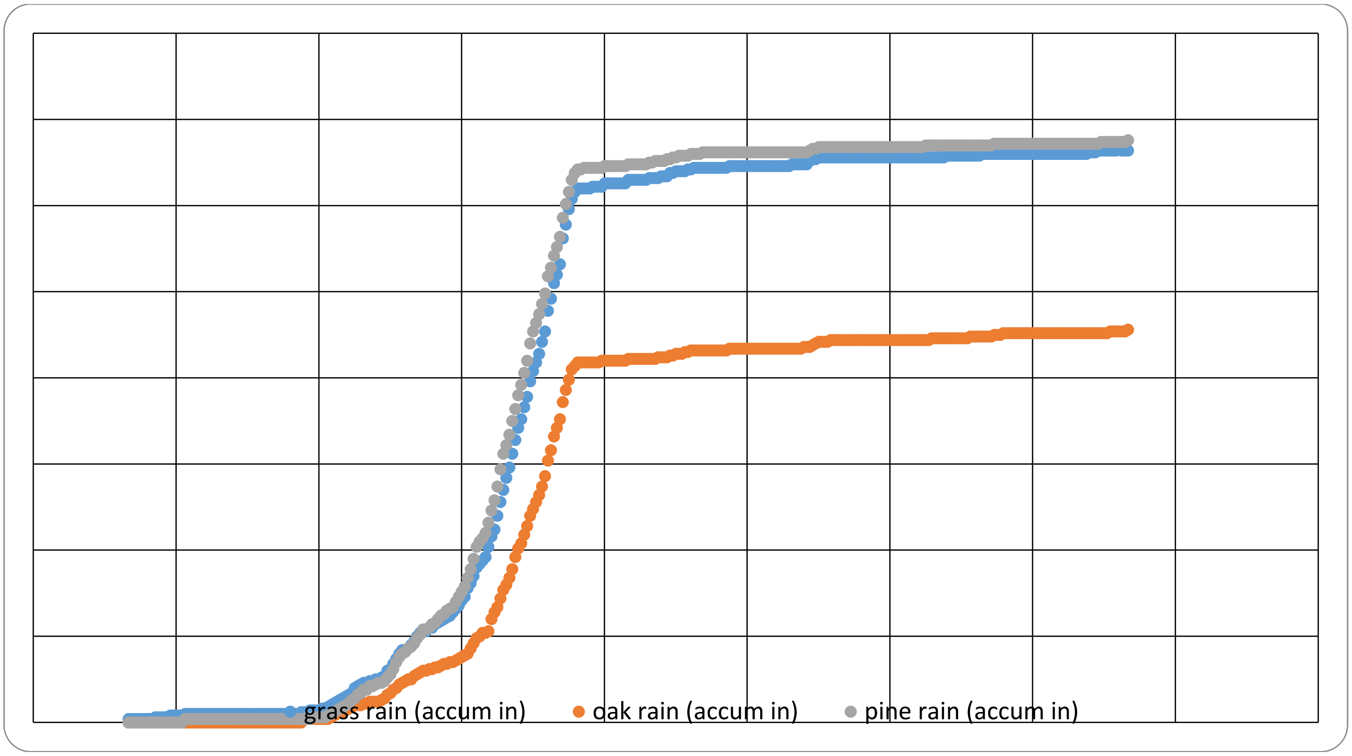
If a tree is located in a pervious area of the watershed (over lawns or other non-paved areas), interception may not affect outfall runoff quantities much; any un-intercepted rainfall (throughfall) is likely to be infiltrated with or without the trees. However, trees likely maintain good soil characteristics and minimize compaction, which would improve the infiltration of rainfall. The largest hydrological benefit of urban trees would be when directly connected impervious areas (such as roofs, walkways, parking areas, and streets) are heavily covered by an overstory of trees. If tree-covered impervious areas are directly connected to the drainage system, these benefits would be the greatest, but if the tree-covered impervious areas drain to pervious areas (such as disconnected roofs or walks surrounded by lawns), the benefits would be lower. Obviously, trees add substantially to the quality of life in urban areas, but nuisance conditions and increased public works leaf removal activities may be needed.

This algorithm description report includes the data plots and resulting equations used to describe throughfall under urban trees (canopy interception) to quantify some of these hydrologic benefits for inclusion in WinSLAMM. The experiments used to develop the equations were conducted to comprehensively examine canopy interception by direct measurements of throughfall under isolated or low density stands of mature urban deciduous and evergreen trees. These measurements resulted in throughfall data for a wide range of rainfall conditions and included 55 (oak) to 75 (pine) rains over all seasons to determine statistically significant relationships for use in the WinSLAMM urban stormwater quality model. This research and the development of the equations are described in the following paper:

Bean, R., R. Pitt, J. Voorhees, and M. Elliott. "Urban tree rainfall interception measurements and modeling in WinSLAMM, the Source Loading and Management Model." *Journal of Water Management Modeling*, Computational Hydraulics International, Guelph, Ontario. 2020. DOI: 10.14796/JWMM.C475. https://www.chijournal.org/C475

Example Rain Data

The following plot is the accumulative rainfall at the background location (surrounded by grass) vs. the accumulative rainfall measured under the pine and oak trees for rainfall between December 7 and 11, 2018:



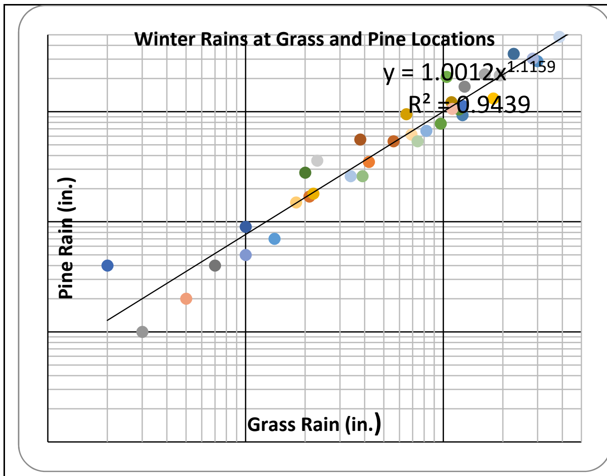
It is obvious that the measured rain under the pines had little difference compared to the background rainfall, while the oak had a substantial rain throughfall reductions. The total rain for this event was about 3.32 inches. The steepest portion of the accumulated rain curve indicated about 2.1 inches over 7.25 hours, for a fairly constant rain intensity of about 0.29 inches per hour for most of this event.

This rain interception measurement test was supplemented with many more rains through January 24, 2020. In the Birmingham, AL, area, about 50 rains occur per year having >0.1 inches of rain (and about 100 rains >0.01 inches). This initial rain was one of the largest expected, but we usually receive a few rains between 2- and 5-inches total per year. This large amount of data enabled the significant factors affecting interception of urban trees to be identified and quantified. The factors examined by factorial analyses included: tree type, season (tree canopy coverage), rain intensity and depth, along with wind speed.

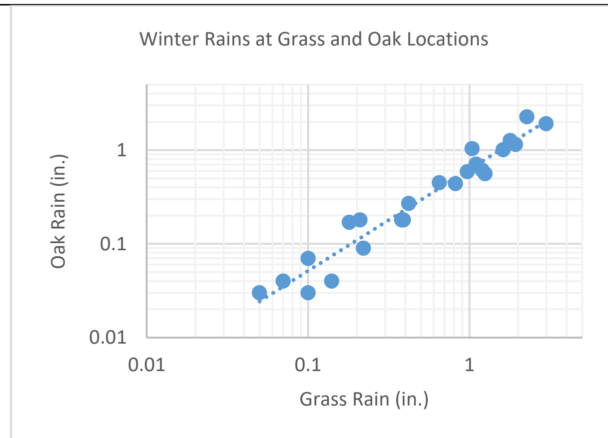
A 2^3 full factorial analysis was conducted and found that all three factors (season, tree type, and rain category) were significant when determining the throughfall (rain depth under the trees vs. rain depth at the grass location). The tree type (oak vs. pine) had the greatest effects on the throughfall, followed by the rain depth, while the seasonal differences had only marginally significant effects.

Tree Canopy Runoff Interception Equations

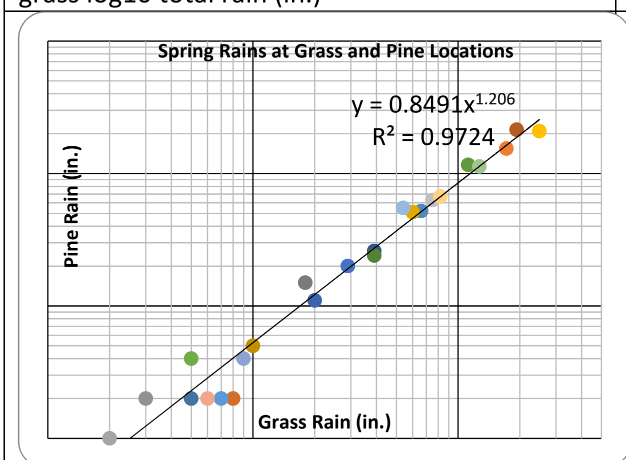
The following scatterplots and regression equations are used in WinSLAMM relate rain throughfall under deciduous and evergreen trees for different rain depths, for the winter, spring, and summer seasons. The scatterplots and ANOVA statistical tests were evaluated using log10 transformed rain depth data and resulted in highly significant regression relationships. The pine data for winter, spring, and summer seasons did not result in significant intercept terms of the regression equation, so the equations for those conditions only have a slope coefficient term. In contrast, the oak data (and the fall pine data) had both significant intercept and slope coefficients, indicating initial rainfall that did not result in any throughfall. The scatterplots show the fitted regression lines along with the actual data. The residual analyses indicated satisfactory patterns (example shown below for winter pine observations).



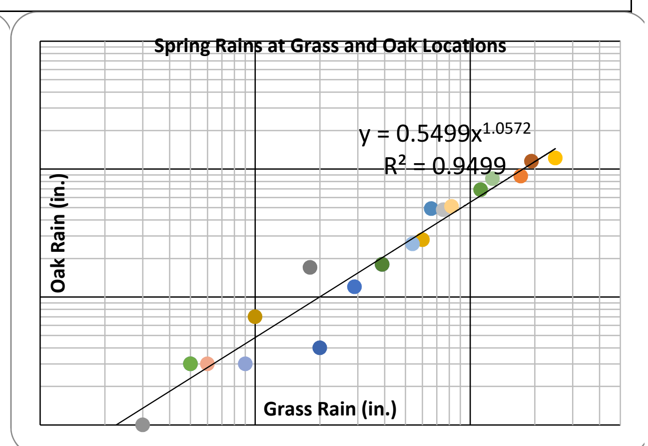
Winter pine log10 total rain (in.) = 1.07 Winter grass log10 total rain (in.)



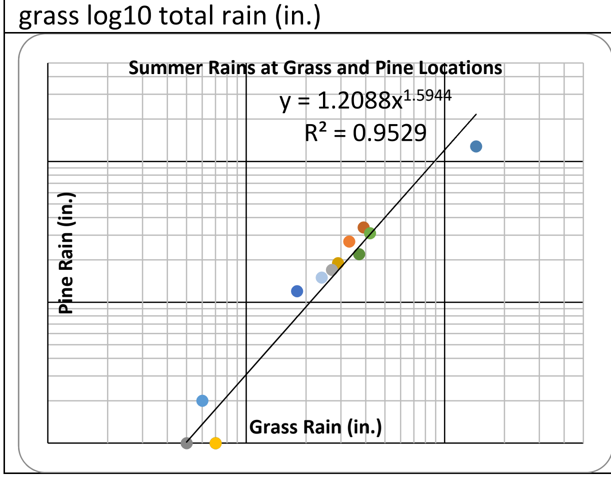
Winter oak log10 total rain (in.) = - 0.203 + 1.17 Winter grass log10 total rain (in.)

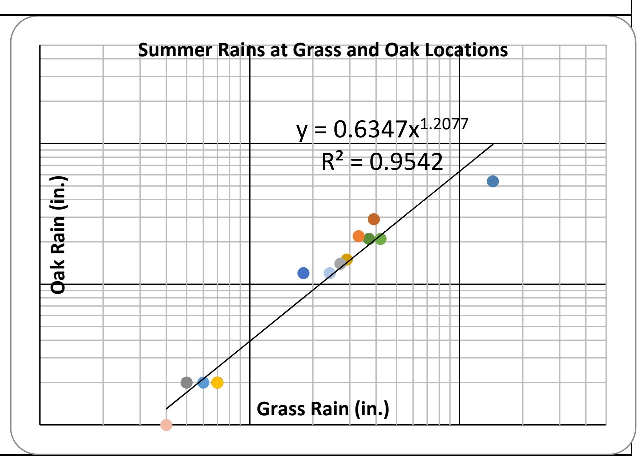


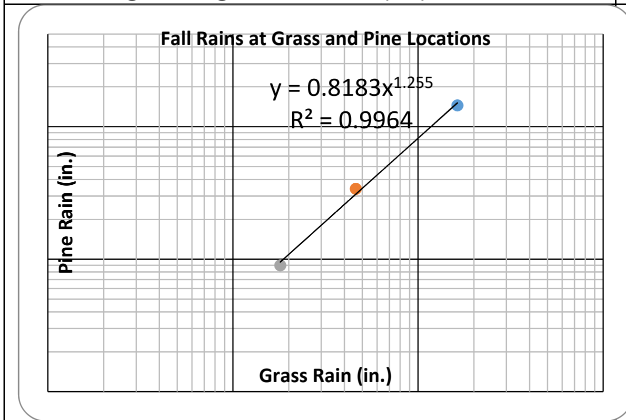
Spring pine log10 total rain (in.) = 1.26 Spring grass log10 total rain (in.)



Spring oak log10 total rain (in.) = - 0.260 + 1.06 Spring grass log10 total rain (in.)





Summer pine log10 total rain (in.) = 1.51 Summer grass log10 total rain (in.)	Summer oak log10 total rain (in.) = - 0.215 + 1.17 Summer grass log10 total rain (in.)
 Fall pine log10 total rain (in.) = -0.0871 +1.255 fall grass log10 total rain (in.)	

Algorithm Summary

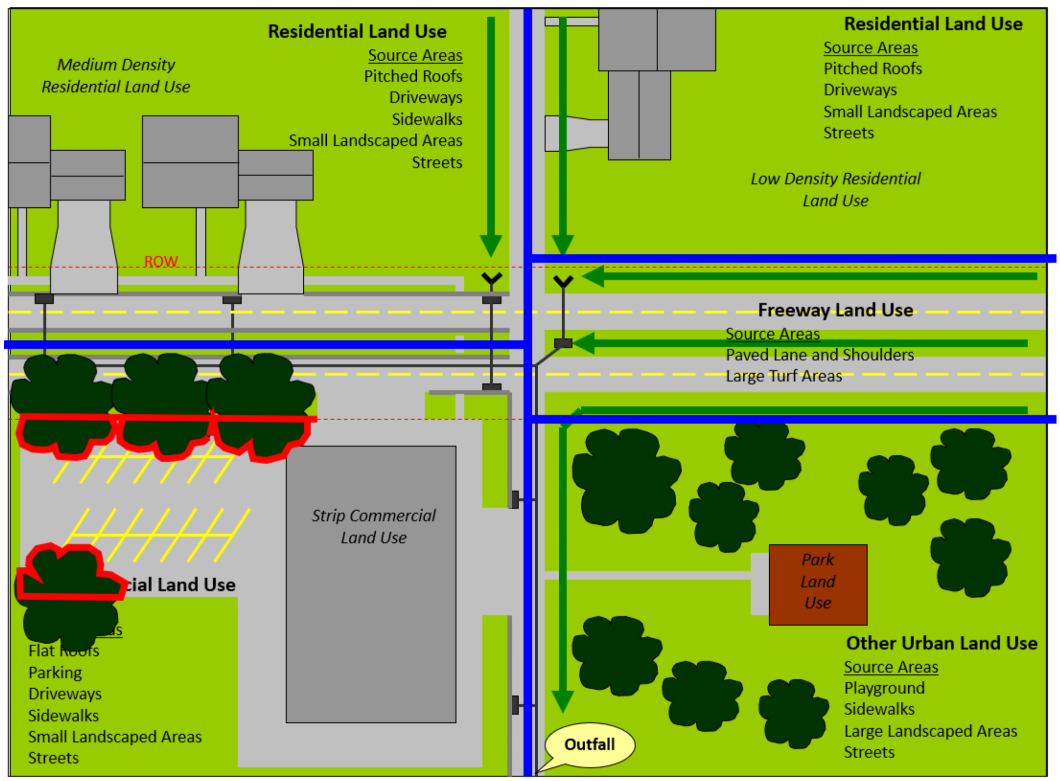
Literature reviews (a selection of references are included in the attached bibliography section) have concluded that the interacting mechanisms of urban trees affecting urban hydrology are poorly understood. Past canopy throughfall measurements of urban trees have identified important differences between tree types. Projected runoff volume reductions due to extensive use of urban trees have been found to be about 10 to 20% for developed urban areas. Field studies have also concluded that stemflow is usually a small portion of the total tree runoff yield to runoff (usually <10% of the canopy throughfall). Soil characteristics under urban trees are also expected to affect understory runoff yields, with trees maintaining good soil structure (decreased compaction and increased organic matter) that enhance infiltration of the throughfall.

As shown above, highly significant regression equations relating rain depth and throughfall were developed for conifer and deciduous trees for the different seasons for implementation in WinSLAMM. As noted previously, tree interception effects on throughfall in stormwater management is only relevant for newly planted trees that shade directly connected impervious areas. Counting the benefits of existing trees in a calibrated model likely would result in double-counting the benefits. Also, the benefits of new trees shading uncompacted soils during small and intermediate rains are likely small as the throughfall would likely be almost completely infiltrated, as would the total rainfall for these areas. During large rains, the canopy interception fraction is much reduced, also resulting in minimal differences in runoff compared to uncompacted soil areas having no trees. WinSLAMM was therefore modified to directly calculate the benefits of trees over directly connected impervious areas, as shown in the following section.

Tree Canopy Data Entry into WinSLAMM

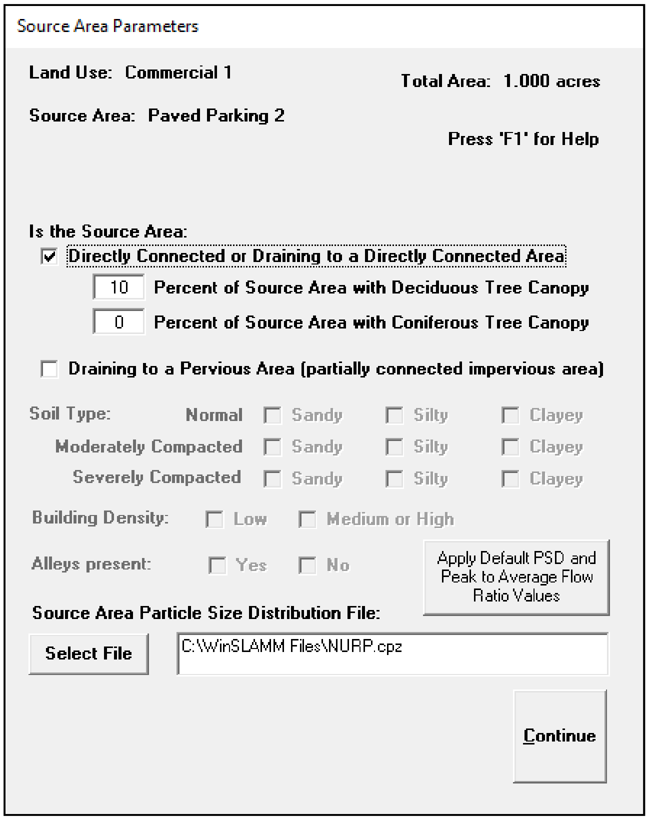
The WinSLAMM user can enter tree canopy data, which is the percent of the source area with a deciduous and/or a coniferous tree canopy, for the source areas that are directly connected or that drain to a directly connected area. You cannot enter tree canopy information for pervious areas because these areas already include some tree canopy cover as part of the runoff coefficients developed for these source areas, as described earlier.

Below is a conceptualization of a set of land uses. The strip commercial land use has tree areas that overhang the parking area that are outlined in red. The percentage of these overhang areas would be, for this example, the value for each tree type that is entered into the source area form to represent the tree canopy coverage over an impervious area. The trees in the park and the trees shading pervious areas in the strip commercial area have little direct runoff reduction benefit as the rain falling on those areas without trees would be beneficially impacted by infiltration into the soils and not significantly contribute to runoff for the small and intermediate rains most affected by rainfall interception by the trees.



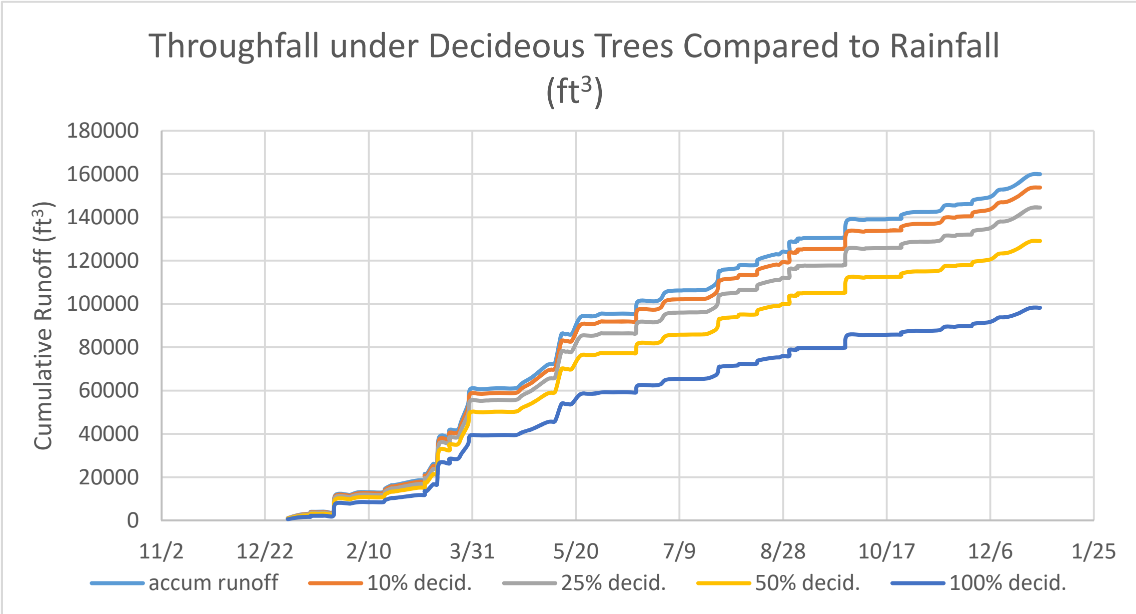
Tree canopy interception shading over directly connected impervious areas (shown in red outline).

The following screen shot of a paved parking area in WinSLAMM shows how the tree canopy shading values are entered for directly connected areas.



Paved parking area information input screen.

The following plot shows modeled cumulative runoff for one year of rains for Birmingham, AL, for a one-acre paved parking area having varying amounts of shading by tree canopies. With 100% shading, the deciduous trees may provide about 35% reductions in runoff from the paved area. The benefits are linear, with half this maximum benefit with 50% canopy shading, for example. A similar plot for conifers would show much smaller benefits, especially for the early months of the year. The maximum benefit of shading of impervious areas by conifer trees are about half of the canopy interception benefit of the oak tree. Areas having more low intensity and smaller rains would have greater runoff benefits associated with tree interception.



There relatively low runoff reduction values are in contrast with rural forested areas where the runoff amounts of heavily wooded areas (both conifers and deciduous trees) is very small. These major forest benefits are mostly associated with the forest duff (thick layers of partially and completely decomposed organic material) beneath the trees and large infiltration rates through uncompacted natural soils. In urban areas (especially for thinly planted or isolated trees, if relatively young and with common leaf removal by homeowners), the benefits of trees on underlying soils is important, but much reduced compared to thick stands of mature trees having deep layers of organic material covering the soil. Duff has no effect on paved areas, although it may build up near the trunk in tree planter boxes or other small areas. Therefore, the main benefit of urban trees on urban hydrology is the limited canopy rainfall interception.

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R. Pitt, J. Voorhees
1 May 2023

Catchbasins and Hydrodynamic Devices

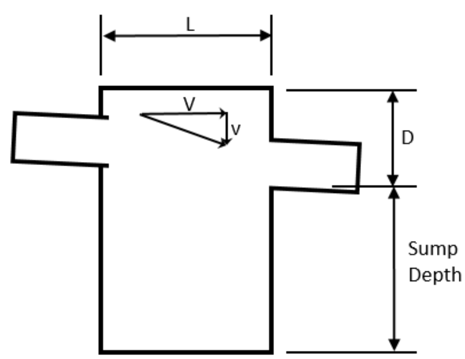
Overall Performance

Catchbasins have been found to be effective in removing pollutants associated with coarser runoff solids (Pitt 1985). Large reductions in total and suspended solids (up to 45% reductions for low gutter flows) were indicated by a number of prior studies (such as Pitt 1979, Aronson, et al. 1983, and Pitt 1985). However, relatively few pollutants are associated with these coarser solids (Pitt 1979 and Pitt 1985). Pitt (1985) found that catchbasins will accumulate sediments until the sediments reach up to about 0.3 m (1 ft) below the catchbasin outlet, or about 60% of the sump capacity for typical catchbasins. After that level, the sediment is at an equilibrium, with scour balancing new deposition. Scour of previously deposited sediment below this critical depth is not likely (Pitt 1979, Avila, et al. 2007, and Avila 2008).

General Description

Catchbasin and hydrodynamic device performance is calculated by assuming flow through a quiescent settling area. 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 most common for most stormwater particles), or Newton's law (for turbulent flow for very large particulates). The path of the settling particles is the vector sum of the particle velocity through the device and the settling velocity of the particle. It is assumed (and verified by field monitoring) that particles settling to the device bottom before the outlet zone is reached are captured in the device. Therefore, if the water velocity is slow, slowly falling particles can be retained. If the water velocity is fast, then only the heaviest (fastest falling) particles are likely to be retained. In catchbasins and hydrodynamic devices, the water velocity is normally large during rain events, reducing fine stormwater particle capture.

The critical ratio of water velocity to particle settling velocity must therefore be equal to the ratio of the device length (L) to depth to the bottom of the outlet (D), as shown in equation (1) and the illustration below.



(1) $$\frac{V}{v} = \frac{L}{D}$$

The water velocity is equal to the water volume discharge rate Q, such as measured by cubic feet per second) divided by the device cross-sectional area (a = depth x width: DW, in equation (2):

(2) $$V = \frac{Q}{a}$$ or $$V = \frac{Q_{out}}{DW}$$

The outflow rate equals the inflow rate under steady state conditions. The critical time period for steady state conditions is the time of travel from the inlet to the outlet. For larger control practices such as wet detention ponds, during critical portions of a storm, the inflow rate (Q_{in}) will be greater than the outflow rate (Q_{out}) due to freeboard storage. Therefore, the outflow rate controls the water velocity through the pond. However, because the storage volume is small for catchbasins or hydrodynamic devices, we assume no freeboard storage and the outflow rate equals the inflow rate. Substituting this definition of water velocity into the critical ratio to results in equation (3):

(3) $$\frac{Q_{out}}{DWv} = \frac{L}{D}$$

and cancel D to get:

(4) $$\frac{Q_{out}}{Wv} = L \quad \text{or} \quad \frac{Q_{out}}{v} = LW$$

- L = Pond Length
- D = Outlet Depth
- V = Water Velocity through Pond
- v = Settling Velocity
- Q_{out} = Outflow from Pond
- *a* = Pond Cross Sectional Area

However, device length (L) times device width (W) equals device surface area (A). Substituting leaves:

(5) $$\frac{Q_{out}}{v} = A$$

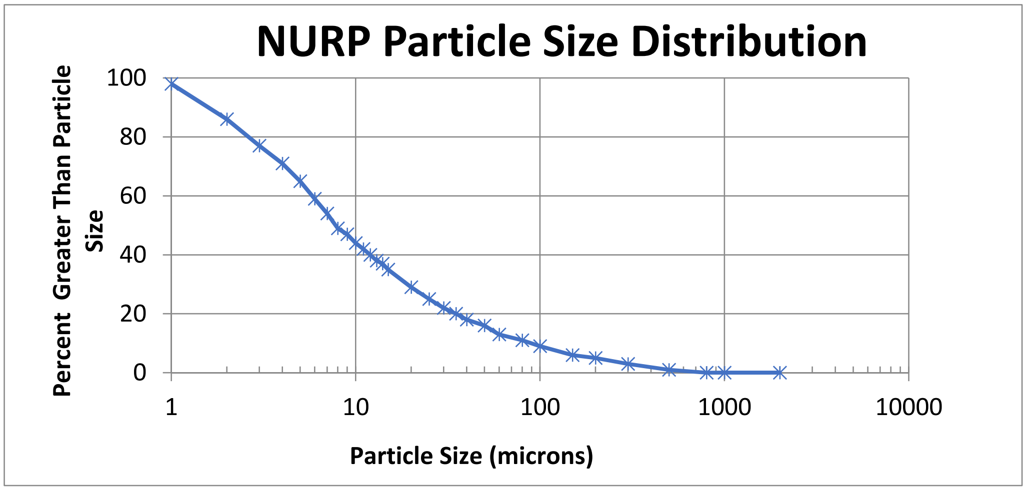
Solving for the settling velocity results in the conventional surface overflow rate (SOR) equation:

(6) $$v = \frac{Q_{out}}{A}$$

- L = Device Length
- D = Outlet Depth
- V = Water Velocity through Pond
- v = Settling Velocity
- Q_{out} = Outflow from Device
- *a* = Device Cross Sectional Area

Therefore, for an ideal sedimentation device, particles having settling velocities greater than this settling velocity will be removed. Only increasing the surface area or decreasing the device outflow rate will increase pond settling efficiency. Increasing the device depth decreases the possibility of sediment scour. Additional depth (below the 0.3 m minimum depth needed for sediment capture) is also needed to provide sacrificial storage volumes for sediment between cleaning operations.

Since the settling velocity increases as particle size increases (using Stokes or Newton's law and appropriate shape factors, specific gravity and viscosity values), the device water quality performance (or percent removal) is determined from the particle size distribution of the solids in the runoff entering the pond. This is done by determining the settling velocity and then calculating the particle size associated with that settling velocity, which is referred to as the critical particle size. The percent of the particles that will settle is then determined from the particle size distribution of the total suspended solids (TSS) concentration of the sediment in the stormwater runoff. An example particle size distribution is shown below (NURP, National Urban Runoff Program, particle size distribution) which is, used for stormwater runoff evaluations in Wisconsin.



For catchbasins and hydrodynamic devices, for each time step WinSLAMM determines the upflow velocity, which is a function of the device area (which is constant) and the inflow rate of the device. WinSLAMM then calculates the particle size that would settle, based upon Stokes (or Newton's) Law, for the calculated upflow velocity. It uses the particle size distribution to map the percent of the particles that are equal to and greater than that calculated particle size to determine the percent removal for that time step. For each storm event, the model calculates the flow weighted percent reduction for each time step to determine the overall percent reduction for that storm event

Calculation Process

The calculation flow chart for catchbasins and hydrodynamic settlers is below, where:

V = Volume

M = Mass

C = Concentration

inf – Influent

eff - Effluent

bypass – Device Mass or Volume bypass, determined by maximum flow rate through the inline sump

WtdTSRed = Weighted Total Solids Reduction fraction due to Settling

Q = Flow

Timestep – Calculation time period, determined by user

botloss – Loss through Device Bottom

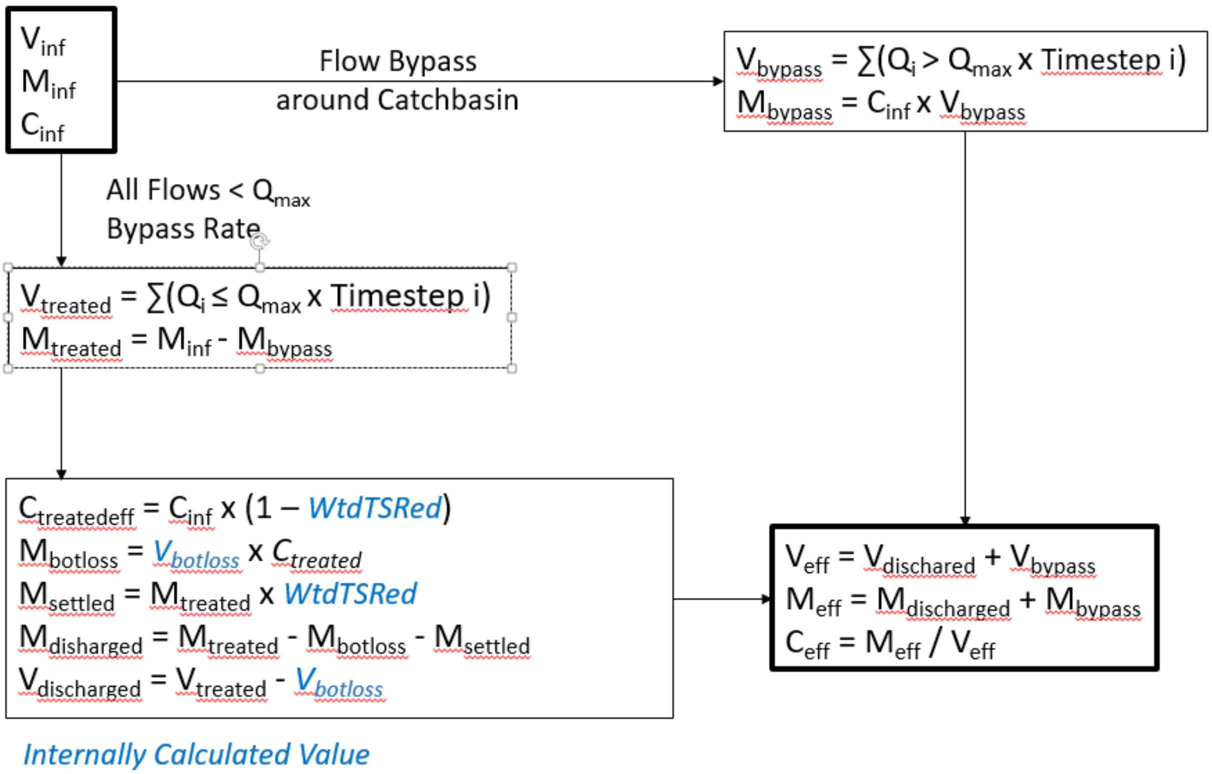
treated – Volume or mass flowing through device that can be treated

$V_{botloss}$ = Volume Lost through Device Bottom

$M_{botloss}$ = Mass Lost through Device Bottom

M_{set} = Mass Settled in Device

Catchbasin and Hydrodynamic Device Calculation Flow Chart



Note that bottom losses, or leakage, are typically very small because the surface area is very small compared to the volume of water flowing through the device.

Device Scour

WinSLAMM calculates sediment capture using Stokes (and Newton's) Law settling as described above. This method has been shown to work well for typical catchbasins and hydrodynamic devices, as reflected during actual performance monitoring. However, sediment capture assumes that there is at least one foot of standing water over the top of the sediment to prevent turbulence-induced scour, as observed during monitoring projects (Pitt 1979, Pitt and Bissonnette 1984, and Avila 2008). WinSLAMM calculates the stored sediment from each rainfall event. Once the level of sediment is less than one foot below the elevation of the lowest outlet invert, WinSLAMM will stop calculating sediment capture until catchbasin is cleaned.

Two protection mechanisms were identified by Avila (2008) when conducting scour tests in catchbasins: the overlaying water depth and an armoring layer. The overlaying water depth protects the sediment surface from the first impact of the plunging water jet. However, if the overlaying water layer is not present, the plunging water jet has enough energy to scour the sediment material directly below it. Then, due to the high shear stresses generated by the first water impact, all particle sizes (large and small) are suspended. Consequently, a *"washing machine effect"* occurs with the suspended sediment while the plunging water jet retreats upward because of the air buoyancy. The washing machine effect consists of the preferential removal of fine material from the suspension of the whole mixture, leaving a layer of large particles on the sediment surface that form the armoring layer. The overlaying water serves as a protection mechanism against scour if armoring is not present.

Lamella Plates or Tube Settlers

This option, which is more commonly used in Hydrodynamic Separators, allows you to model the increased settling efficiency that occurs when the device uses lamella plates or settling tubes. When you select this option, WinSLAMM increases the effective surface area of the device by the number of plates or tubes that a vertical line will intersect. This occurs for each time step when the flow through the device is laminar. Laminar flow is assumed if the Reynolds number is less than 2100. When the Reynolds Number is >2100 (non-laminar flow), there is no additional benefit from the plates or tubes and only the physical surface area of the device is used in the calculations. The Reynolds number is determined from the water velocity through the tubes (and so varies with flow), the kinematic viscosity of the water, and the tube diameter or distance between lamella plates. For more information, see Clark, et al, 2006.

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