R. Pitt
February 5, 2023

WinSLAMM Production Functions for use with SERDP Spreadsheets

Contents

Summary

This report presents a set of stormwater control production functions that describe the effectiveness of various stormwater controls, depending on set factors (size of control device, geographical location, and soil infiltration rates, for example). These are used in conjunction with the previously prepared spreadsheet models that identify the relative contributions of stormwater runoff volume and particulates from different source areas to calculate the expected benefits of the controls for desired conditions. The resulting runoff and particulate discharges can then be used with the particulate strengths and filtered concentrations of the pollutants (heavy metals, PAHs, and PFAS compounds) monitored during the current SERDP project to determine the discharge characteristics of the pollutants.

These calculations were prepared using continuous rain histories from three locations representing different areas of the US: San Diego, CA; Everett, WA, and Norfolk, VA. Obviously, these do not cover all conditions, but were selected to illustrate a range of situations throughout the country and the areas represented in the stormwater pollutant source identification spreadsheets previously prepared for the Navy for use at their facilities. WinSLAMM was used for these production function analyses and the prior source identification spreadsheets.

The spreadsheet tools can be used to identify the most important sources of the runoff and particulate solids at a site. After the sources of the contaminants are identified, it is possible to select candidate stormwater controls that can treat the stormwater from the identified most significant sources. The following are the controls used in developing these production functions, and the source or outfall locations where they can be used:

Sedimentation Controls:

- Wet detention ponds (total mixed land use area)
- Hydrodynamic separators (paved areas)

Proprietary Media Filter Controls:

- Contech StormFilter™ (paved areas)

Infiltration and Media Controls:

- Rain gardens (roofs)
- Biofilters (paved areas)
- Porous pavement (paved areas)
- Curb-cut bioflters (paved streets)
- Green roofs (evapotranspiration) (roofs)

Public Works Controls:

- Street cleaning (paved streets)

- Grass swales (total mixed land use area)

WinSLAMM is used to evaluate the practices through engineering calculations of the unit processes based on typical designs and sizes of the controls specified to determine how effectively the stormwater controls remove runoff volume and particulates. This information enables a stormwater manager to estimate the approximate area needed to provide the level of stormwater control desired. These production functions presented here are only suitable for single controls, as it is not possible to combine the effects from multiple devices at the same area using these production functions. Multiple controls and combinations of controls at source areas, drainage systems, and outfalls require the use of WinSLAMM to correctly calculate the benefits of complex combinations of controls as it tracks particle size distributions, concentrations, and hydrographs through the drainage and stormwater control system.

Brief Description of WinSLAMM

WinSLAMM is a stormwater quality model used in developed urban areas. It was developed to evaluate stormwater runoff volume and pollutant loadings using small/intermediate storm hydrology concepts (in contrast to conventional drainage design approaches that focus on very large storms). The model determines the runoff based on local rain records and calculates runoff volumes and pollutant loadings from each individual source area within each land use category for each rain. Examples of source areas include roofs, streets, paved storage areas, loading docks, small landscaped areas, large landscaped areas, sidewalks, and parking lots.

The model can use any length of rainfall record as determined by the user, from single rainfall events to several decades of rains, depending on the available computer memory. The rainfall files used in these calculations are for three general areas representing some of the different EPA rain zone areas and the data clustering in the National Stormwater Quality Database (NSQD). Rain files representing these areas that were used in these calculations included: San Diego, Everett, and Norfolk. These rain files were developed from hourly data obtained from NOAA data at the main airport near these cities. WinSLAMM can be used to examine a selection of stormwater control practices, including water tanks for stormwater irrigation, pavement and roof disconnections, roof rain gardens, green roofs, infiltration/biofiltration in parking lots and as curb-cut biofilters, street cleaning, wet detention ponds, grass swales and grass filters, porous pavement, catchbasins, media filters, hydrodynamic devices, and selected proprietary devices. The model evaluates the practices through engineering calculations of the unit processes based on the actual designs and sizes of the controls specified and determines how effectively these practices remove runoff volume and pollutants. The calculated benefits of the controls have been calibrated based on data from many stormwater research projects that have been conducted in different locations of the country.

The regional calibrations relied on data contained in the National Stormwater Quality Database which was started by Pitt's research group at the University of Alabama in collaboration with the Center of Watershed Protection in 2001. It began by compiling the results of Phase I NPDES Municipal Separate Sewer Storm Systems (MS4), and has been expanded to include new MS4 data, along with results from special stormwater studies. The database was recently transferred to the International Stormwater BMP

Database web site. Version 4 of the NSQD 4 contains the results of about 9,100 storm sampling events, from about 600 sampling locations throughout the country. The NSQD is now housed with the International BMP Database at: http://www.bmpdatabase.org/nsqd.html. A full explanation of the model's capabilities, calibration, functions, and applications is at http://www.winslamm.com/select_documentation.html.

The most accurate representation of stormwater quality and treatment benefits would be associated with a model that is calibrated for site conditions. Site calibrations of WinSLAMM (which were then used in the source identification spreadsheet for the Navy) were based on extensive monitoring at selected naval facilities in the three areas. The particulate strengths and filtered concentrations to be used with these prior spreadsheets and these new production functions are from the recent SERDP monitoring activities at many locations in the southwest and northwest.

Production Functions Describing Expected Performance of Different Applications of Stormwater Controls

Production functions are normalized curves that graphically illustrate relationships between the "size" of stormwater controls and their expected performance. The following sections of this report briefly describe how WinSLAMM calculates the performance of the controls (unit processes) and shows the data input screens. These are prepared for each of the three geographical regions corresponding to the three source identification spreadsheets previously prepared. As noted, these graphs are only suitable for individual or parallel controls and not for serial (treatment trains) use of controls. The information presented here is to assist stormwater managers with initial sets of information; more detailed analyses with a locally calibrated WinSLAMM model can be used for many combinations of source, drainage system, and outfall controls. Additional models, such as SWMM, are also likely to be needed when detailed hydraulic analyses and drainage design are needed.

The following table shows the locations where the source area production functions can be used in the watershed. The source area categories are the same as used in the source identification spreadsheets where these production functions will be applied. As noted on the table, and in the following stormwater control sections in this report, the production functions can only be applied in parallel, as they do not consider the joint performance associated with treatment trains. Therefore, only a single control can be used in each category. As an example, there are two roof categories (flat and pitched) and each can be different. Green roofs are most readily applied to flat roofs, while rain gardens can be used for pitched roof runoff (and can be used in both categories, if desired). Porous pavement is only shown for sidewalks, driveways, and paved parking areas, as they are not recommended for storage areas due to groundwater contamination potential. Some of the controls (wet ponds, hydrodynamic devices, Contech StormFilter, and street cleaning only directly affect particulate solids concentrations, and have no effect on runoff volume. An alternative to source area stormwater controls would be outfall or drainage system controls. Outfall wet detention ponds and grass swales are in this category, and only one of these controls can be used, and no source area controls if either of these are selected. WinSLAMM can be used if combinations of source area, drainage system, and outfall controls need to be examined. The main purposes of the spreadsheets are to identify the most significant pollutant sources in the watershed and to examine potential stormwater controls.

Select either total area outfall/drainage system control or source area controls	Select only one of these controls for source category		Select only one of these controls for source category				Select only one of these controls for source category		Select only one of these controls for source category	
Source Areas	**Outfall wet pond**	**Grass swales**	**Hydrodynamic device**	**Contech StormFilter™**	**Biofilters**	**Porous pavement**	**Rain gardens**	**Green roofs**	**Curb-cut biofilters**	**Street cleaning**
Roofs flat							runoff vol only	runoff vol only		
Roofs pitched							runoff vol only			
Paved parking			part solids conc only	part solids conc only	runoff vol and part solids conc	runoff vol only				
Driveways/loading dock			part solids conc only	part solids conc only	runoff vol and part solids conc	runoff vol only				
Sidewalks			part solids conc only	part solids conc only	runoff vol and part solids conc	runoff vol only				
Streets - with curb and gutters									runoff vol and part solids conc	part solids conc only
Light laydown paved storage areas			part solids conc only	part solids conc only	runoff vol and part solids conc					
Moderate laydown paved storage areas			part solids conc only	part solids conc only	runoff vol and part solids conc					
Heavy laydown paved storage areas			part solids conc only	part solids conc only	runoff vol and part solids conc					
Total study area	part solids conc only	runoff vol and part solids conc								

The following tables are examples of how the production functions can be used with the prior source identification spreadsheets to estimate the overall runoff volume and pollutant reductions. The initial calculations examine runoff and particulate solids characteristics for the site with various controls. The results of these calculations are then used to calculate the expected outfall concentrations and mass discharges of a wide range of heavy metal, PAH, and PFAS stormwater pollutants, based on the current SERDP monitoring of these constituents at San Diego area and Puget Sound Naval Shipyards, and at Lubbock.

These tables lay out the calculation steps using the source identification spreadsheet data and the production functions. The runoff volume discharges (ft^3/yr) and source area runoff contributions (%) along with the particulate solids mass discharges (lbs/yr) and source contributions (%) for each source area and for the overall drainage area are obtained from the source identification spreadsheets for the drainage area conditions (source area characteristics and location). These examples are from the southwest (San Diego) source identification spreadsheet and the production functions selected in these examples were also based on this location and also assume a soil infiltration rate of 0.5 in/hr.

The source area or outfall/drainage system controls are then selected for trial (including their "size" and soil characteristics, as needed). The percent runoff volume and particulate solids concentration reductions (noted in orange on these tables) are from the production functions graphs. The appendix of this report shows each production function with regression equations (ln, exponent, or linear polynomial forms). Most of the equations have excellent fits and can be directly programmed into the spreadsheets to automate the process. A few of the production functions had poor regression fits and my require look up tables and interpolations in the final spreadsheet. The rest of these tables show the calculation steps. These tables are from a new spreadsheet attached to this report to better understand the calculation processes. These are just examples and can be modified for more efficient calculations.

The percent contributions from each source area should be used to identify the most suitable locations for source controls. In this example, there are substantial unpaved storage and landscaped areas that would not have any source area controls. About 47 percent of the total runoff and 32 percent of the particulate solids mass could be affected by source area controls. The areas having the largest contributions are the paved parking and street areas, so these were selected for controls, with porous pavement covering 30 percent of the parking area and the streets having curb-cut biofilters of 3 percent of the street area. These resulted in about 20 percent reductions in the total runoff volume and about 16 percent reductions in particulate solids mass discharges. The resulting outfall particulate solids concentrations slightly increase due to infiltration of source runoff that had lower concentrations than most of the areas.

Drainage system or outfall control treatment is an alternative to the source area controls examined above. These control locations can potentially treat all of the drainage area flows from the area. In the example shown below, a wet pond having a normal water surface about two percent of the total drainage area was selected. In these production functions, wet ponds only affect particulate solids concentrations as any pond water losses from evaporation or seepage were assumed to be negligible. This control option resulted in zero runoff reductions, but with a high 86 percent particulate solids mass discharge reduction.

Source Area Controls

	selected controls in source area	SW indus total runoff (ft3/yr) from source ID spreadsheet	total runoff (L/yr) unit conversions	indus source area runoff as a % of total indus area runoff from source ID spreadsheet	percent runoff volume reduction for source control from production functions	runoff volume after controls (L/yr)	percent runoff sources after controls
Roofs flat - connected		1,146	32,459	0.22	0.0	32,459	0.3
Roofs flat - disconnected		1,340	37,955	0.26	0.0	37,955	0.3
Roofs pitched - connected		7,619	215,772	1.48	0.0	215,772	1.9
Roofs pitched - disconnected		5,635	159,581	1.10	0.0	159,581	1.4
Paved parking-connected		10,337	292,745	2.01	0.0	292,745	2.5
Paved parking-disconnected	porous pvt (30%)	59,722	1,691,337	11.62	100.0	0	0.0
Driveways/loading dock -disconnected		2,441	69,134	0.47	0.0	69,134	0.6
Sidewalks - disconnected		616	17,458	0.12	0.0	17,458	0.1
Streets - with curb and gutters	curbcut biofilters (3%)	67,666	1,916,303	13.16	64.0	689,869	5.9
Landscaping areas /undeveloped areas (silty soils)	NA	7,238	204,978	1.41	0.0	204,978	1.8
Landscape/undeveloped areas compacted silty soils	NA	814	23,059	0.16	0.0	23,059	0.2
Light laydown paved areas- connected		23,058	652,992	4.49	0.0	652,992	5.6
Moderate laydown paved areas - connected		3,312	93,792	0.64	0.0	93,792	0.8
Light laydown unpaved - disconnected	NA	129,898	3,678,707	25.27	0.0	3,678,707	31.6
Moderate laydown unpaved - connected	NA	136,154	3,855,870	26.49	0.0	3,855,870	33.1
Other galvanized materials paved- disconnected		57,059	1,615,918	11.10	0.0	1,615,918	13.9
Overall total by land use	NA	514,056	14,558,060	100.00	0.0	11,640,289	100.0
					% vol reduction:	20.04	

	SW indus part solids mass (lbs/yr) from source ID spreadsheet	indus source area part solids mass as a % of total indus area part solids from source ID spreadsheet	part solids mass (mg/yr) unit conversions	part solids conc (mg/L) mass/vol calc	percent part solids conc reduction for source control from production functions	part solids conc after controls (mg/L)	flow-weighted conc calc
Roofs flat - connected	5	0.05	2,202,545	67.9	0.0	67.9	0.2
Roofs flat - disconnected	6	0.06	2,624,479	69.1	0.0	69.1	0.2
Roofs pitched - connected	35	0.39	15,809,521	73.3	0.0	73.3	1.4
Roofs pitched - disconnected	27	0.29	12,050,695	75.5	0.0	75.5	1.0
Paved parking-connected	226	2.52	102,819,209	351.2	0.0	351.2	8.8
Paved parking-disconnected	1,305	14.50	592,590,914	350.4	0.0	350.4	0.0
Driveways/loading dock - disconnected	25	0.28	11,441,020	165.5	0.0	165.5	1.0
Sidewalks - disconnected	3	0.04	1,464,477	83.9	0.0	83.9	0.1
Streets - with curb and gutters	129	1.43	58,357,340	30.5	68.0	9.7	0.6
Landscaping areas /undeveloped areas (silty soils)	338	3.75	153,390,204	748.3	0.0	748.3	13.2
Landscape/undeveloped areas compacted silty soils	96	1.07	43,669,419	1,893.8	0.0	1,893.8	3.8
Light laydown paved areas-connected	445	4.95	202,189,521	309.6	0.0	309.6	17.4
Moderate laydown paved areas - connected	82	0.91	37,292,246	397.6	0.0	397.6	3.2
Light laydown unpaved - disconnected	2,779	30.86	1,261,445,735	342.9	0.0	342.9	108.4
Moderate laydown unpaved - connected	2,928	32.53	1,329,380,222	344.8	0.0	344.8	114.2
Other galvanized materials paved-disconnected	574	6.37	260,409,403	161.2	0.0	161.2	22.4
Overall total by land use	9,003	100.00	4,087,136,950	280.7	0.0		295.8 mg/L
			4,087	kg/yr			
							3,442,911,460 mg/yr = 3443 kg/yr

Outfall or Drainage System Control for Total Mixed Land Use Area	**selected controls at outfall or drainage system**	**SW indus Total runoff (ft3/yr) from source ID spreadsheet**	**total runoff (L/yr) unit conversions**	percent runoff volume reduction for outfall from production functions	runoff volume after controls (L/yr)
Total area	wet pond (2%)	514,056	14,558,060	0.0	14,558,060
				0% vol reduction	

	SW indus part solids mass (lbs/yr) from source ID spreadsheet	**part solids mass (mg/yr) unit conversions**	part solids conc (mg/L) mass/vol calc	percent part solids conc reduction for outfall control from production functions	part solids conc after controls (mg/L)
Total Area	9,003	4,087,136,950	280.7	86.0	39.3 mg/L
		4,087	kg/yr		
					572,199,173 mg/yr = 572 kg/yr
					86% part solids mass reduction

The following table lists the constituents monitored during the current SERDP project at locations in San Diego, Puget Sound, and Lubbock. The data were combined into treatment categories and evaluated by particle size (except for PFAS compounds that did not have particle size data). The particulate strength and filtered concentration data for the sites were combined to obtain overall average conditions for these calculations.

Heavy Metals	PAHs (Polycyclic aromatic hydrocarbons)	PFAS compounds (perfluoroalky and polyfluoroalkyl substances)
Cr	Naphthalene	PFPeA
Mn	2-methylnaphthalene	PFHxA
Ni	1-methylnaphthalene	PFHpA
Cu	2-ethylnaphthalene	PFOA
Zn	1-ethylnaphthalene	PFDA
As	2.6-dimethylnaphthalene	PFUdA
Cd	1.3-dimethylnaphthalene	PFNA
Pb	2-isopropylnaphthalene	PFOS
Hg	acenaphthylene	6:2 FTS
	1.2-dimethylnaphthalene	
	1.8-dimethylnaphthalene	
	acenaphthene	
	2.3.5-trimethylnaphthalene	
	fluorene	
	1-methylfluorene	
	phenanthrene	
	anthracene	
	2-methylphenanthrene	
	2-methylanthracene	
	1-methylphenanthrene	
	9-methylanthracene	
	2-ethylanthracene	
	fluoranthene	
	pyrene	
	9.10-dimethylanthracene	
	2-tertbutylanthracene	
	1-methylpyrene	
	benzo(a)anthracene	
	chrysene	
	benzo(b)fluoranthene	
	7.12-methylbenz(a)anthracene	
	benzo(k)fluoranthene	
	benzo(e)pyrene	

	benzo(a)pyrene	
	perylene	
	Indeno(123-cd)pyrene	
	Dibenzo(ah)anthracene	
	benzo(ghi)perylene	
	total PAHs	

The following is an excerpt from the attached spreadsheet that shows resulting outfall concentrations and mass discharges for some of the heavy metals. These can be calculated for untreated conditions and for various treatment scenarios for comparison. The unfiltered untreated concentrations are affected by the runoff volume changes with controls, while the particulate strength values are used with the particulate solids concentrations to calculate the particulate pollutant mass discharges and concentrations. These are then combined with appropriate unit conversions to obtain total concentrations, along with the filtered and particulate pollutant mass discharges and concentrations.

	Cr	Mn	Ni	Cu	Zn
Filtered inlet water concentration (< 0.45 µm), µg/L	1.4	32.8	5.2	70.5	161.0
Total concentration, µg/L	6.5	63.6	10.9	135.1	373.3
Total particulate pollutant strength (> 0.45 µm), mg/kg	129	785	146	1,642	5,402
Total mass discharge, kg/yr	0.09	0.93	0.16	2.0	5.4
% filtered form of pollutant	22.2	51.5	47.6	52.2	43.1
% particulate form of pollutant	77.8	48.5	52.4	47.8	56.9

Production Functions for Total Mixed Land Use Area

The production functions for the wet detention ponds and the grass swales were prepared using a mixed land use area and are only applicable to the total area. Only one of these controls can be used, as the production functions cannot be used simultaneously for the same flows. Similarly, none of the source area controls can be used in conjunction with either of these total area controls, as these total area controls are based on receiving the untreated full runoff amounts and particulate solids loads from the whole area. WinSLAMM, of course, can be configured using many combinations of source area, drainage system, and outfall controls as it tracks the flows and pollutants from the upland sources through the downslope controls and modifies the runoff characteristics with each subsequent treatment stage. The following sections briefly describe these two total area mixed land use controls and presents the corresponding production functions.

The following table summarizes the total mixed land use characteristics used for these calculations. This area is based on one of the monitored mixed land use areas at the Naval Base San Diego base monitored during the first phase of the SERDP project and represents typical mixed use areas for these production functions. Again, WinSLAMM should be used for alternative development characteristics, as needed. The spreadsheet models can use varying characteristics of different land uses and the source area production functions can be applied to the source area calculations. However, the total area controls shown here needed a single representative mixed land use area for the production function calculations for the outfall wet ponds and grass swale drainage systems.

Source area	acres	
Flat roofs	3.81	Directly connected
Flat roofs	0.18	Directed to moderately compacted silty soils
Pitched roofs	1.30	Directly connected
Pitched roofs	1.36	Directed to moderately compacted silty soils
Paved parking	4.15	Directly connected
Paved parking	2.27	Directed to moderately compacted silty soils
Unpaved parking (heavily compacted)	0.78	Directed to moderately compacted silty soils
Driveways	0.52	Directed to moderately compacted silty soils
Sidewalks	0.32	Directly connected
Streets	4.91	50 ft wide, intermediate texture
Large landscaped areas	8.80	Normally compacted silty soils
Other pervious areas	4.02	Normally compacted silty soils
Other impervious areas	0.17	Directly connected
Total area	32.59	

Wet Detention Pond at Outfall of Mixed Land Use Area

WinSLAMM replicates the physical processes occurring in wet detention pond stormwater controls. For example, the model uses the following information when calculating pond performance for each rain event:

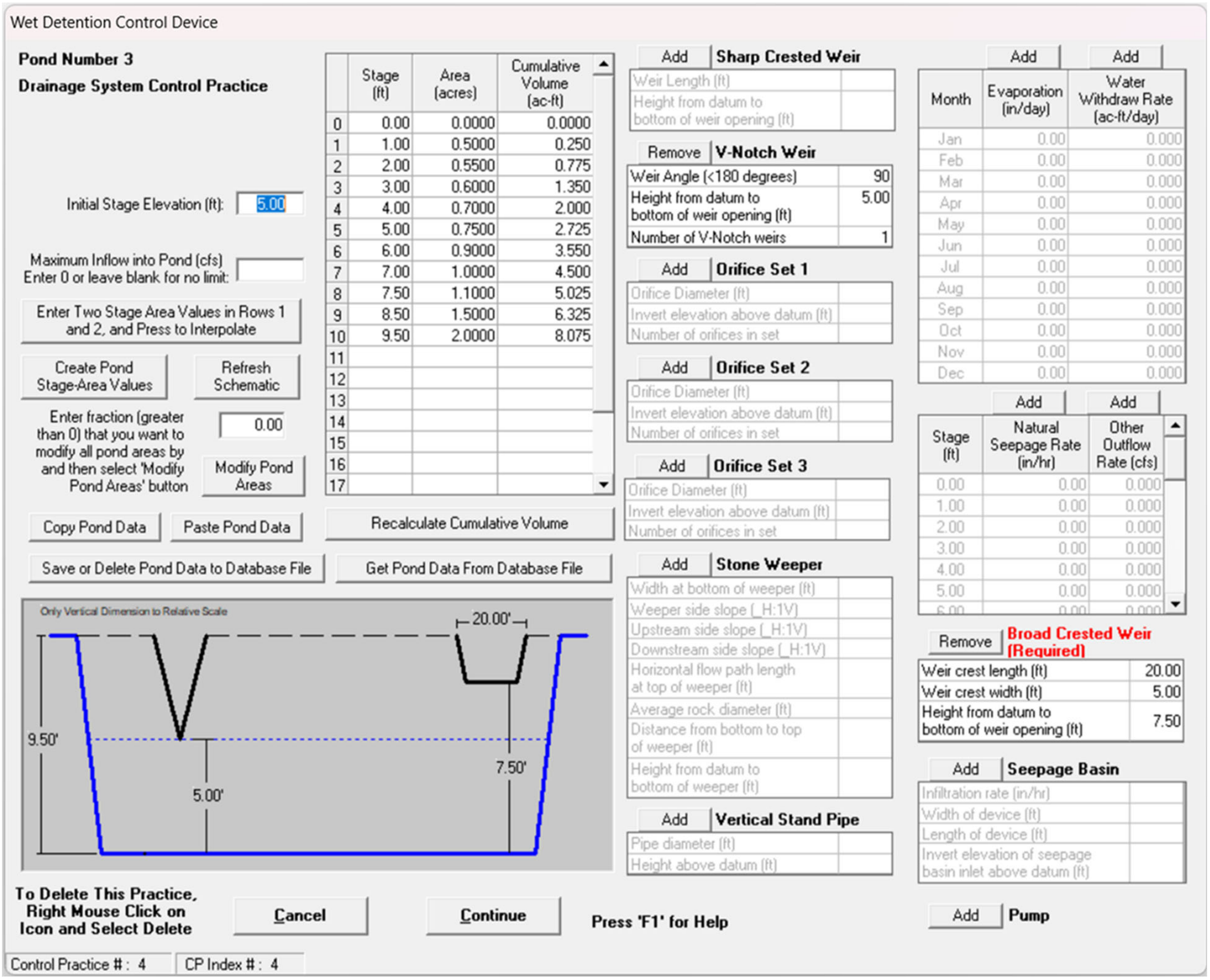
1. Runoff hydrograph, pollution load, and sediment particle size distribution from the drainage basin to the pond
2. Pond geometry (depth, area)
3. Hydraulics of the outlet devices
4. Particle settling time and velocity in the pond based on retention time

Stokes Law and Newton's settling equations are used in conjunction with conventional surface overflow rate calculations and modified Puls-storage indication hydraulic routing methods to determine the sediment amounts and characteristics that are trapped in a pond. It is important to note that WinSLAMM does not apply default percent efficiency values to a control practice. Each rainfall is analyzed, and the pollutant control effectiveness varies according to each rainfall and the pond's antecedent condition.

The following table indicates the basic input information used for these analyses. The evaluations are presented as a function of pond size, reflecting the area of the pond at its lowest elevation (lowest invert elevation, ignoring evaporation or seepage) compared to the paved drainage area. For the 32.59-acre mixed land use area examined for these analyses, this 0.75 acre wet pond (the surface area at the 5 ft normal water elevation) is about 2.3 percent of the paved drainage area (generally found to offer very good pollutant control for particulate pollutants). Other sized wet ponds were evaluated for the production functions by increasing or decreasing the areas at each stage. This basic design also has a live storage volume (water quality volume) associated with the expected runoff from a 1.25 inch rainfall. Two feet of sediment storage and three feet of scour protection are also provided. The emergency spillway has one foot of stage and an extra foot of freeboard is also provided.

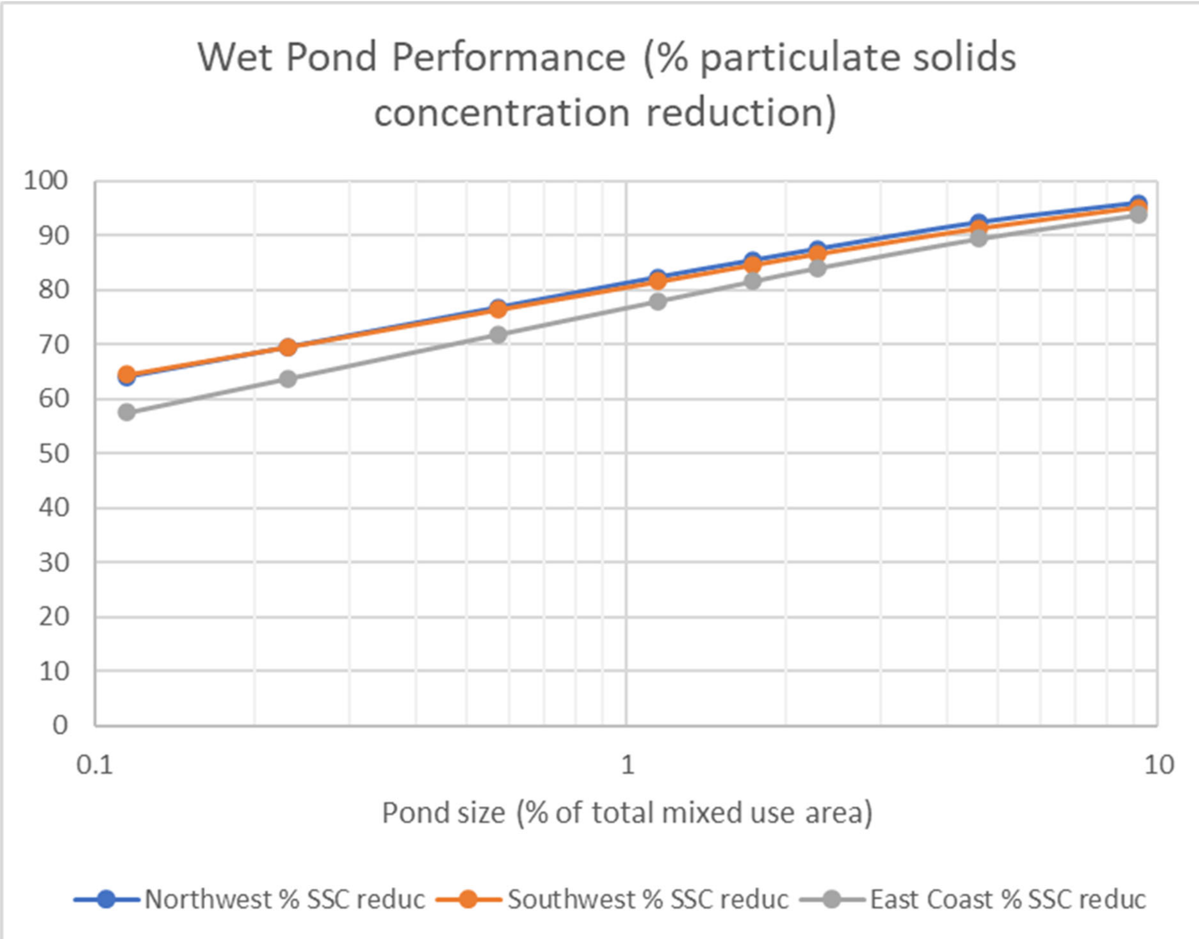
Stage (ft)	Cumulative area (acres)	Cumulative volume (ac-ft)	Notes
0	0	0	Pond bottom, bottom of sediment storage
1	0.5	0.25	
2	0.55	0.775	bottom of dead storage
3	0.6	1.35	
4	0.7	2	
5	0.75	2.725	bottom of water quality volume and invert of 90 degree V-notch weir
6	0.9	3.55	
7	1	4.5	
7.5	1.1	5.025	bottom of emergency spillway broad crested weir
8.5	1.5	6.325	
9.5	2	8.075	extra foot freeboard

The following is the input screen image for wet ponds with these values:



The pond must have at least 3 feet of standing water below the lowest invert for these removal equations to be valid because of potential sediment scour. If shallow, particulate sedimentation is linearly reduced from 3 feet to zero feet water depth below the lowest invert. There are eleven outlet device options for wet detention ponds which can be used together or individually, although a broad crested weir is always required: sharp crested weir, v-notch weir, broad-crested weir, vertical stand pipe, stone weeper, orifices, seepage basin, natural seepage, evaporation, and water withdrawal (such as for irrigation or firefighting).

The following production functions plot the expected performance of the ponds for three different geographical locations examined, showing calculated removals and effluent quality as a function of pond size. No water losses were considered for these calculations (no seepage or evaporation), so the production functions are only available for particulate solids concentration reductions.



Ponds about 3% of the paved drainage areas provide excellent performance (85 to 90% particulate solids concentration reductions) for these conditions. The lowest effluent concentrations are dependent on the particle size distributions and the fraction of the total pollutant forms that are in the filterable fraction. These characteristics can vary greatly for different conditions and even for different rains. Ponds in the northwest perform better than similar sized ponds in other locations (but almost identical to southwest ponds) due to the milder rain intensities and associated lower stormwater flow rates, for example. Therefore, these plots should be considered an approximation of expected conditions and illustrate the benefits of different sized ponds and the effects of different locations and rainfall patterns.

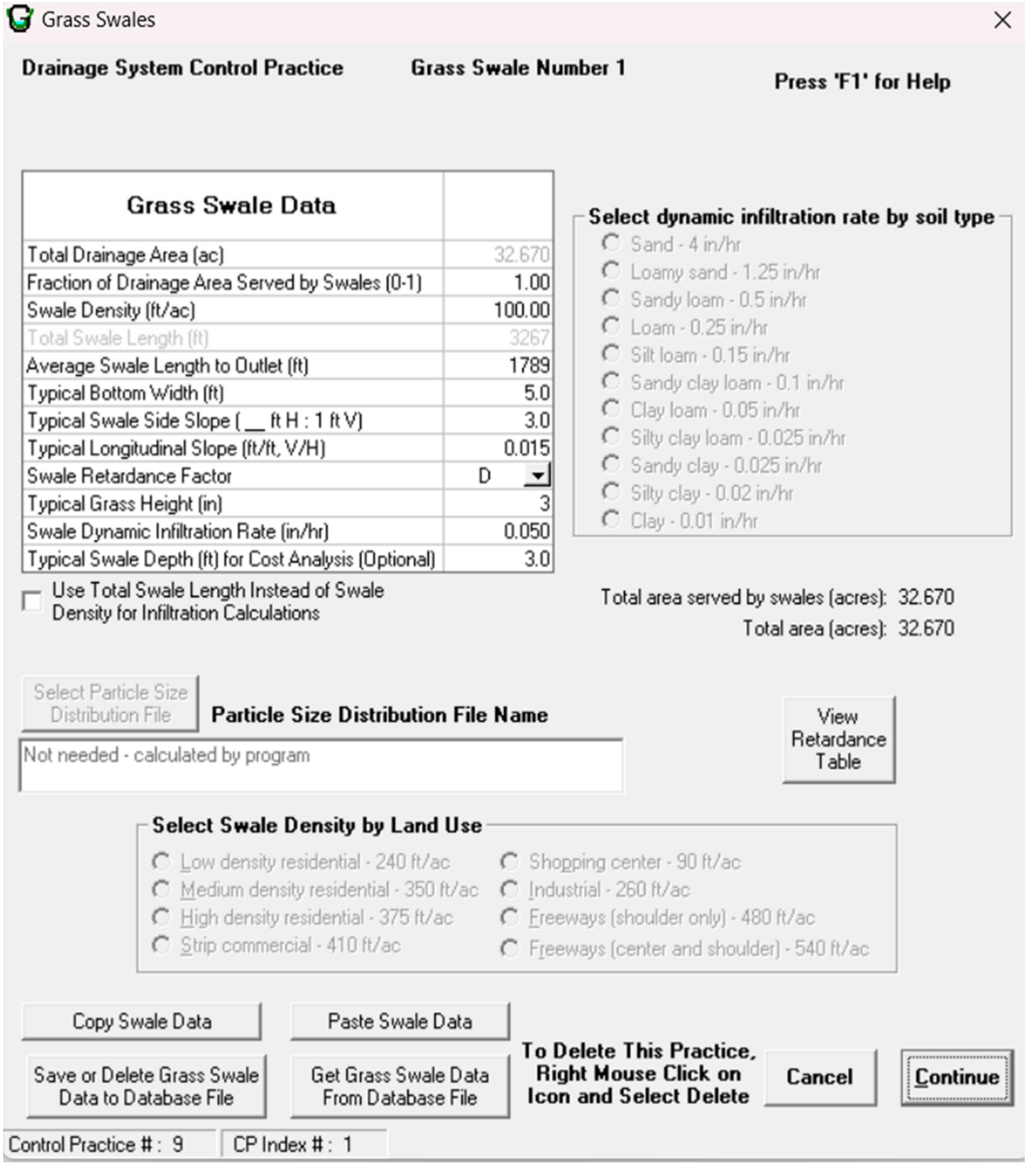
Grass Swales at Mixed Land Use Area

For the development of these production functions, grass swales are assumed to receive runoff from the entire mixed land use area and not from isolated source areas. As noted above, the production functions for either outfall wet detention ponds or grass swales can be used, not both simultaneously.

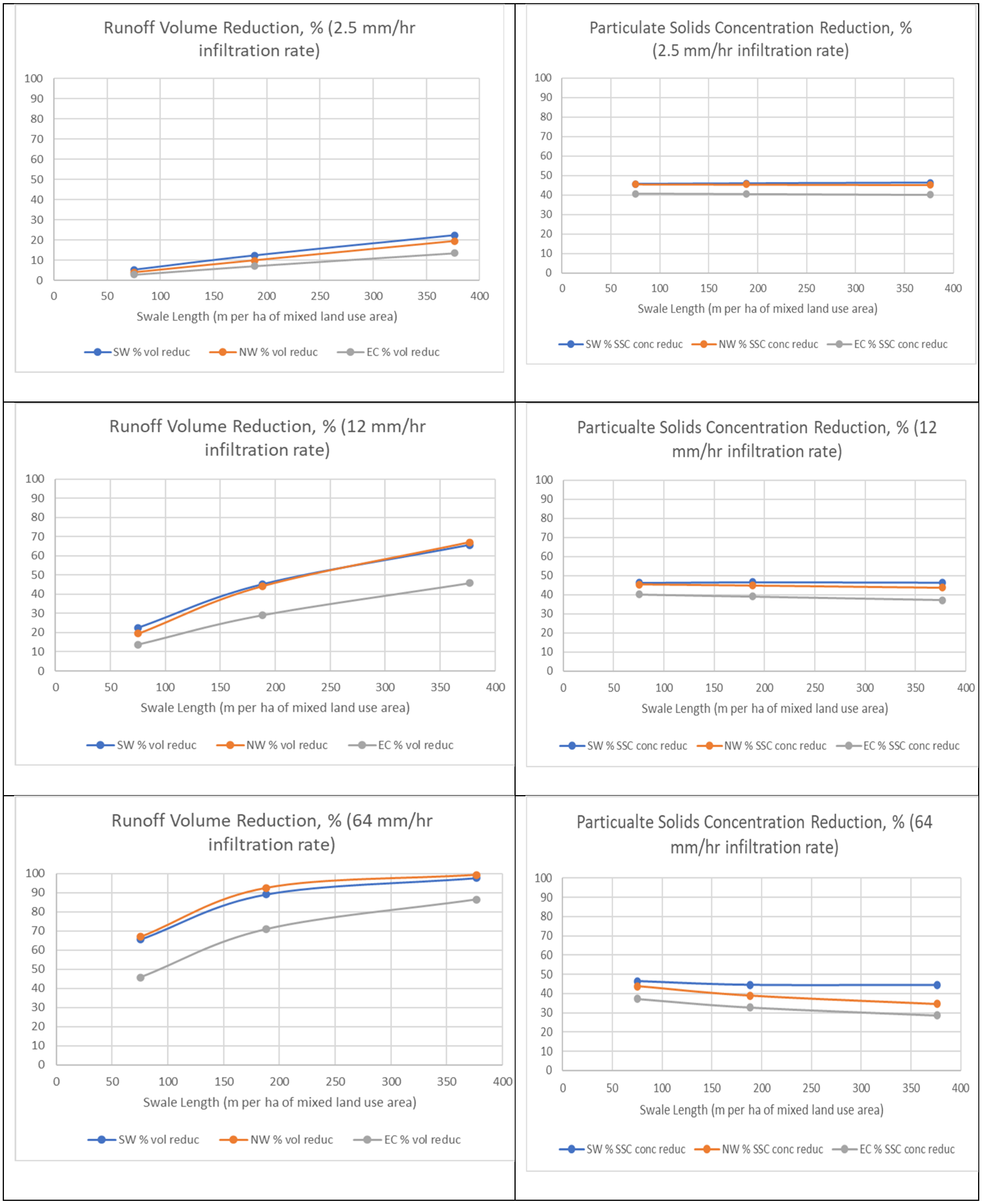
Under their most effective conditions, grass swales have shallow flows that are submerged in the grass. Under most conditions, the main pollutant removal mechanisms are through infiltration into the underlying soil and trapping of particulates as they settle in the flowing water. During deeper flows, particulate trapping is not as effective. The runoff infiltration is dependent on the wetted perimeter of the swale and the soil infiltration rate. If swales are along most of the roadways and with highly pervious soils, all of the runoff may be eliminated. For marginal soils, particulate trapping may be more important by removing particulate solids and particulate-bound pollutants which are then incorporated into the surface soils.

WinSLAMM determines the runoff volume reductions by calculating the infiltration losses for each calculation time step. The particulate reductions are based on the settling frequency of the particles entering the grassed area and the height of the grass relative to the flow depth. The grass "filters" the runoff using the settling frequency and the length of the flow path. The algorithms used to determine the Manning's n values were developed by Kirby, *et al.* (2005) as part of a WERF-supported research project (Johnson, *et al*. 2003). The particle trapping algorithms were based on research conducted by Nara, *et al*. (2006) and Nara and Pitt (2005), supported by the University Transportation Center for Alabama.

The data entry form for grass swales is shown below. The swales evaluated to develop the production functions had varying swale densities (ranging from 100 to 500 ft of swale per acre of drainage area), had 5 ft bottom widths with 3:1 side slopes and 0.015 longitudinal slopes. The grass height was 3 inches and with good grass densities. Production functions were developed for three different soil infiltration rates, corresponding to clay loam, loam, and loamy sand.



The following production functions show the expected performance of grass swales under these different geographical, soil, and design conditions. Typical industrial areas have roadside swale of about 260 ft/acre and medium density residential areas have about 350 ft/acre swale density. These production function plots show the runoff volume and particulate solids concentration reductions associated with these different conditions.



As expected, the grass swale performance improves (increased runoff volume and pollutant reductions) with increasing lengths per acre and increasing infiltration rates. For loam soil conditions, the runoff volume reductions range from about 20 to 70%, depending on geographical area (northwest with milder rains having larger benefits while the East Coast with more intense rains have less benefit). Benefits are much greater for soils having greater infiltration rates (40 to 100% for the same swale density as above for loamy sand soil), and less for soils having reduced infiltration rates (5 to 25% for clay loam soil). Particulate solids removals are very similar for all geographical areas, even though their concentrations vary greatly. Particulate solids control in grass swales is mostly determined by the particle size distribution (and the swale geometry). SSC removals of about 40 to 50% occur for all areas and soils when the swale densities are greater than about 100 ft/acre. This leveling off in performance is due to fine particles not being able to be permanently removed by the turbulent flows in the grass swales (resuspension and scour likely balances their deposition).

Other swale longitudinal slopes were also examined (ranging from 0.5 to 15%), but not shown here. Typical swale slopes (up to about 3%), had greater runoff volume removals than larger slopes (the larger slopes would be problematic due to instability of the swale lining as the shear stresses increase with increased slopes and are therefore rarely used). The different slopes had minor effects on particulate solids capture.

Production Functions for Paved Parking Lots and Storage Areas

This series of production functions are for stormwater controls that are used at paved parking and storage areas. Only one of these controls can be selected for each area category, and these cannot be used simultaneously with the outfall or drainage controls described above. Again, WinSLAMM can be used to consider many controls at various source areas and with drainage and outfall controls.

Hydrodynamic Devices at Paved Source Areas

Hydrodynamic devices can be used at paved source areas. These can range from catchbasins with sumps to hydrodynamic separators. In WinSLAMM, hydrodynamic device performance is calculated using standard surface overflow rate concepts based on the effluent flow rate and the surface area of the tank, coupled with Stoke's and Newton's particle setting equations. Additional features available in WinSLAMM for hydrodynamic devices include bypass options to divert large flows around the device to minimize mobilization of the captured sediment, and the optional use of lamella plates used to increase the effective surface area and associated settling. These are not included in these production functions.

The following is the WinSLAMM input screen for hydrodynamic devices showing the dimensions and selections used in preparing these production functions (the tanks surface areas varied from 10 to 200 ft^2 per paved drainage area).

The following production functions compare the performance of hydrodynamic devices for particulate solids concentration reductions. Typically sized hydrodynamic separators are intended to capture mostly grit and other large materials, and possibly as pre-treatment devices for other stormwater controls, such as the cartridge media filters. These production functions are only for particulate solids concentration reductions as no runoff volume reductions are associated with their use.

Hydrodynamic Device

First Source Area Control Practice
Hydrodynamic Device Number 6
Land Use: Commercial 36
Source Area: Paved Parking 1

Hydrodynamic Control Device General Information - Enter for Both Single Chamber and Proprietary Devices

Device Drainage Area (ac)	1.000
Fraction of Drainage Area Served by Device (0-1)	1.000
Number of Devices	1
Device Density (units/ac)	1.000

☐ **Model Hydrodynamic Device with Lamella Plates or Settling Tubes**

Fraction of device area with plates or tubes	
Average tube diameter or distance between plates (ft)	
Number of plates or tubes a vertical line will intersect	

For Device Cleaning, Select Either

Device Cleaning Dates

Device Cleaning No.	Device Cleaning Date (mm/dd/yy)
1	
2	
3	
4	
5	

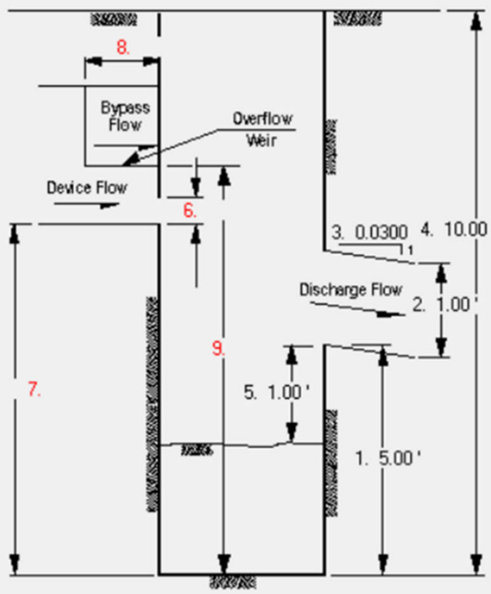
OR

☑ **Device Cleaning Frequency**

- ○ Monthly
- ○ Three Times per Year
- ○ Semi-Annually
- ● Annually
- ○ Every Two Years
- ○ Every Three Years
- ○ Every Four Years
- ○ Every Five Years
- ○ Never

Single Chamber Device Characteristics

1 - Average Sump Depth below Device Outlet Invert (ft)	5.00
Depth of Sediment in Device at Beginning of Study Period (ft)	0.00
2 - Typical Outlet Pipe Diameter (ft)	1.00
Typical Outlet Pipe Manning's n	0.014
3 - Typical Outlet Pipe Slope (ft/ft)	0.0300
Typical Device Sump Surface Area (sf)	200.0
4 - Device Depth from Sump Bottom to Street Level (ft)	10.00
Inflow Hydrograph Peak to Average Flow Ratio	3.8
5 - Minimum Allowable Scour Depth Below Outlet Invert (ft)	1.0
Maximum Flow to In-Line Sump (cfs)	N/A - Click to Activate
6 - Diameter of Orifice that Controls Flow to In-Line Sump (ft)	0.00
7 - Inflow Orifice Invert Elevation (ft)	0.00
8 - Length (ft) of Overflow Structure Acting as a Sharp-Crested Weir	0.00
9 - Elevation of Overflow Structure to Bypass In-Line Sump (ft above sump base)	0.00



☐ **Or Use Proprietary Hydrodynamic Control Device Information**

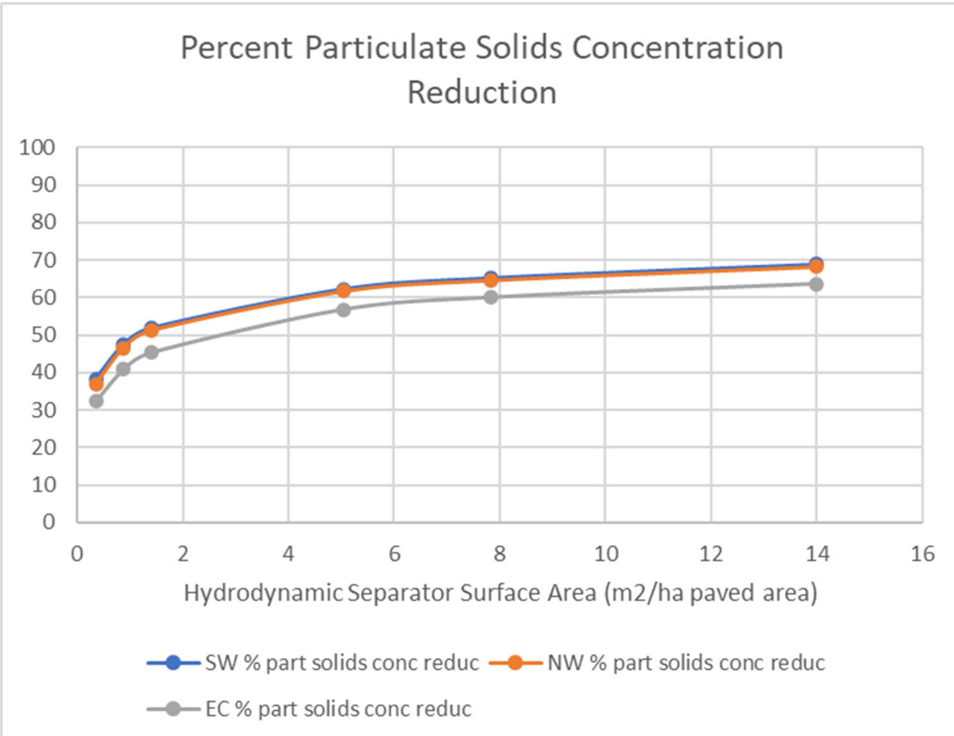
Manufacturer - Model

1 - Average Sump Depth below Device Outlet Invert (ft)	
Depth of Sediment in Device at Beginning of Study Period (ft)	
2 - Typical Outlet Pipe Diameter (ft)	
Typical Outlet Pipe Manning's n	
3 - Typical Outlet Pipe Slope (ft/ft)	
Inflow Hydrograph Peak to Average Flow Ratio	
5 - Minimum Allowable Scour Depth Below Outlet Invert (ft)	
Device Sump Surface Area (sf)	

Copy Hydrodynamic Device Data | Paste Hydrodynamic Device Data

Save or Delete Hydrodynamic Device Data to Database File | Get Hydrodynamic Device Data From Database File | Delete Control | Cancel | Continue

Control Practice # : 12 | Land Use # : 6 | Source Area # : 13



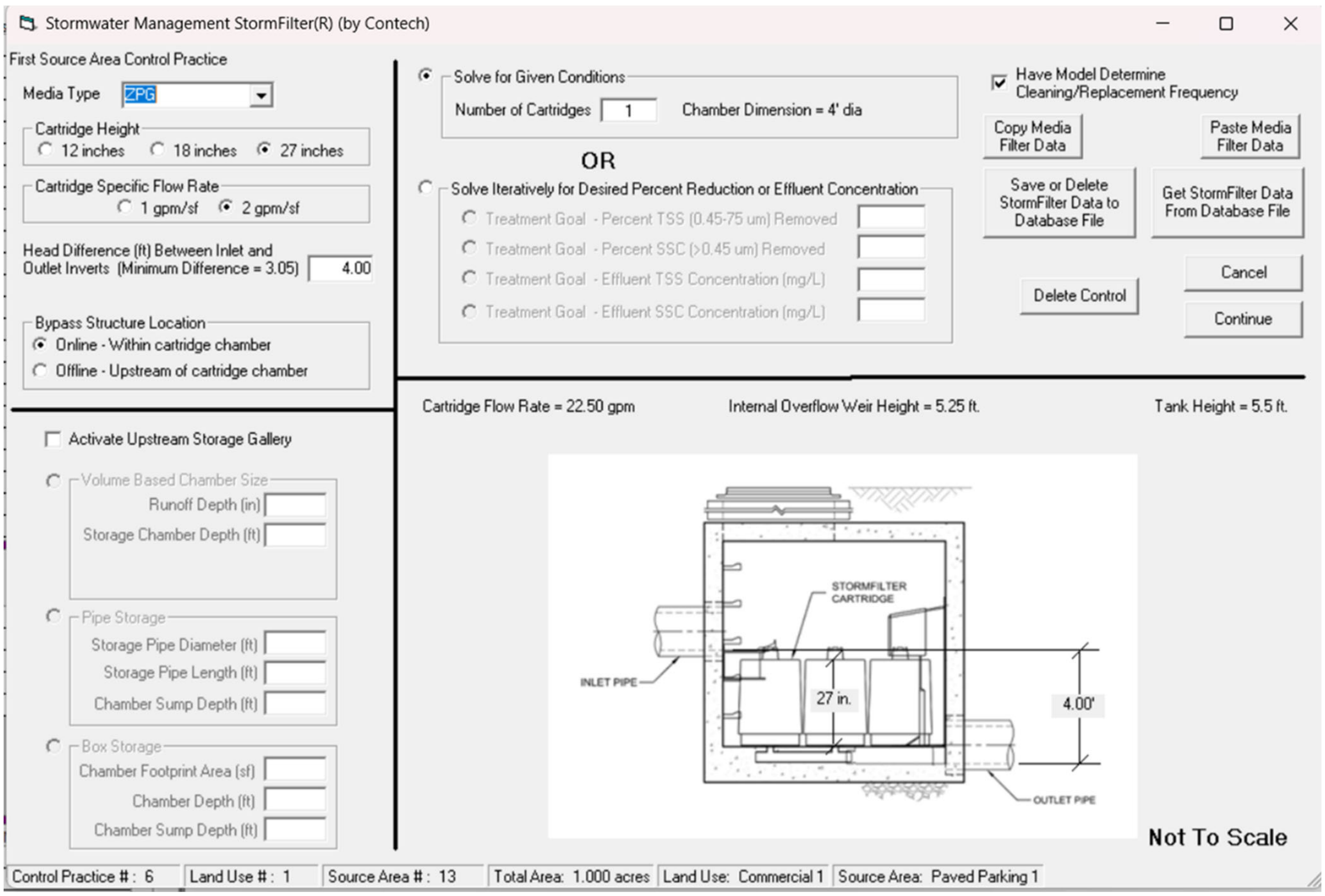
Contech StormFilter™ Proprietary Media Filters at Paved Source Area

The Contech StormFilter™ (http://www.conteches.com/Products/Stormwater-Management/Treatment/Stormwater-Management-StormFilter) has been available for many years as a proprietary stormwater treatment device incorporating various media. It has been used at many types and scales of locations, from treating runoff from small roofs to large paved areas. The StormFilter has undergone many laboratory and field evaluation performance tests for a variety of conditions, providing much performance information for its use in WinSLAMM.

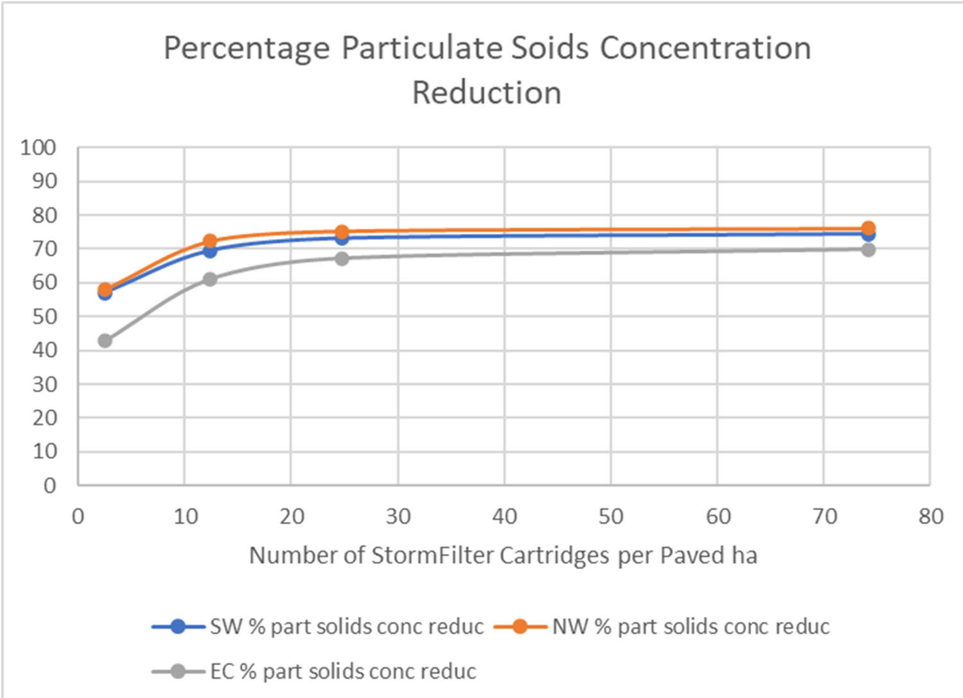
The stormwater treatment performance of the StormFilter is affected by many different factors, specifically including drainage area/rainfall characteristics and particle size distributions of the particulate solids, along with the fraction of the pollutants in filterable forms. The StormFilter system reduces particulate solids through both sedimentation in the cartridge chambers and by filtering in the cartridges themselves. The Contech StormFilter is described in WinSLAMM using many different options and routines. The production functions are simplified and are for the use of these cartridge filters at paved areas only.

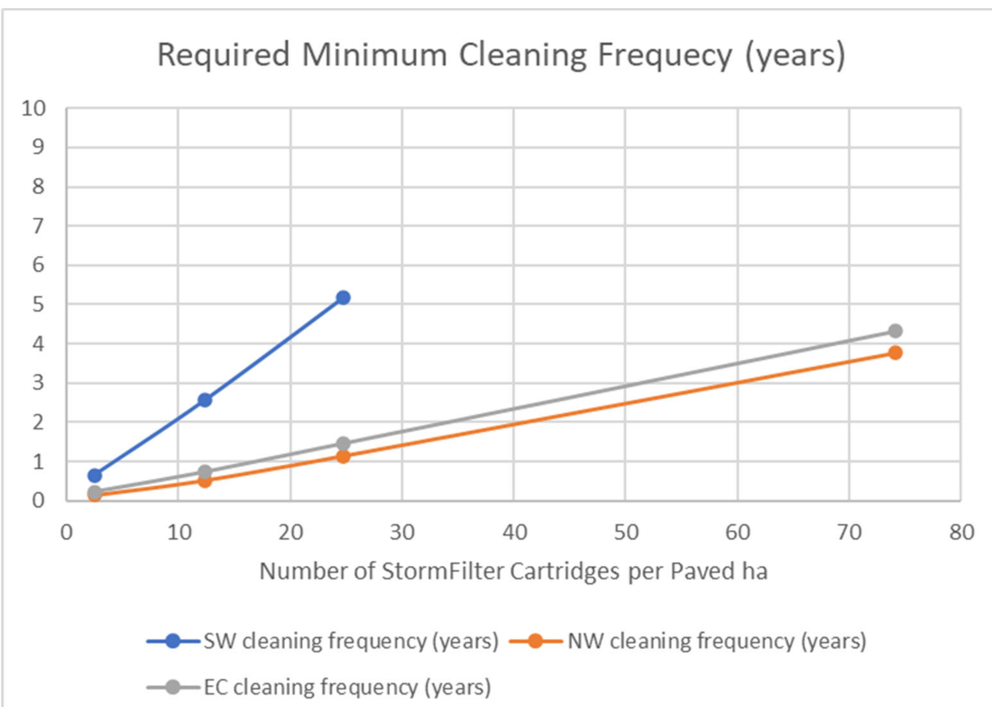
The following is the input screen for the StormFilter in WinSLAMM. For the production function calculations, the ZPG media was selected in 27 inch cartridges having 2 gpm/ft^2 flow rates. The model determined the cleaning frequency based on the accumulated sediment material in the vaults (the filter vault was cleaned before the sediment interfered with the filter operation). The following table shows the relationship between the number of cartridges used per acre and the corresponding tank size. The production function calculations examined 1, 5, 10, and 30 cartridges per acre.

# of cartridges per paved acre	1/ac	5/ac	10/ac	20/ac	40/ac
corresponding tank size	4 ft D = 12.5 ft^2	5 ft D = 20 ft^2	72 ft^2	112 ft^2	160 ft^2
tank size as a % of paved drainage area	0.03%	0.046%	0.17%	0.26%	0.37%



The following production functions illustrate the calculated performance of the StormFilters for particulate solids. The model examined the StormFilters for one acre of paved parking/storage areas in commercial areas (without unusual activities in the area). As stated previously, these are long-term average performance expectations and do not illustrate the storm-to-storm highly variable conditions. Also shown is a plot of the required minimum cleaning frequency needed to remove captured sediment before interference with the filter operation. These production functions are only for particulate solids concentration reductions as no runoff volume reductions are associated with their use.





These plots show that about 15 cartridges per hectare of paved drainage area are approaching the maximum levels of control. This is likely affected by the particle size distribution used in these calculations. The performance calculated are within the range of the levels of performance stated by the manufacture and certified by regulatory agencies. Increased numbers of cartridges per acre correspond to larger vaults and therefore require less frequent cleaning. Fifteen cartridges per acre would require cleaning frequencies of about once every one to three years.

Biofilters at Paved Source Areas

The WinSLAMM biofilter control is one of the most comprehensive tools in the model. It was recently updated (version 10.5) to include a wider range of treatment media supported by large amounts of laboratory and field monitoring data. This control option was used to represent several types of stormwater controls for the production functions in this report (biofilters at paved areas, street side curb-cut biofilters, rain gardens, and green roofs). This section describes the biofilters used at paved areas. These are more complex than rain gardens, as they usually have deeper excavations and are partially filled with a treatment media and may have underdrains. They also usually have substantially larger amounts of hydraulic storage in both surface impoundments and subsurface pore space storage, enabling better capture and treatment of stormwater flows (but at typically higher cost and maintenance) compared to rain gardens.

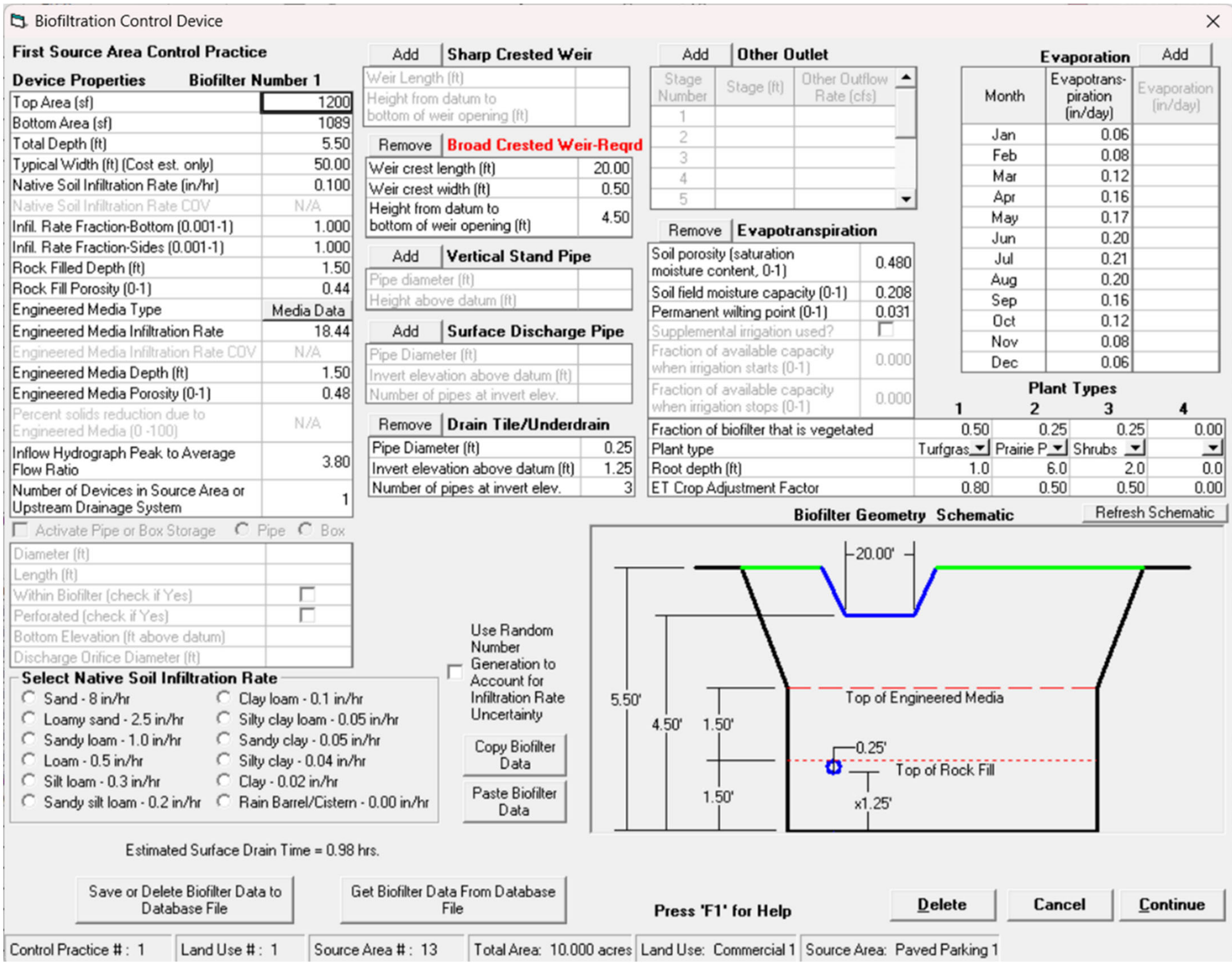
In WinSLAMM, biofilter performance is calculated using the characteristics of the flow entering the device, the infiltration rate into the native soil, the filtering capacity and infiltration rate of the treatment media fill if used, the amount of rock fill storage, and the sizes of the device and the outlet structures for the device. Pollutant retention by the treatment media (usually containing amendments) is based on the media type and the particle size distribution of the particulates in the inflowing water. If the treatment media flow rate is lower than the flow rates entering the device, the media will affect the device performance by forcing the excess water to bypass the device through surface discharges, if the storage capacity above the media is inadequate.

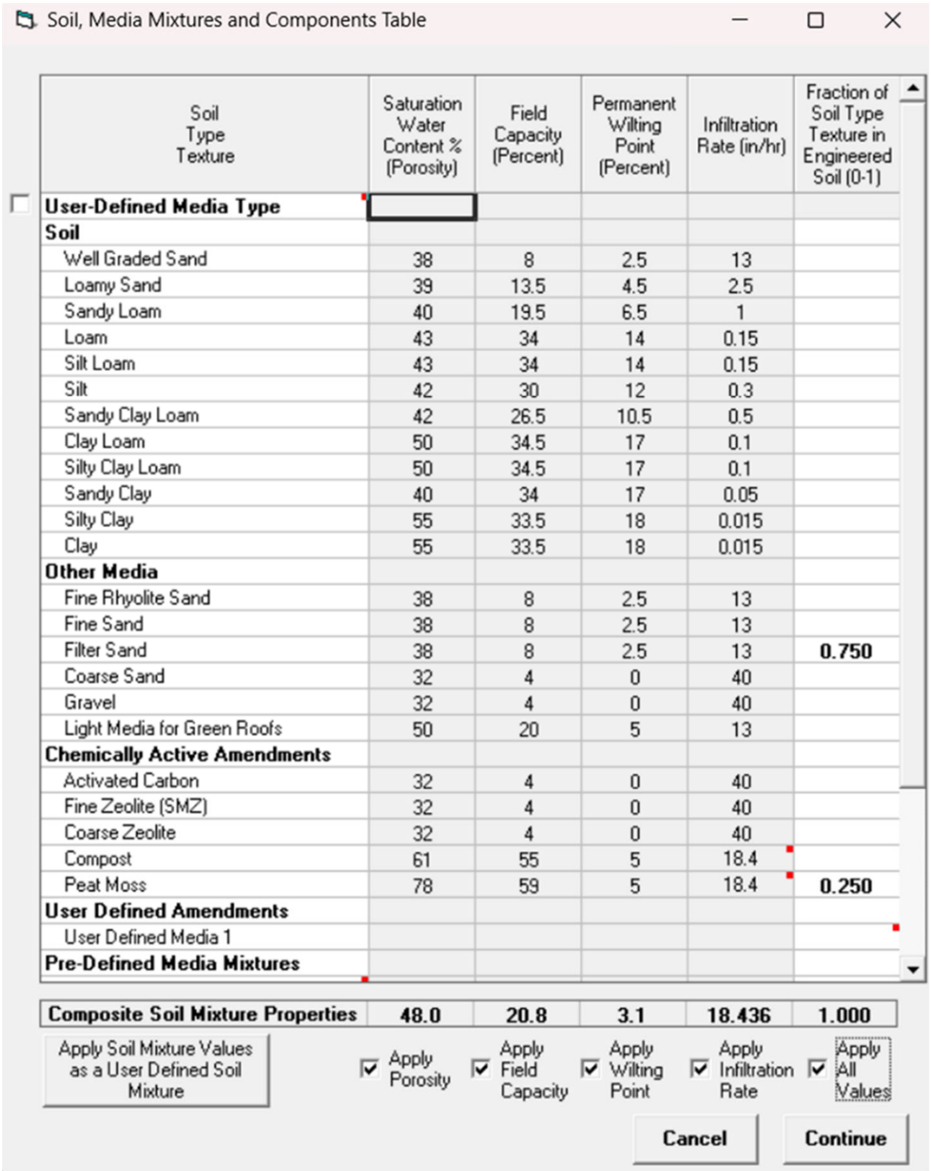
The device operation is modeled using the Modified Puls Storage-Indication method and is analyzed differently depending on whether rock storage and treatment media layers are in the model. WinSLAMM calculates the inflow and outflow hydrographs using a time interval selected by the user (typically 6 minutes), although this interval is reduced automatically by the program if the simulation calculations approach becoming unstable.

The inflow hydrograph is divided into the selected time intervals, which are routed to the surface of the biofilter. The biofilter is evaluated in two basic sections: the above ground section (or above the treatment media) and the below ground section (below the surface of the treatment media). If there is a rock layer and a treatment media layer, separate details are entered for each. The available surface outflow devices include broad crested weirs (required to have at least one as the surface overflow outlet), and optional crested weirs, vertical stand pipes, and evaporation/ET. An underdrain is also optional that discharges back to the drainage system (but with “filtered” water at a delayed time).

As water enters the device, the flow only enters the below ground section if the treatment media infiltration rate is greater than the inflowing water rate. If the inflow rate increases to be greater than the media infiltration rate, the above ground storage begins to fill. If the inflowing rate is high enough and the excess runoff volume exceeds the available storage, the water discharges from the device through the above ground surface broad crested weir outflow, and any other surface outlet. As water enters the below ground section of the device, it passes through the media and, as the bottom section fills, it may enter an underdrain (if used). All water that flows through the underdrain is treated by the media. The treatment performance changes according to the type of media selected and by the particle size of the particulates and the filtered pollutant concentrations in the water. If the water level in the below ground section of the device reaches the top of the treatment media layer, infiltration from the surface layer into the belowground layer stops until the water level in the below ground section is below the top of the media layer. If there are no rock and treatment media layers, flow into the native soil is considered to be an outflow: there is no below ground section, and all treatment by the device is assumed to be through volume loss by infiltration into the native soil and by evapotranspiration (this is the typical way rain gardens operate, since they have no media or underdrain, but do have surface storage).

The following are images of the input screens for biofilter devices. For developing the production functions for this device, 18 inches of the treatment media (75% filter sand and 25% peat) was placed on top of 18 inches of a coarse rock storage layer. An underdrain was placed near the top of the rock storage layer to maximize the benefits of the device by reducing underdrain short-circuiting potential if the underdrain was placed on the bottom of the rock fill. The native soil infiltration rates examined were 0.1 in/hr (clay loam soil), 0.5 in/hr (sandy clay loam soil), and 2.5 in/hr (loamy sand soil). Plants were used in the biofilter to better incorporate trapped sediment in the soil layers to improve maintenance issues, enhance aesthetics, soil structure, and evapotranspiration (50% turf grass, 25% prairie plants, and 25% shrubs). There was also a surface overflow to direct any excess flows out of the device.


Biofiltration Control Device
First Source Area Control Practice
Device Properties
Biofilter Number 1
Top Area (sf) 1200
Bottom Area (sf) 1089
Total Depth (ft) 5.50
Typical Width (ft) (Cost est. only) 50.00
Native Soil Infiltration Rate (in/hr) 0.100
Native Soil Infiltration Rate COV N/A
Infil. Rate Fraction-Bottom (0.001-1) 1.000
Infil. Rate Fraction-Sides (0.001-1) 1.000
Rock Filled Depth (ft) 1.50
Rock Fill Porosity (0-1) 0.44
Engineered Media Type Media Data
Engineered Media Infiltration Rate 18.44
Engineered Media Infiltration Rate COV N/A
Engineered Media Depth (ft) 1.50
Engineered Media Porosity (0-1) 0.48
Percent solids reduction due to Engineered Media (0 -100) N/A
Inflow Hydrograph Peak to Average Flow Ratio 3.80
Number of Devices in Source Area or Upstream Drainage System 1
Activate Pipe or Box Storage Pipe Box
Diameter (ft)
Length (ft)
Within Biofilter (check if Yes)
Perforated (check if Yes)
Bottom Elevation (ft above datum)
Discharge Orifice Diameter (ft)
Select Native Soil Infiltration Rate
Sand - 8 in/hr
Loamy sand - 2.5 in/hr
Sandy loam - 1.0 in/hr
Loam - 0.5 in/hr
Silt loam - 0.3 in/hr
Sandy silt loam - 0.2 in/hr
Clay loam - 0.1 in/hr
Silty clay loam - 0.05 in/hr
Sandy clay - 0.05 in/hr
Silty clay - 0.04 in/hr
Clay - 0.02 in/hr
Rain Barrel/Cistern - 0.00 in/hr
Add Sharp Crested Weir
Weir Length (ft)
Height from datum to bottom of weir opening (ft)
Remove Broad Crested Weir-Reqrd
Weir crest length (ft) 20.00
Weir crest width (ft) 0.50
Height from datum to bottom of weir opening (ft) 4.50
Add Vertical Stand Pipe
Pipe diameter (ft)
Height above datum (ft)
Add Surface Discharge Pipe
Pipe Diameter (ft)
Invert elevation above datum (ft)
Number of pipes at invert elev.
Remove Drain Tile/Underdrain
Pipe Diameter (ft) 0.25
Invert elevation above datum (ft) 1.25
Number of pipes at invert elev. 3
Add Other Outlet
Stage Number Stage (ft) Other Outflow Rate (cfs)
1 2 3 4 5
Remove Evapotranspiration
Soil porosity (saturation moisture content, 0-1) 0.480
Soil field moisture capacity (0-1) 0.208
Permanent wilting point (0-1) 0.031
Supplemental irrigation used?
Fraction of available capacity when irrigation starts (0-1) 0.000
Fraction of available capacity when irrigation stops (0-1) 0.000
Evaporation Add
Month Evapotrans-piration (in/day) Evaporation (in/day)
Jan 0.06
Feb 0.08
Mar 0.12
Apr 0.16
May 0.17
Jun 0.20
Jul 0.21
Aug 0.20
Sep 0.16
Oct 0.12
Nov 0.08
Dec 0.06
Plant Types 1 2 3 4
Fraction of biofilter that is vegetated 0.50 0.25 0.25 0.00
Plant type Turfgras Prairie P Shrubs
Root depth (ft) 1.0 6.0 2.0 0.0
ET Crop Adjustment Factor 0.80 0.50 0.50 0.00
Biofilter Geometry Schematic
Refresh Schematic
20.00'
5.50'
4.50'
1.50'
Top of Engineered Media
0.25'
Top of Rock Fill
1.50'
x1.25'
Use Random Number Generation to Account for Infiltration Rate Uncertainty
Copy Biofilter Data
Paste Biofilter Data
Estimated Surface Drain Time = 0.98 hrs.
Save or Delete Biofilter Data to Database File
Get Biofilter Data From Database File
Press 'F1' for Help
Delete
Cancel
Continue
Control Practice #: 1
Land Use #: 1
Source Area #: 13
Total Area: 10.000 acres
Land Use: Commercial 1
Source Area: Paved Parking 1



Soil, Media Mixtures and Components Table

Soil Type Texture	Saturation Water Content % (Porosity)	Field Capacity (Percent)	Permanent Wilting Point (Percent)	Infiltration Rate (in/hr)	Fraction of Soil Type Texture in Engineered Soil (0-1)
User-Defined Media Type					
Soil					
Well Graded Sand	38	8	2.5	13	
Loamy Sand	39	13.5	4.5	2.5	
Sandy Loam	40	19.5	6.5	1	
Loam	43	34	14	0.15	
Silt Loam	43	34	14	0.15	
Silt	42	30	12	0.3	
Sandy Clay Loam	42	26.5	10.5	0.5	
Clay Loam	50	34.5	17	0.1	
Silty Clay Loam	50	34.5	17	0.1	
Sandy Clay	40	34	17	0.05	
Silty Clay	55	33.5	18	0.015	
Clay	55	33.5	18	0.015	
Other Media					
Fine Rhyolite Sand	38	8	2.5	13	
Fine Sand	38	8	2.5	13	
Filter Sand	38	8	2.5	13	**0.750**
Coarse Sand	32	4	0	40	
Gravel	32	4	0	40	
Light Media for Green Roofs	50	20	5	13	
Chemically Active Amendments					
Activated Carbon	32	4	0	40	
Fine Zeolite (SMZ)	32	4	0	40	
Coarse Zeolite	32	4	0	40	
Compost	61	55	5	18.4	
Peat Moss	78	59	5	18.4	**0.250**
User Defined Amendments					
User Defined Media 1					
Pre-Defined Media Mixtures					
Composite Soil Mixture Properties	**48.0**	**20.8**	**3.1**	**18.436**	**1.000**

Apply Soil Mixture Values as a User Defined Soil Mixture | Apply Porosity | Apply Field Capacity | Apply Wilting Point | Apply Infiltration Rate | Apply All Values

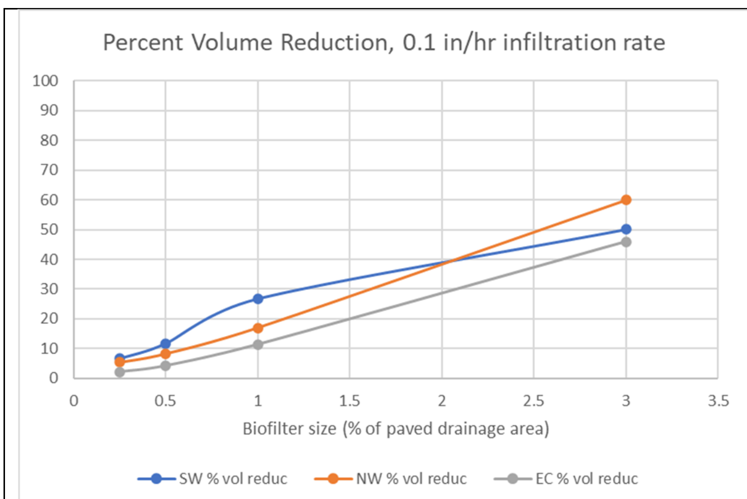
Cancel | Continue

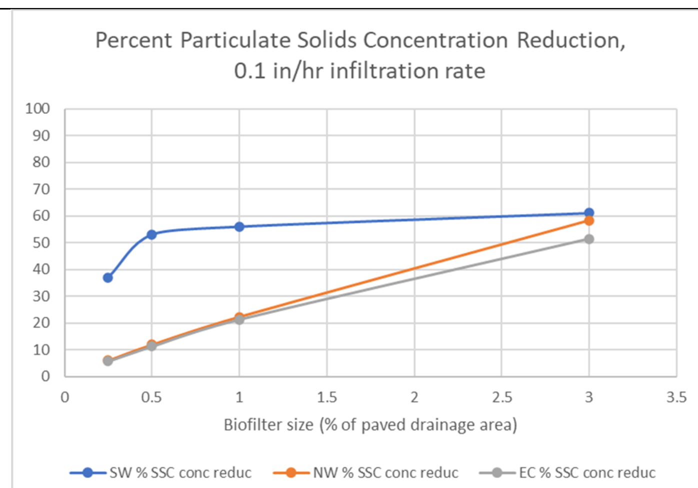
As noted, evapotranspiration (ET) was also considered in the operation of the biofilter. ET values (average in/day for each month) are shown below for the three locations evaluated. The model uses the ET values to remove moisture from the root zones of the media between storms that does not drain by gravity. The model selects appropriate ET correction factors and root depths for the plants selected, along with soil porosity saturation and field moisture wilting values.

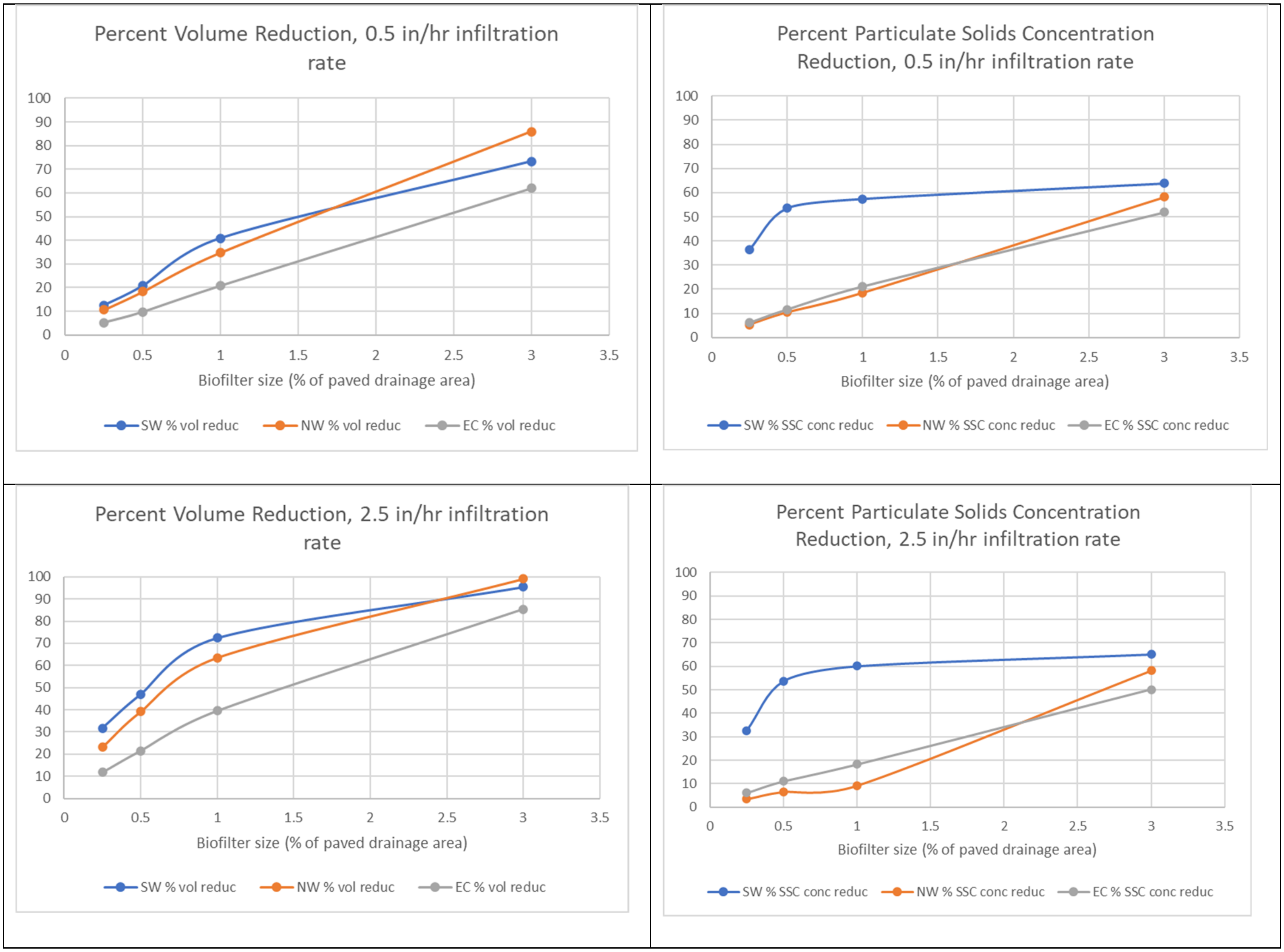
Evapotranspiration (in/day)	LAX	SeaTac	Newark
Jan	0.06	0.03	0.02
Feb	0.08	0.04	0.03

March	0.12	0.06	0.09
April	0.16	0.10	0.14
May	0.17	0.11	0.17
June	0.20	0.14	0.17
July	0.21	0.16	0.18
Aug	0.20	0.13	0.16
Sept	0.16	0.08	0.14
Oct	0.12	0.06	0.10
Nov	0.08	0.04	0.09
Dec	0.06	0.03	0.04
Annual total ET (inches/yr)	48.96	28.33	40.52

The following production functions show the runoff volume and particulate solids concentrations reductions for the different locations, native soil infiltration rates, and biofilter sizes. Stormwater particulates are trapped in the media as the water flows through the biofilter. The underdrain water therefore has reduced particulate solids concentrations compared to the influent water. As the biofilter area in relation to the paved drainage area increases, more water and particulate solids (and associated pollutants) are removed from the stormwater, as expected.

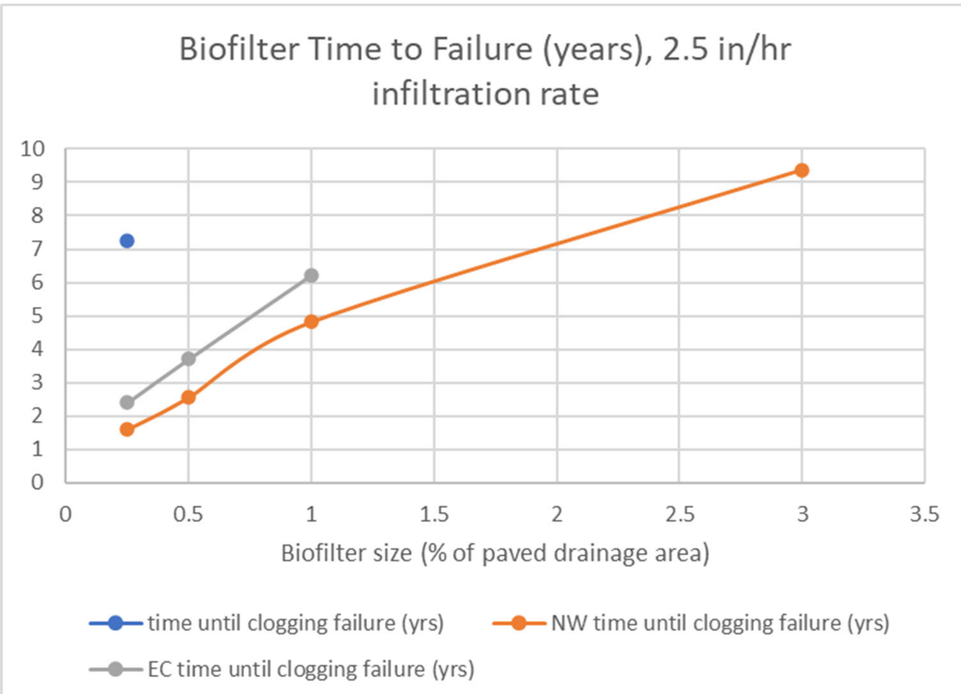






As expected, the surface bypass was quite large for the small biofilters while the infiltration was the largest loss process for the large biofilters. In all cases, evapotranspiration was quite small. WinSLAMM can also be used to evaluate the extent of surface and subsurface ponding (and the need for underdrains). Many areas limit the maximum surface ponding to less than 72 hours to prevent mosquito nuisance and public health concerns. For these examples, this was shown to occur for most biofilters with poorly draining native soils, especially for the East Coast rain conditions, but was infrequent for larger biofilters having well drained soils.

The following figure is a plot indicating the clogging potential for biofilters. Biofilter media material can fail due to clogging resulting in very low infiltration rates with rapid and excessive particulate solids loadings. Generally, cumulative particulate loads of between 10 and 25 kg/m^2 could be indicative of significantly reduced infiltration performance. With a planted biofilter in good condition, and if this critical cumulative load occurs over at least 10 years, the biofilter is likely to be able to incorporate this additional material into the soil, and the plants can help retain the infiltration rate at a desired level (but with reduced surface storage volumes). However, if this load occurs within just a few years, it is likely to overwhelm the system, resulting in premature clogging. This is more of a problem for small biofilters receiving runoff having high particulate solids concentrations, such as parking lots where space is limited for larger biofilters. The following plot shows that if the biofilters are at least 1% (southwest rains) to 3% (northwest rains) of the drainage area, clogging due to particulate loading is not likely to be a problem.



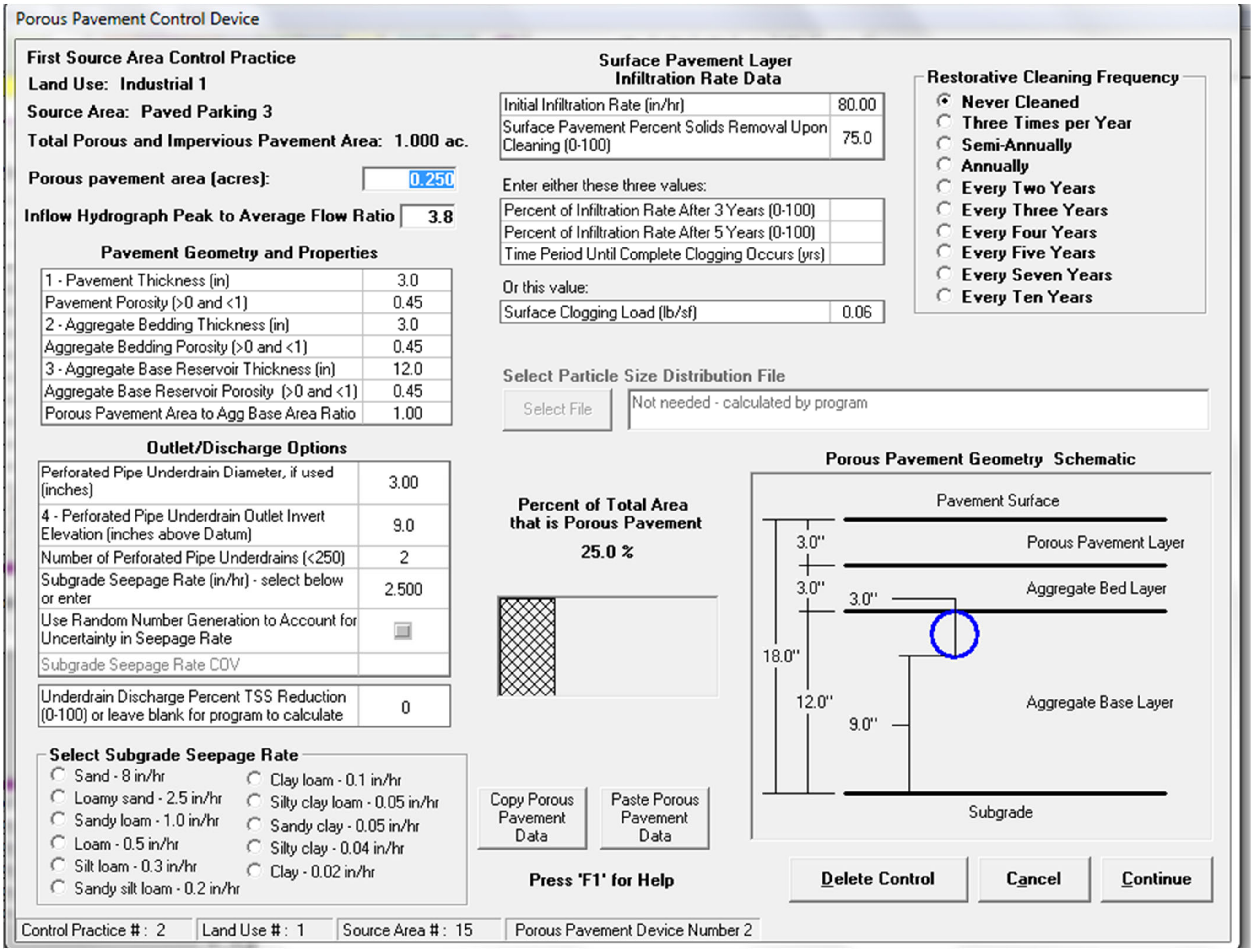
Porous Pavement

Porous pavements are typically used at paved parking and storage areas, paved playgrounds, paved driveways, or paved walkways. They should be used in relatively clean areas (walkways or driveways or other surfaces that receive little traffic, for example), to minimize groundwater contamination potential and premature clogging and failure. Porous pavements direct the infiltrating water to subsurface soil layers (usually at several feet in depth), where the soils likely have reduced organic matter that assist in retaining pollutants. Salts used for ice control in northern areas are also problematic when considering infiltrating stormwater. Biofiltration devices to infiltrate water from more contaminated sites may be preferred because they can use amended soils and treatment media targetted to help trap contaminants before infiltration, or use other appropriate pre-treatment before infiltration, and are easier to restore. No common pretreatment device is available for removing salts, however, so minimizing the use of deicing chemicals is the preferred control option.

The WinSLAMM porous pavement control has full routing calculations associated with subsurface pond storage and also allows runon from adjacent paved areas that do not have porous pavement. The outlet options for porous pavement include subgrade seepage and an optional underdrain, which is modeled as an orifice. The porous pavement control device has a surface seepage rate that limits the amount of runoff that can enter the storage system. The seepage rate is usually much greater than the rain intensity, so surface bypass would be unusual, except if it is significantly reduced by clogging or if substantial runon occurs from adjacent paved areas. This surface seepage rate is reduced in WinSLAMM to account for clogging with time and can be partially restored with cleaning. The runoff volume reaching the porous pavement surface is equal to the rainfall volume directly falling on the porous pavement, plus runoff volume from any runon from the adjacent paved areas. The porous pavement surface can be paver blocks, porous concrete, porous asphalt, or any other porous surface, including reinforced turf or clean aggregate. Porous pavements are usually installed over a subsurface storage layer (normally with underdrains, especially for locations having poorly draining soils) that can dramatically increase the infiltration performance of the device by providing storage of runoff during periods of high rainfall intensities that are greater than the native soil infiltration rates.

Particulate pollutants are captured in porous pavement systems by capturing large materials on the surface through physical straining, and by settling of finer particulates in the rock storage layer. Surface capture is the most obvious and if not removed by restorative cleaning, can eventually cause clogging of the system. The percolating water ponds in the rock storage layer and slowly drains into the native soil, depending on the infiltration rate. The subsurface ponded water may reach the elevation of the underdrains (commonly used in porous pavement installations) and be discharged to the drainage system. The discharged underdrain water therefore undergoes partial treatment due to the settling during the ponding in the rock layers. WinSLAMM calculates the settling based on Stoke's law settling and the movement of the water as it infiltrates or is discharged through the underdrains. The captured fine sediment accumulates in the rock storage pore space, and eventually can bind the infiltration layer on the bottom of the porous pavement system. When this occurs, the only outlet is through the underdrain system. It is not possible to remove this captured material in the storage rock pores without excavation and replacement of the material. However, for most porous pavement systems, this accumulation rate is very slow, and this failure is rare, except if only a small portion of the paved drainage area has porous pavement. For small porous pavement systems capturing runon from large adjacent areas, this failure would be more frequent, especially as pre-treatment of pavement runoff before porous pavements is unusual. Biofilter systems may be more suitable in more contaminated areas, or if only a small fraction of the pavement can be used with a porous surface.

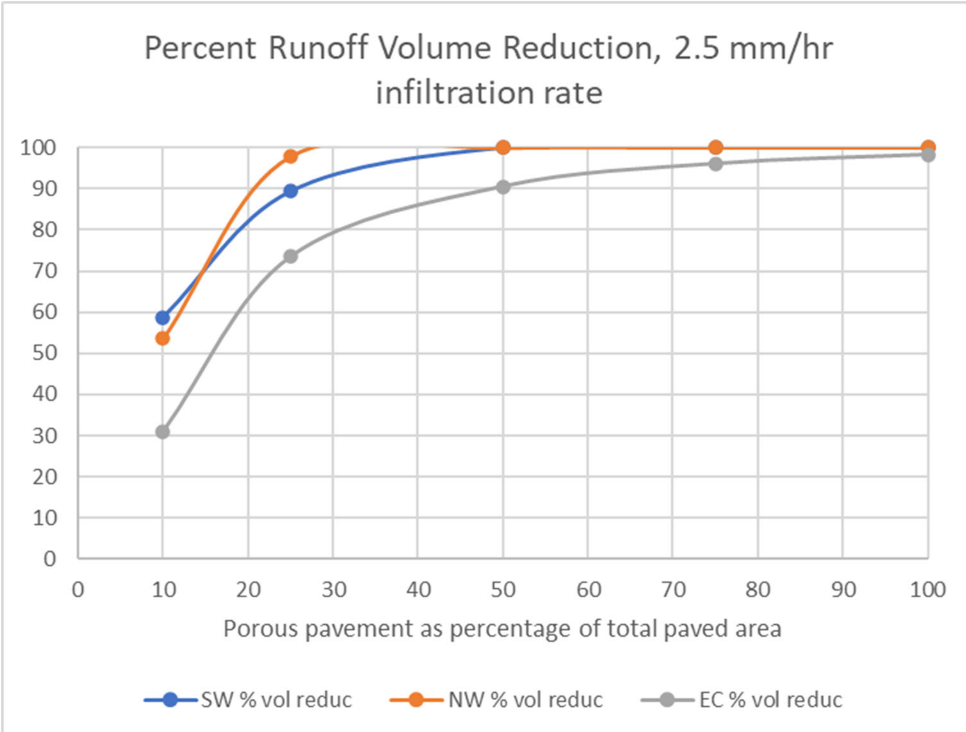
The following is the input screen for porous pavement in WinSLAMM. This input screen describes the geometry and other characteristics of the porous pavement surface and subsurface features. The model computes the runoff volume, equal to the rainfall volume plus any runon, and then creates an influent hydrograph that is routed through that porous pavement system.

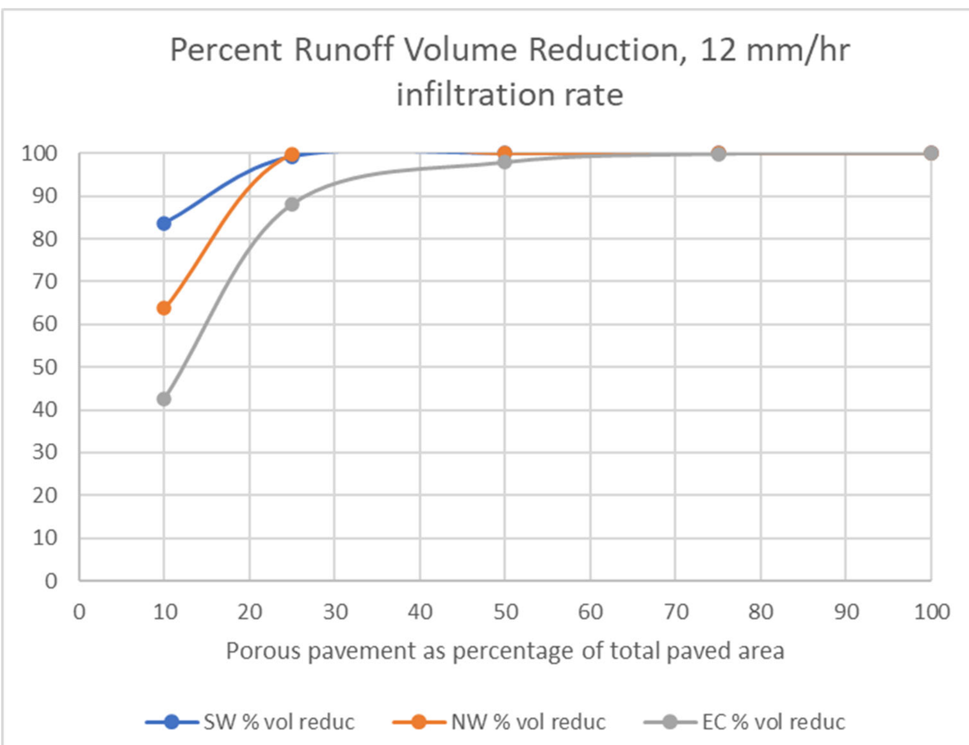


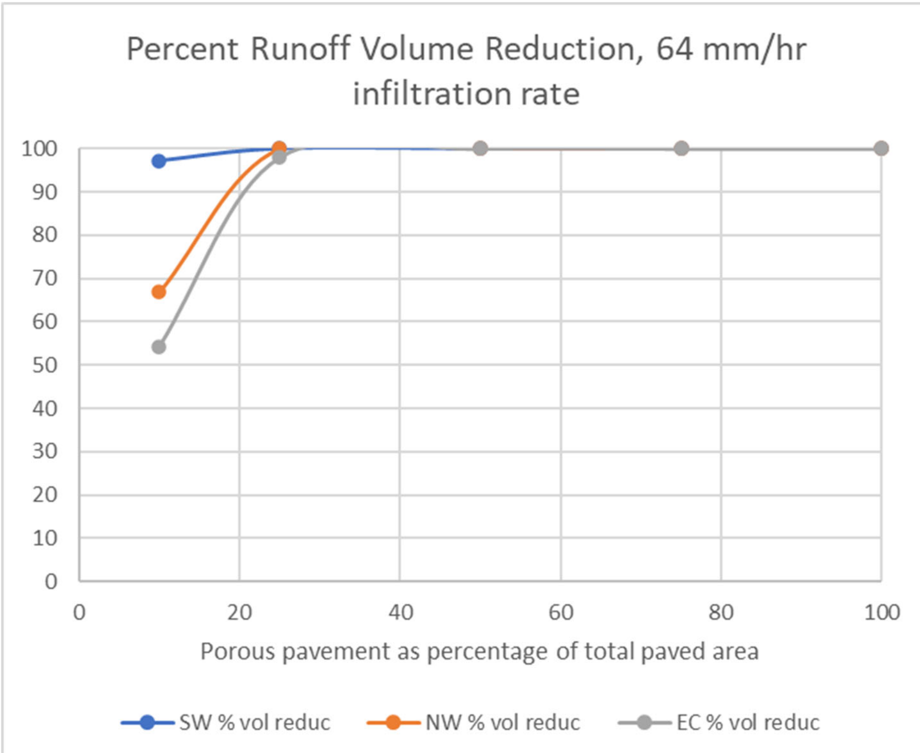
The following production functions show the runoff volume reductions, for the three geographical areas and three soil characteristics examined. The soils included the following native infiltration rates and general corresponding soil textures (assuming minimal compaction):

- 2.5 in/hr (64 mm/hr) (loamy sand soil)
- 0.5 in/hr (12 mm/hr) (loam soil)
- 0.1 in/hr (2.5 mm/hr) (clay loam soil)

Porous pavement covering 10 to 100% of the pavement surface are considered in these plots. These production functions are only for runoff volume reductions as no significant particulate solids concentration reductions are associated with their use.


Percent Runoff Volume Reduction, 2.5 mm/hr infiltration rate
100
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90 100
Porous pavement as percentage of total paved area
SW % vol reduc
NW % vol reduc
EC % vol reduc


Percent Runoff Volume Reduction, 12 mm/hr infiltration rate
100
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90 100
Porous pavement as percentage of total paved area
SW % vol reduc
NW % vol reduc
EC % vol reduc



The above production functions indicated at least 90% runoff reductions with porous pavements that are at least 25 to 50% of the total paved area for poorly draining soils (depending on the location) and at least 25% of the total paved area for all areas for the well-drained conditions. Even though small areas of porous pavement can be very effective, small porous pavement areas are subject to premature failure. The most common and obvious failure mode of very small porous pavement areas is associated with surface clogging. Surface clogging rapidly occurred (even with typical yearly restorative cleaning) for the smallest (10%) porous pavement areas. Subsurface clogging of rock storage pores will also occur more frequently for small installations relative to the total paved area. It only requires a few mm of silt on the native soil interface (or geotextile) to clog that layer, leaving only the underdrain to discharge water from the system. As the silt further accumulates, it may also eventually reach the underdrain which would shut off any system drainage. Small fractional areas will result in pore clogging more rapidly than larger fractional areas. The only way to correct this problem would be to excavate and rebuild the porous pavement system. Therefore, if only small areas are available, it may be best to utilize biofilters that can be more conveniently repaired if clogged.

Production Functions for Roof Areas

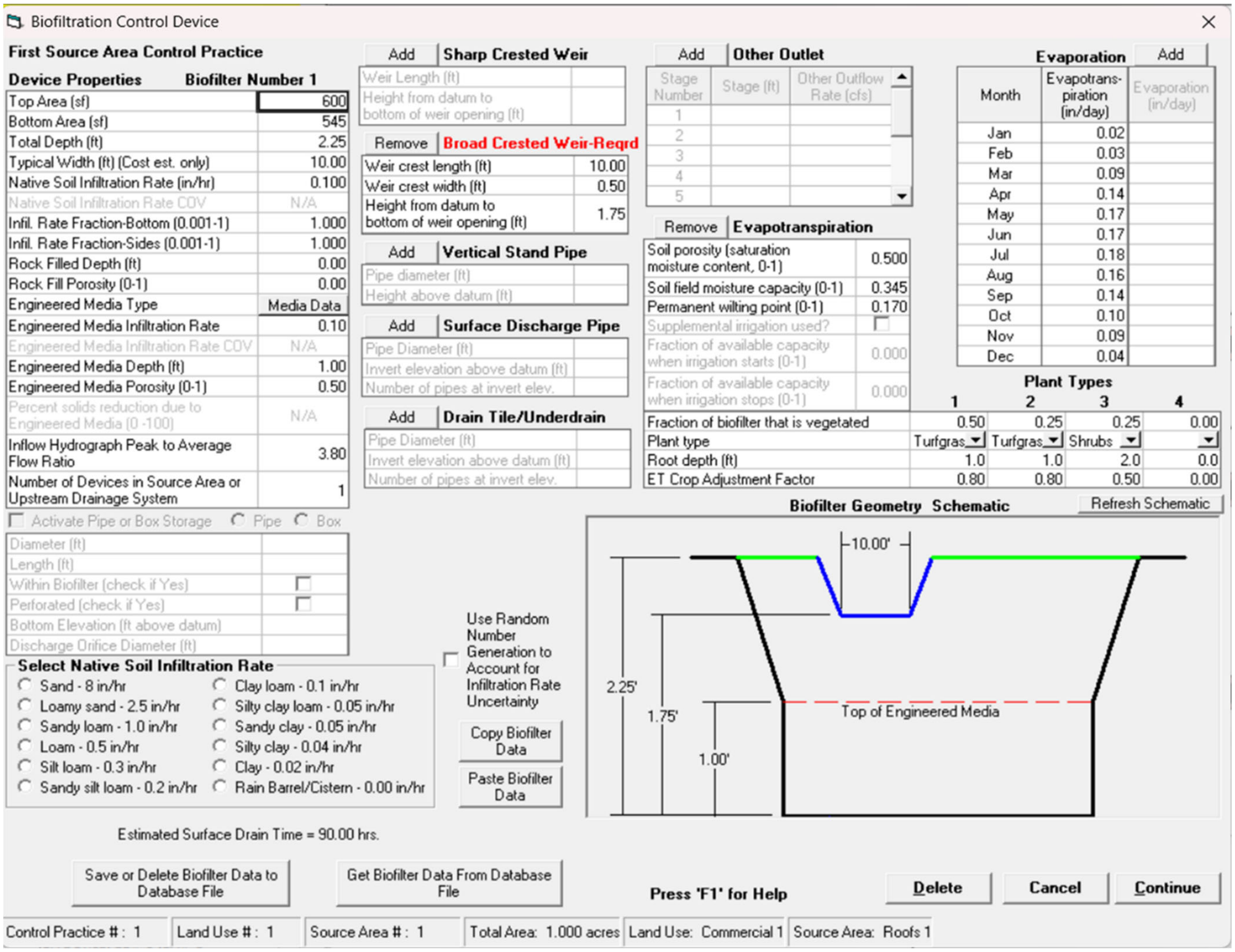
Like for paved areas, only one of the production functions for the following controls for roof runoff can be selected for each roof area category (either rain gardens or green roofs), as the production functions cannot consider treatment trains having multiple controls in the same area. WinSLAMM can be used to consider many combinations of source area, drainage system, and outfall controls simultaneously, if needed.

Rain Gardens for Roof Runoff

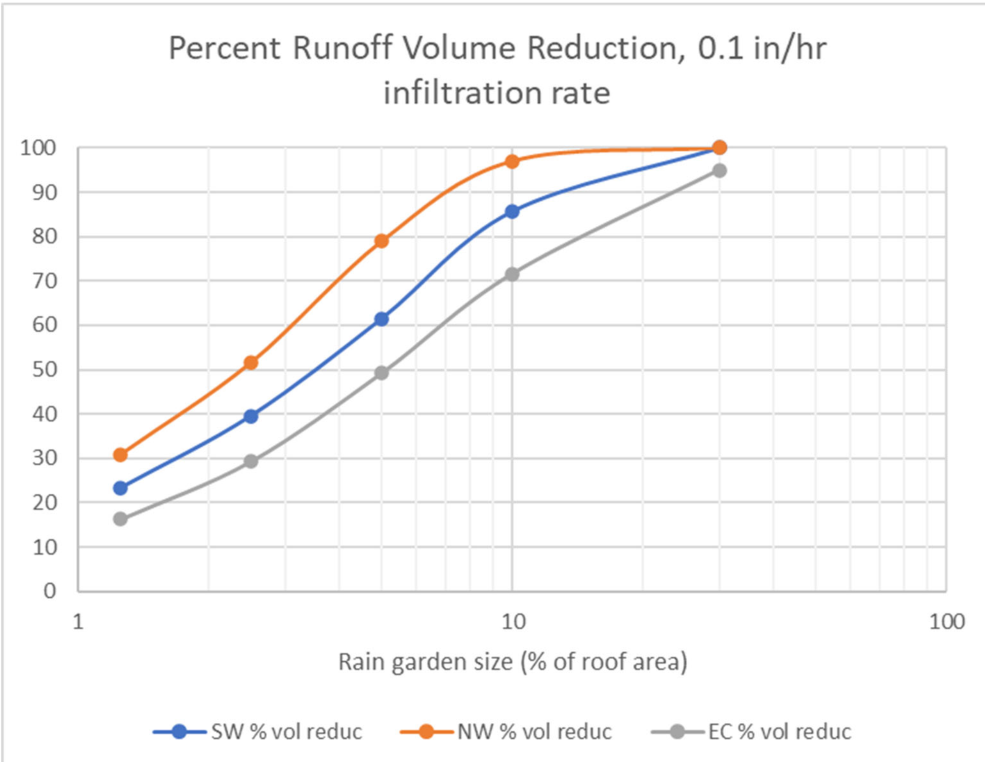
Rain gardens are a category of biofiltration devices in that they are much simpler by usually not having underdrains or special treatment media. They are most suitable for roof runoff and therefore located near buildings in areas having suitable soils. Even though they are simple devices, they do usually provide additional control compared to disconnecting roof drains through the addition of moderate to large amounts of surface runoff storage. This surface storage enables the retention of runoff in the device during short periods of high flows which would normally exceed the infiltration rates of the soils.

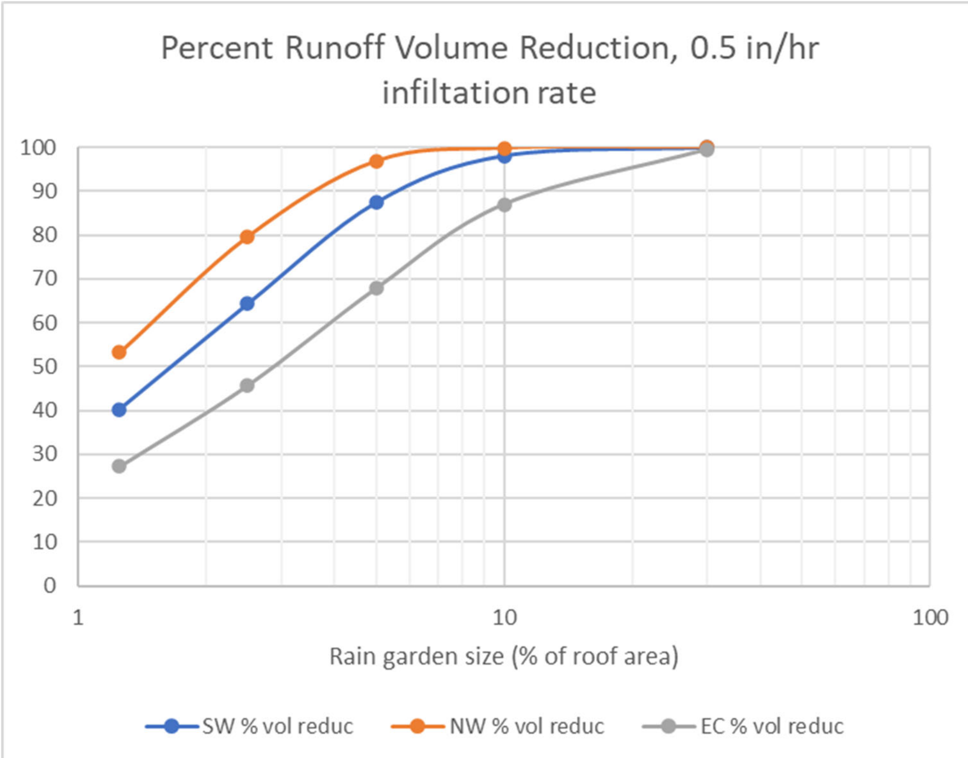
The performance of a rain garden is affected by hydraulic routing and the native soil infiltration which are simultaneously modeled in WinSLAMM. Modified puls hydraulic routing, with surface overflow calculations, are the basic processes used. As runoff enters the device, water infiltrates through the natural soil lining the bottom and sides of the rain garden. If the entering rain cannot all be infiltrated, the water ponds. If the ponding becomes deep, it can overflow through the surface outlet. Evapotranspiration (ET) can also be included in the analysis for additional runoff volume benefits but is usually relatively small compared to the infiltration losses. The runoff, along with all associated pollutants, are therefore removed from the surface drainage system. The water is diverted to shallow groundwater which may slowly flow to receiving waters, while the pollutants can be captured in the soils. Highly mobile pollutants (such as chlorides, nitrates, and some insecticides) are not attenuated by the soils and may enter the receiving water when the percolating water enters these bodies of water. Pollutant concentrations and loads are usually less in roof runoff than in other stormwater source flows and are the preferred water for this simple type of infiltration.

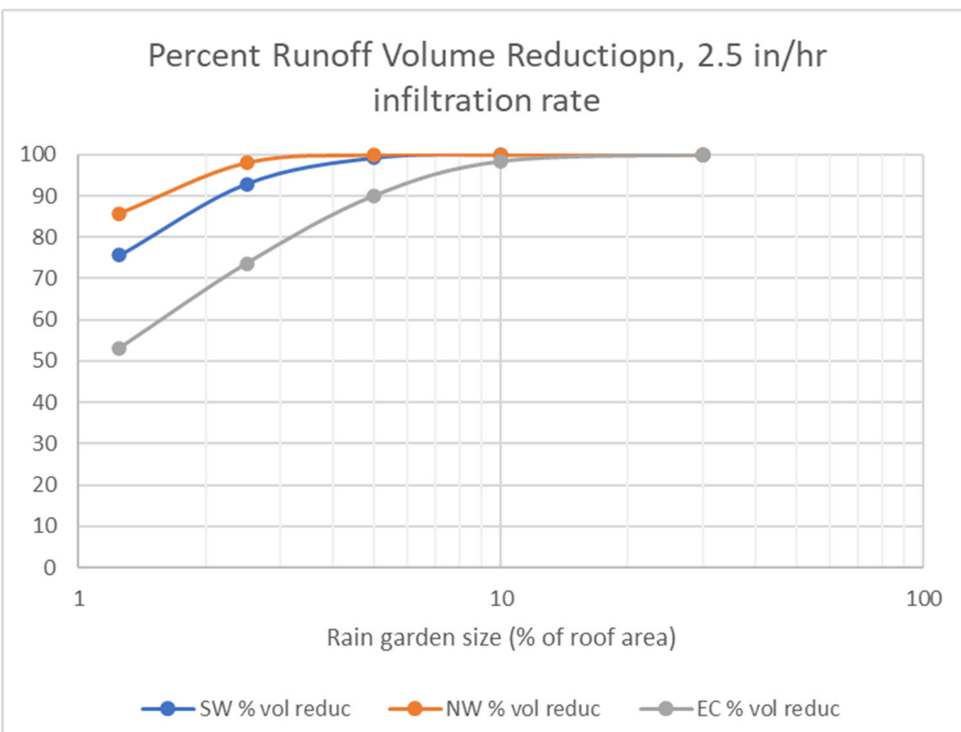
The following is the main WinSLAMM input screen used for biofilters, with example rain garden values used in these production function analyses. This is a general form that is also used for other infiltration devices, including more complex biofilters and bioinfiltration devices. This form includes the geometry of the device and material placed in the device (usually none for rain gardens). Most simple rain gardens do not have any special media, using only soils, nor do they have underdrains, so only some of the form is used. In this example, the treatment media is selected as the soil associated with the infiltration rate used. As indicated, it is possible to also incorporate a Monte Carlo routine to better represent the variable infiltration rates that usually occur with individual units. All the devices using this input screen require a hydraulic overflow outlet described as a broad crested weir (rain gardens can use the lower edge of the rain garden, as in this example).



Production functions indicating how rain gardens can control roof runoff are shown in the following figures for the three geographical areas and three soils types (clay loam, loam, and loamy sand having infiltration rates of 0.1, 0.5, and 2.5 in/hr, respectively). As a rain garden increases in size in relationship to the roof area, less water is discharged to the surface drainage system through the overflow. Rain gardens are relatively robust controls, if they are large enough. Roof runoff rain gardens are usually larger (percentage basis of drainage area) compared to typical paved area biofilters as the roofs are smaller and the area available for locating the rain garden can be incorporated into the landscaping adjacent to the buildings. Extensive monitoring projects have shown that even in challenging (clayey) soils, almost complete infiltration can occur, if sufficiently sized. Rain gardens about 20% of the roof areas can infiltrate more than 80% of the long-term roof runoff for all of the conditions examined in these calculations. This is a large area dedicated for stormwater management, but is suitable for relatively small buildings when the rain garden can be used as part of the landscaping plan. Better soils can utilize smaller rain gardens, but small areas can have significant maintenance issues. Northwest areas show greater performance benefits associated with the less intense rains compared to the other areas. These production functions are only for runoff volume reductions associated with the evapotranspiration and infiltration losses as no significant particulate solids concentration reductions are associated with their use.

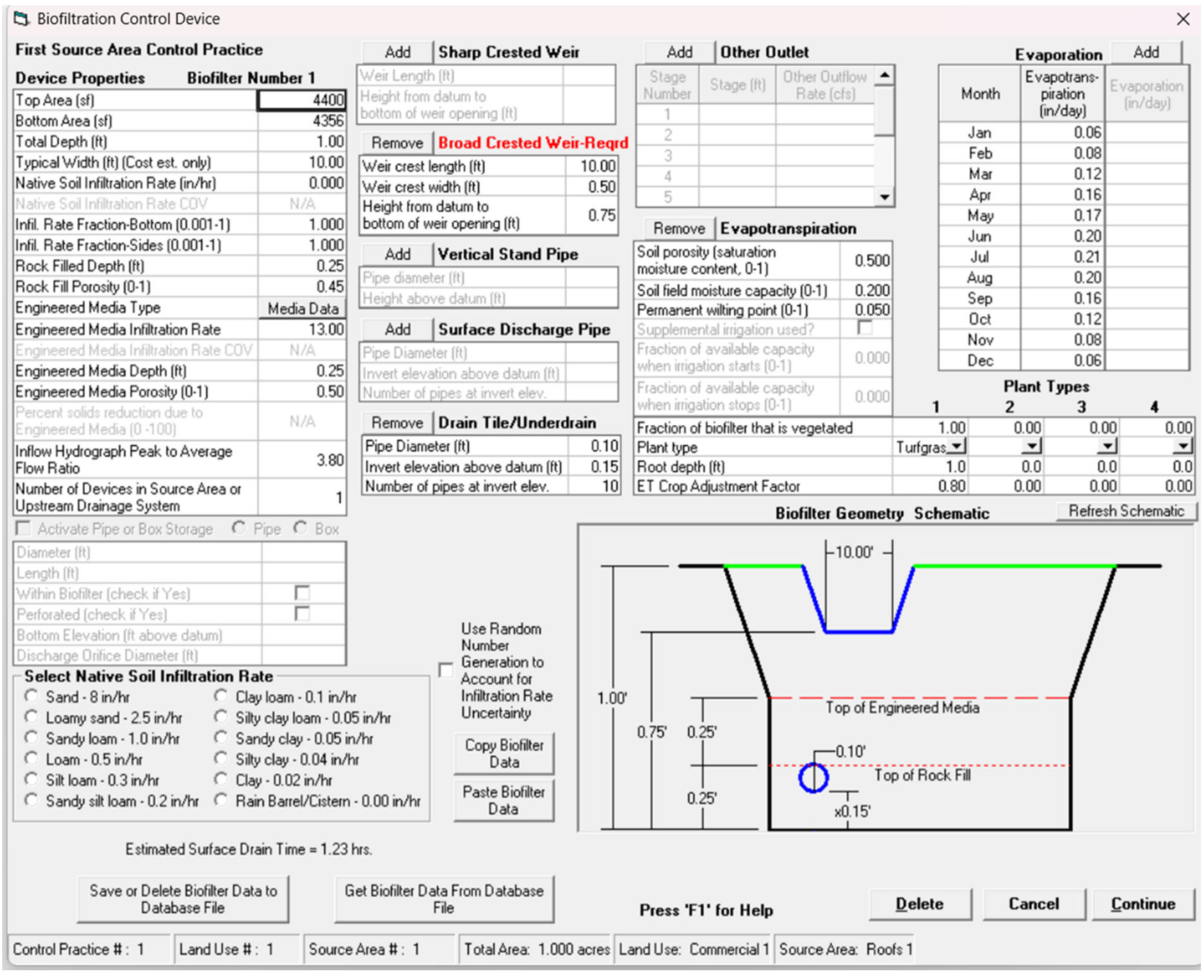


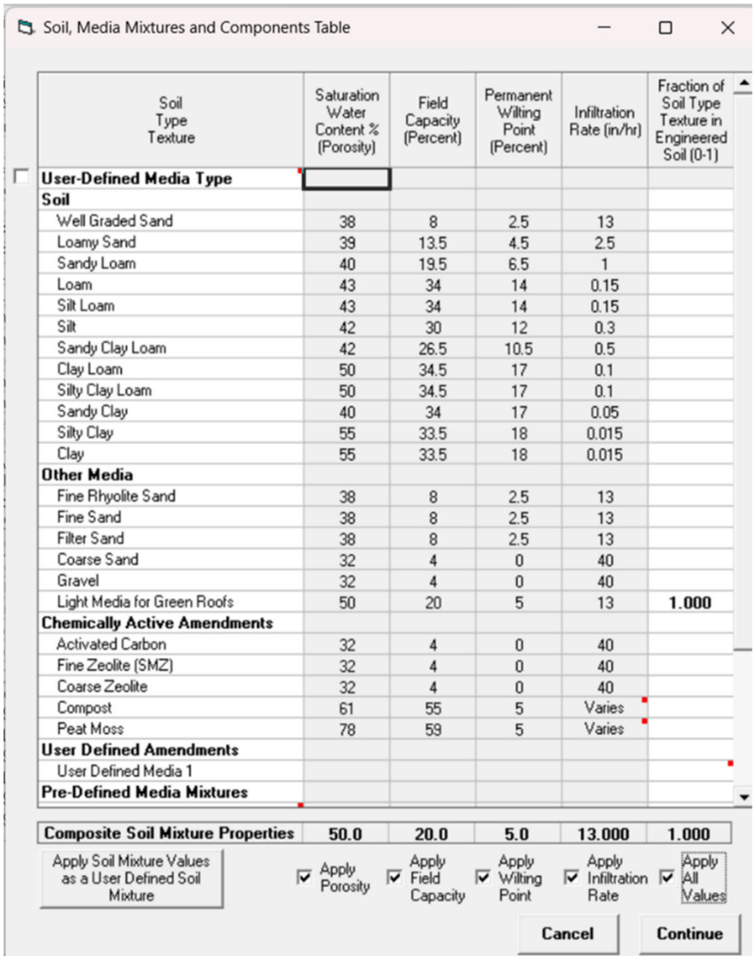

Percent Runoff Volume Reduction, 0.5 in/hr infiltation rate
100
90
80
70
60
50
40
30
20
10
0
1
10
100
Rain garden size (% of roof area)
SW % vol reduc
NW % vol reduc
EC % vol reduc


Percent Runoff Volume Reductiopn, 2.5 in/hr infiltration rate
100
90
80
70
60
50
40
30
20
10
0
1
10
100
Rain garden size (% of roof area)
SW % vol reduc
NW % vol reduc
EC % vol reduc

Green Roofs

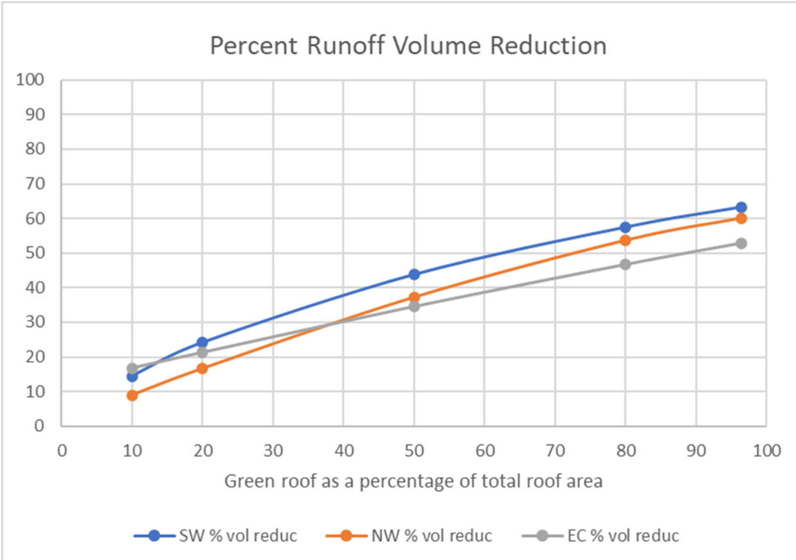
The production functions for green roofs also used the biofilter tools in WinSLAMM. Specific green roof input options are being incorporated into future model versions, but the calculation mechanisms would be similar. The following input screen was used for the green roof calculations, A thin layer of a light-weight media was used with underdrains. The only runoff removal mechanism for green roofs is evapotranspiration, requiring relatively extensive roof coverages of plants for most locations for high runoff reductions.





Soil Type Texture	Saturation Water Content % (Porosity)	Field Capacity (Percent)	Permanent Wilting Point (Percent)	Infiltration Rate (in/hr)	Fraction of Soil Type Texture in Engineered Soil (0-1)
User-Defined Media Type					
Soil					
Well Graded Sand	38	8	2.5	13	
Loamy Sand	39	13.5	4.5	2.5	
Sandy Loam	40	19.5	6.5	1	
Loam	43	34	14	0.15	
Silt Loam	43	34	14	0.15	
Silt	42	30	12	0.3	
Sandy Clay Loam	42	26.5	10.5	0.5	
Clay Loam	50	34.5	17	0.1	
Silty Clay Loam	50	34.5	17	0.1	
Sandy Clay	40	34	17	0.05	
Silty Clay	55	33.5	18	0.015	
Clay	55	33.5	18	0.015	
Other Media					
Fine Rhyolite Sand	38	8	2.5	13	
Fine Sand	38	8	2.5	13	
Filter Sand	38	8	2.5	13	
Coarse Sand	32	4	0	40	
Gravel	32	4	0	40	
Light Media for Green Roofs	50	20	5	13	1.000
Chemically Active Amendments					
Activated Carbon	32	4	0	40	
Fine Zeolite (SMZ)	32	4	0	40	
Coarse Zeolite	32	4	0	40	
Compost	61	55	5	Varies	
Peat Moss	78	59	5	Varies	
User Defined Amendments					
User Defined Media 1					
Pre-Defined Media Mixtures					
Composite Soil Mixture Properties	50.0	20.0	5.0	13.000	1.000

The following production functions were calculated for green roofs covering 10 to about 96% of the roof areas. The southwest location has the best performance compared to the other two locations, for the same roof coverage of plants. Fifty percent roof coverage results in about 30 to 45% runoff volume reductions (the green roof receives runon from the unplanted roof areas). Fifty to 65 percent runoff reductions can be expected when almost all of the roof is covered with plantings for these conditions. These production functions are only for runoff volume reductions as no significant particulate solids concentration reductions are associated with their use.

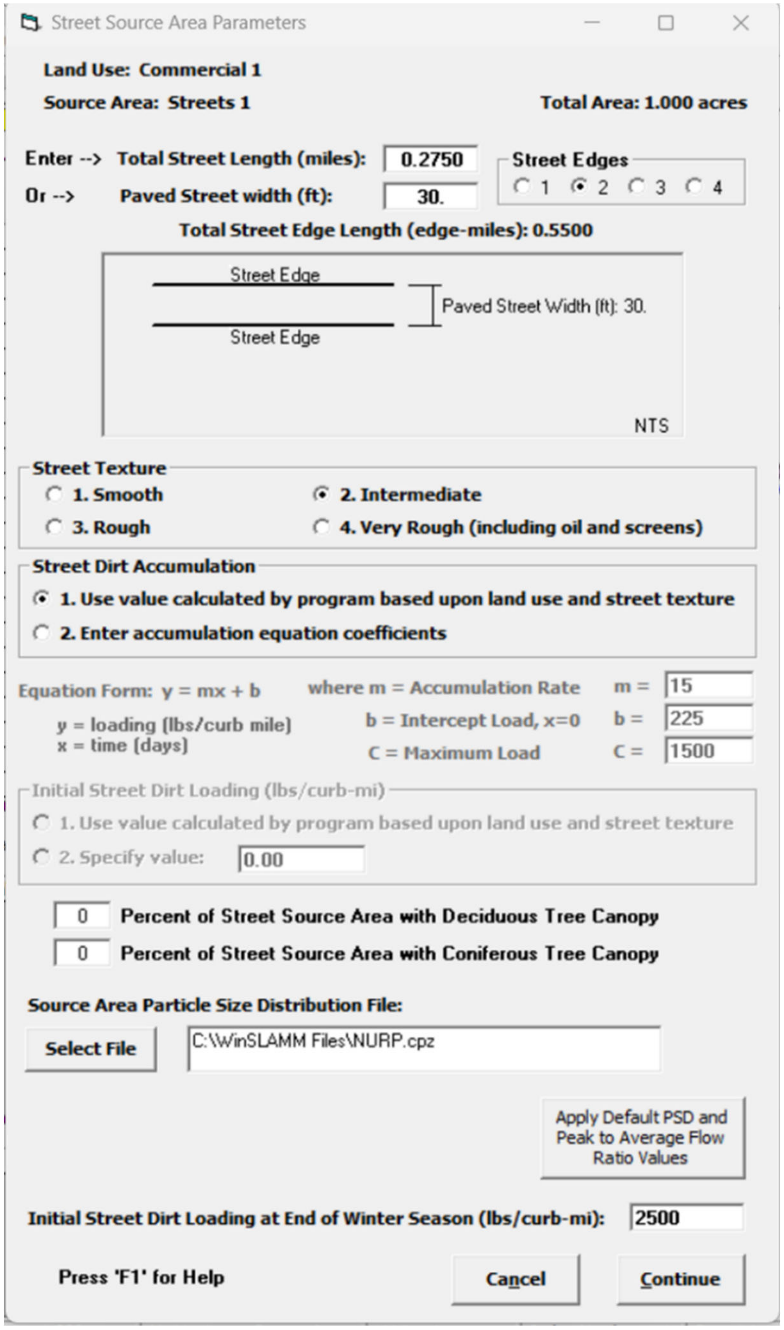

Percent Runoff Volume Reduction
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Green roof as a percentage of total roof area
SW % vol reduc
NW % vol reduc
EC % vol reduc

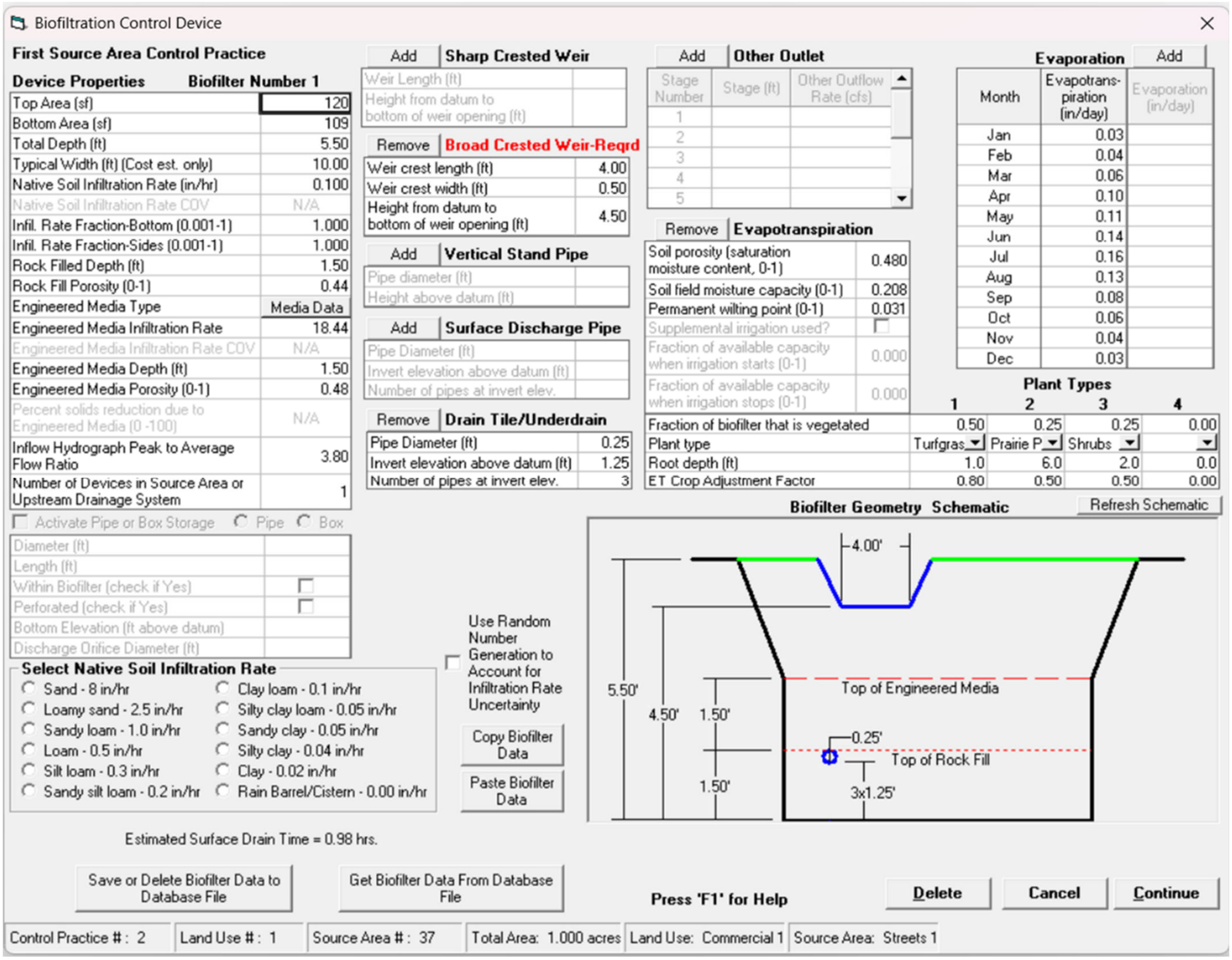
Production Functions for Street Areas

Production functions were prepared for two alternative stormwater controls for street areas: streetside curb-cut biofilters and street cleaning. As for the other source area controls, only one of these controls can be selected for each street area.

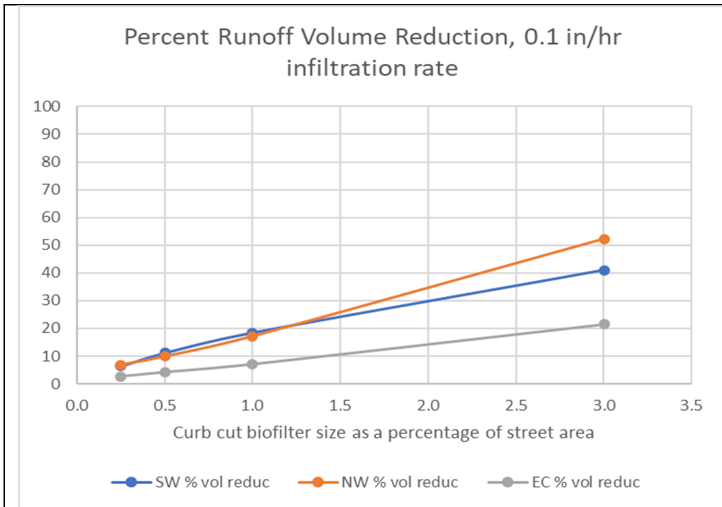
Streetside Curb-cut Biofilters

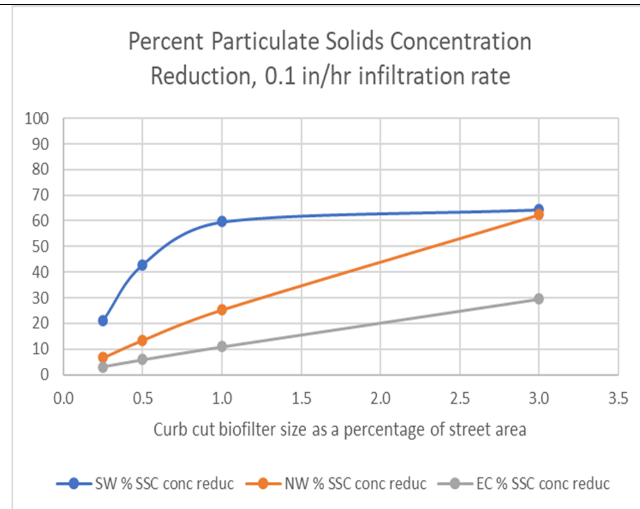
Streetside curb-cut biofilters are also based on the standard biofilter calculations in WinSLAMM and use the same input form. The following screen shots show the street source area description form and the biofilter form for these controls. The curb-cut biofilter is similar to the previously described paved area biofilter, and the production functions were calculated for biofilter areas ranging from 0.3 to 3 percent of the street area draining to the biofilters, for the three locations, and three soil infiltration rates.

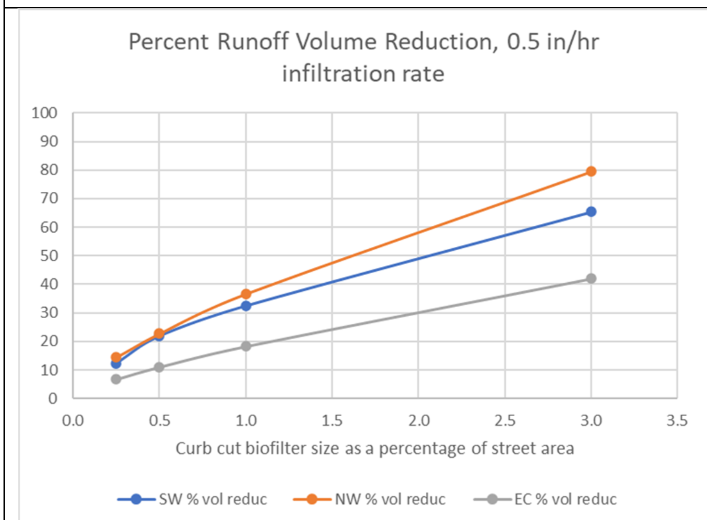

Street Source Area Parameters
Land Use: Commercial 1
Source Area: Streets 1
Total Area: 1.000 acres
Enter --> Total Street Length (miles): 0.2750
Or --> Paved Street width (ft): 30.
Street Edges
1 2 3 4
Total Street Edge Length (edge-miles): 0.5500
Street Edge
Paved Street Width (ft): 30.
Street Edge
NTS
Street Texture
1. Smooth
2. Intermediate
3. Rough
4. Very Rough (including oil and screens)
Street Dirt Accumulation
1. Use value calculated by program based upon land use and street texture
2. Enter accumulation equation coefficients
Equation Form: y = mx + b
where m = Accumulation Rate
m = 15
y = loading (lbs/curb mile)
x = time (days)
b = Intercept Load, x=0
b = 225
C = Maximum Load
C = 1500
Initial Street Dirt Loading (lbs/curb-mi)
1. Use value calculated by program based upon land use and street texture
2. Specify value: 0.00
0 Percent of Street Source Area with Deciduous Tree Canopy
0 Percent of Street Source Area with Coniferous Tree Canopy
Source Area Particle Size Distribution File:
Select File
C:\WinSLAMM Files\NURP.cpz
Apply Default PSD and Peak to Average Flow Ratio Values
Initial Street Dirt Loading at End of Winter Season (lbs/curb-mi): 2500
Press 'F1' for Help
Cancel
Continue

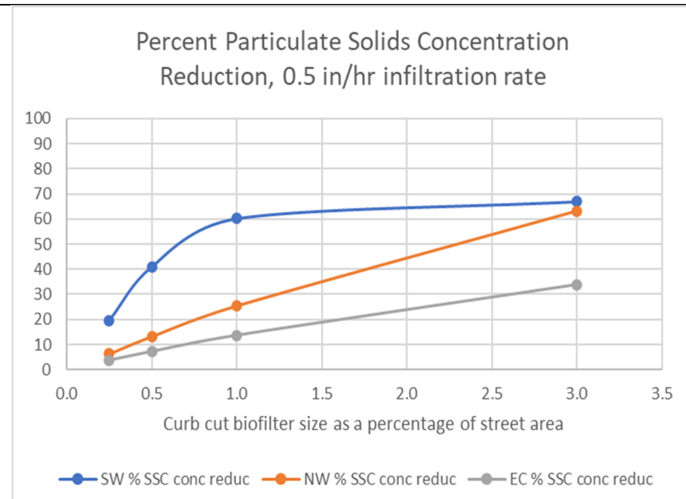


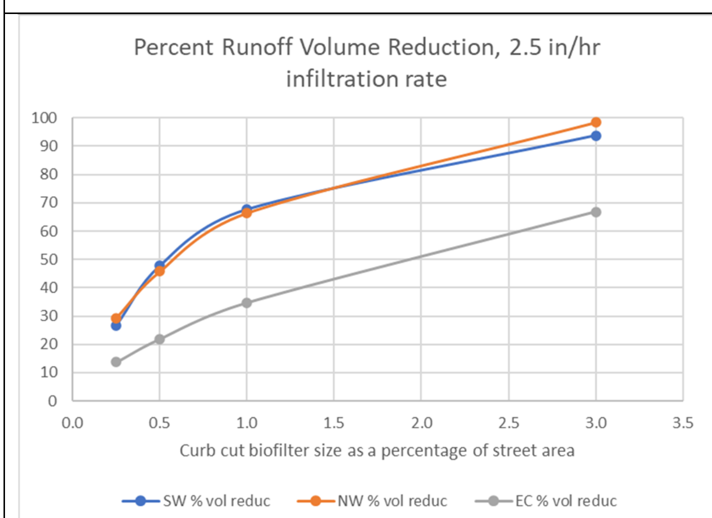
Forty to 80 percent runoff volume reductions are shown for the maximum size of 3 percent of the street drainage area as a biofilter with soils having 0.5 in/hr infiltration rates. The particulate strength concentration reductions top out at about 70 percent for all three soils, with the highest reductions shown for southwest rain conditions.

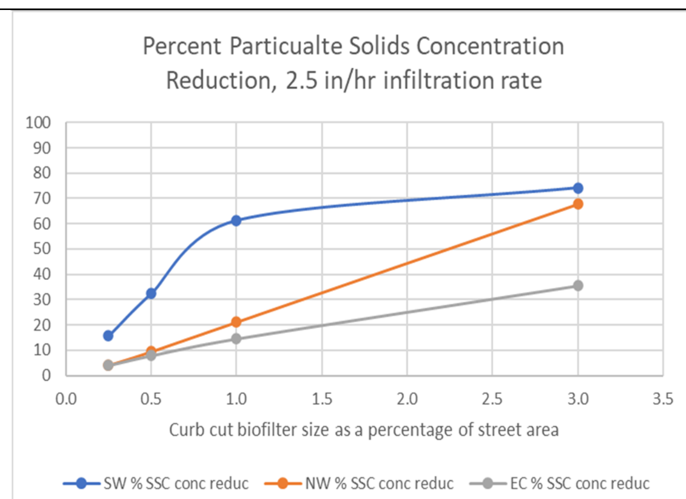

Percent Runoff Volume Reduction, 0.1 in/hr infiltration rate
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Curb cut biofilter size as a percentage of street area
SW % vol reduc
NW % vol reduc
EC % vol reduc


Percent Particulate Solids Concentration Reduction, 0.1 in/hr infiltration rate
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Curb cut biofilter size as a percentage of street area
SW % SSC conc reduc
NW % SSC conc reduc
EC % SSC conc reduc

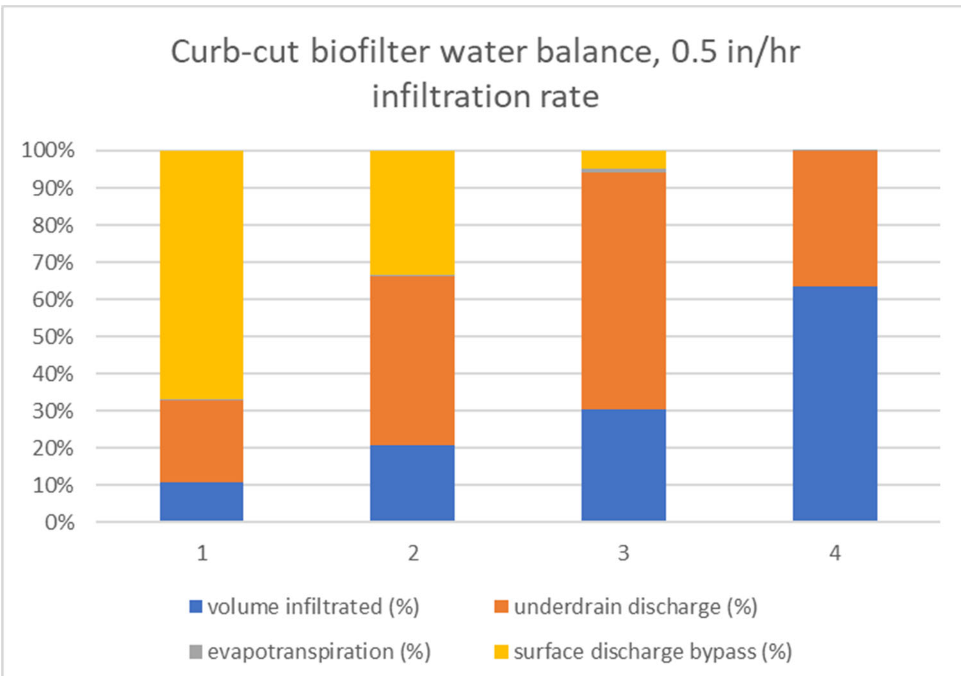

Percent Runoff Volume Reduction, 0.5 in/hr infiltration rate
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Curb cut biofilter size as a percentage of street area
SW % vol reduc
NW % vol reduc
EC % vol reduc


Percent Particulate Solids Concentration Reduction, 0.5 in/hr infiltration rate
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Curb cut biofilter size as a percentage of street area
SW % SSC conc reduc
NW % SSC conc reduc
EC % SSC conc reduc


Percent Runoff Volume Reduction, 2.5 in/hr infiltration rate
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Curb cut biofilter size as a percentage of street area
SW % vol reduc
NW % vol reduc
EC % vol reduc

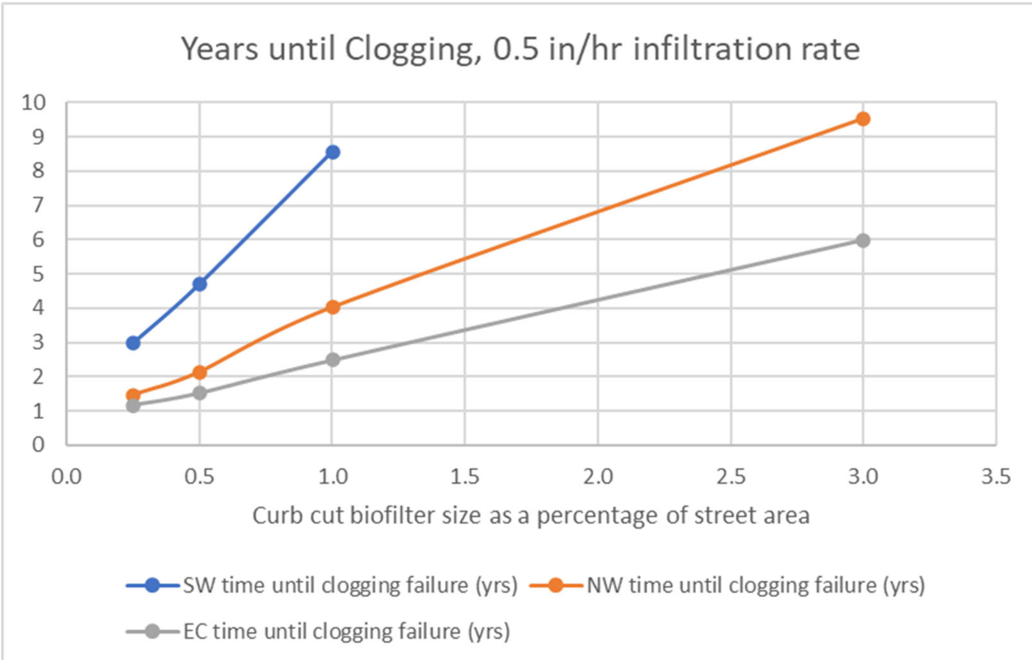

Percent Particualte Solids Concentration Reduction, 2.5 in/hr infiltration rate
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Curb cut biofilter size as a percentage of street area
SW % SSC conc reduc
NW % SSC conc reduc
EC % SSC conc reduc

The following plot shows the water balance for the southwest conditions and 0.5 in/hr soil infiltration rates. The volume infiltrated increases substantially and the surface discharge bypass decreases substantially as the biofilter area increases. In all cases, volume losses associated with evapotranspiration is very small. However, the plantings are needed to minimize clogging issues, especially for the smaller treatment systems.



Southwest street side curb-cut biofilter water balance example for 0.25, 0.5, 1, and 3 percent of street area as curb-cut biofilter.

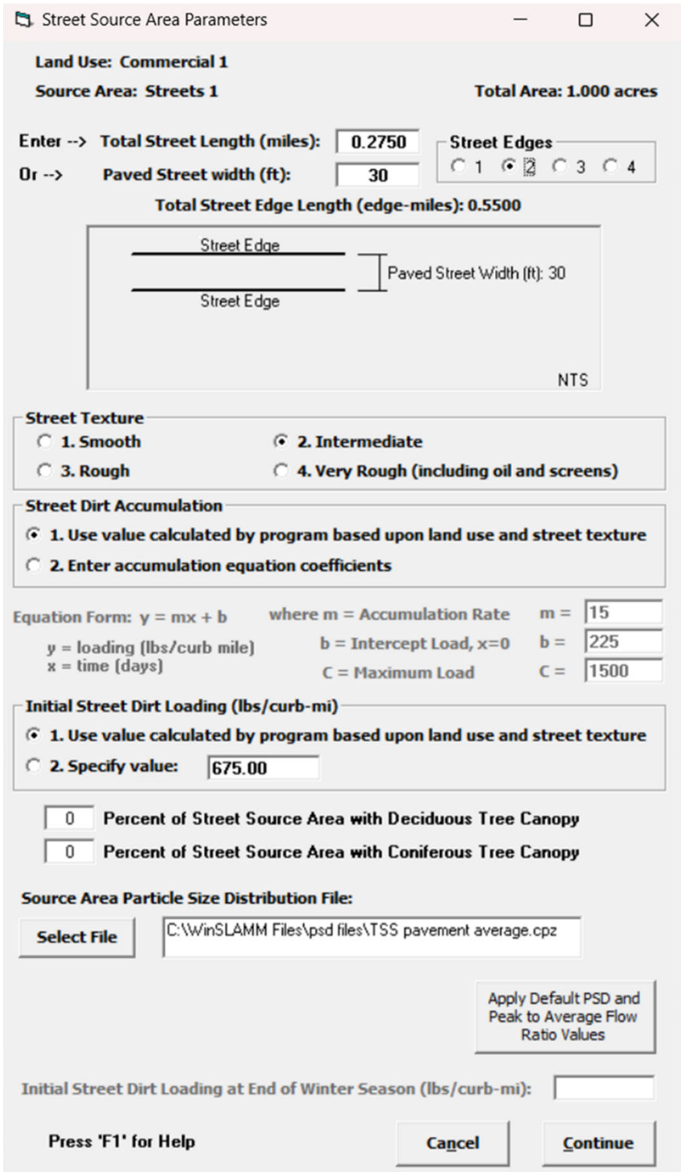
The following plot shows the years until clogging likely occurs for the three locations and different biofilter sizes for 0.5 in/hr soil infiltration rates. For southwest conditions, the streetside biofilter should be at least about 1.25 percent for a ten-year period before the biofilter needs to be reconstructed. This increases to more than three percent biofilter size for east coast conditions.



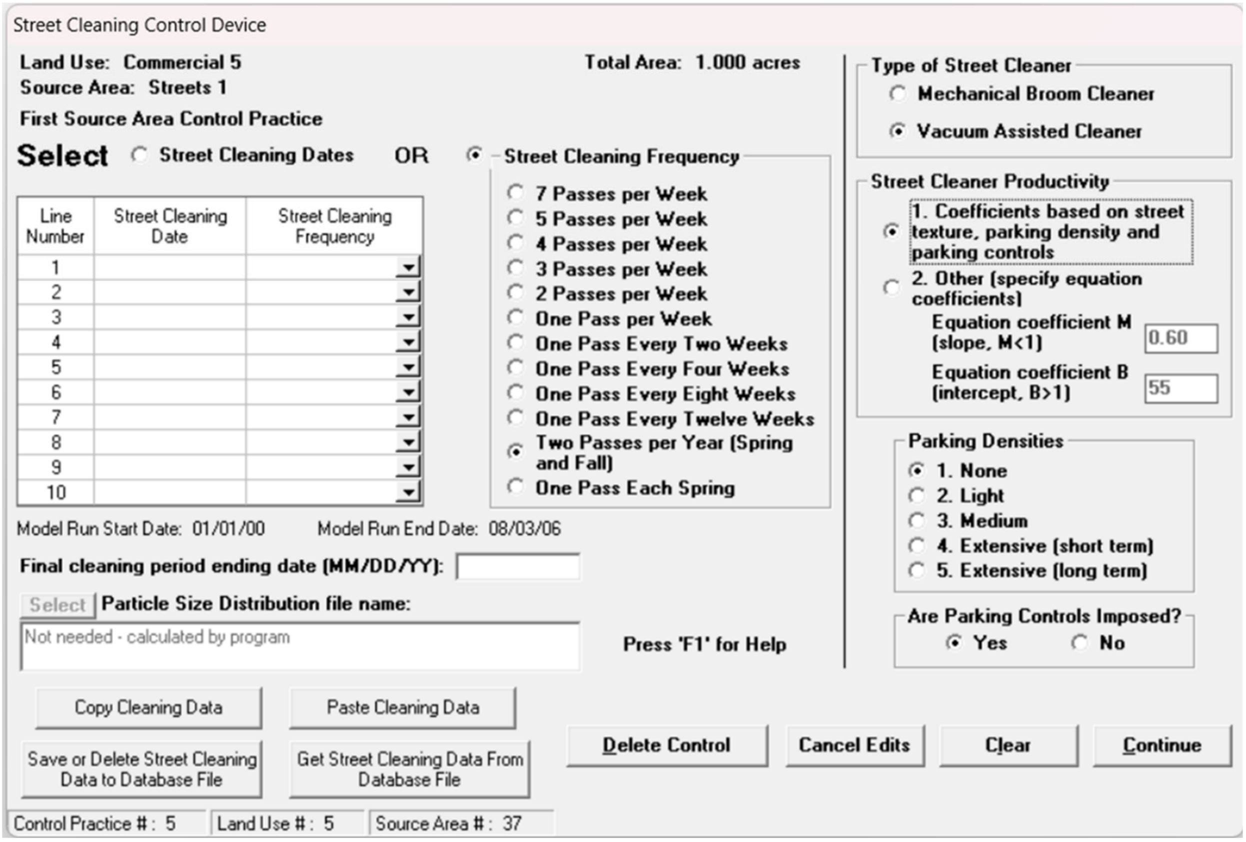
Street Cleaning

The street cleaning calculations in WinSLAMM are based on many field research projects conducted under a wide range of conditions and locations. Street cleaners remove large amounts of street dirt and debris, but only a small portion of this material is able to be mobilized by rains and contribute to runoff loads. Street cleaning plays an important role in most public works departments as an aesthetic and safety control measure. Street cleaning is also important to reduce massive dirt and debris buildups present in the spring in northern regions after snowmelt. Leaf cleanup by street cleaning is also necessary in most areas in the fall. However, it has been difficult to statistically demonstrate that street cleaning has a measurable benefit on outfall stormwater quality during numerous monitoring projects. The main issue adversely affecting the benefits of street cleaners are caused by limited rain energy that preferentially removes very little of the large particles that are most effectively removed by street cleaning.

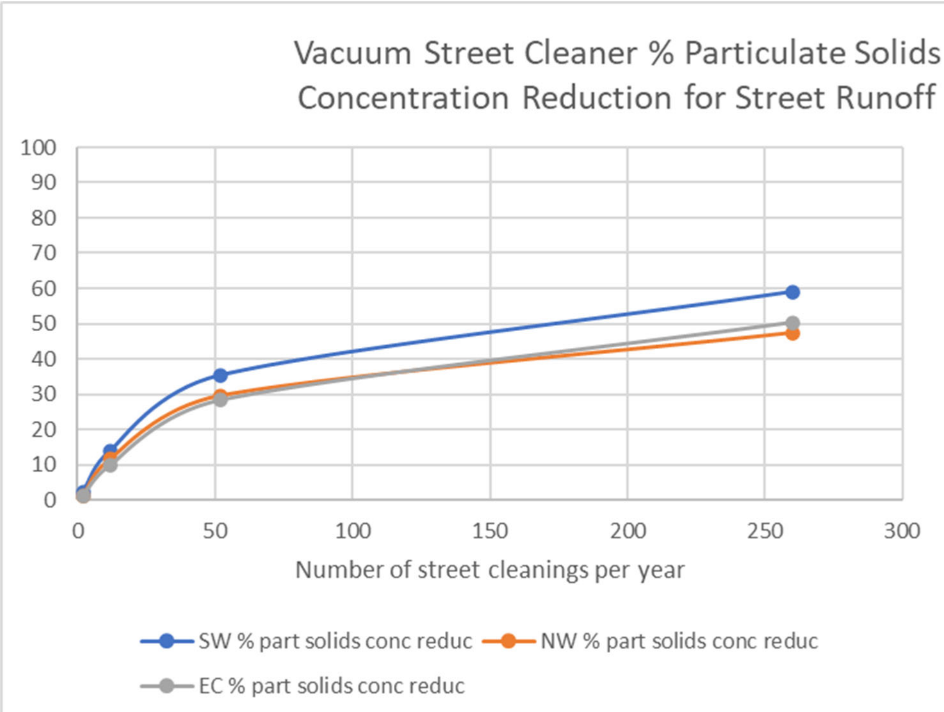
The following are screen shots for the street characteristics inputs and for the street cleaning activities. the high-efficiency vacuum-assisted street cleaner option was selected and no parked cars were present.



The high-efficiency vacuum-assisted street cleaner option was selected, and no parked cars were present. Several street cleaning frequencies were used to calculate the production functions ranging from twice per year to five times in a week.



The following production functions show that under all conditions, few benefits are shown for infrequent street cleaning as it requires about weekly, or greater, cleaning to have at least a 30 percent particulate solids concentration reduction for the street runoff. Monthly cleaning only results in about 10 percent particulate solids concentration reductions, while the maximum particulate solids concentration reductions are about 50 to 60 percent associated with street cleaning five times a week. These production functions are only for particulate solids concentration reductions as no runoff volume reductions are associated with street cleaning.

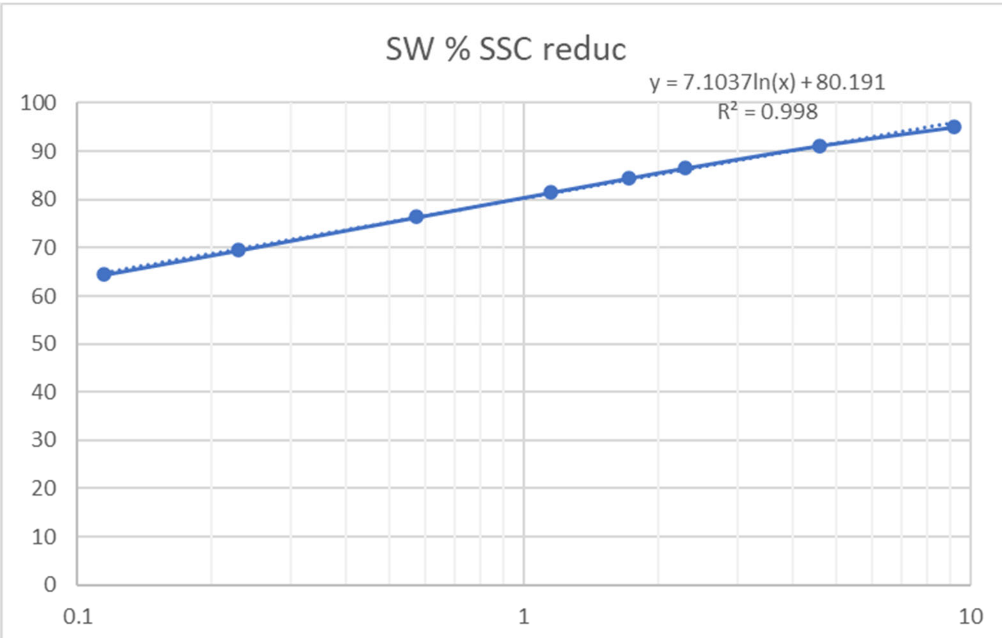


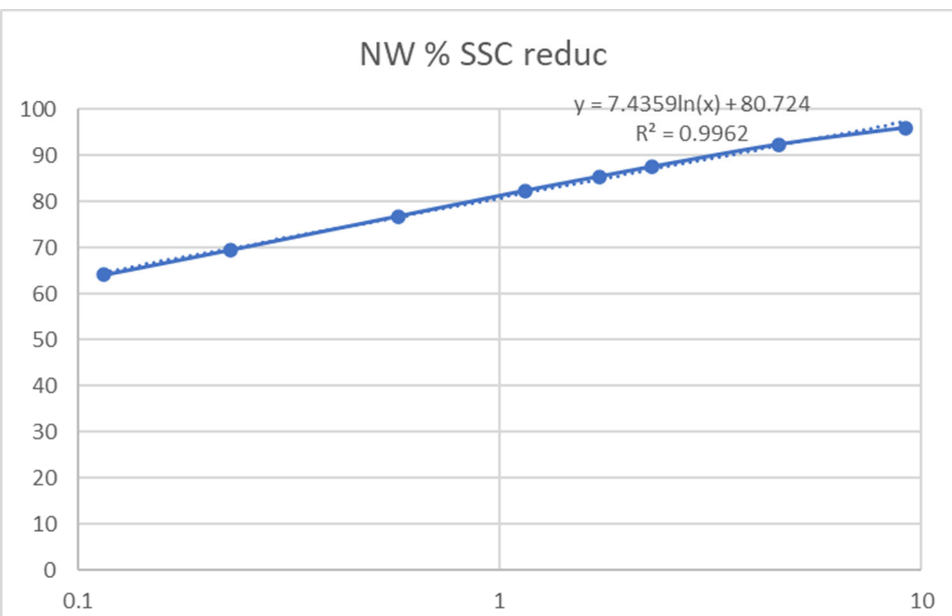
Vacuum Street Cleaner % Particulate Solids Concentration Reduction for Street Runoff
100
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of street cleanings per year
SW % part solids conc reduc
NW % part solids conc reduc
EC % part solids conc reduc

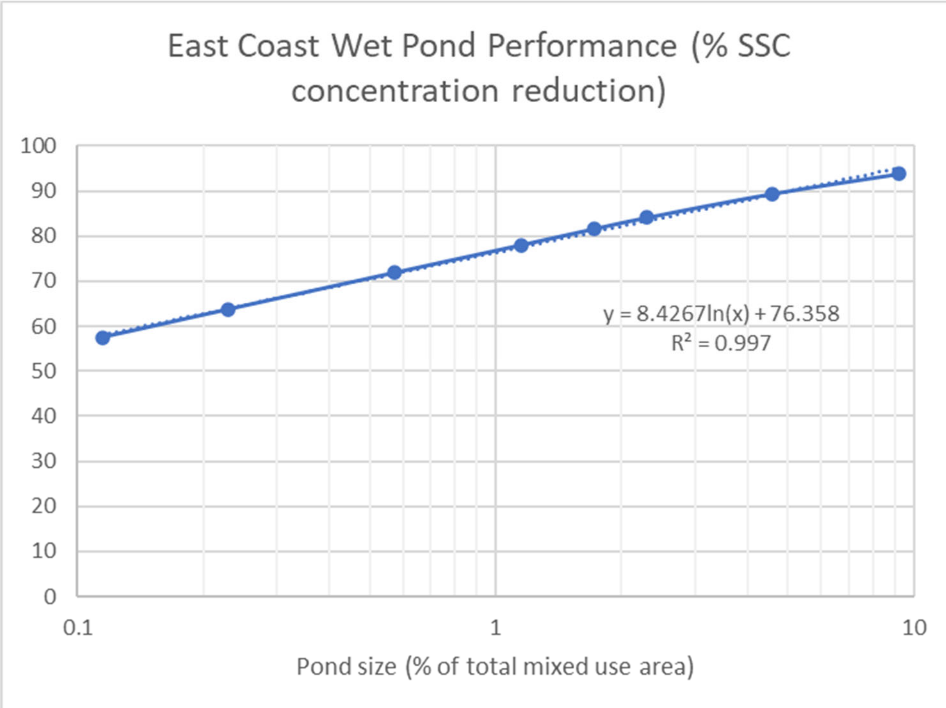
Appendix Production Functions with Regression Estimates

Wet Detention Ponds

The x-axes of these plots are the percentage of the total watershed area that corresponds to the normal water surface area of the wet pond.

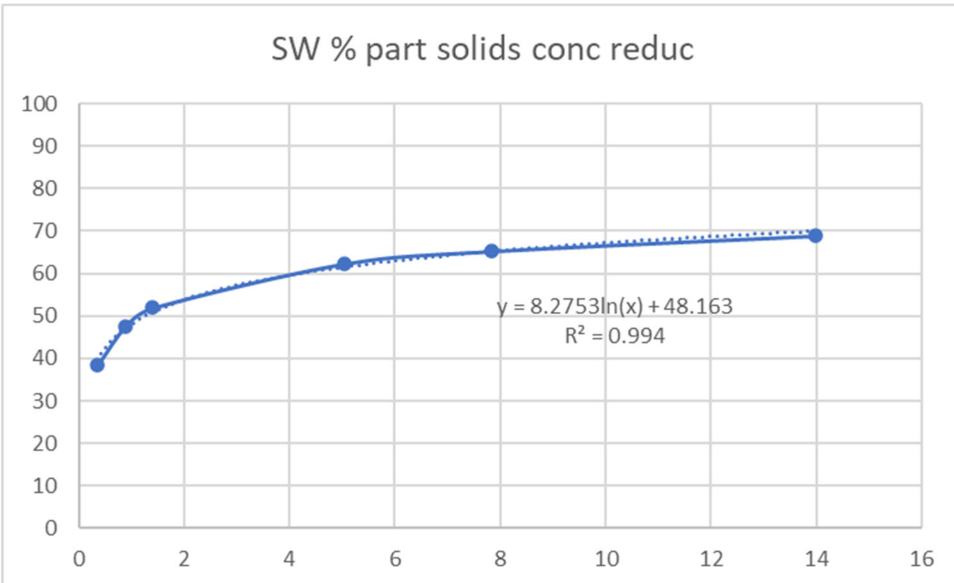


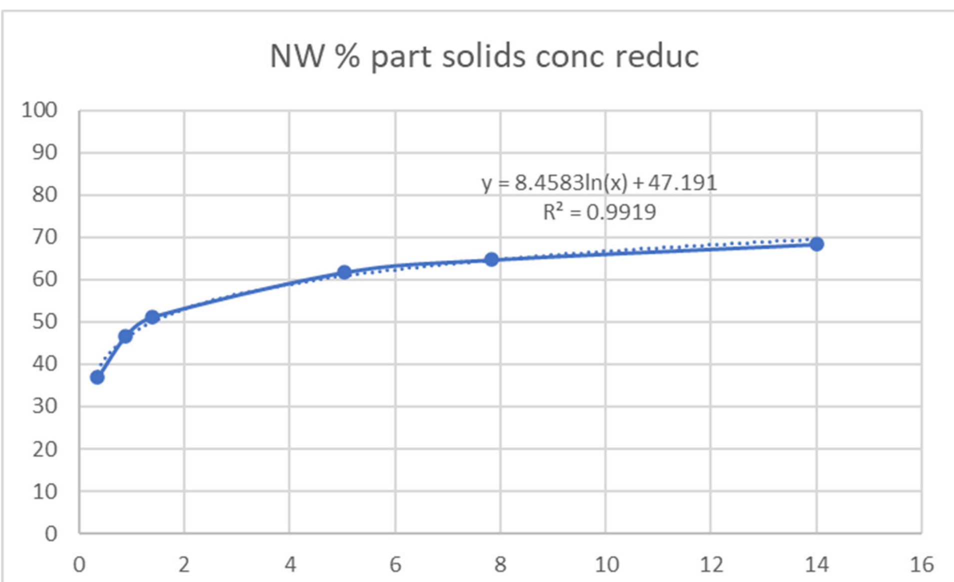


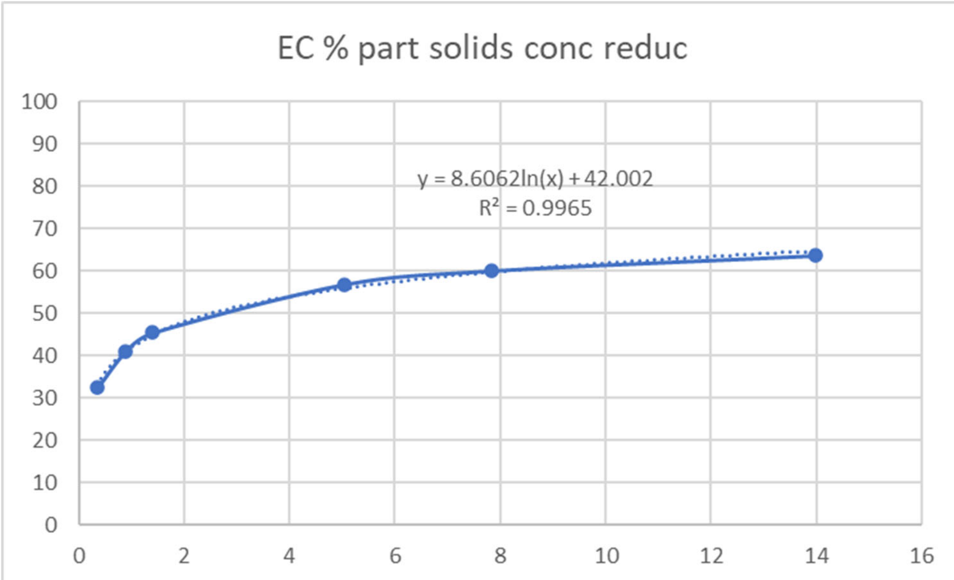

East Coast Wet Pond Performance (% SSC concentration reduction)
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
y = 8.4267ln(x) + 76.358
R² = 0.997
Pond size (% of total mixed use area)

Hydrodynamic Devices

The x-axes of these plots are the total size of the hydrodynamic devices expressed in m^2 per hectare of paved drainage area.



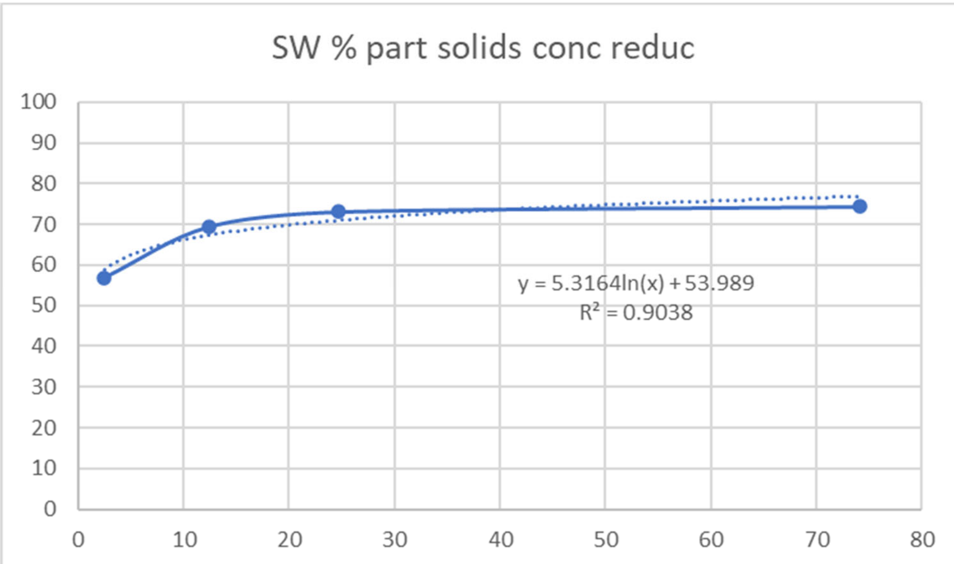


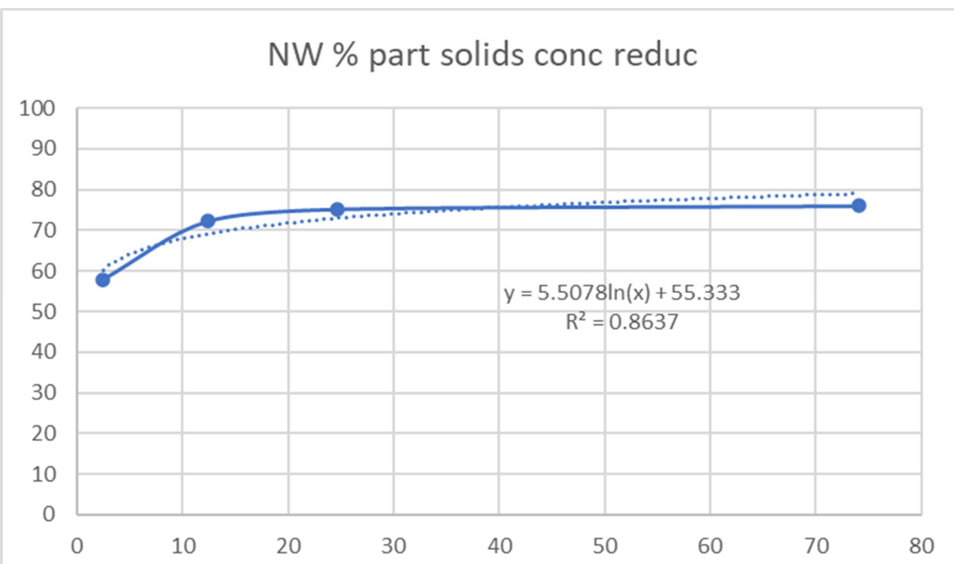


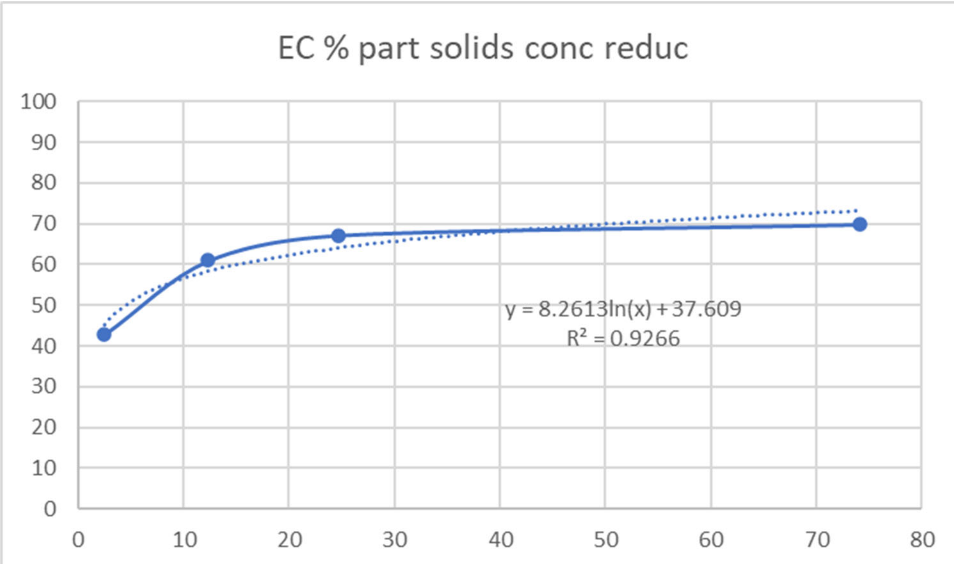
EC % part solids conc reduc
y = 8.6062ln(x) + 42.002
R² = 0.9965
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16

Contech StormFilter

The x-axes of these plots are the total number of cartridge filters per hectare of paved drainage area.



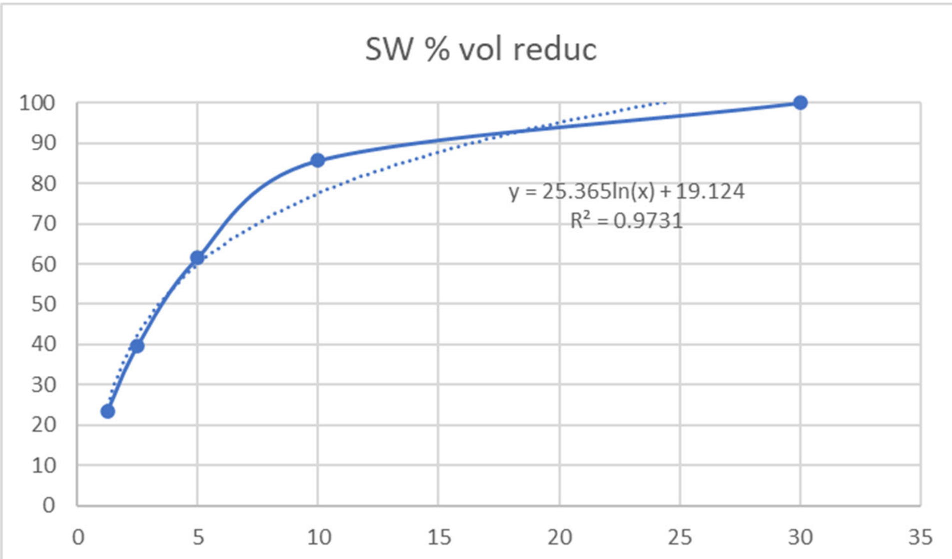




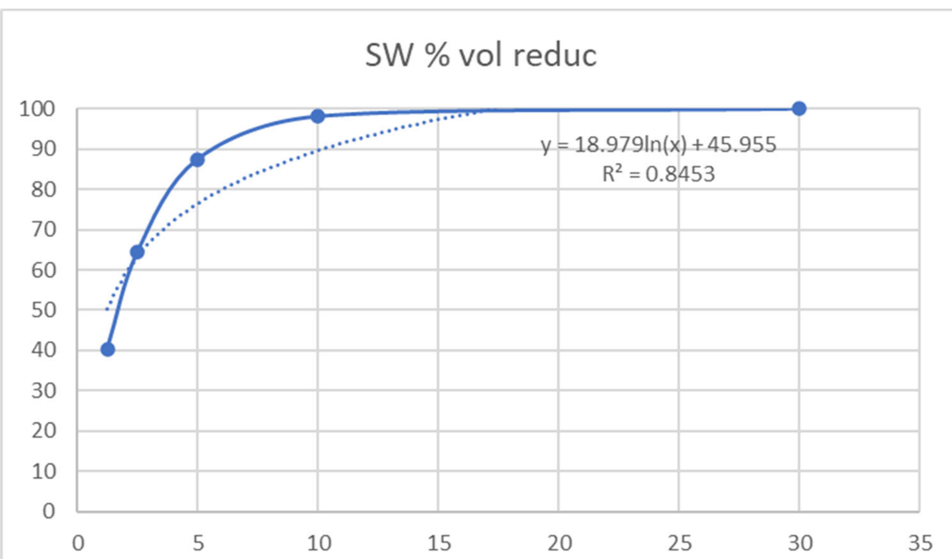
EC % part solids conc reduc
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
y = 8.2613ln(x) + 37.609
R² = 0.9266

Roof Runoff Rain Gardens

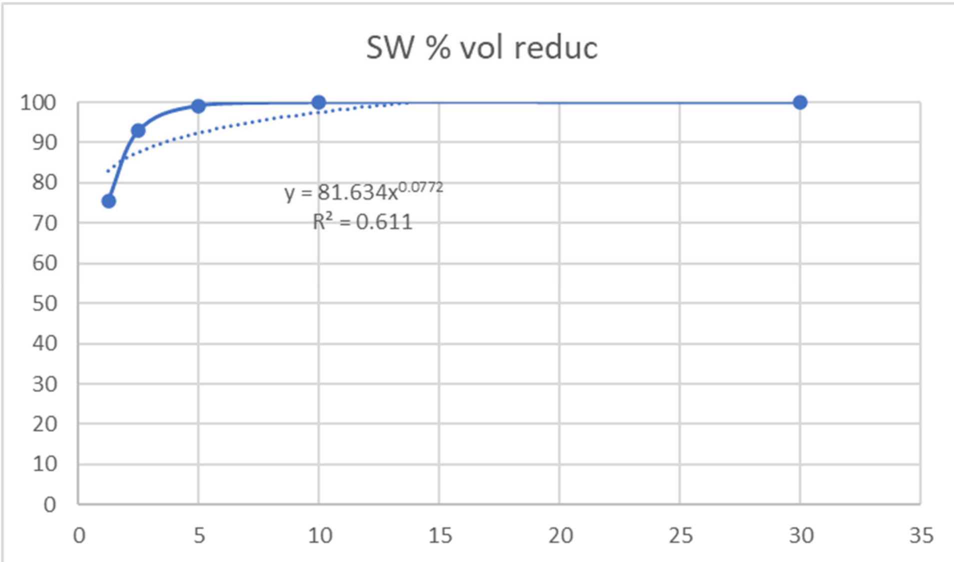
The x-axes of these plots are the percentage of the roof areas that corresponds to the total areas of the rain gardens.



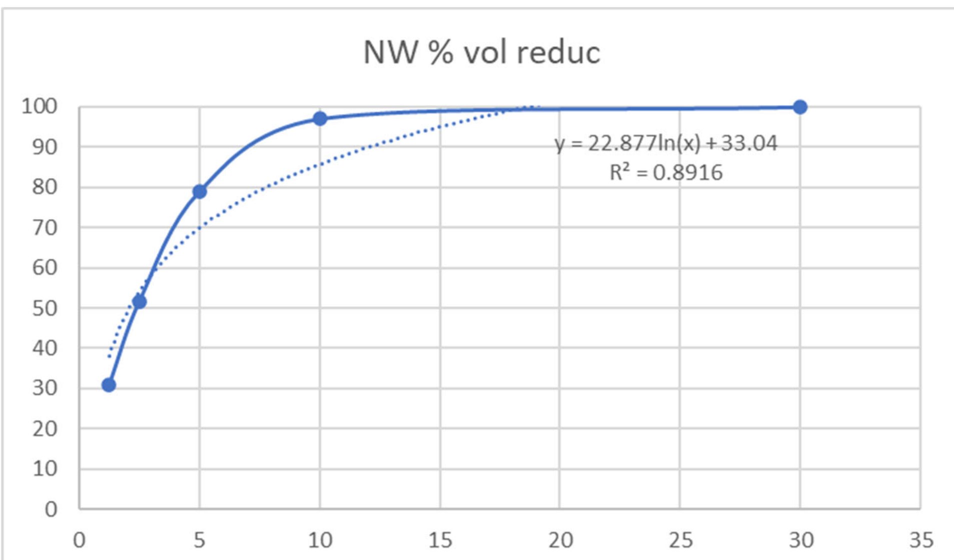
2.5 mm/hr soil infiltration rate



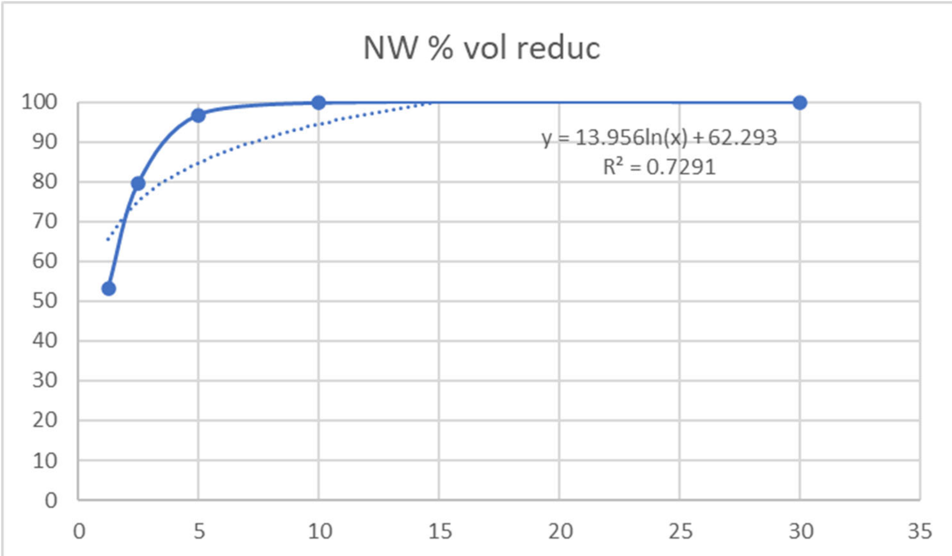
12 mm/hr soil infiltration rate



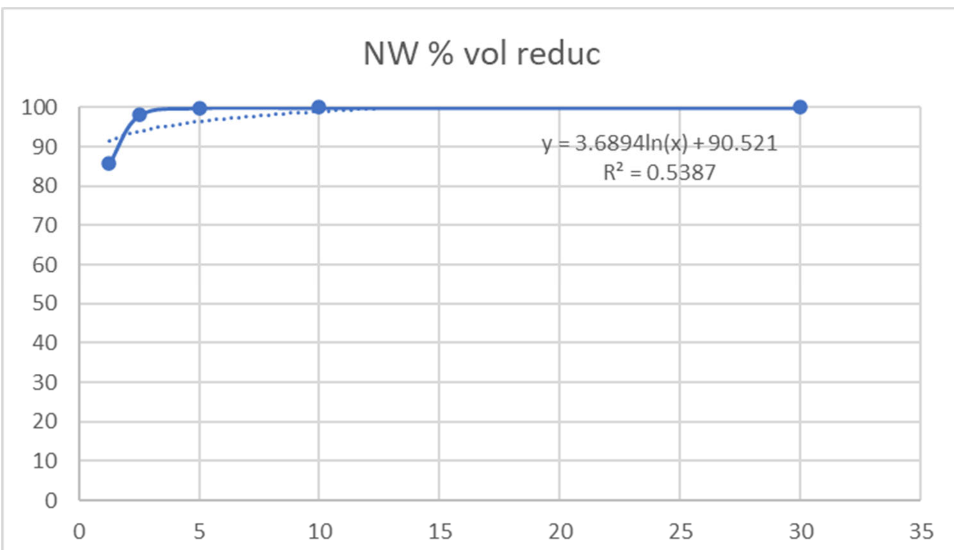
64 mm/hr soil infiltration rate



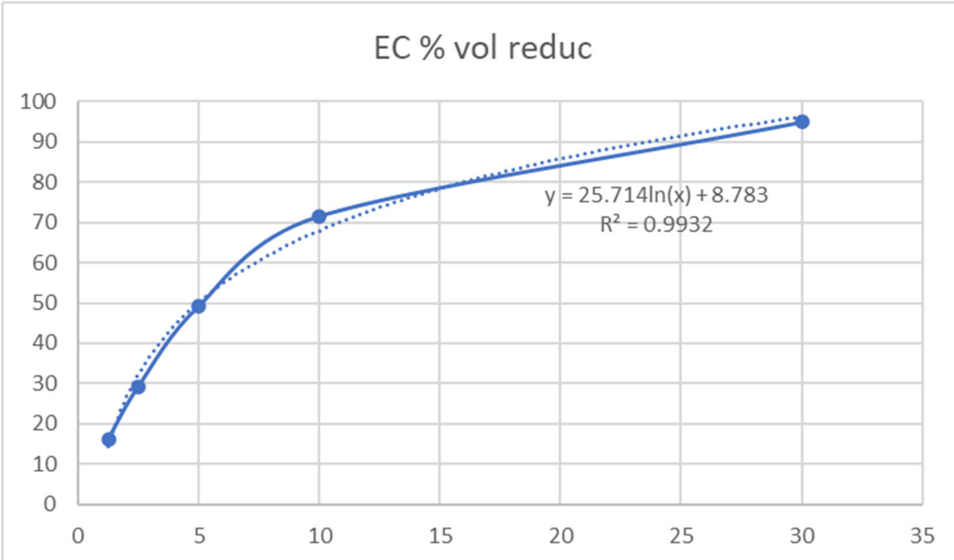
2.5 mm/hr soil infiltration rate



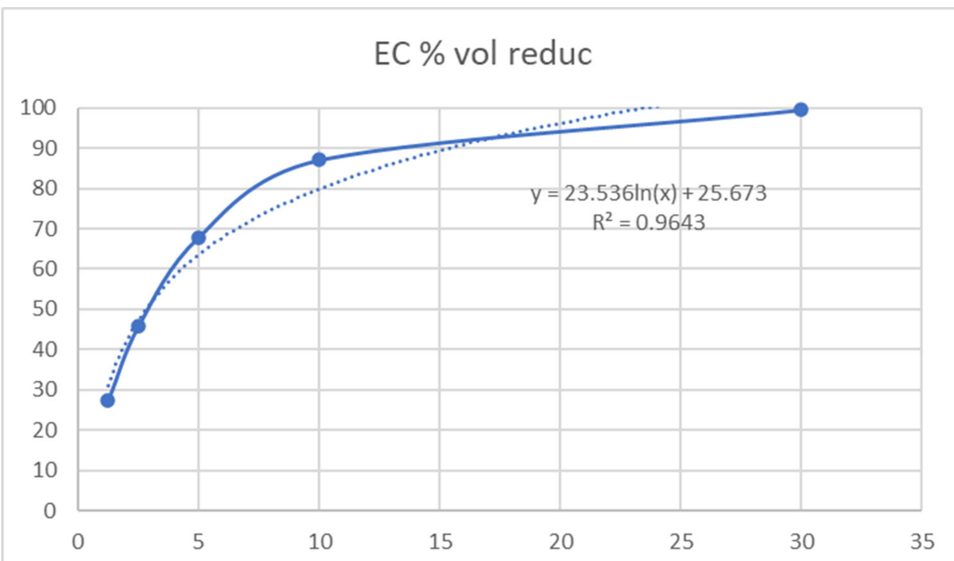
12 mm/hr soil infiltration rate



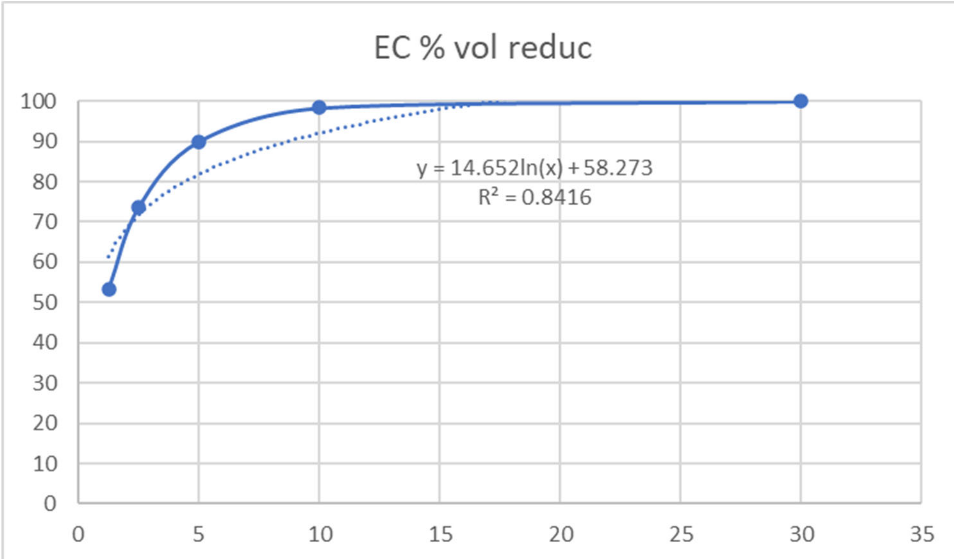
64 mm/hr soil infiltration rate



2.5 mm/hr soil infiltration rate



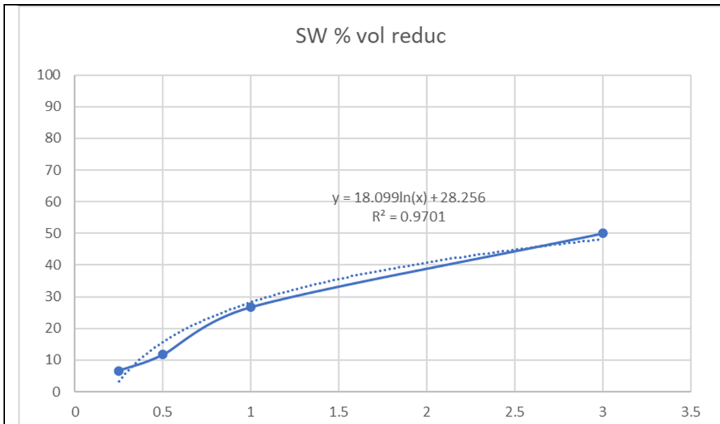
12 mm/hr soil infiltration rate



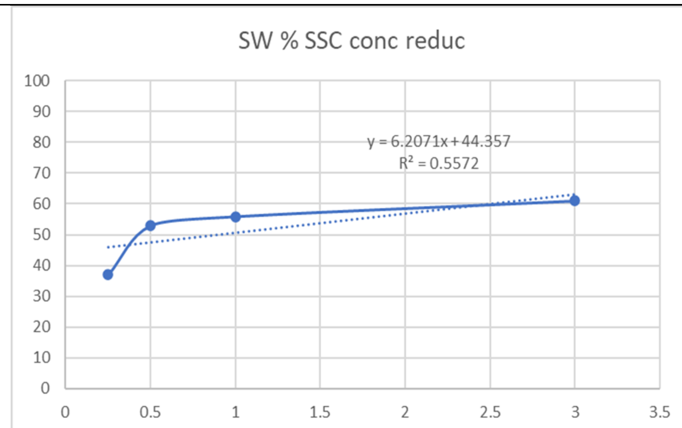
64 mm/hr soil infiltration rate

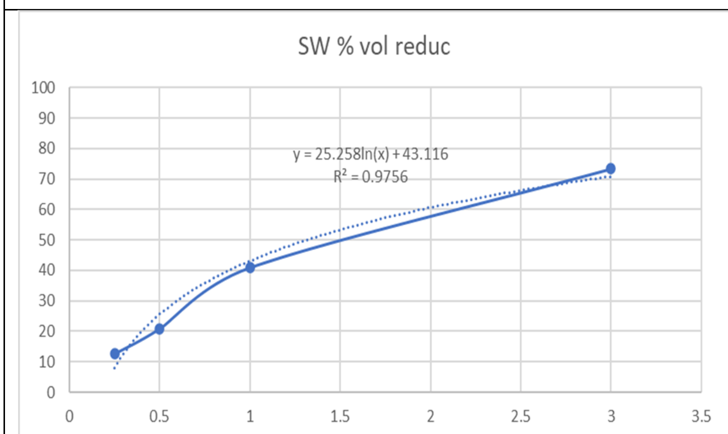
Biofilters at Paved Areas

The x-axes of these plots are the percentage of the paved drainage area that corresponds to the total areas of the biofilters.

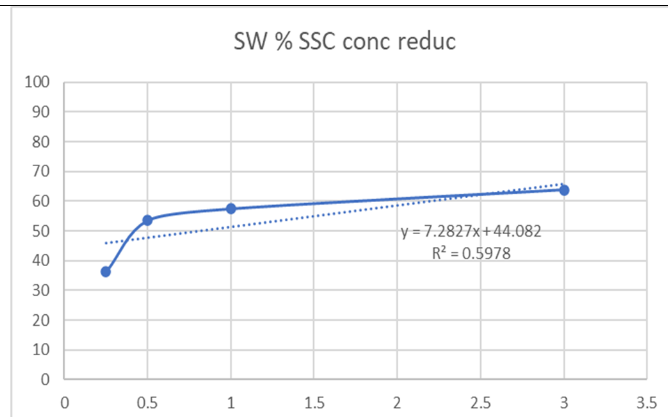


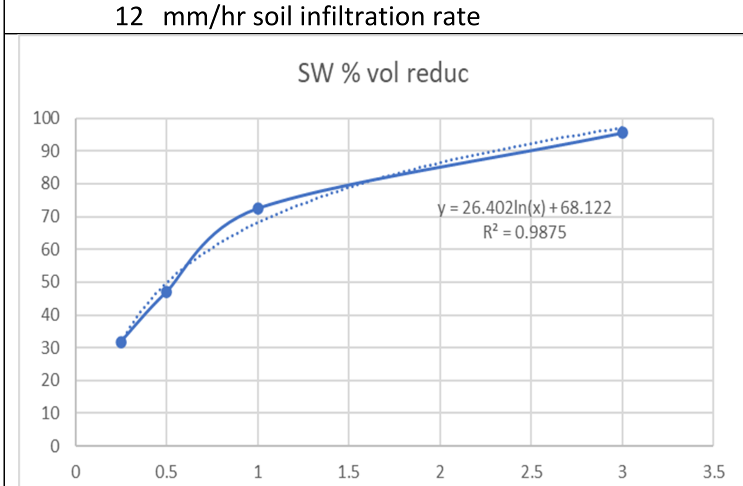
2.5 mm/hr soil infiltration rate



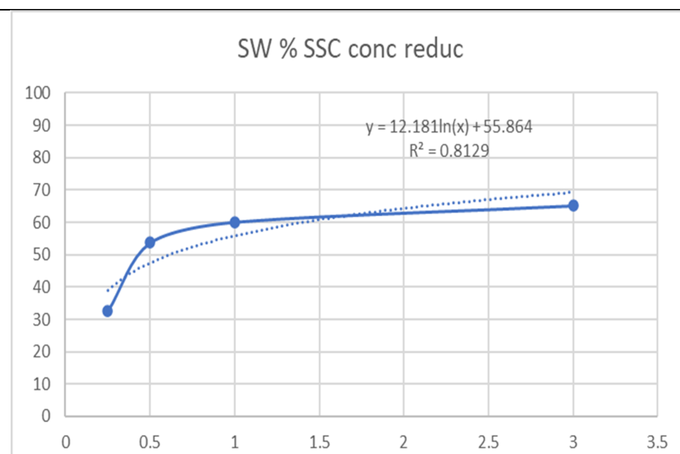


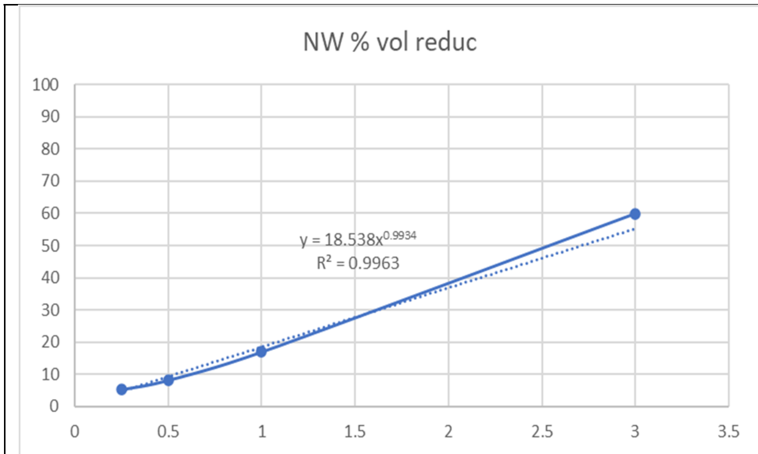
12 mm/hr soil infiltration rate

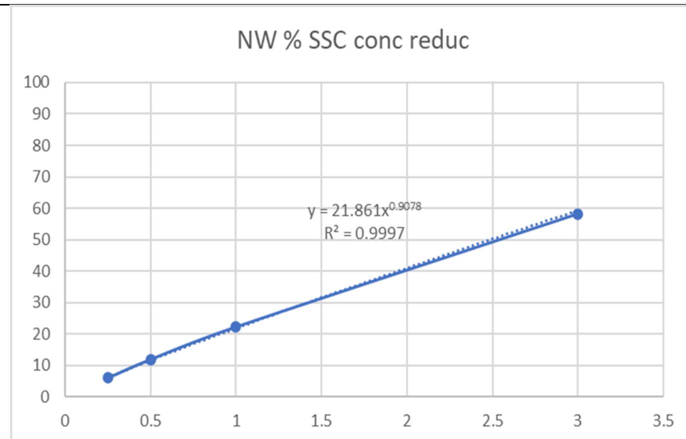




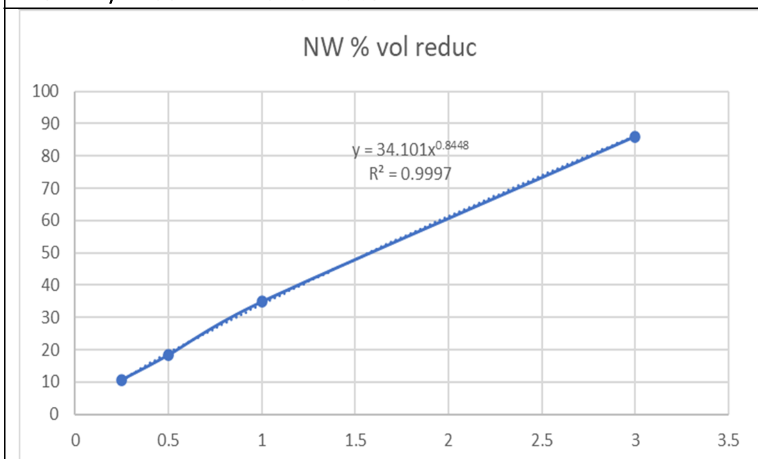
64 mm/hr soil infiltration rate

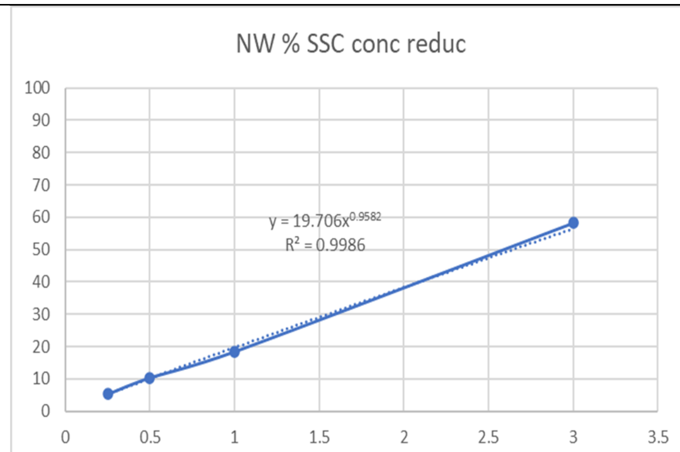




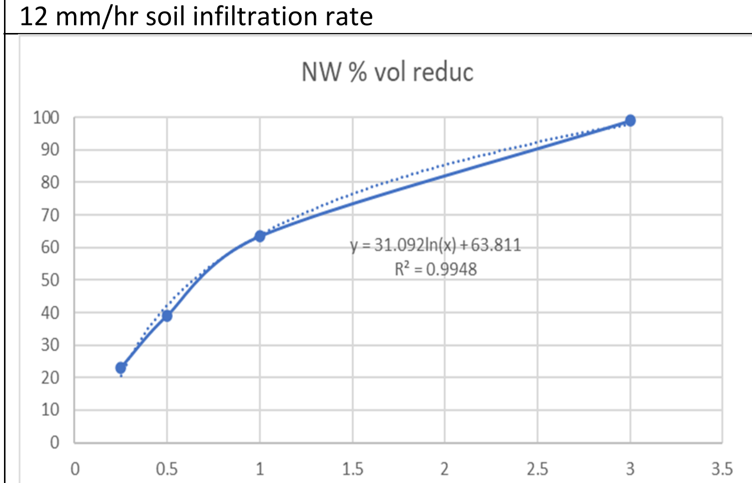


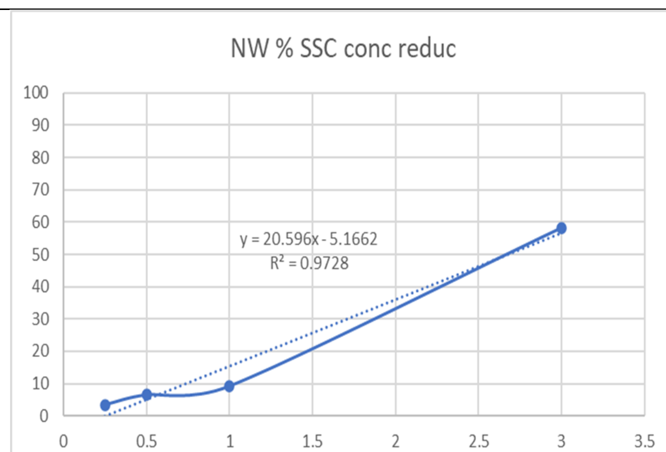
2.5 mm/hr soil infiltration rate



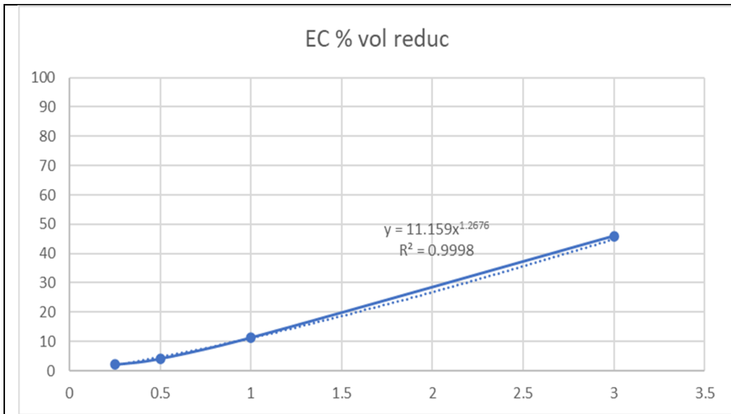


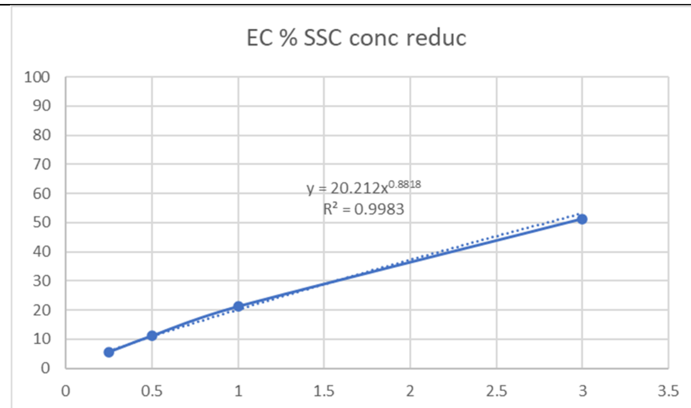
12 mm/hr soil infiltration rate



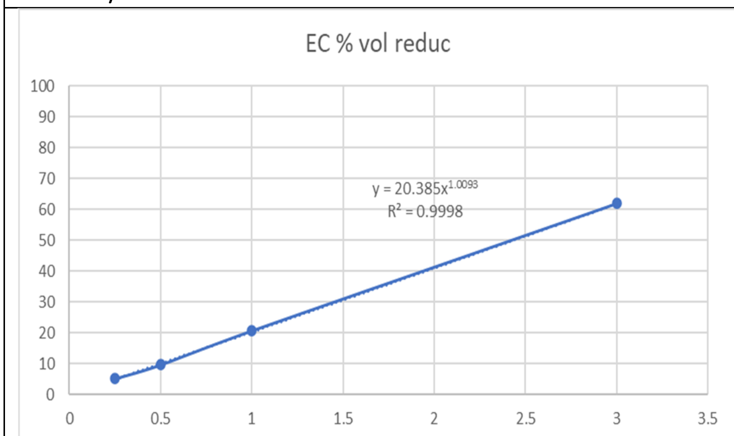


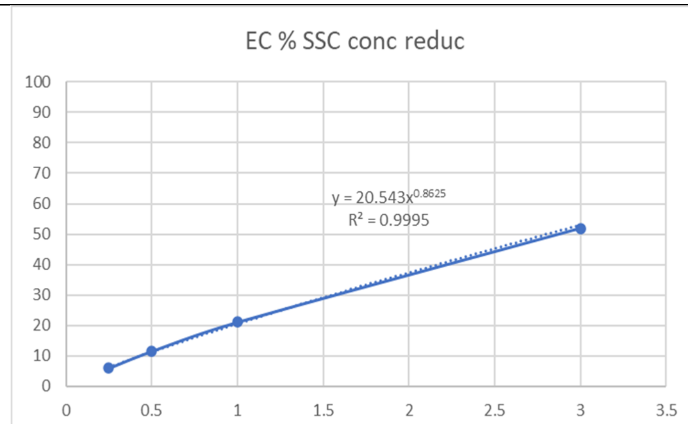
64 mm/hr soil infiltration rate



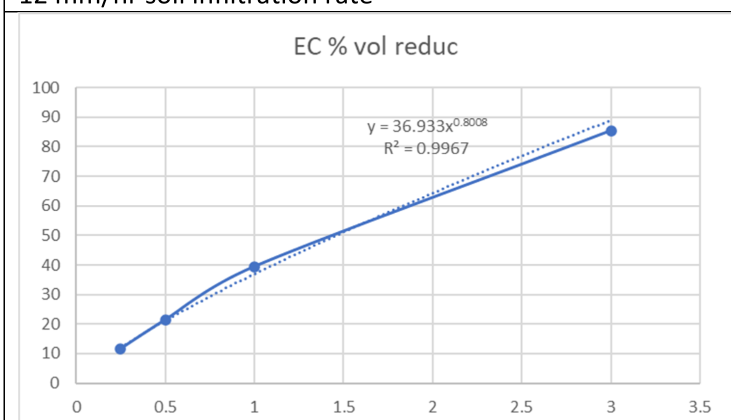


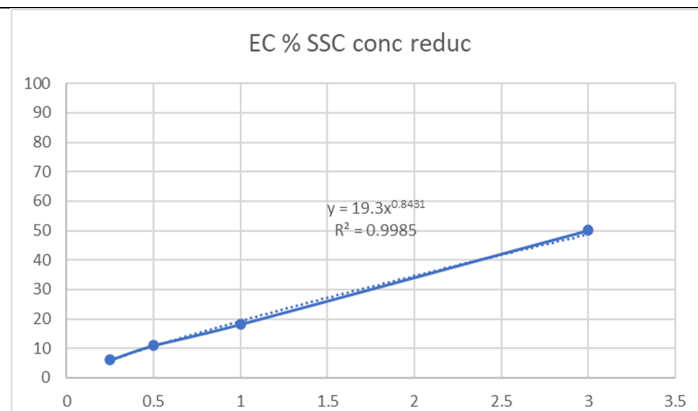
2.5 mm/hr soil infiltration rate





12 mm/hr soil infiltration rate

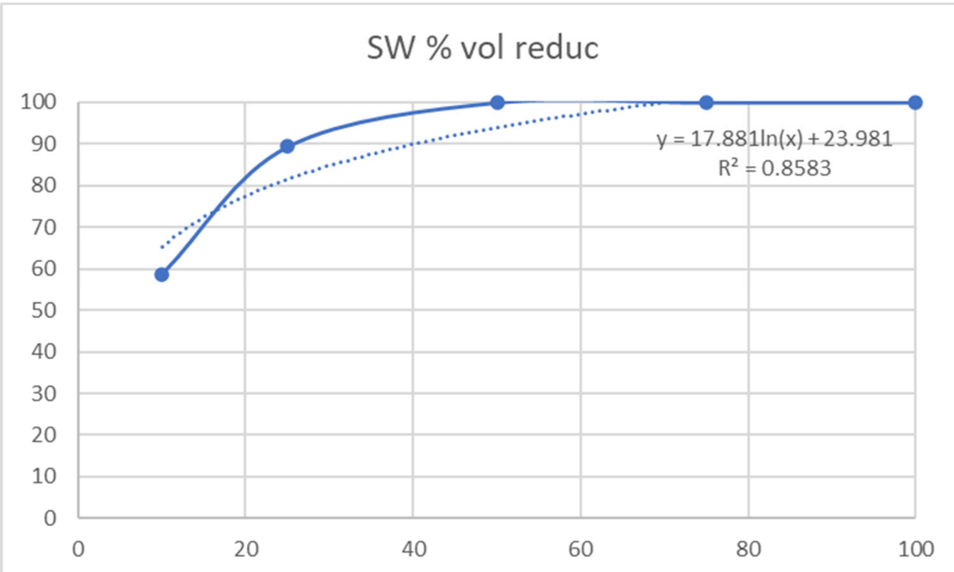




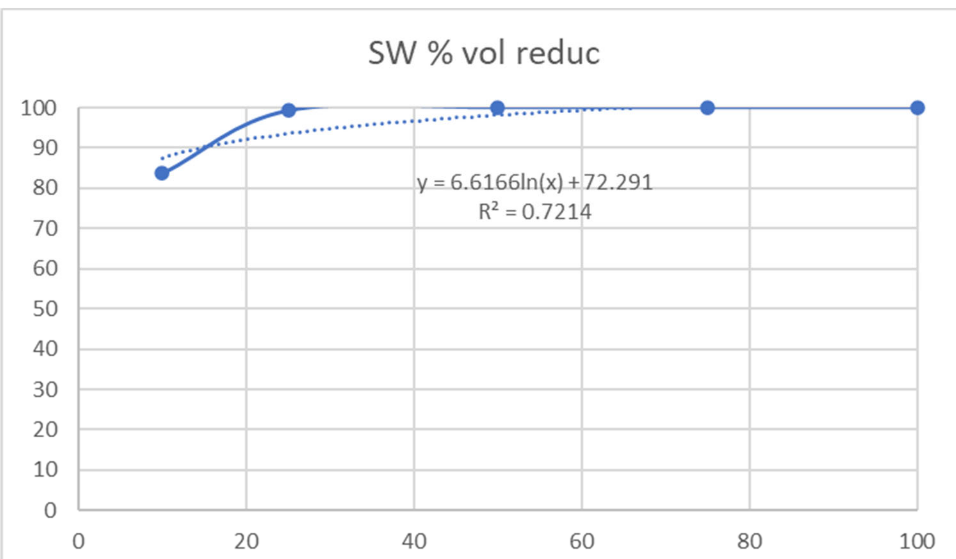
64 mm/hr soil infiltration rate

Porous Pavement

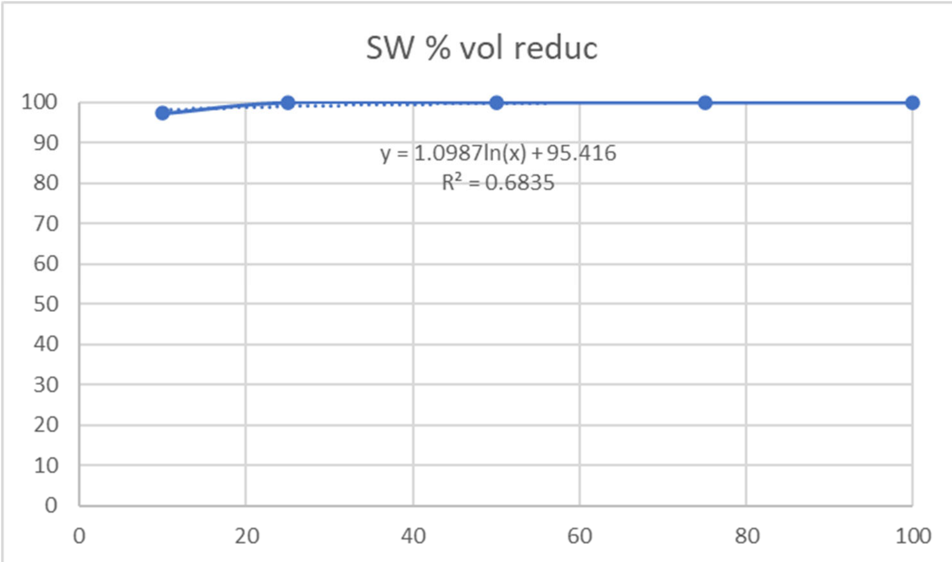
The x-axes of these plots are the percentages of the paved drainage areas that have porous pavement.



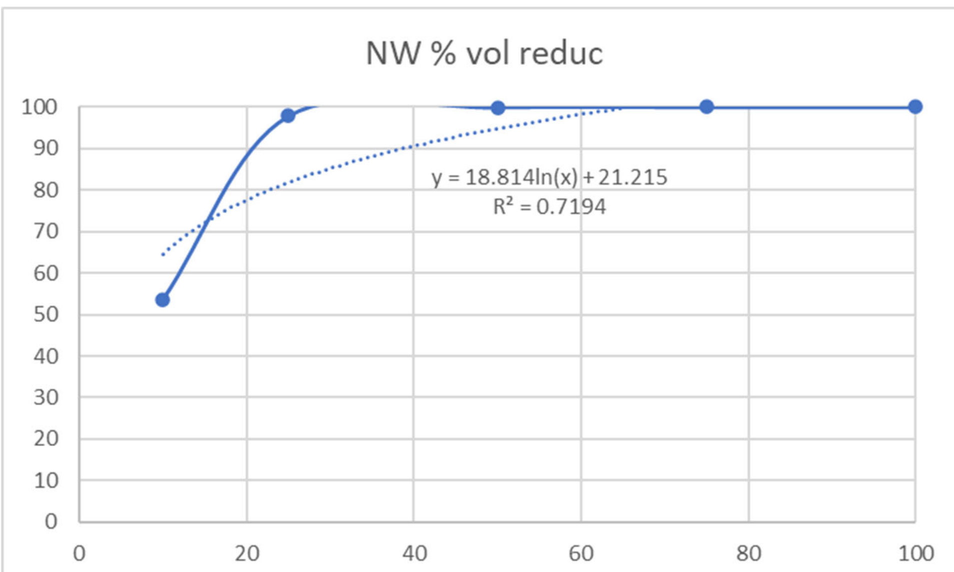
2.5 mm/hr soil infiltration rate



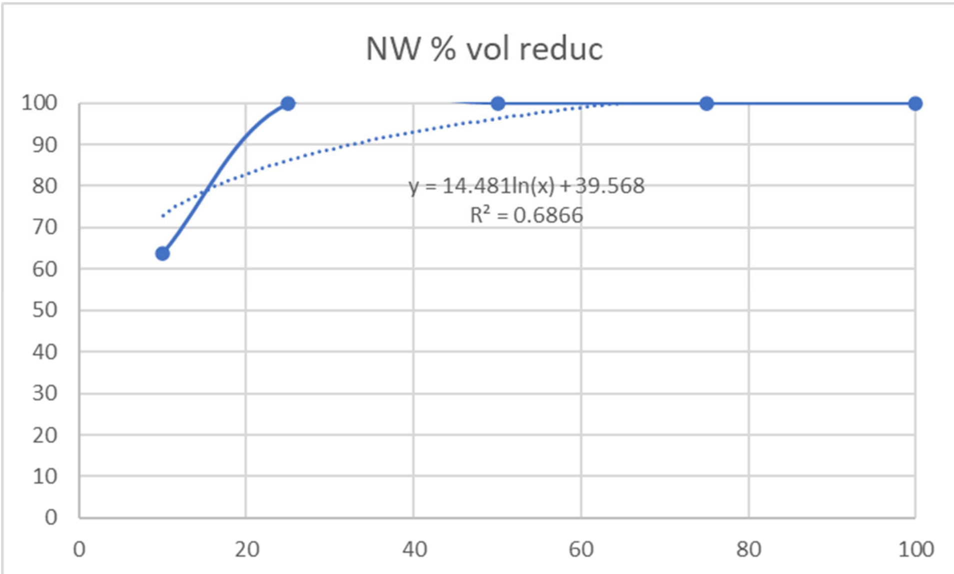
12 mm/hr soil infiltration rate



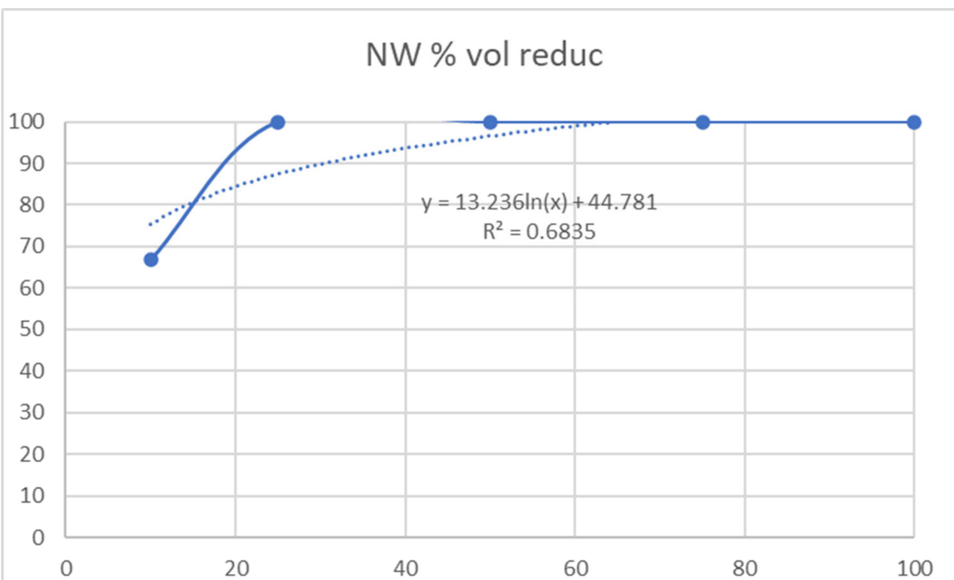
64mm/hr soil infiltration rate



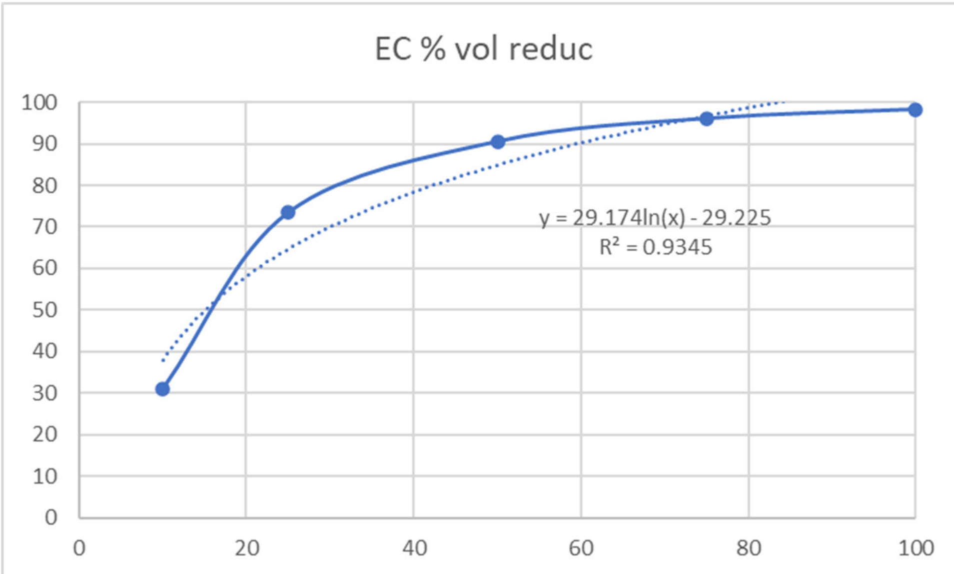
2.5 mm/hr soil infiltration rate



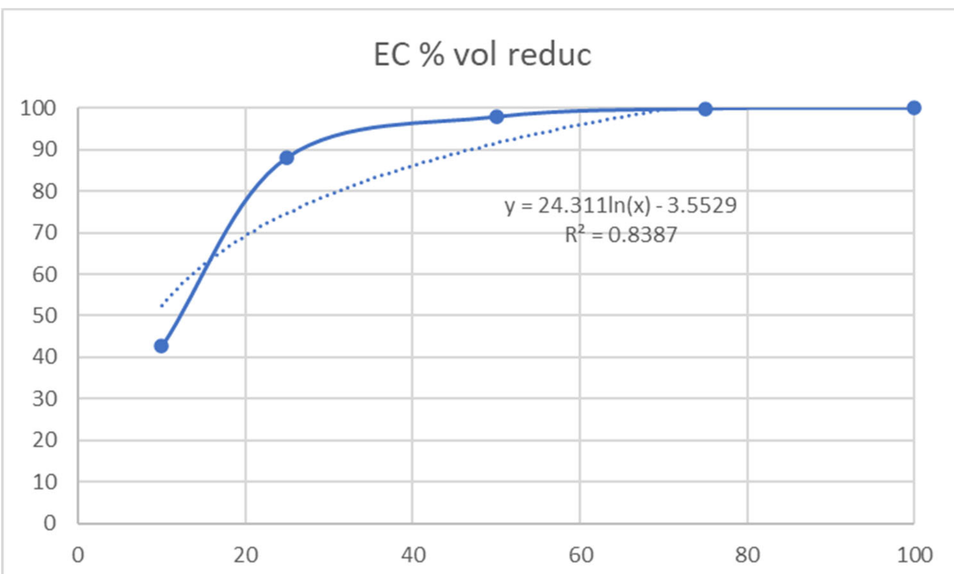
12 mm/hr soil infiltration rate



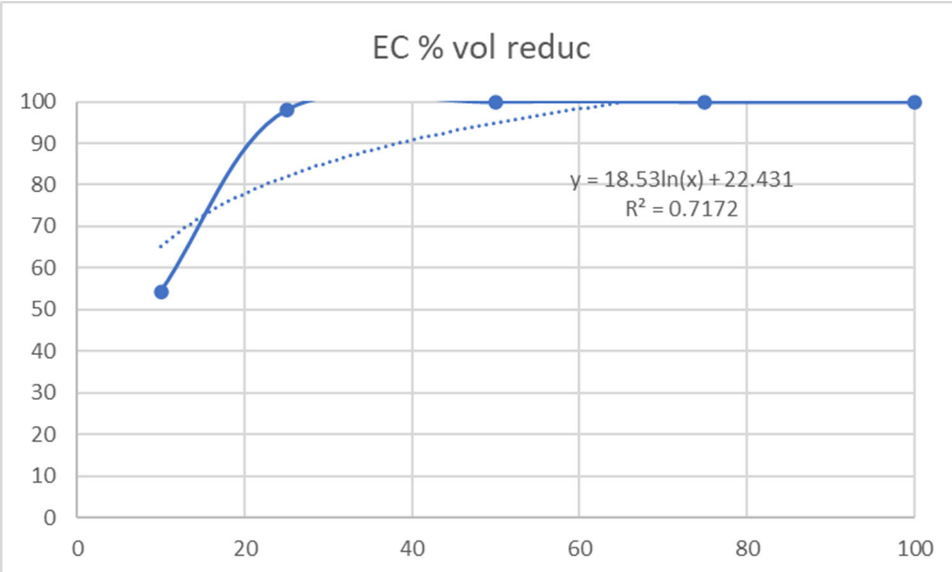
64 m/hr soil infiltration rate



2.5 mm/hr soil infiltration rate



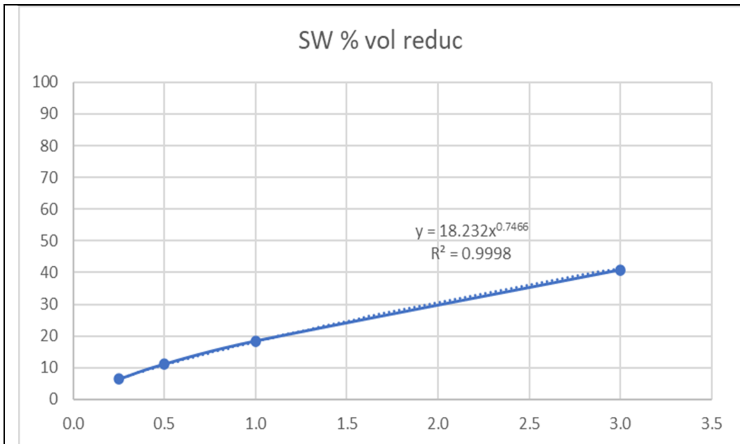
12 mm/hr soil infiltration rate



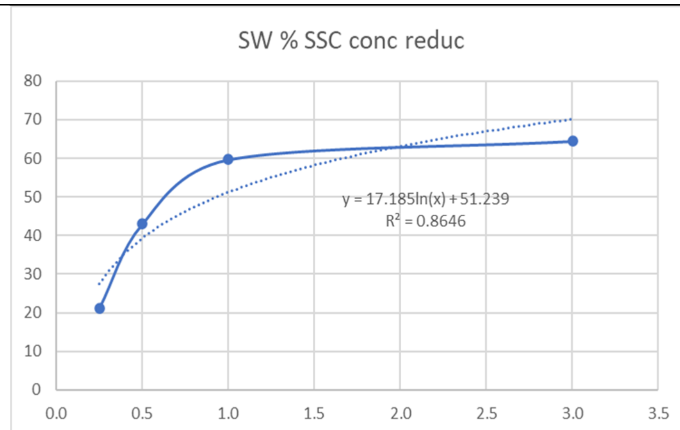
64 mm/hr soil infiltration rate

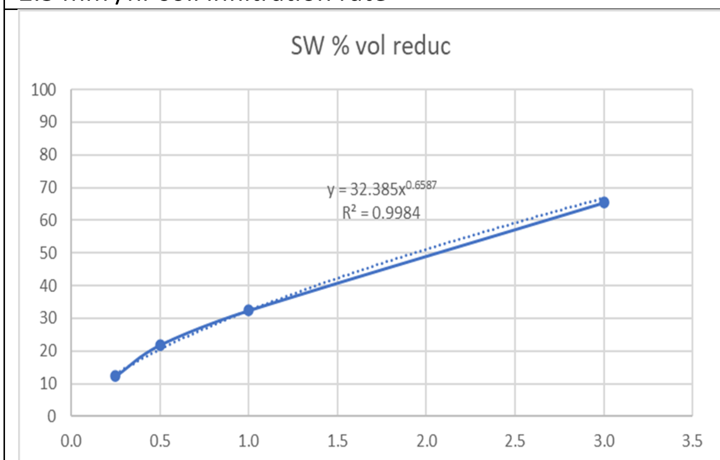
Streetside Curb-cut Biofilters

The x-axes of these plots are the percentages of the street areas that are the curb-cut biofilters.

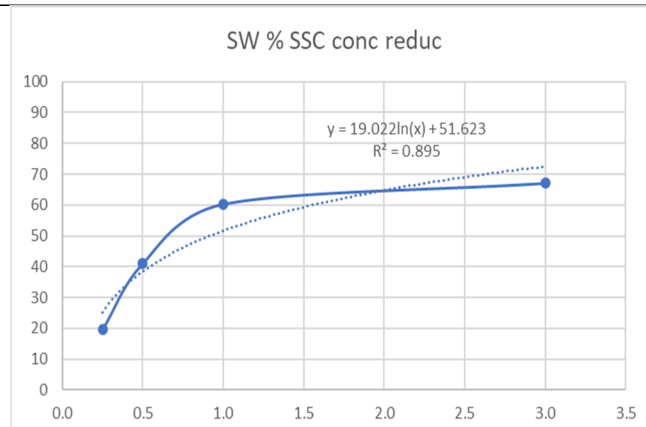


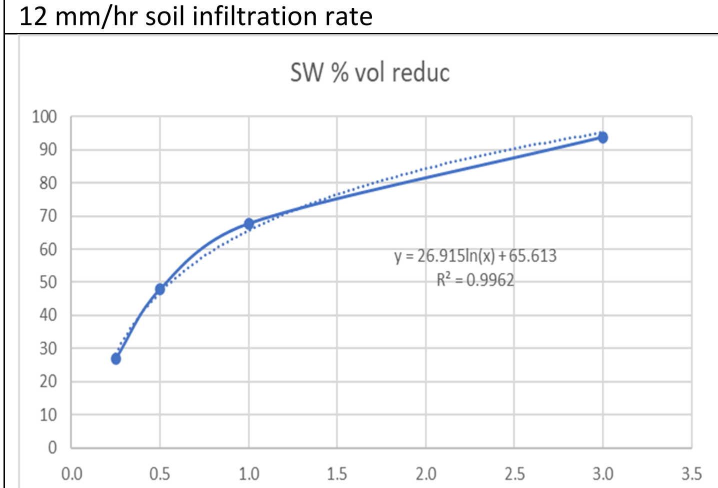
2.5 mm /hr soil infiltration rate



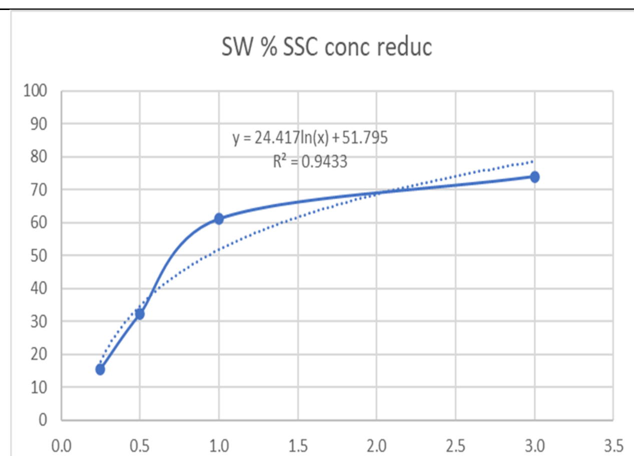


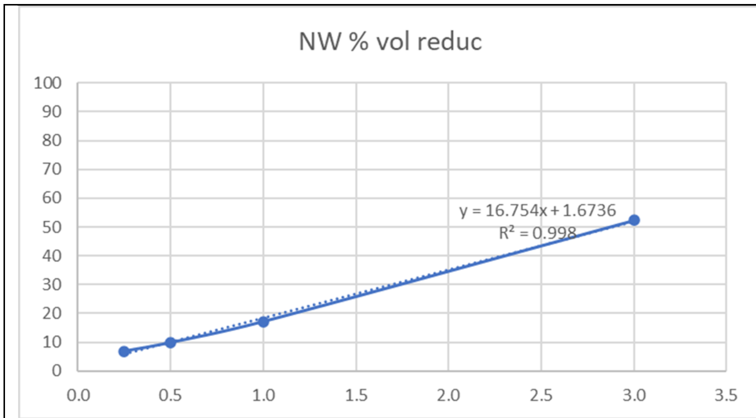
12 mm/hr soil infiltration rate

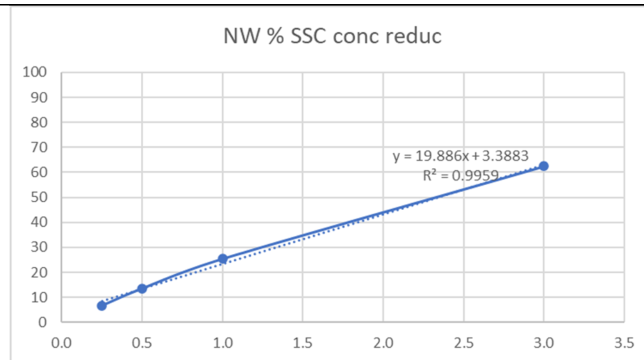




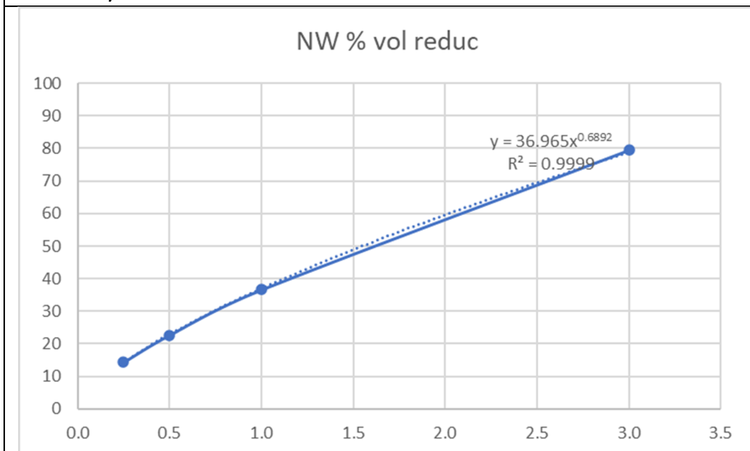
64 mm/hr soil infiltration rate

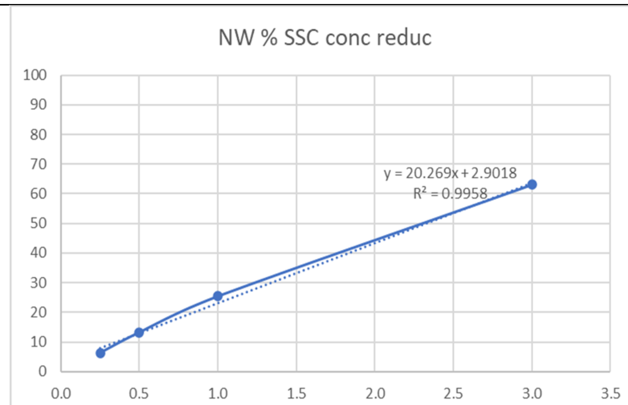




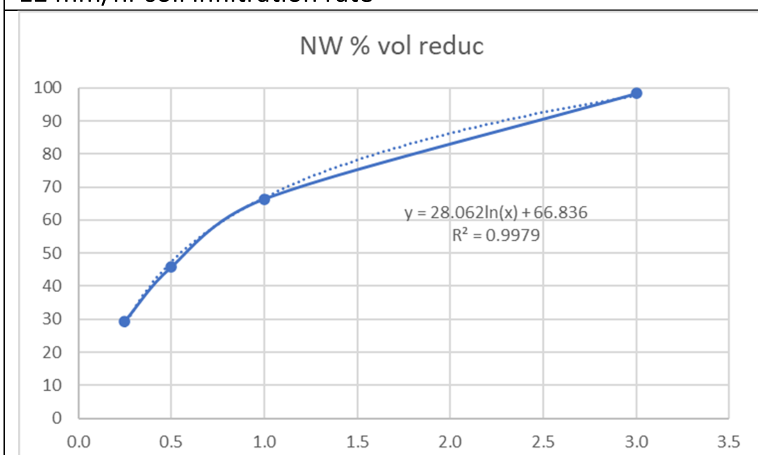


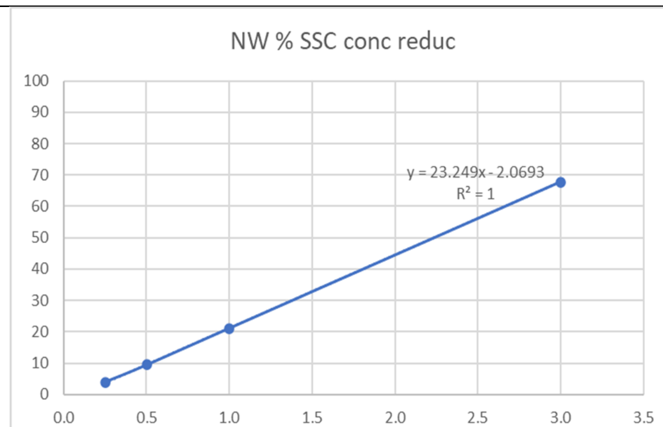
2.5 mm/hr soil infiltration rate



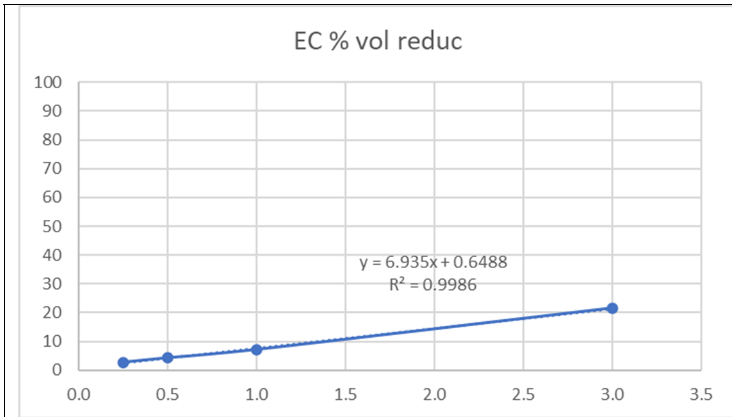


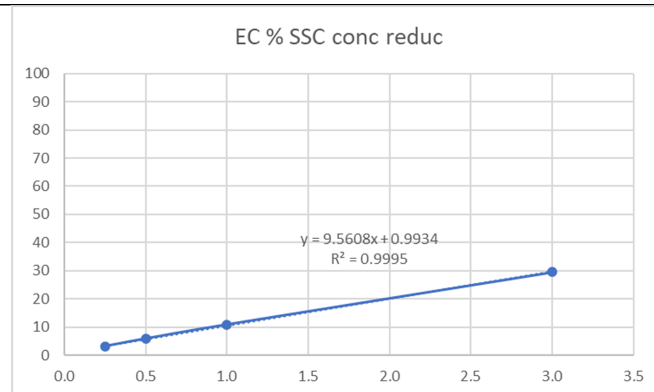
12 mm/hr soil infiltration rate



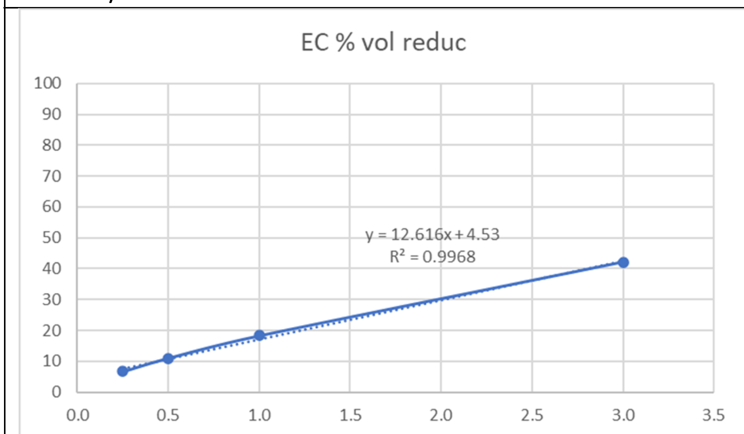


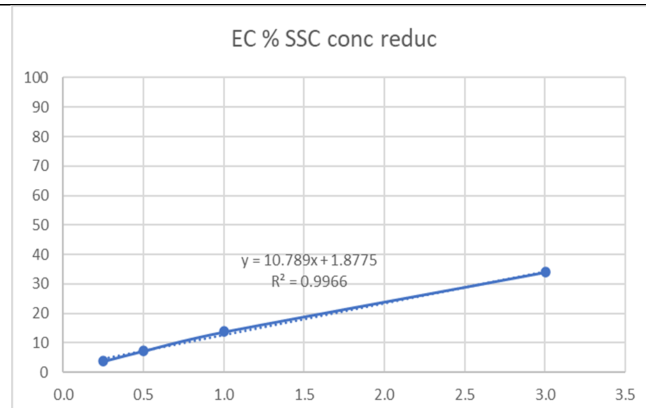
64 mm/hr soil infiltration rate



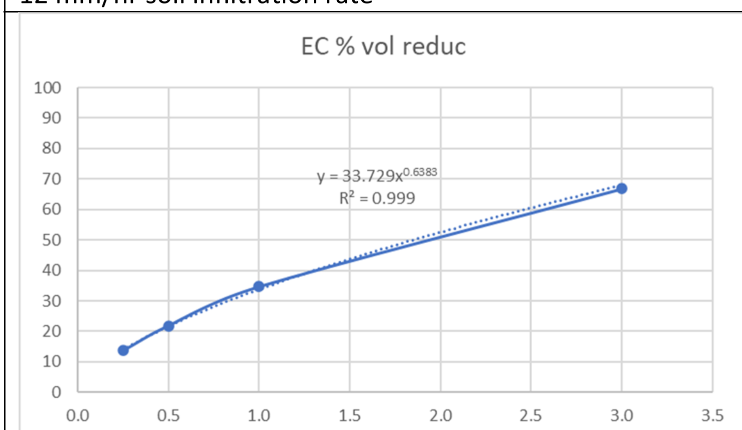


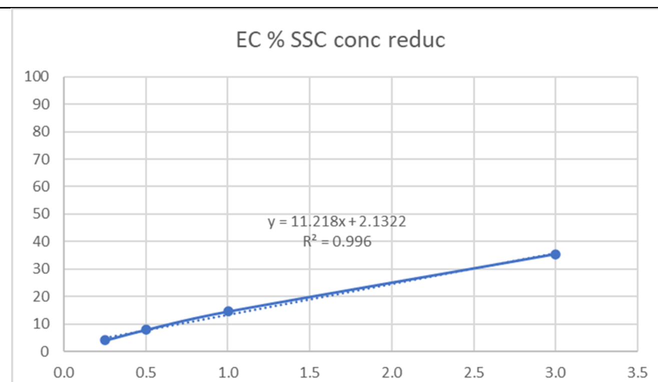
2.5 mm/hr soil infiltration rate





12 mm/hr soil infiltration rate

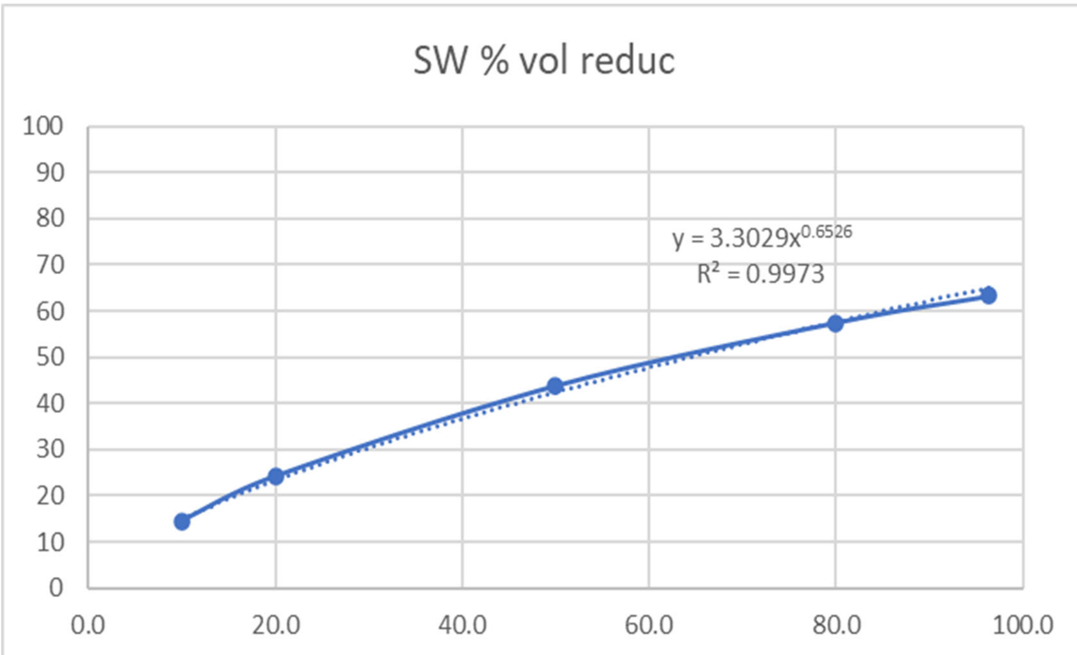


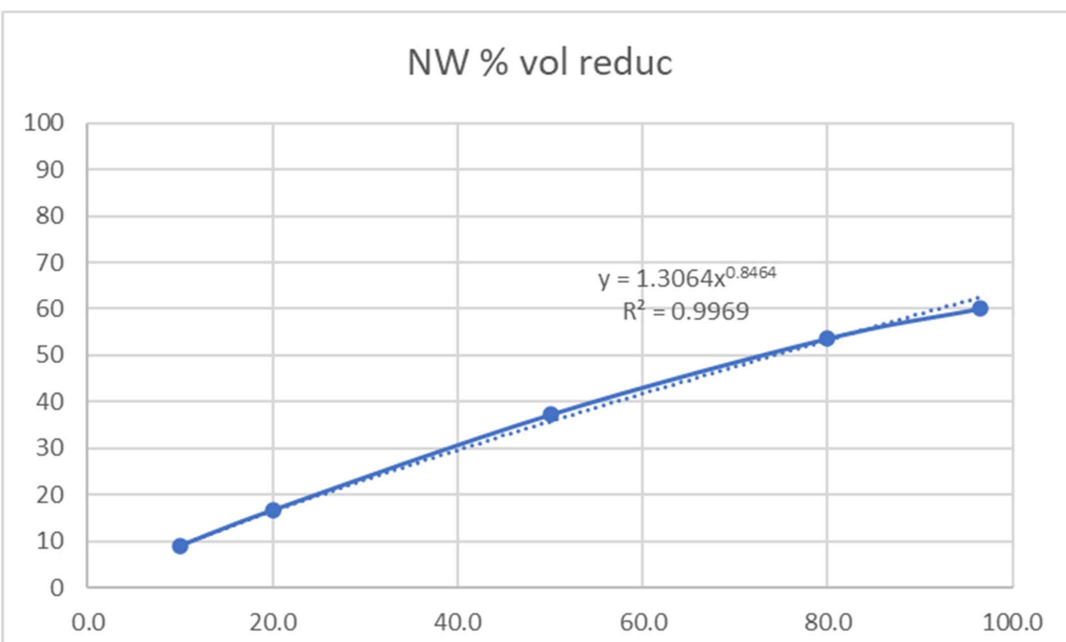


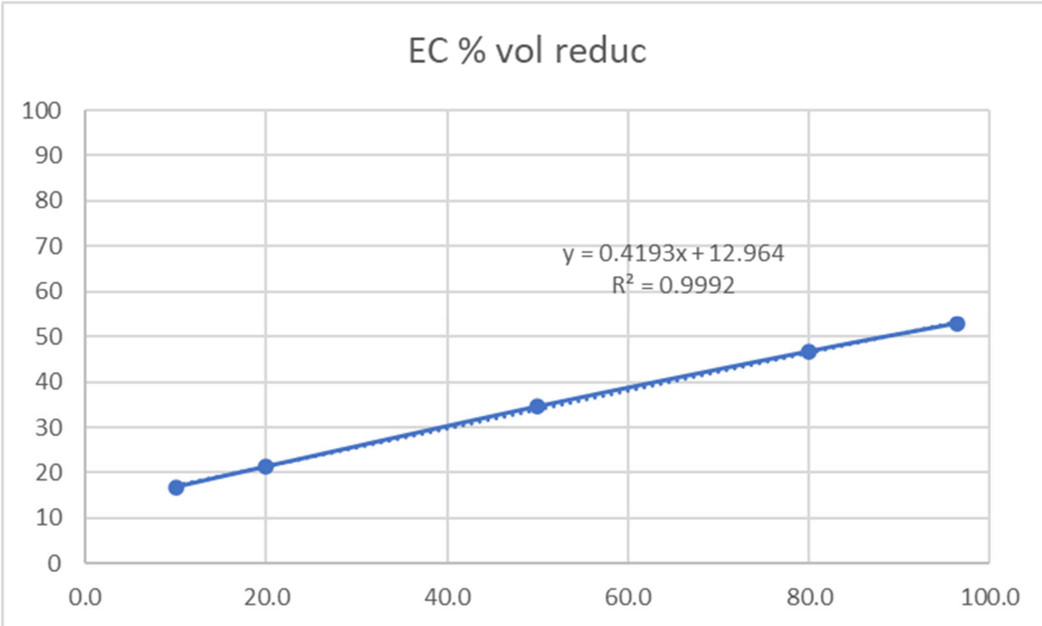
64 mm/hr soil infiltration rate

Green Roofs

The x-axes of these plots are the percentage of the roof areas that corresponds to the total areas of the green roofs.

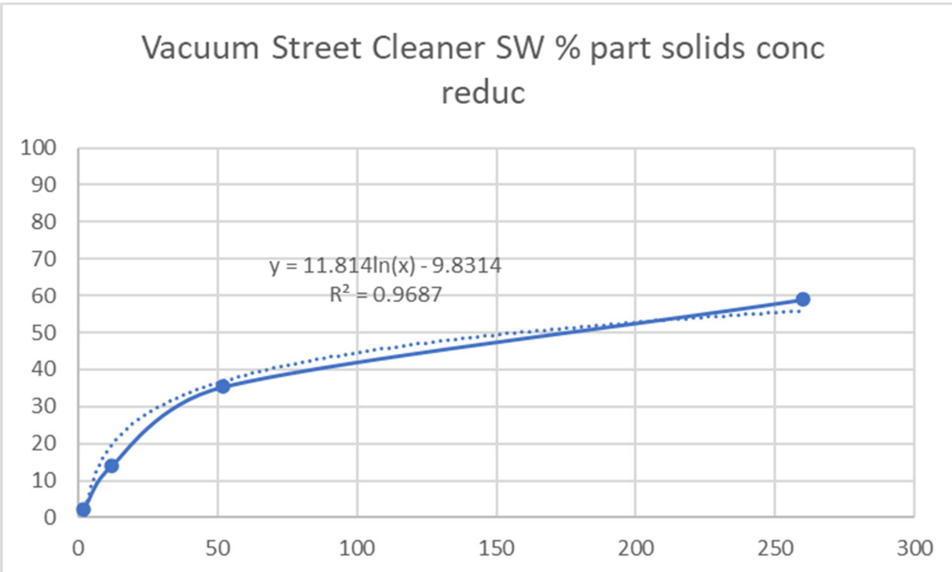


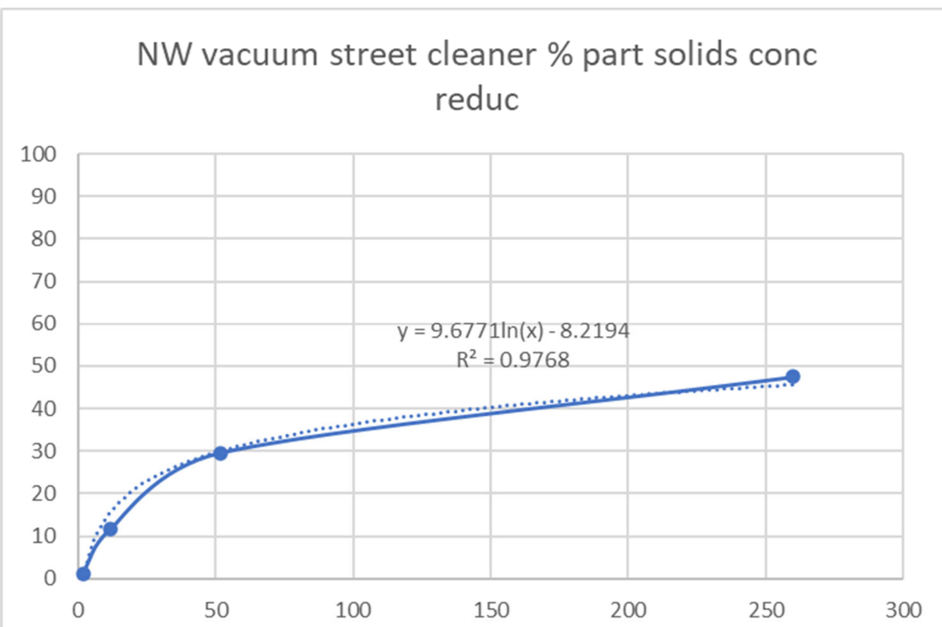


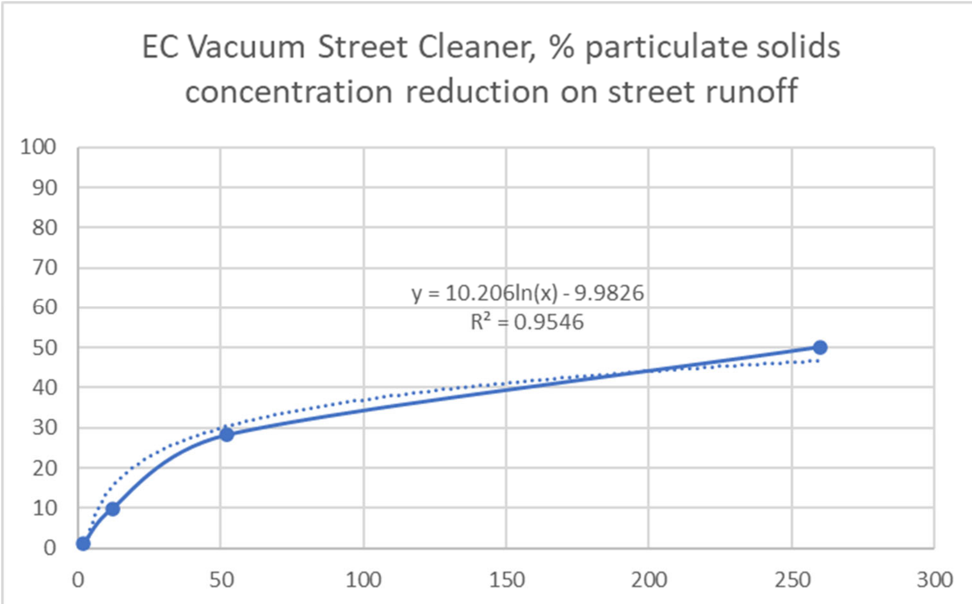

EC % vol reduc
y = 0.4193x + 12.964
R² = 0.9992
100
90
80
70
60
50
40
30
20
10
0
0.0
20.0
40.0
60.0
80.0
100.0

Street Cleaning

The x-axes of these plots are the numbers of street cleanings per year.



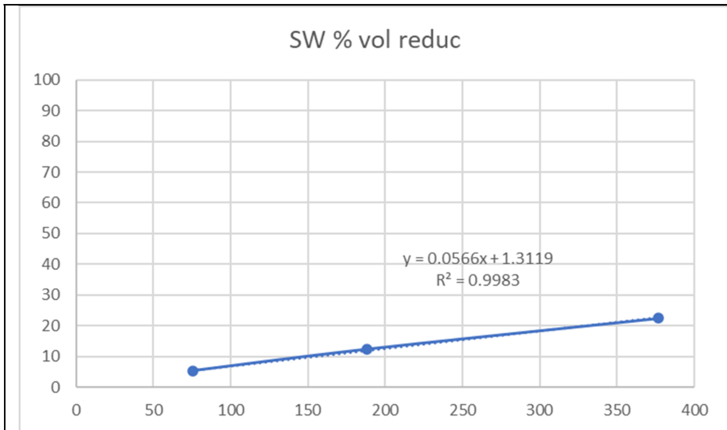


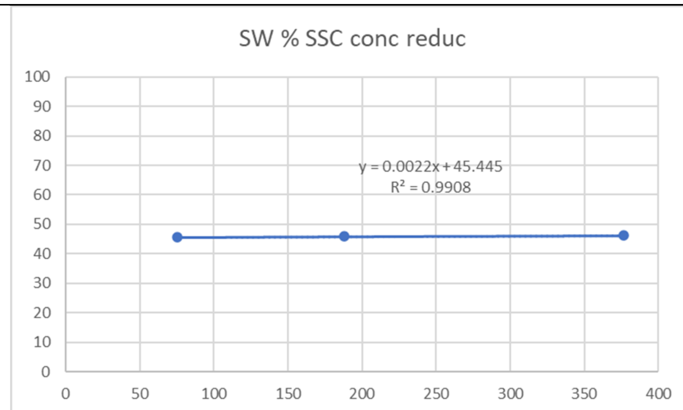


EC Vacuum Street Cleaner, % particulate solids concentration reduction on street runoff
y = 10.206ln(x) - 9.9826
R² = 0.9546
100
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300

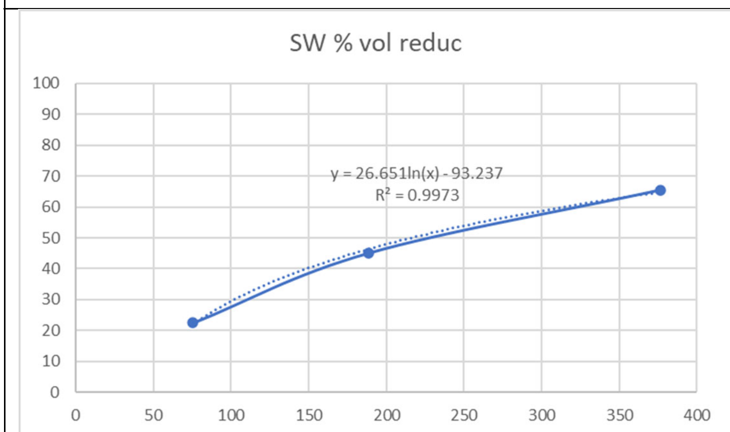
Grass Swales

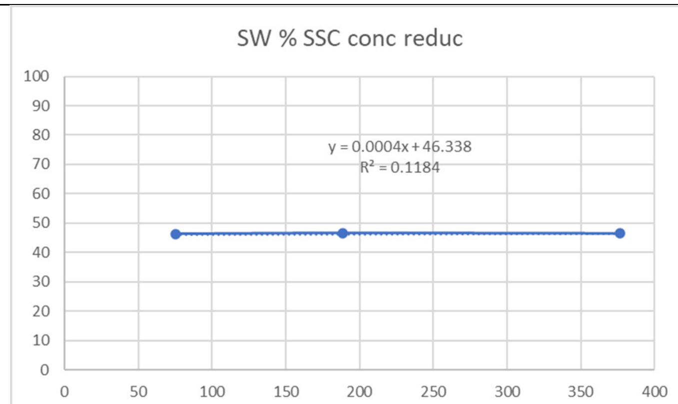
The x-axes of these plots are the total length of grass swales (m) per hectare of the total drainage area.



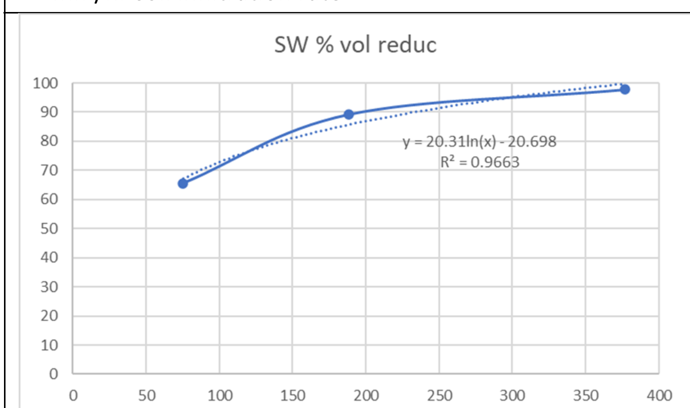


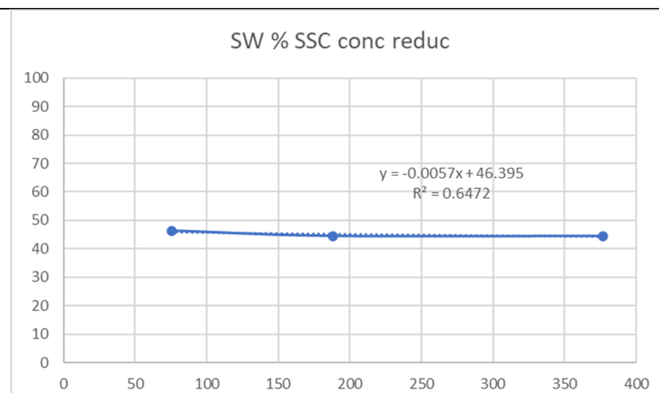
2.5 mm/hr soil infiltration rate



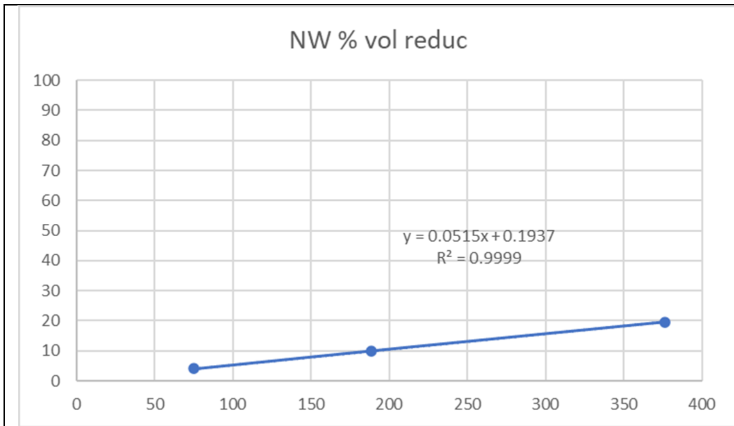


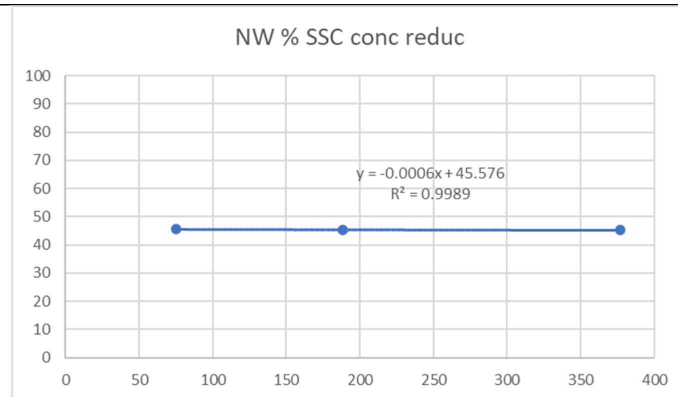
12 mm/hr soil infiltration rate



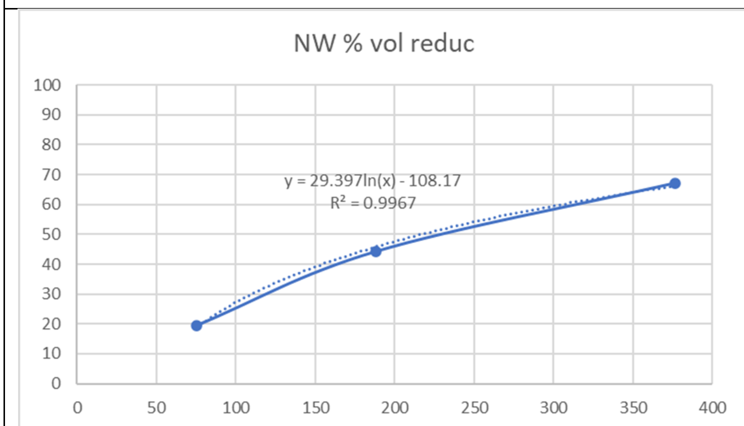


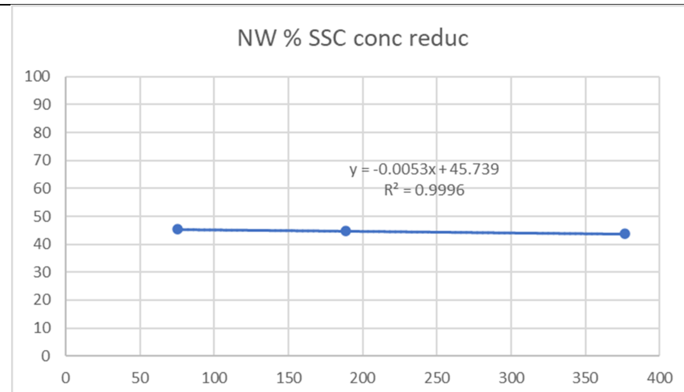
64 mm/hr soil infiltration rate



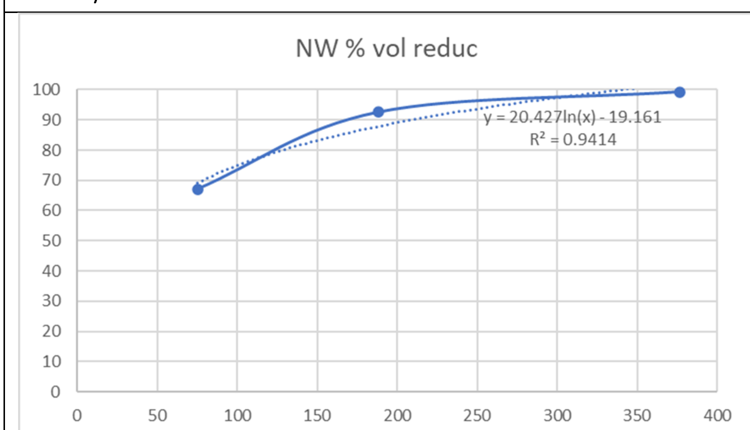


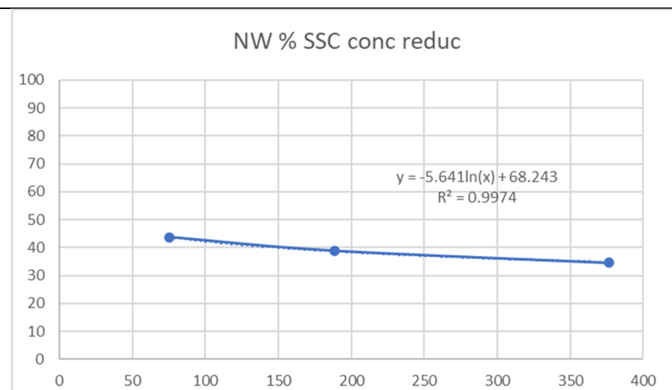
2.5 mm/hr soil infiltration rate



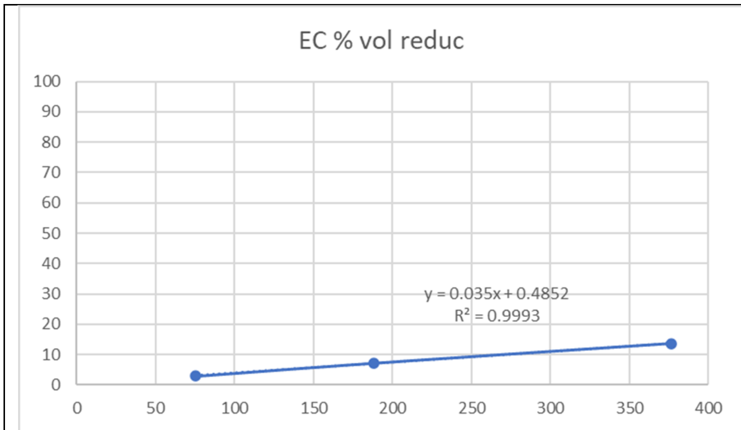


12 mm/hr soil infiltration rate

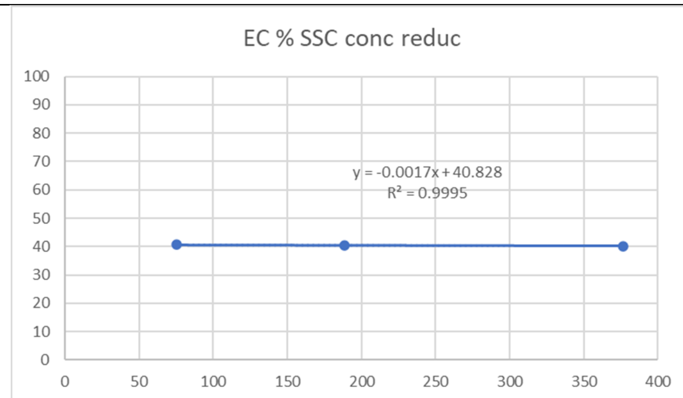


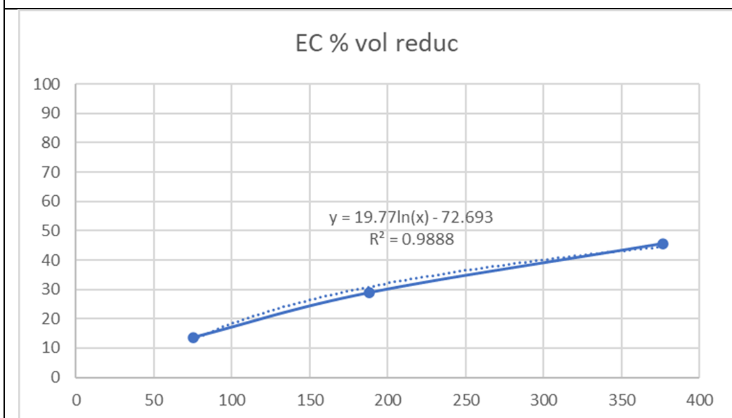


64 mm/hr soil infiltration rate

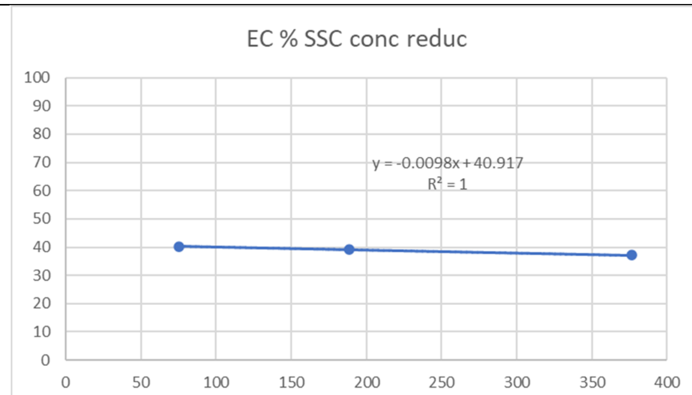


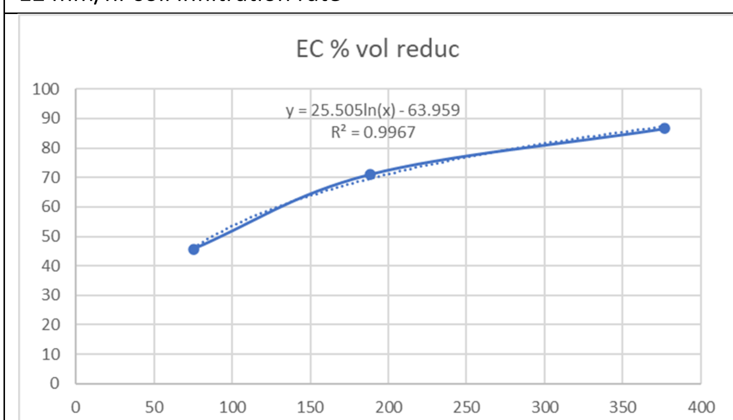
2.5 mm/hr soil infiltration rate





12 mm/hr soil infiltration rate





64 mm/hr soil infiltration rate