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Appendix D

Common Methods and Tools used to Evaluate Phosphorus Sources, Discharges, and Control in Urban Areas

Contents

There are many tools that can be used to quantify stormwater phosphorus sources, discharges, and its control by treatment devices. These range from "simple" methods that use concentration values and percentage removal rates selected from the literature, multiplying them by the rainfall for the time period of interest and by the fraction of the rain that occurs as direct runoff (or uses a "curve number" method to calculate runoff characteristics). In contrast, more complex stormwater computer models have been used in drainage design and for evaluating and controlling combined sewer overflows for many years. These models usually include all (or most) of the hydraulic elements in the study area, including all pipes and junctions and use traditional hydraulic methods to route the flows. The runoff portion of these models calculates the runoff hydrographs from the source areas (usually separated into pervious and impervious areas). Stormwater controls focus on hydraulic routing through storage systems. These general approaches all have strengths and weaknesses that must be considered by the potential model user. In all cases, local data is needed to calibrate and verify the stormwater model selected, when going beyond very preliminary evaluations.

Many stormwater models are continuously being updated, but comprehensive reviews are not common. An example of a comprehensive review of stormwater models was prepared as part of a NRC committee report (National Research Council, Committee on Reducing Stormwater Discharge Contributions to Water Pollution, National Academy of Science. *Urban Stormwater Management in the United States*. ISBN: 13: 978-0-309-12539-0. National Academies Press, Washington, D.C. *2009*. 598 pages). The models described and reviewed in this NRC report include the following, in order of general complexity:

- The Rational Method, or $Q = C*I*A$, where Q is the peak discharge for small urban catchments, A is the catchment area, I is the rainfall intensity associated with the time of concentration, and C is a rainfall-runoff coefficient.
- The Simple Method, which classifies stormwater generation and impact regimes by the percent impervious cover.
- TR-20 and TR-55
- The Generalized Watershed Loading Function (GWLF)
- Program for Predicting Polluting Particle Passage through Pits, Puddles, and Ponds (P8)
- Model for Urban Stormwater Improvement Conceptualization (MUSIC)
- Stormwater Management Model (SWMM)
- Source Loading and Management Model (WinSLAMM)
- Soil and Water Assessment Tool (SWAT)
- Hydrologic Simulation Program–Fortran (HSPF)
- Western Washington Hydrologic Model (WWHM)
- Chesapeake Bay Watershed Model (CBWM)

The Urban Water Resources Research Council (UWRRC) of the American Society of Civil Engineers (ASCE) has a Low Impact Development (LID) computational committee that has been preparing an updated stormwater modeling review report. The report is expected to be available in 2018 and would be a source of current information for these and other models. In addition, specialized technical conferences, such as the annual modeling of urban and rural water systems conference (Computational Hydraulics Institute http://www.chiwater.com/Home) presents updated information on stormwater models. The associated eJournal (*Modeling of Urban and Rural Water Systems*) also presents current information on stormwater models. Descriptions of the stormwater models presented in the 2009 NRC report are summarized below.

Descriptions of Example Stormwater Models

Table D-1 (from the NRC 2009 report) lists models that can be used for evaluating stormwater and its management ranging in complexity from very basic models, that make use of simple land cover/runoff and loading relationships from historical drainage design approaches, to more detailed models requiring much more information. Table D-1 includes brief descriptions of some of the attributes of these models, such as: their common usage, typical application scales, the degree of model complexity, some data requirements (for the hydrologic component), whether the model addresses groundwater, and whether the model has the ability to simulate stormwater controls. Some of the models addressing water quality rely on EMC (event-mean-concentration) data, while other models include a simple build-up/wash-off approach for water quality simulations (SWMM, WinSLAMM, and MUSIC), or simulate more complex geochemistry relationships (SWAT and HSPF).

The Rational Method is a highly simplified calculation method widely used in sizing storm sewer pipes. The method assumes a rainfall rate (intensity) corresponding to the time of concentration (T_c). The time of concentration is the minimum time all of the drainage area under consideration will contribute flow at an outlet (maximum travel time). The rain intensity corresponding to this rain duration is determined from an intensity-duration-frequency (IDF) curve for the site that incorporates historical rainfall data. Runoff coefficients for a variety of land surface types and slopes have been compiled in standard tables (Chow, *et al.* 1988). This equation is most suitable for very simple situations and is only applied to single "design" storms. It is seldom suitable for long-term continuous simulations of stormwater quality which are needed to calculate stormwater discharges and controls under a variety of precipitation conditions.

The Simple Method estimates stormwater pollutant loads for urban areas. It is most useful for assessing and comparing relative stormwater pollutant load changes due to different land use and stormwater management options, when adequate data exists. Drainage area, the amount of impervious cover, stormwater runoff pollutant concentrations, and annual precipitation are used in this calculation. Stormwater pollutant concentrations are usually estimated from local, regional, or national data sources. The Simple Method estimates pollutant loads by multiplying the runoff volume by the corresponding concentrations, using unit conversions, as needed.

Some of the most commonly used stormwater models were initially developed decades ago by the Soil Conservation Service (SCS), now the National Resource Conservation Service (NRCS) of the U.S. Department of Agriculture (USDA). These models were developed to assist the drainage design for single "design" storms and not for continuous simulations or for water quality evaluations. Despite the availability of a number of more rigorous, updated stormwater modeling methods, the curve number (CN) methods within NRCS Technical Releases (TR) 20 and 55 are widely used by many municipalities. The CN method is based on actual monitoring data for large storms. However, its application results in increasing errors in the calculated runoff characteristics for smaller rainstorms. Small and intermediate sized rains contribute most of the annual flows in urban areas and are therefore of most interest in stormwater quality management, in contrast to rare large storms which are of most interest in drainage design.

An example of a model that uses the NRCS curve number method for calculating stormwater discharge volumes is the Generalized Watershed Loading Function (GWLF) model (Haith and Shoemaker 1987) which uses EMC values with NRCS curve numbers to calculate runoff characteristics. GWLF is a continuous model with a simple linear aquifer component to account for groundwater interactions with surface flow. Sediment erosion and delivery are calculated using the Universal Soil Loss Equation (USLE) and delivery coefficients. These components are linked to a Geographical Information System (GIS) providing land-use stormwater calculations at the subwatershed level.

P8 (Program for Predicting Polluting Particle Passage through Pits, Puddles, and Ponds) is another NRCS curve number-based model for calculating stormwater discharges in urban watersheds. It was originally developed to help design and evaluate nutrient control in wet detention ponds (Palmstrom and Walker 1990; http://wwwalker.net/p8/ P8 performs continuous simulations using hourly rainfall and daily air temperature time series. The model was initially calibrated using the EMCs from the EPA's Nationwide Urban Runoff Program (NURP) projects

(EPA 1983). Stormwater control measures included in P8 include detention ponds (wet, dry, extended), infiltration basins, swales, and buffer strips. Groundwater and baseflows are also included in the model using linear reservoir processes.

MUSIC (Model for Urban Stormwater Improvement Conceptualization) is a component of the Catchment Modeling Toolkit (www.toolkit.net.au) developed by the Cooperative Research Center for Catchment Hydrology associated with Monash University, Melbourne, Australia (Wong, *et al.* 2001). The model addresses urban stormwater quality and quantity, and evaluates multiple stormwater control measures. Life-cycle costing is also incorporated in the model. The model's hydrology uses a simplified rainfall–runoff model (Chiew and McMahon 1997) based on impervious area and shallow and deep soil moisture components. EMCs for total suspended solids (TSS), total nitrogen, and total phosphorus are represented with lognormal distributions. MUSIC is intended as a planning tool.

The US EPA's SWMM (Stormwater Management Model) is probably the most common urban stormwater model in use, and has been incorporated within many other models since its development in the 1970s. It was originally developed to design and evaluate storm, sanitary, and combined sewer systems. It can be used for both single design storm events or for continuous simulations. SWMM utilizes time-varying rainfall, evaporation, snow accumulation and melting, depression storage, infiltration into soil, percolation to groundwater, interflow between groundwater and the drainage system, and nonlinear reservoir routing of overland flow. Spatial variability can also be modeled by dividing a study area into a collection of smaller, subcatchment areas, each having unique features, and routing the flows through a series of links and junctions. SWMM can also be used to estimate pollutant loads associated with runoff for a number of user-defined water quality constituents. Transport processes include dry-weather pollutant buildup over different land uses, pollutant wash-off from specific land uses, direct contribution of rainfall deposition, and various stormwater control measures, such as street cleaning, source control, and treatment in storage units. SWMM is unique in that it can be configured using very detailed site and system data that are needed for design, or it can be used in a relatively simple manner for screening analyses.

The model I developed with others, WinSLAMM, can be used for single urban lots to complex urban catchment areas. WinSLAMM is based on field monitoring observations covering a wide range of scales and land uses with unique hydrologic and pollutant related components that focus on urban systems. It is mainly used as a planning tool to assess both stormwater and pollutant runoff production and the capability of many stormwater control strategies to reduce stormwater discharges from urban sources (Pitt and Voorhees 2002 and http://winslamm.com/). WinSLAMM is based on high-resolution descriptions of the catchment composition, including both type and relative position (drainage sequence) of land elements (roofs, streets, landscaped areas, etc.). WinSLAMM calculates comprehensive runoff and pollutant loadings from different urban land elements. It uses continuous simulations for some aspects, such as the build-up of street pollutant loads between storms and hydraulic routing at stormwater controls. It also uses event-based simulations for runoff generation. It is normally used with rain time series from 1 to

50 years. The model incorporates a wide range of stormwater controls and can also calculate life-cycle costs for different stormwater control options. The benefits of the controls are modeled based on unit processes and specific device designs, using verified field observations. Version 10.3 of WinSLAMM also has an extension available (ArcSLAMM) that interfaces GIS with WinSLAMM to automatically develop the necessary detailed descriptions of the land development types and to present the model output in the GIS environment.

Other watershed models such as the Soil and Water Assessment Tool (SWAT) (Arnold, *et al.* 1998) or the Hydrologic Simulation Program–Fortran (HSPF) (Bicknell, *et al.* 1997, 2005) were developed for mostly large scale rural applications. They contrast with other models in that they incorporate interception, infiltration, runoff, routing, and biogeochemical transformations. Hydraulic units are based on land use, soils, vegetation (and crop) type, etc., and are considered uniformly distributed through a subbasin. Within each unit, simplified representations of unsaturated (upper) soil and saturated (lower) soil components are integrated with a conceptual groundwater storage-release component. There is no overland surface routing and all runoff is assumed to flow to the river reach, with the use of a delivery ratio for sediment and other constituents. SWAT models are typically not intended to estimate loadings from individual dischargers, but are used to help guide and develop total maximum daily load (TMDL) values for large watersheds. SWAT and HSPF are integrated within the EPA's BASINS (Better Assessment Science Integrating point & Non-point Sources) system (https://www.epa.gov/exposure-assessment-models/basins) using GIS tools that incorporate available spatial data for watersheds within the United States.

The Chesapeake Bay Watershed Model (CBWM) is a detailed watershed model based on HSPF, and includes additional components to incorporate stormwater controls. Model implementation at the scale of the full Chesapeake Bay Watershed requires fairly coarse resolution land information. Agricultural runoff controls are implemented at the field scale. Stormwater controls are applied using constant efficiency factors, irrespective of flow conditions or season. The Western Washington Hydrologic Model (WWHM) is another example of a regionally calibrated model that uses HSPF for its core processes.

1 **Table D-1. Example Models Used in Stormwater Modeling (NRC 2009)**

Model	Common Use	Typical Scale	Complexity	Data Requirements	Ground-water	Stormwater Control Measures (SCM)	Reference
Rational Method	Urban hydraulic design—peak flow	Small	Simple	Land cover, rainfall intensity, T_c	None	None	Standard hydrology text
Simple Method	Urban annual runoff, loads	Small to medium	Simple	Impervious surface cover, land use, annual rainfall	None	None	http://www.stormwatercenter.net/monitoring%20and%20assessment/simple%20meth/simple.htm
TR-20 TR-55	Rural/urban runoff production for simple stormwater models, hydraulic design	Small to medium	Simple to medium	Land use, soil texture, T_c	None	Pond sizing for hydraulic benefits and others through CN modification	http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models
GWLF	Rural/urban runoff, pollutant loading	Medium to watershed	Simple to medium	Land use, soil texture, precipitation time series	Simple linear reservoir	Runoff reduction with CN modification	Haith and Shoemaker (1987) http://www.avgwlf.psu.edu/overview.htm
P8	Urban runoff, pollutant loading	Small to large	Simple to medium	Land use, soil texture, precipitation time series, Stormwater Control Measure (SCM) type and sizing	Simple linear reservoir	Runoff reduction with CN modification, ponds (evaluation and sizing), infiltration, street cleaning	Palmstrom and Walker (1990) http://www.wwwalker.net/p8/
MUSIC	Urban runoff, pollutant loading, hydraulic design,	Small to large	Medium to complex	Land use, soil texture, precipitation/potential evapotranspiration time series, drainage	Simple linear reservoir	Comprehensive evaluation of SCM presystems	Wong (2000) (proprietary) http://www.toolkit.net.au/cgi-

Model	Common Use	Typical Scale	Complexity	Data Requirements	Ground-water	Stormwater Control Measures (SCM)	Reference
	simple receiving water			system details, SCM type and sizing			bin/WebObjects/toolkit.woa/wa/productDetails?productID=1000000
SWMM	Urban runoff, pollutant loading, hydraulic design	Small to large	Medium to complex	Land use, soil texture, meteorological time series, drainage system details, SCM type and sizing	Simple linear reservoir?	Infiltration practices, ponds, street cleaning	http://www.epa.gov/ednnrmrl/models/swmm
PCSWMM	Same as above	Same as above	Same as above	Same as above	Same as above	Enhanced SCM compared to SWMM	(proprietary) http://www.computationalhydraulics.com/Software/PCSWMM.NET
WinSLAMM	Urban runoff, pollutant loads	Small to large	Intermediate	Land cover, land use, development characteristics, soil texture, compaction, rainfall event time series, monthly PET, monthly water evaporation, SCM type and sizing	Mounding under infiltration controls	Comprehensive evaluation of SCM systems	(proprietary) http://www.winslamm.com/
SWAT	Rural runoff, loading	Medium to watershed	Intermediate	Land cover/land use, soil texture, precipitation, temperature, humidity, solar radiation time or PET series	Simple subbasin reservoir	Impoundments, agricultural conservation practices, nutrient management, buffers	http://www.epa.gov/waterscience/BASINS/bsnsdocs.html#swat
HSPF	Comprehensive watershed evaluation,	Medium to watershed	Complex	Land cover/land use, soil texture, precipitation,	Subbasin reservoir	Infiltration, ponds	Bicknell et al. (2005)

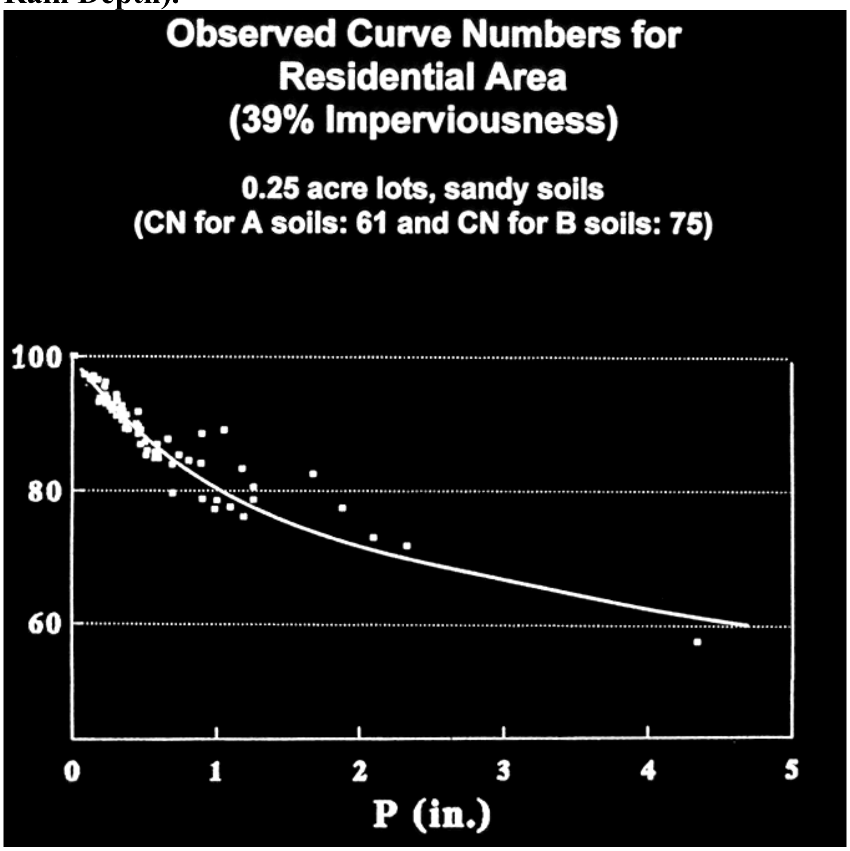
Model	Common Use	Typical Scale	Complexity	Data Requirements	Ground-water	Stormwater Control Measures (SCM)	Reference
	receiving water dynamics			temperature, humidity, solar radiation or PET time series			http://www.epa.gov/ceampubl/swater/hspf/index.htm http://www.epa.gov/waterscience/BASINS/bsnsdocs.html#hspf
WWHM	HSPF engine with regional modifications,	Puget Sound	Complex	Same as above	Same as above	Enhanced infiltration, ponds (from HSPF)	http://www.ecy.wa.gov/programs/wq/stormwater/wwhm_training/index.html
CBWM	HSPF engine with regional modifications, integration specific spatial data processing	Chesapeake Bay Watershed	Complex	Same as above	Same as above	Enhanced infiltration, ponds (from HSPF)	http://www.chesapeakebay.net/phase5.htm

1 Note: CN, curve number

Urban Stormwater Characteristics Affecting Model Selection
As noted above, many of the stormwater models and procedures currently in use were originally developed to assist drainage design engineers. These models focused on large, single event, analyses. Some of these tools have been used in semi-continuous models by applying the hydrologic processes to many individual rain events. Unfortunately, field monitoring has shown that the extrapolation of these methods to common smaller rains results in distorted outcomes.

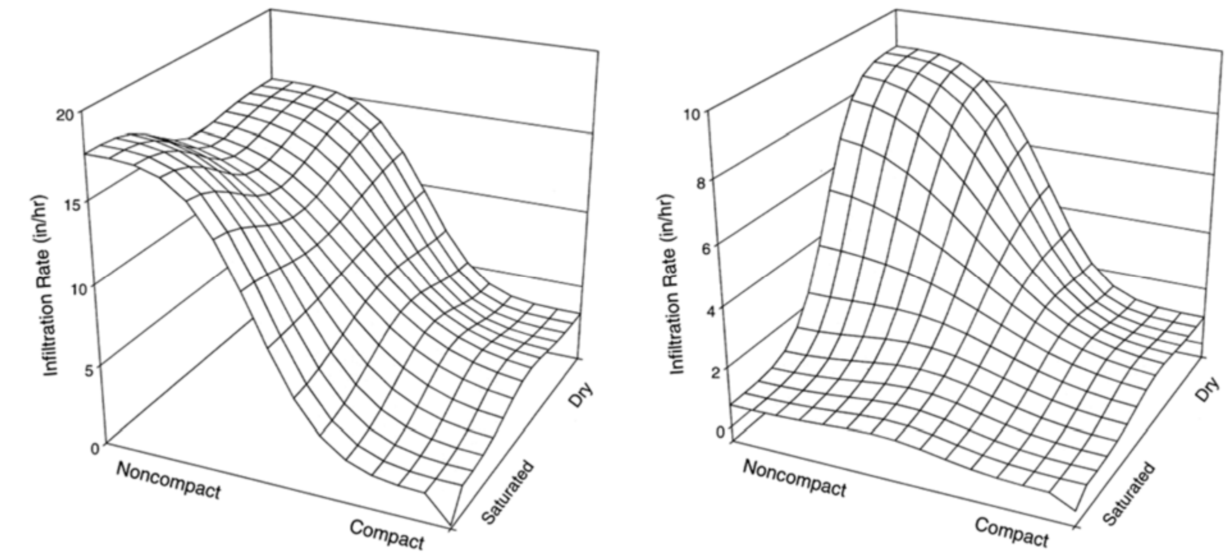
Figure D-1 illustrates the problem when applying the NRCS curve number method to a wide range of rains. The use of the CN procedure assumes a constant CN value for all rains. For large rains, observed CN values are similar to the CN values used in design work. However, Figure D-1 indicates that the actual CN values obtained during rainfall and runoff monitoring can be much different for the more common smaller rains. If the same smaller CN is used for all rains, runoff for the smaller rains would be severely under-predicted (CN is directly related to runoff; larger CN values result in larger fractions of the rain occurring as runoff). This is difficult to remedy during model calibration (which many users do not attempt, as they feel the CN method is accurate).

Figure D-1. Varying Values of Curve Numbers for Different Sized Rains (CN vs. Total Rain Depth).



Another hydrologic issue associated with stormwater modeling concerns soil characteristics. The NRCS's Web Soil Survey (https://websoilsurvey.nrcs.usda.gov/app/HomePage.htm) addresses soil texture for relatively undisturbed or agricultural soils, and acknowledges that information on urban soils is not available. So, for large precipitation events of interest in drainage design, worst case saturation conditions are usually assumed for urban soils. However, Figure D-2 shows that compaction may be more critical than moisture levels when determining infiltration, and few models consider this soil aspect.

Figure D-2. Effects of Soil Compaction and Soil Moisture on Infiltration Rates (Pitt, *Et Al.* 1999).



Sandy soils	Clayey soils

Figure D-3 is a rainfall-runoff plot for tests conducted on an urban street. For large events, the fraction of rainfall that occurs as direct runoff is similar to the 0.85 to 0.95 value used in drainage design models, while the runoff fraction for the more frequent smaller events is much less (as low as 0.5 on this figure). This, in conjunction with the effects of soil compaction, can lead to under-predicting runoff from “pervious” areas and over-predicting runoff from “impervious” areas, when calibrating a traditional model using end-of-pipe monitoring data. The modeled relative sources of stormwater flows and pollutants are therefore incorrect, resulting in errors when evaluating application of stormwater controls at source locations in the drainage area.

A hydraulic issue also occurs when traditional flow routing is used in small urban grass waterways (grass swales and grass filters). Figure D-4 is a plot of the retardance curves used to calculate the Manning’s n roughness coefficient based on the product of velocity and hydraulic radius (approximate depth). Models that calculate flow routing in grass systems (not pipes) use the original values on this figure in the calculations. Unfortunately, this results in significantly reduced roughness values compared to field observations of smaller flows that are most common in urban systems.

Figure D-3. Rainfall-Runoff Curves for Typical Urban Street (Pitt 1987).

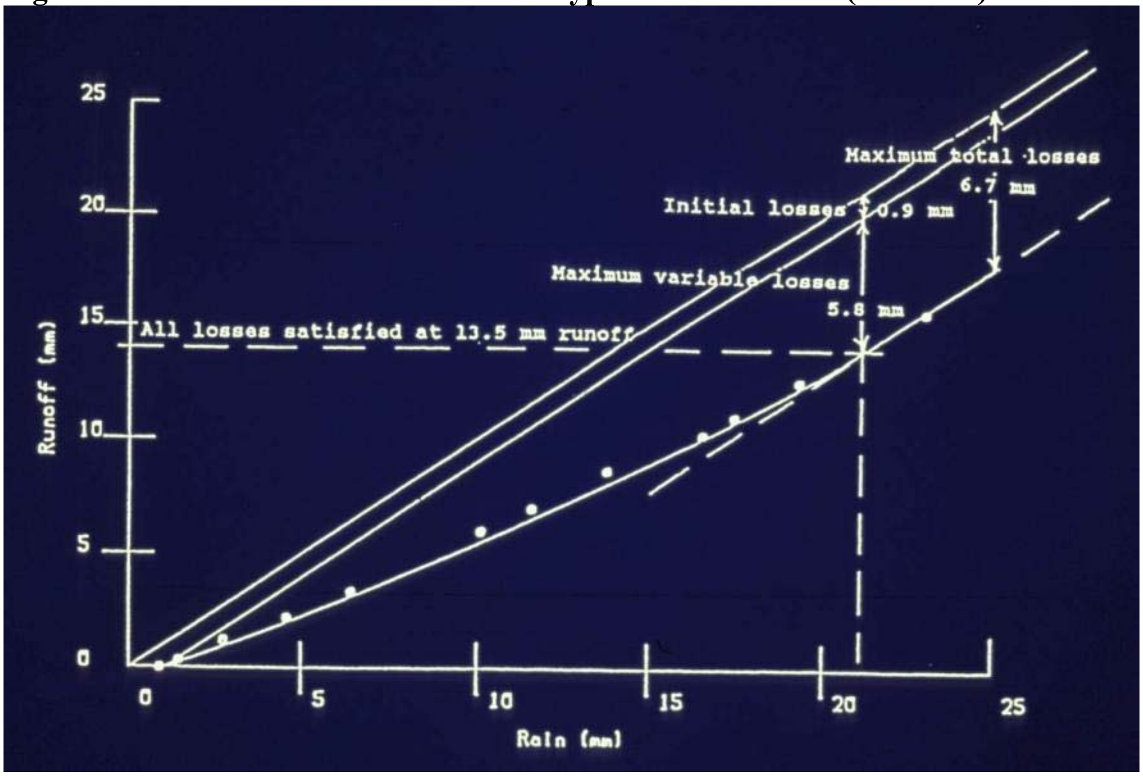
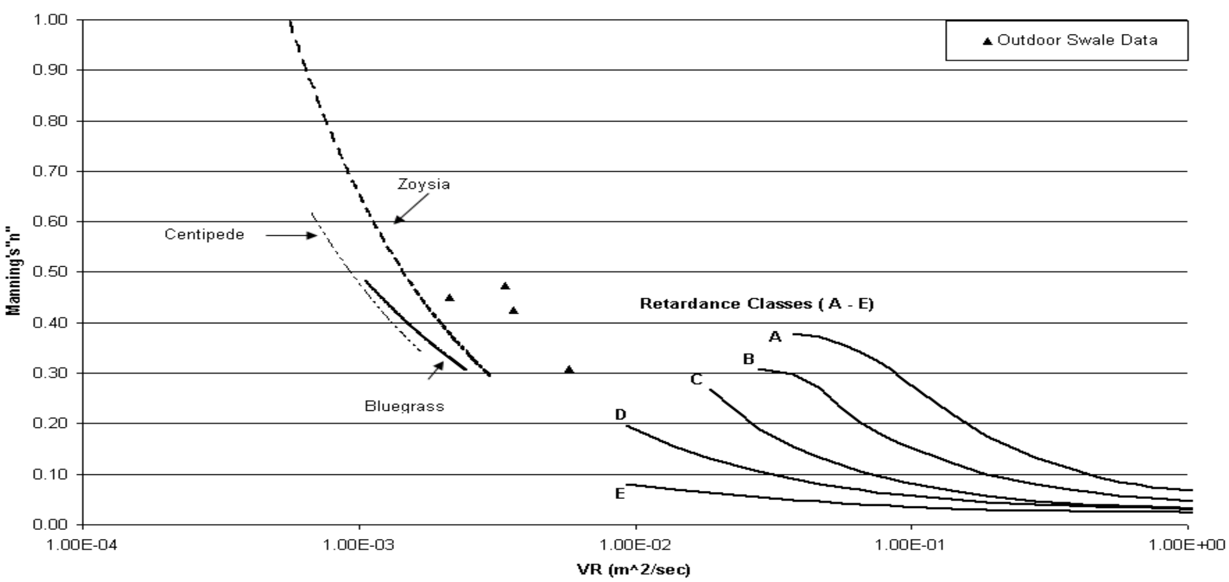
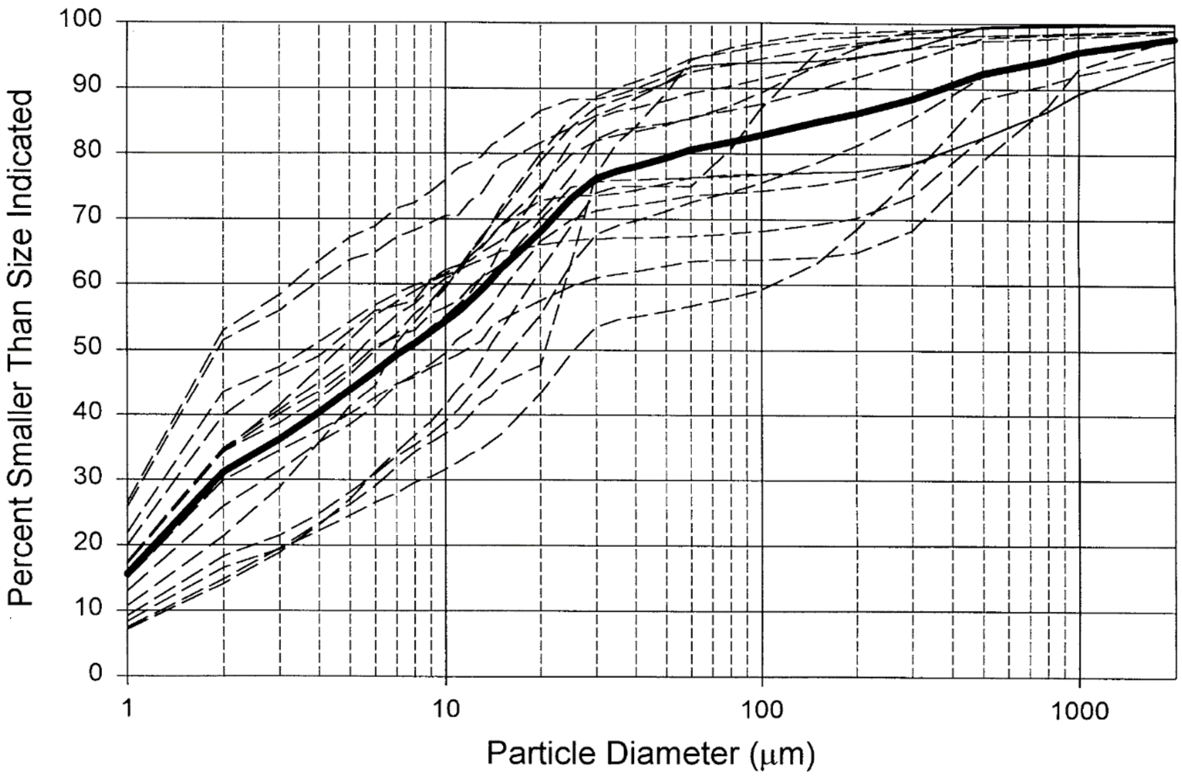


Figure D-4. Changes in Manning's N for Small Runoff Events Compared to Traditional Retardance Curves (Kirby, *Et Al.* 2005).



Another important need for stormwater quality models is for accurate and complete routing of stormwater particulates. Large particles are more readily removed by most stormwater control practices, but also are not transported well in urban drainage systems, as they have relatively fast settling rates. Small particles, on the other hand, are easily eroded (or washed off) and transported in stormwater from their source locations, but are more difficult to remove in stormwater controls. In addition, particulate-bound pollutants are not evenly distributed across all particle sizes. As an example, total phosphorus has about half of its concentration associated with particulates, and the remainder as filterable phosphorus. The particulate bound phosphorus is correlated to the organic content of the particulates, which usually is more abundant in the larger particle sizes. It is therefore necessary to track different particle size ranges in stormwater quality modeling, and not just use total phosphorus concentrations alone. Figure D-5 shows the range of particle sizes that can be found in stormwater over time. Most of the particulate mass is in the size range of about 2 to 200 μm. As noted above, each category of particle size behaves differently as they are transported or retained in urban areas. Again, stormwater quality models need to be able to route these different particle sizes separately, and not just calculate a lumped particulate solids concentration, especially when calculating the trapping effectiveness of stormwater controls for particulate-bound pollutants.

Figure D-5. Stormwater Particle Size Distributions.



WinSLAMM Features
WinSLAMM was developed beginning in the mid-1970s when it was noted that stormwater monitoring data collected during research projects did not agree with conventional urban stormwater hydrology and water quality assumptions. Detailed monitoring at small areas was then conducted and modeling procedures were developed to better explain the observed conditions (as described by Pitt 1987). Over the years, WinSLAMM was expanded to include many stormwater control practices as research results supported the calculation processes. Table D-2 shows the list of stormwater controls included in WinSLAMM as of 2016 (see

http://winslamm.com/ for detailed descriptions of model capabilities), and also shows source areas where these controls are readily applicable. Figures D-6 and D-7 are example production functions prepared using WinSLAMM for biofilters and grass filter strips developed as part of a project setting up and using the model for U.S. Navy facilities (2014). These were calculated using standard designs at these facilities with the only element changed being the size (biofilters) or length (filter strip) relative to the drainage areas. The model used local soil and rainfall conditions during the analyses, and was locally calibrated using naval base monitoring data to supplement regional calibrations using the National Stormwater Quality Database (NSQD, described Appendix A and available at: http://bmpdatabase.org/nsqd.html).

Table D-2. Stormwater Controls Source Area and Outfall Controls in WinSLAMM version 10.2 ("green infrastructure" controls are noted in green lettering)

Source Areas	Wet Ponds	Hydro-dynamic Separator	Biofilter	Cistern	Benefic. Uses	Grass Filter Strip	Disconnect Pavement	Porous Pavement	Compacted Soil Restoration	Catch-basin	Storm-water Filter	Upflow Filter	Grass Swale	Street Cleaning
Roofs	X	X	X	X	X	X	X				X	X	X	
Paved parking/storage	X	X	X	X	X	X	X	X		X	X	X	X	
Unpaved parking/storage	X	X	X	X	X	X	X			X	X	X	X	
Driveways	X	X	X	X	X	X	X	X			X	X	X	
Sidewalks	X	X	X	X	X	X	X	X			X	X	X	
Streets		X	X			X		X		X	X	X	X	X
Large landscaped areas	X	X	X	X	X	X			X				X	
Small landscaped areas	X	X	X	X	X	X			X				X	
Undeveloped areas	X	X	X	X	X	X			X				X	
Paved playgrounds	X	X	X	X	X	X	X	X			X	X	X	
Other impervious areas	X	X	X	X	X	X	X	X		X	X	X	X	
Other non-paved areas	X	X	X	X	X	X	X	X	X	X	X	X	X	
Paved lane/shoulders	X	X	X			X	X	X		X	X	X	X	X

High traffic urban highways	X	X	X			X	X	X		X	X	X	X	X
High traffic urban pervious	X	X	X			X	X	X		X	X	X	X	X
Drainage system	X	X	X			X				X			X	

Figure D-6. Winslamm Calculated Production Functions for Biofilters Prepared for U.S. Navy Facilities (Pitt 2014).

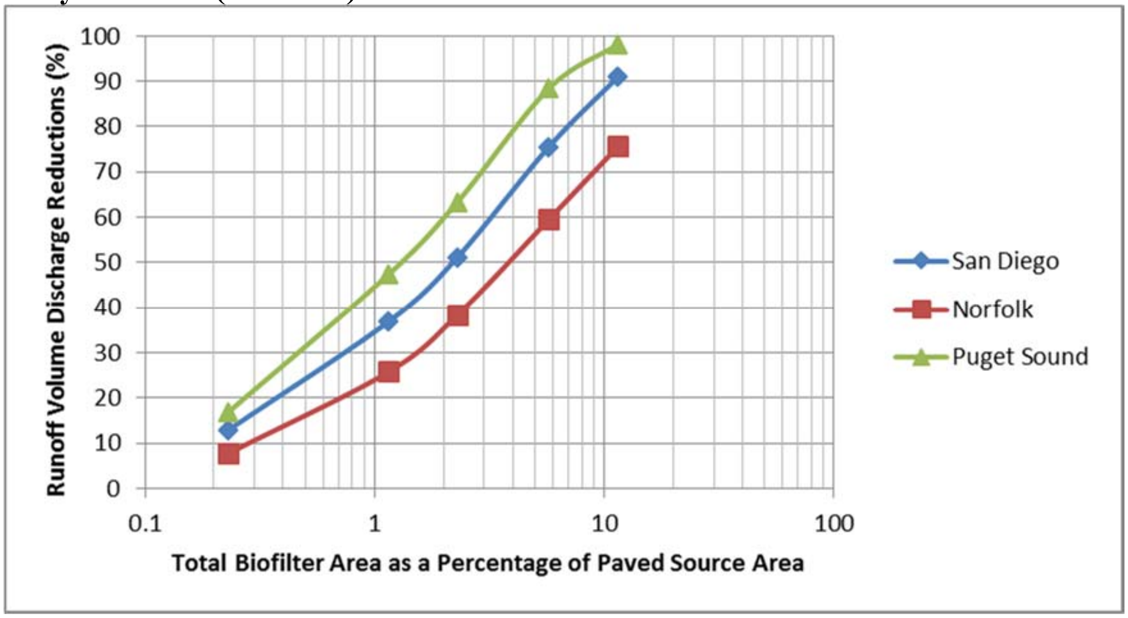
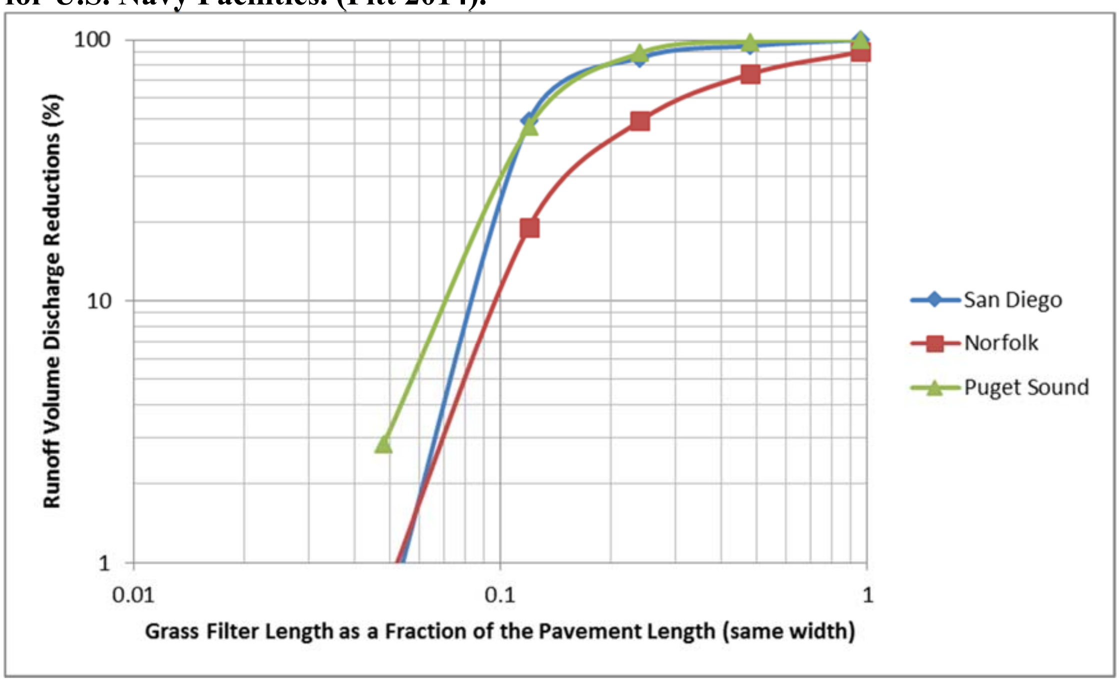


Figure D-7. Winslamm Calculated Production Functions for Grass Filter Strips Prepared for U.S. Navy Facilities. (Pitt 2014).



These plots enable rapid performance assessments for different stormwater control practices in an area. These plots are shown for runoff volume reductions, but similar plots can also be prepared for pollutant concentrations and for mass discharges. WinSLAMM can then be used to evaluate many different stormwater management options using combinations of controls. The associated life cycle costing data can be used in conjunction with these modeling results to assist in selecting the most appropriate stormwater controls for a site or area, as described by Pitt and

Voorhees (2007). WinSLAMM was also used during the EPA Green Infrastructure demonstration project in Kansas City (Pitt, *et al.* 2011). Monitoring data collected at various watershed scales was used to calibrate and verify WinSLAMM and other decision support tools for use to assist in the design and evaluation of retrofitting stormwater controls in areas served by combined sewers.

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