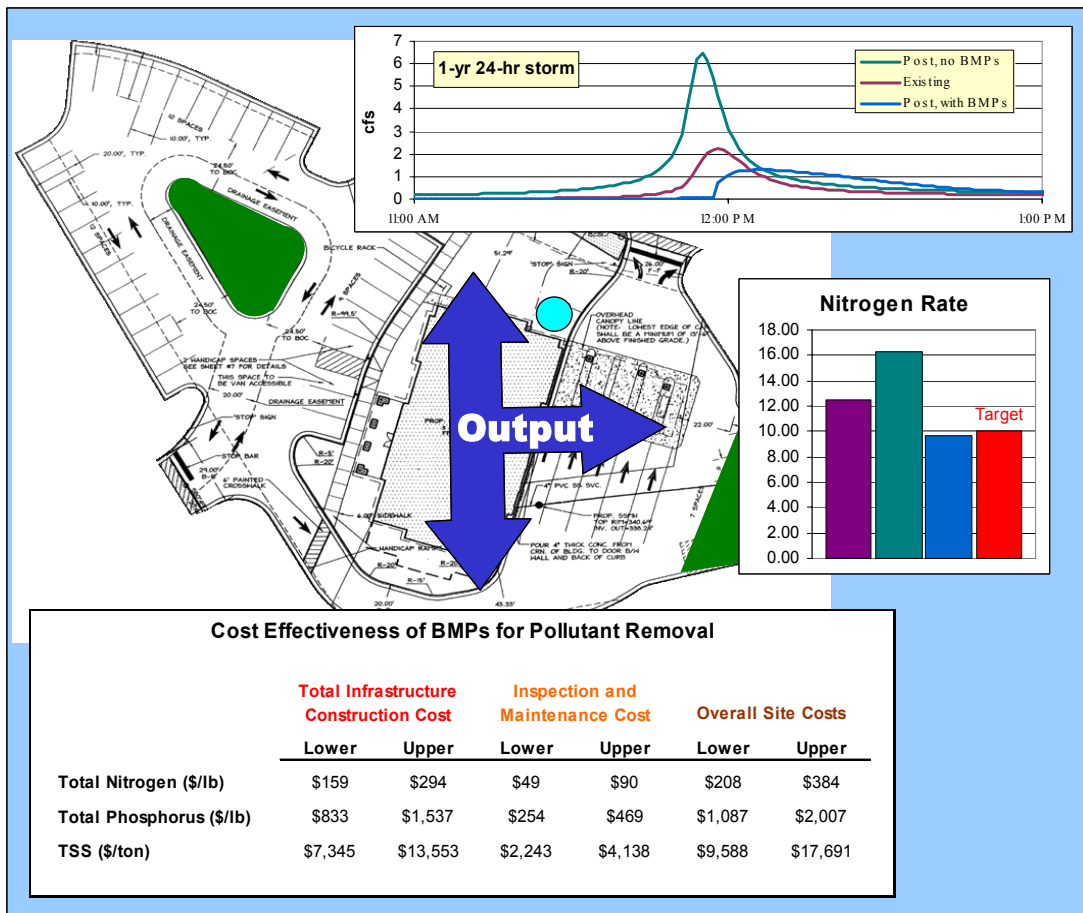
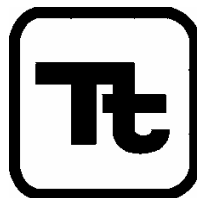


Upper Neuse Site Evaluation Tool Model Documentation



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Table of Contents

1	Foreword	1
2	Hydrology/Pollutant Component.....	3
2.1	Annual Pollutant Loads and Annual Infiltration and Runoff	4
2.1.1	Hydrology.....	4
2.1.2	Pollutant Loading	6
2.2	Storm Event Runoff Volume.....	7
2.3	Storm Event Peak Flow and Hydrograph.....	9
2.3.1	Peak Flow Calculation Using Rational Method	9
2.3.2	Calculation of Pre- and Post-development Hydrographs Using SCS Method.....	10
2.3.3	BMP Influence on SCS Post-development Hydrograph.....	13
2.3.3.1	Storage-Release Model	14
2.3.3.2	Peak Control Model	16
2.3.3.3	BMP Groups and Assumptions.....	18
3	Cost Component	23
3.1	Construction Cost Data	23
3.1.1	General Methods for all BMPs.....	23
3.1.2	BMPs with Economies of Scale	24
3.2	Additional Conveyance Structures and Site Paving.....	25
3.3	Design and Engineering	26
3.4	Overhead and Profit	26
3.5	Inflation.....	26
3.6	Cost Effectiveness Ratios.....	26
3.7	Maintenance Cost.....	27
3.8	Land Opportunity Cost.....	27
3.9	User-Defined Inputs	28
3.10	Updating Cost Data	28
Appendix A.	Parameters for Hydrology and Pollutant Loading.....	A-1
Appendix B.	BMPs and Efficiencies Used in Site Evaluation Tool.....	B-1
Appendix C.	SET Cost Component Cost Data Sources	C-1

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1 Foreword

The Site Evaluation Tool (SET) is a Microsoft Excel spreadsheet, and is designed to aid in the assessment of development plans and available Best Management Practices (BMPs) to achieve the region's water quality objectives.

This document discusses the underlying models and methodologies used in the Hydrology/Pollutant Component and the Cost Component of the SET. It provides details on key assumptions used by the SET, including BMP pollutant removal efficiencies, parameters used to calculate pollutant loads, and equations used to estimate BMP and infrastructure costs. A separate User's Manual and Guidance document (Tetra Tech, Inc., 2005) is also available for this tool. The User's Manual discusses in detail the use of the SET, includes screen shots and descriptions of required inputs, and gives an example of its application.

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2 Hydrology/Pollutant Component

The Upper Neuse River Basin faces many challenges for the protection of its water quality. The SET contains both a hydrology and a pollutant component to address development impacts that can threaten watershed health if not managed properly.

Overview of the Hydrology Component

Development changes the hydrology of sites, with the potential for decreased infiltration, and increased runoff and peak flows. These changes often lead to streambank erosion and channel downcutting, causing impairment of physical habitat and biological communities. Two factors are especially relevant – peak flows in receiving streams during high volume storm events may increase substantially after a site is developed (due in large part to an increase in impervious surface) and the duration of time increases during which erosive flows take place. The SET evaluates these factors directly by estimating pre- and post-development peak flows (and the projected influence of BMPs on peak flow), and indirectly by estimating the change in total runoff during high volume rainfall events that occur on a fairly frequent basis (the 1-year 24-hour storm and the 2-year 24-hour storm). Storm event runoff volume is calculated using the SCS Runoff Curve Number method (USDA, 1986). Hydrographs and peak flow are calculated using an SCS method that combines excess runoff with a unit hydrograph to estimate discharge at discrete timesteps (USDA, 1972). Peak flow is also calculated using the Rational Method for comparison. The influence of BMPs on the post-development hydrograph is estimated using relationships that describe how various BMPs store and release runoff. The SET also estimates annual infiltration and runoff using the Simple Method (Schueler, 1987). Parameters related to hydrology are detailed in Appendix A.

Overview of the Pollutant Component

Excessive nutrient loading can lead to nuisance algae in both streams and lakes, leading to conditions that are unfavorable for supporting recreation and aquatic life and that can pose problems for public water supplies. The SET addresses this by calculating the total phosphorus and nitrogen load leaving a site before and after development, accounting for the influence of various BMPs used on the site. Protection of aquatic life and physical habitat is also a critical issue throughout streams in the Upper Neuse River Basin, so the SET calculates upland sediment load in the same way as total phosphorus and total nitrogen. It is important to note that the SET does not include estimates of nutrient and sediment loading during the construction phase of a project; it assumes that development is completed and all bare soils are properly vegetated. All of the pollutant loading indicators (total nitrogen, total phosphorus, and upland sediment) and overall site hydrology are calculated on an annual basis using a modified version of the Simplified Urban Nutrient Output Model (SUNOM) developed by the Center for Watershed Protection (Caraco et al., 1998). Parameters related to pollutant loading are detailed in Appendix A.

How BMPs Are Addressed in the Hydrology and Pollutant Components

The SET allows the user to test how well various site designs that implement properly designed BMPs will perform with regard to mitigating changes in runoff volume and pollutant loading. The model has built-in assumptions for infiltration and pollutant removal efficiency for various types of BMPs. BMP storage volume is also estimated, or the user may provide estimates of storage volume. It is important to note that the SET does not perform the engineering design for a BMP. Rather, the model assumes that BMPs will be designed according to specifications established by the state and/or local governing authority.

There are many types of BMPs with flow control and pollutant removal capabilities. The majority of these BMPs fall into the following general categories: detention ponds/wetlands, open channels, filtering systems, and infiltration devices (Winer, 2000). These practices use a variety of techniques to reduce the impact of the increased runoff and pollutant loadings including reduction in flow velocity and quantity,

runoff control, biological uptake, and filtration. BMPs vary in their ability to remove pollutants, and BMPs of the same type also vary in pollutant removal depending on their size, the quality of their design, and how well they are maintained over time. The SET has a menu of the most common BMPs used for water quality benefits. The terminology and pollutant removal efficiencies are taken from a number of information sources, some local to North Carolina and some from national databases. BMPs included in the SET and their removal efficiencies are shown in Appendix B. More information about most of these BMPs is available in the North Carolina Stormwater Best Management Practices Manual (NCDENR, 1999), available as of this writing at:

http://h2o.enr.state.nc.us/su/PDF_Files/SW_Documents/BMP_Manual.PDF.

2.1 ANNUAL POLLUTANT LOADS AND ANNUAL INFILTRATION AND RUNOFF

The Site Evaluation Tool uses a modified approach based on the Simplified Urban Nutrient Output Model (SUNOM) developed by the Center for Watershed Protection (Caraco et al., 1998). Annual water balance and annual pollutant loads are calculated, and inputs include land use, annual precipitation and infiltration, soil hydrologic group information, event mean concentrations of pollutants by land use, and BMP pollutant removal efficiencies. Annual surface runoff is determined using the Simple Method (Schueler, 1987), which relates runoff depth to annual precipitation and the fraction of the area in impervious cover. The Simple Method can be rearranged to estimate runoff from pervious and impervious areas separately. Infiltration is calculated for pervious areas using area averaged infiltration rates based on the soil type. BMPs that infiltrate water transfer surface runoff to infiltration. Annual loads for total suspended solids, total nitrogen, and total phosphorus are calculated for existing conditions, for the proposed site without treatment, and for the proposed site with BMPs.

Loads from surface runoff are calculated from the product of annual runoff depth, pollutant event mean concentration (EMC), and land area, and are determined separately for impervious surfaces, and natural and managed pervious areas. An event mean concentration is the theoretical average pollutant concentration across large and small storm events over a long period of time. The BMP reduces the load based on the fraction of the runoff it treats and its removal efficiency (for removal efficiencies, see Appendix B).

The SET addresses loads from multiple land area types. This allows it to utilize EMCs from each type of land area. Data from a number of sources were used to fit estimates of distinct EMCs for two types of impervious surfaces (residential/light industrial and commercial/heavy industrial) and six types of pervious surfaces (lawn, meadow, forest, wetland, pasture, and row crops).

2.1.1 Hydrology

The model begins with an annual hydrologic balance relevant to the SET:

Equation 2-1.

$$P = R + E + I_{SW} + I_{BMP}$$

where

P = annual precipitation

R = runoff

E = annual evaporation and transpiration

I_{SW} = annual groundwater recharge of storm water

I_{BMP} = annual groundwater recharge via BMPs

All units are in inches. Terms on the left side of the equation are inputs and terms on the right side of the equation are outputs. Evaporation is not calculated directly, but is accounted for implicitly. Each of the remaining terms is calculated and used for subsequent loading calculations. It is important to note that

each of these calculations is performed separately for each land use/drainage area combination, and then summed to produce total runoff or load.

Runoff is calculated using the SIMPLE Method:

Equation 2-2.

$$R = 0.9 \times P \times \left(0.05 + 0.9 \frac{A_{imp}}{A_{tot}} \right) \quad \text{where}$$

A_{imp} = impervious area
 A_{tot} = total site area

As the impervious fraction increases, runoff increases. The terms of the equation account for two aspects of annual runoff – that the majority of rainfall on pervious areas ends up as infiltration and evapotranspiration rather than runoff, while most of rainfall on impervious surfaces becomes runoff. Runoff from each land use is treated separately in subsequent calculations, but the reported total site annual runoff is calculated using an area-weighted average.

Stormwater infiltration is calculated as follows:

Equation 2-3.

$$I_{SW} = I_B m \quad \text{where}$$

I_B = annual base infiltration rate (in/yr)
 m = multiplier based on type of surface

The base infiltration rate is related to the hydrologic group of the underlying soil. This ranges from a base infiltration rate of 18 inches per year for Group A soils to 3 inches per year for Group D soils. The multiplier is 0 for impervious surfaces (no infiltration), 1 for undeveloped land uses (full infiltration) or 0.8 for developed pervious land uses, which are generally compacted and have somewhat lower infiltration rates. An aggregate I_B is calculated based on an area average of the proportion of the site in each soil hydrologic group.

Infiltration through BMPs is calculated as follows:

Equation 2-4.

$$I_{BMP} = R \times f_s f_i \quad \text{where}$$

f_s = fraction of runoff in site reaching BMP
 f_i = fraction infiltrated on an annual basis

BMPs influence annual hydrology by intercepting runoff and converting it to infiltration. The fraction of the runoff reaching the BMP is handled internally in the model by the assignment of land use to drainage areas. f_i is dependent on the type of BMP; most BMPs convert very little runoff to infiltration, but some are designed to store runoff and allow it to drain to the underlying soil. When there are multiple BMPs in a single drainage area, an aggregated f_i is calculated as detailed at the end of Section 2.1.2.

The influence of BMPs on annual runoff is also calculated. The runoff that BMPs trap may leave either through infiltration (f_i) or evapotranspiration. Note that the calculation is performed separately for each land use, within each drainage area.

Equation 2-5.

$$R_{BMP} = R \times [1 - (f_i + f_e)] \quad \text{where}$$

R_{BMP} = adjusted runoff
 f_e = fraction evaporated on an annual basis

The sum of f_i and f_e is the fraction of annual runoff entering a BMP that does not leave as runoff. The fraction that does become runoff is 1 minus the sum of f_i and f_e . Note that when there are multiple BMPs in a single drainage area, an aggregated f_e is calculated as detailed at the end of Section 2.1.2.

2.1.2 Pollutant Loading

Terms not defined here are used in the previous section. Total loading is calculated as follows:

Equation 2-6.

$$L = L_R - L_{BMP}$$

where

L = total load

L_R = load from runoff

L_{BMP} = BMP load reduction

Loading from runoff is calculated as follows:

Equation 2-7.

$$L_R = RC_R A$$

where

C_R = event mean concentration in runoff

A = land area

Since the runoff (as well as each of the other hydrologic terms) is expressed in inches, the product of runoff and land area produces runoff volume. The product of runoff volume and concentration results in an annual load.

The BMP load reduction is calculated as follows:

Equation 2-8.

$$L_{BMP} = L_R E_i$$

where

E_i = BMP pollutant reduction efficiency

BMP efficiencies are generally reported in research literature in terms of percent removal of annual load, so the load reduction is applied directly to the calculated annual load. Current model assumptions for BMP removal efficiencies and their sources are provided in Appendix B.

In cases where there are multiple BMPs utilized in the same drainage area (called a “treatment train”), E_i is calculated as follows:

Equation 2-9.

$$E_i = 1 - (1 - E_{i1})(1 - E_{i2}) \dots (1 - E_{iN})$$

where

N = number of BMPs in treatment train

$E_{i1} \dots E_{iN}$ = Reduction efficiency for each BMP in the treatment train

For example, if the removal efficiencies of two BMPs in a treatment train are 45 percent and 35 percent, the overall removal efficiency of the treatment train is not 80 percent; rather it is $1 - (1 - 0.45)(1 - 0.35)$, or 64.25 percent. If the first BMP removes 45 percent, it passes 55 percent of the load. The second BMP treats 35 percent of the 55 percent remaining (19.25 percent), for a total of 64.25 percent. Note that the same calculation applies to f_i and f_e discussed in Section 2.1.1.

Removal efficiencies for forest buffers are handled differently. While other BMPs are given fixed removal efficiencies in the SET, forest buffer removal efficiencies are estimated dynamically based on several factors – the width of the buffer, the portion of the site treated by the buffer, and an adjustment specific to the Neuse River Basin that potentially reduces credit for the portion of a buffer already protected by law.

A body of literature shows that removal efficiency is strongly correlated with buffer width. Desbonnet et al. (1994) report removal efficiencies for total nitrogen, total phosphorus, and sediment for various buffer widths, and show best-fit logarithmic curves for each. While the overall shape of the curves is reasonable, the removal efficiency for very wide buffers is much higher than the maximum removal efficiencies reported by Schueler (1995) for urban areas. The Site Evaluation Tool therefore uses the logarithmic relationships reported by Desbonnet et al., normalized by Schueler's maximum removal efficiencies. The relationships used are as follows (efficiencies as percent, buffer width in feet):

Equation 2-10.
$$N \text{ efficiency} = \frac{10.928 \times \ln(\text{Buffer Width}) + 23.586}{85.9} \times 40$$

Equation 2-11.
$$P \text{ efficiency} = \frac{10.693 \times \ln(\text{Buffer Width}) + 20.851}{81.8} \times 50$$

Equation 2-12.
$$TSS \text{ efficiency} = \frac{8.0769 \times \ln(\text{Buffer Width}) + 36.323}{82.4} \times 75$$

The numerator of the equations reflects a best fit of the Desbonnet et al. curves. The denominator is the Desbonnet removal for a 300 foot buffer; therefore, the ratio of the two terms is a number from 0 to 1, provided the buffer width is less than 300 feet. The last term reflects the maximum reasonable removal rates in an urban setting reported by Schueler, effectively capping the removal rate. The 300 foot limitation reflects a maximum reasonable width; for buffers larger than 300 feet, Schueler's maximum efficiencies are used. Example removal efficiencies for a range of buffer widths are shown in Appendix B.

Forest buffer removal efficiencies are further reduced by taking into account the forest buffer "treatment zone." The treatment zone is the percentage of the drainage area that lies within the buffer width plus 150 feet (for instance, 180 feet for a 30-foot buffer). This represents the maximum effective distance over which dispersed, unchannelized flow can be maintained (Schueler, 1995). Additional areas within the watershed can be added to the treatment zone if engineered structures, such as level spreaders, are used to divert concentrated to sheet flow into the buffer. The net removal efficiency is the product of the calculated removal efficiency and the treatment zone percentage.

Finally, removal from within existing forest buffers of a certain width – which are already protected under the Neuse Buffer Rules – is factored out of the credit given for forest buffers. NC DWQ has already accounted for this removal in their load reduction and nutrient delivery models for the Neuse River Basin Nitrogen TMDL, so giving credit for its removal would amount to double-counting. For this reason, credit is given for additional forest buffer protected beyond the requirement. The additional removal is calculated as the difference between removal for the total buffer width minus removal for the protected width of the buffer.

The Site Evaluation Tool also allows for a minimum buffer width to be specified. Buffers less than the minimum width (set at 25 feet) have zero removal efficiencies. While it is possible for narrower buffers to achieve pollutant removal, there is a high risk in urban settings that the integrity of the buffer may be compromised by human activity.

2.2 STORM EVENT RUNOFF VOLUME

Annual runoff and infiltration estimates drive the nutrient and sediment load calculations discussed previously. However, the risk of downstream channel erosion should be evaluated through an analysis of peak flow and runoff volume resulting from storm events. Peak flow analysis is routinely performed to meet stormwater control requirements. Measures that reduce the erosive force of high peak flows certainly mitigate stream channel erosion, but development still results in an increase in peak flow and

discharge. The cumulative impact of development is an increase in the duration of flows at which channel erosion takes place. The Site Evaluation Tool calculates storm event flow volume for existing land use conditions and for proposed land use conditions. In the current application, a 24-hour storm with either a 1-year or a 2-year recurrence is used to approximate the conditions under which stream channel degradation may occur. Runoff volume from the one-inch storm is also calculated; this volume is frequently associated with water supply protection regulations – many BMPs have design criteria requiring them to capture this volume. A uniform ½ inch of runoff is also offered as an option for local governments using this capture volume as part of their requirements.

Most peak flow analyses focus on storm events with a minimum recurrence interval of two years. The Site Evaluation Tool evaluates the 1-year 24-hour storm and the 2-year 24-hour storm for volume control for a specific reason. It is important to evaluate storms that occur more frequently than the storms used for conventional flood control analysis. The greatest potential for channel erosion occurs for storms with a recurrence interval of one to two years. Certainly storms that occur every 5, 10, or even 100 years are more erosive, but those storms do not occur often enough to move the same amount of sediment overall as the more frequent storms.

The combined influence of runoff volume and peak flow can be evaluated through the judicious use of runoff volume storage criteria. A drawback of traditional peak flow detention structures is that while they effectively attenuate peak flow, they release stormwater at relatively high rates. These higher rates are sustained for longer periods of time than occurred in the pre-developed watershed, often leading to high rates of bank failure. In addition, waters released from multiple structures at adjacent sites can combine into even higher flows downstream.

Simply attenuating peak flows is not always protective of stream channels. If the peak is reduced **and** the flow is released slowly, the combination imparts greater protection to streams. The SET calculates the additional volume (i.e., post-development minus pre-development) of runoff resulting from a 1-year 24-hour storm or a 2-year 24-hour storm that must be controlled and released slowly to provide for water quality protection. The increase in volume between pre- and post-developed conditions for the 1-year 24-hour storm is also the basis for NPDES Phase II stormwater requirements, which apply to many of the jurisdictions of the Upper Neuse River Basin.

Runoff estimates in the SET are developed using the NRCS Runoff Curve Number method (USDA, 1986). This method relates total rainfall, potential losses, and the runoff curve number to total runoff volume. Total precipitation estimates are based on a design storm event as recommended by the applicable stormwater regulation. The potential losses and runoff factor are developed based on the soil type and vegetation/land use within the watershed, which are captured in an index called the curve number. Curve numbers are specified for each of the model land uses for average antecedent moisture conditions (AMC II). The curve number is used to calculate the storage factor, which is the maximum potential storage of precipitation for each land use:

Equation 2-13.

$$S = \frac{1000}{CN} - 10$$

where

S = storage (inches)

CN = area weighted curve number for site

The NRCS method produces total event runoff depth:

Equation 2-14.

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad \text{for } P > 0.2S$$

$$Q = 0 \quad \text{for } P \leq 0.2S$$

where
 Q = runoff (inches)
 P = storm event precipitation (inches)

When combined with watershed area, it produces total runoff volume:

Equation 2-15.

$$V = \frac{Q \times A}{12}$$

where
 V = runoff volume (ac-ft)
 A = land area (ac)

Runoff volume is calculated for each land use, and runoff from all land uses is summed to produce total site runoff volume. Note that summing runoff from each land use is more accurate than producing a single area-averaged curve number; runoff is not a linear function with respect to curve number, and using area-averaged curve numbers frequently underestimates runoff.

It is important to note that runoff that is stored and released slowly is still technically a portion of the storm event runoff. Developers are encouraged to investigate and adopt site design practices and BMPs that actually prevent runoff from leaving the site (through infiltration or plant uptake). Doing so more closely mimics the pre-development site hydrology and potentially saves money if the size of structural BMPs can be reduced.

2.3 STORM EVENT PEAK FLOW AND HYDROGRAPH

Engineers use fairly sophisticated methods and tools to estimate storm event peak flows and hydrographs, and often must consider areas outside of the development when estimating the impact of site discharge. Detailed engineering calculations are beyond the scope of the SET for several reasons. Considering multiple physical drainage areas would be difficult and unwieldy in a spreadsheet environment; users would have to specify details about drainage area configuration and routing, and presentation of results could become unwieldy if several drainage areas are used. If the user desires more accurate results, the site may be divided into its composite physical drainage areas and a separate SET created for each drainage area.

However, even with its limitations, the SET provides a robust environment for testing various BMP configurations and viewing the impact on the post-development hydrograph. By having a tool that quickly shows how combinations of BMPs, site conditions, and capture volume criteria influence a hydrograph, users can more easily understand and learn about how conventional and innovative BMPs mitigate changes in a site's hydrology.

2.3.1 Peak Flow Calculation Using Rational Method

The primary method used by the SET for estimating peak flow is the SCS method discussed in the next section. However, the SET also calculates peak flow using the Rational Method, and presents it for comparison with the SCS peak. An advantage of the Rational Method is that many local stormwater departments already support its use (City of Durham Public Works Department, 2003; City of Raleigh and Wake County, 2001). Peak flow is calculated for each selected design storm for pre- and post-developed conditions (not including BMPs). Parameters used for the Rational Method are detailed in Appendix A.

The Rational Method is a simple but effective and proven way to estimate peak flow for a site. The equation itself is quite simple:

Equation 2-16.

$$q_p = CIA$$

where

q_p = peak flow (cfs)

C = coefficient of runoff (dimensionless)

I = rainfall intensity (in/hr)

A = land area (ac)

The model is highly sensitive to the assumed parameters, so great attention is given in engineering handbooks about the proper selection of C and calculation of I . Values of C used by the SET are based on those provided by the City of Durham, NC, as a starting point (City of Durham Public Works Department, 2003), refined by information from McCuen (McCuen, 1998). The SET calculates a weighted C based on land use, soil hydrologic group, and average site slope.

The rainfall intensity factor, I , is calculated as follows:

Equation 2-17.

$$I = \frac{g}{h + t_c}$$

where

g = empirical factor

h = empirical factor

t_c = time of concentration (min)

g and h are empirical factors which differ depending on the selected design storm. The SET uses g and h values published by Malcom (1989) for the Raleigh-Durham region. t_c is calculated using the Kirpich Equation (Kirpich, 1940), which is recommended by Malcom, and also by the City of Raleigh/Wake County, NC (City of Raleigh and Wake County, 2001).

Equation 2-18.

$$t_c = \frac{(L^3/H)^{0.385}}{128}$$

where

L = total length of flow path (ft)

H = elevation difference along hydraulic length

H is the product of L and the slope s , which is provided by user-input within the SET. For L , the site is assumed to be circular in shape, and L is calculated as the diameter of the circle. This distance is assumed to represent the length of the channel, the total distance from the most remote point to the outlet. t_c is assigned a lower limit of five minutes, as recommended by Malcom. t_c can also be optionally input by the user, if known, for undeveloped and developed site conditions, separately for the 1-year, 2-year, and 10-year 24-hour storm events. Note that the t_c used for this method is calculated differently than for the SCS Method (Equation 2-22), which is appropriate since the two methods measure t_c across different distances.

2.3.2 Calculation of Pre- and Post-development Hydrographs Using SCS Method

The SET's development of storm event hydrographs (and the primary method for calculating peak flow) is based on an SCS method (USDA, 1972) that calculates excess rainfall (precipitation that is not captured and stored) in set time increments, and assumes that the runoff resulting from each excess rainfall volume can be described as a unit hydrograph with a specified shape. An instantaneous hydrograph is therefore calculated for each incremental excess rainfall volume; each of these hydrographs is summed at every time step to produce a final site hydrograph. In other words, all of the instantaneous hydrographs from each timestep are superimposed across the storm duration to form a single final output hydrograph.

The SCS 24-hour Type II rainfall distribution is used to generate input precipitation. The storm distributions were originally published by SCS in six minute increments in tabular form. The methods used by the SET require a timestep as small as one minute, and storing a rainfall distribution in Excel with a one-minute timestep would unnecessarily increase the file size of the SET. A fitted formula representing the distribution is used instead (Haan et al., 1994), and cumulative precipitation is calculated using the formula. An optimization of the parameters of the original Haan et al. formula was performed, and the new parameters produced a better RMS error and overall fit (Figure 1). The formula for cumulative rainfall (dimensionless) is as follows:

Equation 2-19.

$$p(t) = 0.5 + \frac{(t - 11.857)}{24} \left(\frac{23.978}{2|t - 11.857| + 0.0774} \right)^{0.76} \quad \text{where}$$

$p(t)$ = cumulative precipitation at time t
 t = time (hrs)

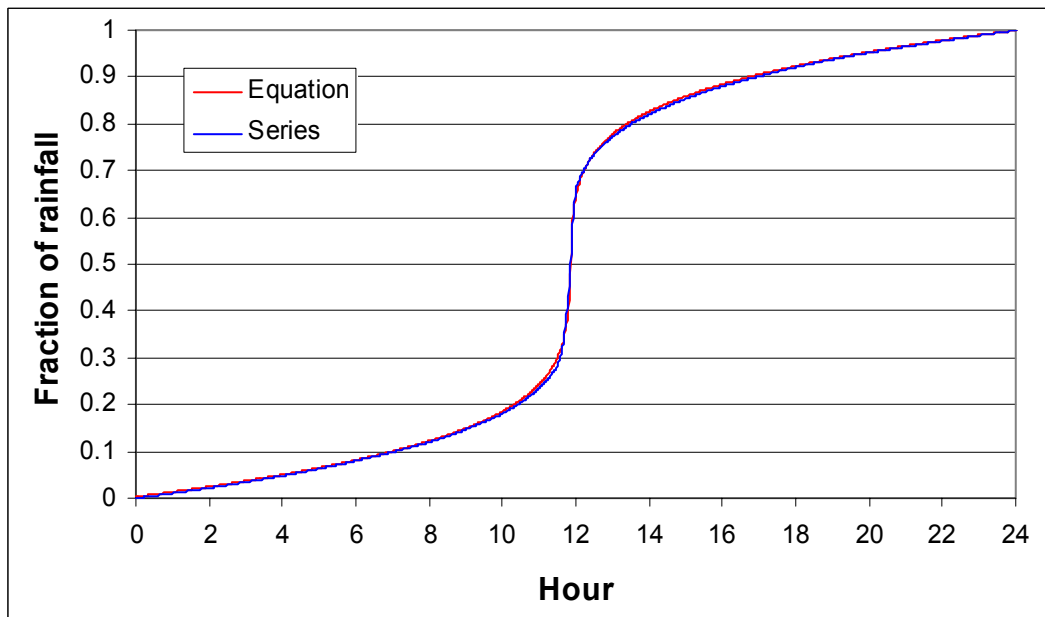


Figure 1. SCS 24-hour Type II Storm – Comparison of Tabular Values to Fitted Equation

Cumulative rainfall is calculated as the product of storm event rainfall depth and $p(t)$. At each timestep, cumulative rainfall is entered into Equation 2-14, the NRCS equation for runoff.

Equation 2-20.

$$Q(t) = \frac{(p(t) - 0.2S)^2}{(p(t) + 0.8S)} \quad \text{for } p(t) > 0.2S \quad \text{where}$$

$Q(t)$ = cumulative runoff volume at time t

$$Q(t) = 0 \quad \text{for } p(t) \leq 0.2S$$

Storage, S , is related to the curve number. Since the rainfall-runoff calculations are performed for the site as a whole, an aggregate curve number is needed to calculate storage. As stated previously, area-weighted curve numbers tend to underestimate runoff. The SET uses a novel approach for determining the site curve number. The runoff volume calculated previously is compared to a lookup table containing

all runoff volume/curve number combinations, and the curve number corresponding to the runoff volume is used. S is then calculated from the site curve number using Equation 2-13.

$Q(t)$ represents the cumulative runoff volume at time t . The incremental runoff volume (or excess rainfall) is defined as:

Equation 2-21.

$$q(t) = Q(t) - Q(t - 1) \quad \text{where} \\ q(t) = \text{incremental runoff volume at time } t$$

Two parameters are needed to create the SCS unit hydrograph: q_p , the peak discharge for the unit hydrograph (cfs), and t_p , the time to peak for the unit hydrograph (min). t_p is equal to $\frac{2}{3} t_c$, the time of concentration (min). t_c is calculated using the SCS lag formula (including a conversion of t_l , lag time, to t_c using $t_c = 1.667 t_l$):

Equation 2-22.

$$t_c = 0.00526 L^{0.8} \left(\frac{1000}{CN} - 9 \right)^{0.7} s^{-0.5} \quad \text{where} \\ L = \text{distance of overland flow (ft)} \\ s = \text{slope, (ft/ft)}$$

s is provided by user-input within the SET. For L , the site is assumed to be circular in shape, and L is calculated as the radius of the circle. This distance is assumed to represent the average length of overland flow within a site to a center channel. t_c can also be optionally input by the user, if known, for undeveloped and developed site conditions, separately for the 1-year, 2-year, and 10-year 24-hour storm events. Note that the t_c used for this method is calculated differently than for the Rational Method (Equation 2-18), which is appropriate since the two methods measure t_c across different distances.

q_p for a unit hydrograph with $\frac{3}{8}$ of its area under the rising limb, appropriate for areas with moderate topographic variation such as the NC Piedmont region (McCuen, 1998), can be found as follows:

Equation 2-23.

$$q_p = \frac{484 A / 640}{t_p / 60} \quad \text{where} \\ A = \text{land area (ac)}$$

Wu (1963) described a formula for calculating the ordinates of the unit hydrograph:

Equation 2-24.

$$q(t) = q_p \left[\frac{t}{t_p} e^{\left(1 - t/t_p \right)} \right]^{3.7} \quad \text{where} \\ q(t) = \text{unit peak flow at time } t \text{ (cfs)}$$

The unit hydrograph can be plotted generically by scaling the axes to q_p and t_p (Figure 2).

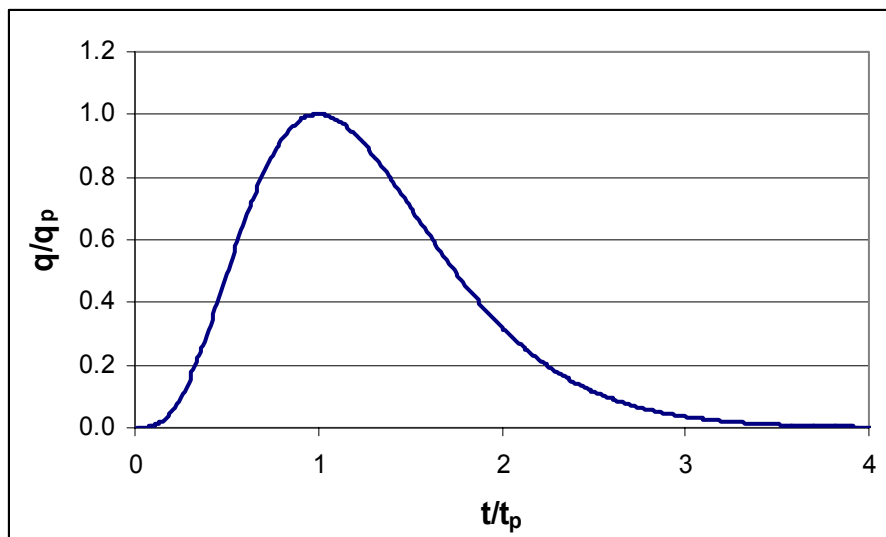


Figure 2. Unit Hydrograph as Represented by Wu Formula

$q(t)$ approaches but does not reach zero. When $q(t) < 0.01 q_p$, then calculations of $q(t)$ are ceased; in testing, this threshold produced the best representation of runoff volume under the output hydrograph versus the runoff volume calculated previously by the TR-55 method.

With the ordinates of the incremental runoff time series and unit hydrograph time series, the resulting site hydrograph is ready to be calculated, or convoluted, as the process is generally called in engineering textbooks and stormwater design manuals. For each timestep t , the discharge $r(t)$ in cfs is equal to:

Equation 2-25.

$$r(t) = p(t)q(1) + p(t-1)q(2) + p(t-2)q(3) \dots p(t-n-1)q(n)$$

where

n is number of ordinates of the unit hydrograph

In other words, the total runoff at time t is the sum of the contributing runoff values from each of the previous timesteps, going back as far as the duration of the unit hydrograph. At time t , the incremental runoff from time $t-n-1$ has run its course, and in between $t-n-1$ and t , each of the incremental runoff volumes are contributing runoff to time t .

Each value of the output site hydrograph is stored internally in a hidden Excel worksheet. These calculations are performed for pre- and post-development conditions, for the selected peak flow storm events. The maximum value of each hydrograph is reported as the storm event peak, and the discharge values are plotted in an Excel chart in the SET Model Output sheet.

2.3.3 BMP Influence on SCS Post-development Hydrograph

The hydrographs produced by the SET provide a screening and educational tool for the user, and offer insight into how land use change and BMP choice can affect storm event runoff. Note that this is not a substitute for detailed engineering design – many simplifying assumptions are made to reduce user inputs and retain the SET's value as a screening tool. The challenge lies in satisfactorily representing the volume released over time by BMPs without orifice and weir heights and sizes for detention basins, infiltration rates and underdrain configurations for bioretention and water quality swales, and other related details. To meet this challenge, the SET makes assumptions about BMP capture volume based on North

Carolina design standards and North Carolina State University (NCSU) guidance (in the absence of user-entry BMP storage volume), and outflow based on storage volume and release rate relationships. Just as the pre- and post-development hydrographs are calculated for the site as a whole, BMP influence on the post-development hydrograph is calculated for the entire site as if it is a single drainage area. A complex set of rules and equations govern how the selected BMPs capture, store, and release runoff, which is referenced within this document as the Storage-Release Model. The post-development hydrograph is routed through the Storage-Release Model in one-minute timesteps, with cfs being converted to cubic feet within the model, and back to cfs for the post-BMP hydrograph.

2.3.3.1 Storage-Release Model

The foundation of the Storage-Release Model is a formula that calculates outflow from a BMP that is independent of stage, outlet size and configuration, soil permeability, etc. Outflow volume is simply a function of storage volume (e.g., the water quality volume for a wet pond), the release time for the storage volume (e.g., 48 hours), and the current volume stored. The relationship was developed by examining a plot of volume released by a detention basin through time. A simplified version of a basin with straight sides and an outlet orifice was modeled over a short timestep, by using the orifice equation to estimate outflow, subtracting the outflow volume from the stored volume, recalculating stage, and performing the same set of calculations until the basin was empty. Several variations of storage volume, initial stage, and orifice size were tested, all of which resulted in the same general result: a decreasing linear function. If this function can be described in terms of total storage volume and release time, it should be possible to integrate it to describe release volume in terms of total storage volume, current volume, and overall release time frame, independent of time. It is important to note that the linear relationship is true only for basins with straight sides and an orifice outlet.

Design guidance in the NC BMP Manual specifies that many BMPs store and release the water quality volume (calculated from the Simple Method or from the one inch storm) over a minimum of 48 hours. The x-intercept of the release function is the point where the basin empties, and is therefore equal to the release time, T_R (Figure 3). The volume under the line is equal to the total storage volume (V_{ST}). Since the release function is linear, the following is also true:

Equation 2-26.

$$q_{ave} = \frac{V_{ST}}{T_R} \quad \text{where} \quad q_{ave} = \text{average release rate over duration of function}$$

q_{ave} occurs when the basin is half empty. The y-intercept is therefore equal to $2 \cdot q_{ave}$ (Figure 3).

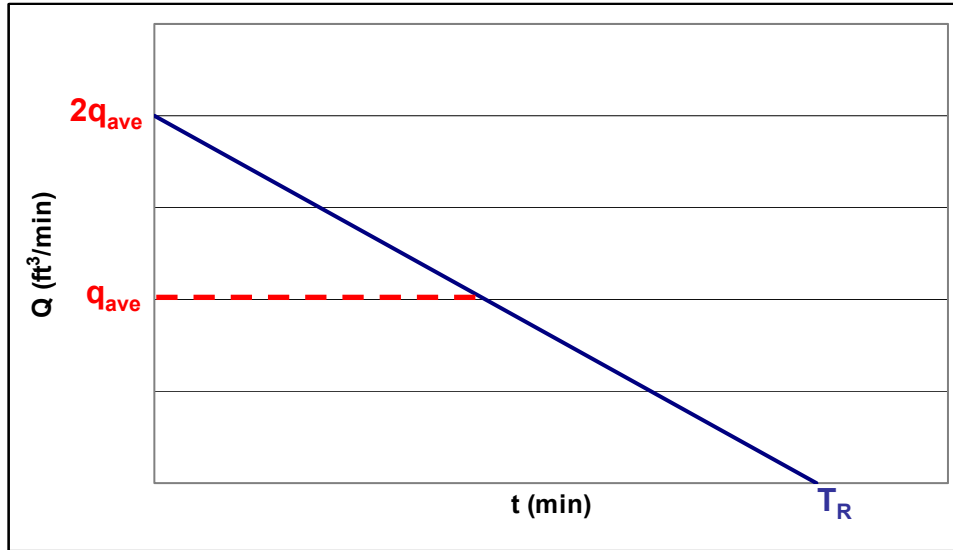


Figure 3. Graphical Representation of Release Function and Its Parameters

With two points defined, the function can now be described. The slope is $-2 \cdot q_{ave} / T_R$, and the function is:

Equation 2-27.

$$Q(t) = \frac{-2q_{ave} t}{T_R} + 2q_{ave} \quad \text{where} \quad Q(t) = \text{release rate at time } t$$

The volume released at time T (a specific time) can be found from the definite integral of the function:

Equation 2-28.

$$V(T) = \int_0^T \frac{-2q_{ave}}{T_R} t \, dt + \int_0^T 2q_{ave} \, dt$$

The definite integral reduces to:

Equation 2-29.

$$V(T) = \frac{-q_{ave}}{T_R} T^2 + 2q_{ave} T$$

Since V(T) is the volume released at time T, the volume remaining to be released can be represented as:

Equation 2-30.

$$V_{REM} = V_{ST} - V(T) \quad \text{where} \quad V_{REM} = \text{Volume remaining at time } T$$

By substituting Equation 2-30 into Equation 2-29 and rearranging the terms, both relationships can be placed into a form that can be used with the quadratic equation:

Equation 2-31.

$$0 = \frac{-q_{ave}}{TR} T^2 + 2q_{ave}T + (V_{REM} - V_{ST})$$

After plugging the terms into the quadratic equation, simplifying the result, and using the relationship that $q_{ave} = V_{ST} / T_R$ (Equation 2-26), T is equal to the following:

Equation 2-32.

$$T = \frac{V_{ST} - \sqrt{V_{ST} V_{REM}}}{q_{ave}} \quad (\text{only one solution shown; the other is not applicable})$$

While the integral was performed at a definite time, T can occur anywhere along the volume release function. Substituting T for t into Equation 2-27,

Equation 2-33.

$$Q(t) = \frac{-2q_{ave} \left(\frac{V_{ST} - \sqrt{V_{ST} V_{REM}}}{q_{ave}} \right)}{T_R} + 2q_{ave}$$

and $Q(t)$ simplifies to:

Equation 2-34.

$$Q(t) = \frac{2\sqrt{V_{ST} V_{REM}}}{T_R}$$

Outflow volume can now be calculated using the total storage volume, release time, and current volume (V_{REM}). Note that while this relationship was developed for a basin with no active inflow (i.e., after runoff has finished entering it), it can just as easily be used for a basin that is filling. V_{ST} and T_R are static, and outflow volume can be calculated so long as current volume is tracked.

This relationship is used for all of the BMPs that store and release runoff in a gradual fashion. While the linear decrease in release rate over time is strictly true for a straight sided basin with orifice outflow only, it provides a reasonable approximation for weir flow, basins with sloped sides, and infiltration-controlled outflow (e.g., percolation of capture volume through bioretention into an underdrain over a 24-hour period).

2.3.3.2 Peak Control Model

In almost all cases, the volume stored for water quality purposes is not sufficient to mitigate the increase in peak flow for large storm events. Additional storage is needed, as well as a larger outlet that allows greater output during these storm events. Many BMPs that perform extended detention are also frequently configured to perform peak matching for larger storm events, by using multiple outlets at different stages. The SET models both extended detention release and peak control for wet ponds, stormwater wetlands, and extended dry detention basins. Peak control alone is modeled for conventional dry detention. The Peak Control Model is discussed first as it pertains to BMPs that offer both extended detention release and peak matching (referred to as Peak and Extended Detention BMPs, see Table 1), and a simplified version for conventional dry detention is discussed afterwards.

The Peak Control Model for Peak and Extended Detention BMPs assumes a two outlet configuration – one for extended detention and one for peak control. The goal of peak matching, of course, is to set the post-development peak at or below the pre-development peak, so the sum of the flow rates from both outlets must be less than or equal to the pre-development peak. The Storage-Release Model is employed for both outlets. Two separate volumes are calculated – the extended detention storage volume, and the additional peak storage volume. The extended detention storage volume is routed through the lower outlet, with one Storage-Release Model specified for that outlet. The peak storage volume is routed through the upper outlet, with another Storage-Release Model specified for that outlet. Recalling that $2 \cdot q_{ave}$ is equal to the outflow when the storage is “full,” peak matching is achieved when the following is true:

Equation 2-35.

$$2q_{ave} + 2q_{ave-peak} < Q_{PRE}$$

where

$q_{ave-peak}$ = average release rate for additional peak storage volume

Q_{PRE} = pre-development maximum peak flow rate from site

The outflow from the lower orifice would actually be larger, since the additional stage would increase the flow beyond $2 \cdot q_{ave}$; however, the lower orifice is likely to be small compared to the upper orifice and the error is small. Since $q_{ave} = V_{ST} / T_R$, the equation can be modified to incorporate both Storage-Release Models (Equation 2-34 used for two models simultaneously):

Equation 2-36.

$$2 \frac{V_{ST}}{T_R} + 2 \frac{V_{STpeak}}{T_{Rpeak}} < Q_{PRE}$$

where

V_{STpeak} = average release rate for additional peak storage volume

T_{Rpeak} = time frame to release runoff through upper outlet.

V_{ST} is calculated by the SET (discussed in Section 2.3.3.3) or input directly by the user. T_R is set at 48 hours, per NC design criteria. Q_{PRE} is known from the pre-development hydrograph calculations. V_{STpeak} can be found using the NRCS TR-55 method for determining storage volume for basins, using the formula and parameters for the Type II storm:

Equation 2-37.

$$V_{STpeak} = V_{total} \left[0.682 - 1.43 \left(\frac{Q_{PRE}}{Q_{POST}} \right) + 1.64 \left(\frac{Q_{PRE}}{Q_{POST}} \right)^2 - 0.804 \left(\frac{Q_{PRE}}{Q_{POST}} \right)^3 \right]$$

where

V_{total} = total storm event runoff volume

Q_{POST} = post-development maximum peak flow rate from site

The other terms are known or estimated, so T_{Rpeak} can be found by rearranging Equation 2-36:

Equation 2-38.

$$T_{Rpeak} = \left[\frac{V_{STpeak}}{\frac{Q_{MAX}}{2} - \frac{V_{ST}}{T_R}} \right]$$

As an additional precaution, the calculated discharge is capped at $0.98 \cdot Q_{PRE}$ to prevent the post-development discharge from exceeding the pre-development peak, since the methods used here are inexact. It is likely that the basin and outlets can be configured for peak matching, so the SET assumes that peak matching will occur successfully.

Outflow is modeled through both orifices whenever the storage volume exceeds the extended detention volume. Once the current storage volume is less than V_{ST} , default values in Equation 2-34 for extended detention is used.

If Conventional Dry Detention is selected, then Equation 2-36 is not used. Instead, V_{STpeak} is calculated using Equation 2-37, T_{Rpeak} is calculated from Equation 2-38 with V_{ST} set to zero, and V_{STpeak} and T_{Rpeak} are used in Equation 2-34.

2.3.3.3 BMP Groups and Assumptions

In order to simplify calculations, BMPs are grouped as follows within the Storage-Release Model according to their storage volume and peak control characteristics (Table 1):

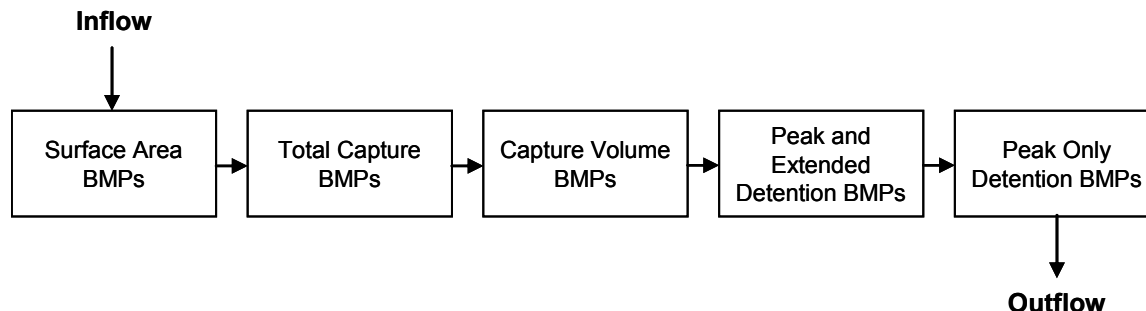
Table 1. BMP Groupings for Runoff Influence Calculations

Class	BMPs in Class	Characteristics
No Control	Grass Swale Vegetated Filter Strip w/ LS 50' Restored Buffer w/ LS	No significant volume or peak control; influence not considered.
Surface Area BMPs	Green Roof Permeable Pavement	Store some runoff and prevent it from leaving site; provide some peak attenuation via slow percolation through matrix.
Total Capture BMPs	Infiltration Trench Cistern/Rain Barrels	Store significant runoff (runoff from the 1-inch storm) and prevent it from leaving site; pass additional volume without any peak control.
Capture Volume BMPs	Bioretention Sand Filter Water Quality Swale	Store significant runoff (runoff from the 1-inch storm) and release gradually over a 24-hour period; pass additional volume without any peak control.
Peak and Extended Detention BMPs	Extended Dry Detention Wet Ponds Stormwater Wetlands	Store extended detention volume (runoff from the 1-inch storm, or difference in runoff between pre- and post-developed conditions for 1-yr/2-yr storms) and release gradually over 48-hour period; store additional runoff and provide complete peak control via outlet structure.
Peak Only Detention BMPs	Conventional Dry Detention	No extended detention storage; store runoff and provide complete peak control via outlet structure.

For user-defined BMPs, the SET allows the user to choose the appropriate BMP class.

Some elements of stormwater hydraulics are not taken into account. For instance, bioretention does offer minimal peak control as excess runoff passes over an overflow structure; an open channel may provide minimal peak control depending on configuration. However, for the purposes of the SET, these aspects of site design have little effect on the output hydrograph.

Runoff is passed through the BMP groups within the Storage-Release Model in the following order:



The order is based on the following rationale:

1. Surface Area BMPs (green roofs and permeable pavement) receive direct runoff from precipitation. Any additional runoff routed to these BMPs (such as untreated rooftop or areas on the fringe of a peaking lot) would not be treated by another BMP.
2. Total Capture BMPs and Capture Volume BMPs are likely to be located upstream of BMPs that offer peak control.
3. A BMP that provides peak control would be sited at the downstream end of its drainage area. While it is unlikely for a Peak and Extended Detention BMP (such as a wet pond) and a Peak Only Detention BMP (conventional dry detention) to be located in the same drainage area, the Storage-Release Model does allow for the possibility.

Within each BMP class, the following assumptions are made about how BMPs store and release runoff (Table 2). Each is discussed in detail below. Sources of information used to develop the assumptions include the following:

- Design guidance provided by Bill Hunt of NCSU in his Urban Stormwater BMP Design course (2003).
- The North Carolina BMP Manual (NC DENR, 1999).
- For water quality swales, the Maryland Stormwater Design Manual (Maryland Department of the Environment, 2000).

Table 2. BMP Group Properties for Runoff Influence

Class	Extended Detention Volume	Release Time for Extended Detention Volume	Additional Peak Control
Surface Area BMPs	Completely captures and evaporates some runoff and provides short-term detention for additional runoff	12 hours	Shaves post-development peak by 50%
Total Capture BMPs	Runoff from one-inch storm	N/A - completely infiltrates into soil	None
Capture Volume BMPs	Runoff from one-inch storm	24 hours	None
Peak and Extended Detention BMPs	Runoff from one-inch storm, or difference in runoff between pre- and post-developed conditions for 1-yr/2-yr storms	48 hours	Matches pre-development peak for large design storms
Peak Only Detention BMPs	No extended detention	No extended detention	Matches pre-development peak for large design storms

Surface Area BMPs

Green roofs and permeable pavement have unique properties for both storage and release of runoff. First, the entire surface area of these BMPs acts to intercept precipitation. Each is able to store a significant amount of precipitation and prevent it from becoming runoff. A greenroof with 3 inches of a specially designed soil mix can hold the first ½ inch of precipitation and evaporate it completely between storms (Hunt, 2003 and Moran, 2004). In addition, a greenroof provides significant peak control via percolation through a storage layer. Even for the largest storm event measured, Moran measured peak control in the neighborhood of 50 percent reduction. Less is known about permeable pavement behavior in the Piedmont, where design guidance from Hunt calls for a drainage layer and outlet; however, permeable pavement is likely to have similar properties. The SET makes the following assumptions for calculating the impact on the post-development hydrograph:

- Greenroofs store the first ½ inch of runoff and do not release it. Permeable pavement stores the first ¼ inch of runoff and does not release it. Note that intercepted runoff will generally be equal to the precipitation depth, since neither BMP should be designed to receive significant runoff from surrounding areas.
- After the initial storage is filled, 50 percent of the volume from each timestep of the input hydrograph is stored temporarily and 50 percent is released as runoff (resulting in a 50 percent reduction of the peak).
- During the descending limb of the hydrograph, the accumulated volume is compared to the inflow. When the release rate calculated by the Storage-Release Model exceeds the inflow volume, the Storage-Release Model is used from that point forward, and the stored volume is released over a 12-hour period.

Total Capture BMPs

Total Capture BMPs are designed to capture runoff and prevent it from leaving the site as runoff. This category includes infiltration trenches and cisterns/rain barrels. Capture volume is calculated for the contributing drainage areas only.

Infiltration trenches are assumed to capture the runoff from the first inch of rainfall. This portion of the runoff is completely infiltrated into underlying soil. After the capture volume has been filled, the remaining runoff passes through the BMP without further peak reduction. Siting an infiltration trench requires that the underlying soil have a very high infiltration rate. While these are highly effective BMPs, few sites in the North Carolina Piedmont would support them.

Rain barrels and cisterns vary widely in storage volume, so estimating capture volume is more difficult. Frequently, the user will have some idea about the capture volume, and can input it directly into the SET. If the capture volume is not specified, the SET assumes that rain barrels have been selected. One rain barrel per 500 ft² of roof area is assumed, and the rain barrel storage volume is assumed to be nine ft³ (67 gallons). The stored rain water is assumed to be used for irrigation needs at a later time, and does not contribute to storm event runoff.

Capture Volume BMPs

These are generally configured to temporarily store a quantity of runoff, gradually infiltrate it through a sand or soil media, and release the filtered runoff via an underdrain. Given the low infiltration rates of North Carolina Piedmont soils, the SET assumes that Capture Volume BMPs will always have an underdrain. After the capture volume has been filled, the remaining runoff passes through the BMP without further peak reduction. The volume leaving the underdrain is added to the hydrograph as well. Capture volume is calculated for the contributing drainage areas only.

These BMPs are assumed to capture the runoff from the first inch of rainfall only, and no more (unless the user specifies a larger capture volume). There is a two to three fold increase in capture volume between the 1-inch storm and the 1-year 24-hour or 2-year 24-hour capture volume. Doubling the size of these BMPs is rarely feasible. Water quality swales are already usually wider than a conventional grass channel. The hydrologic regime of bioretention requires that plants can withstand dry and very wet periods, and changing that regime (by doubling the size of the cell treating the same drainage area) could make it difficult for bioretention to support its plant life.

Peak and Extended Detention BMPs

These BMPs are generally designed as basins that capture runoff from large portions of a site. They serve a dual purpose – to store runoff from frequent, smaller storm events and release it gradually over a two- to five-day period, and to provide peak matching for larger design storm events. They frequently are designed with multiple outlets at various heights for releasing design storms of increasing volume. The capture volume for extended detention is assumed to be the target volume specified by the user, which is one of the following:

- The runoff from the first inch of rainfall.
- The difference in runoff between pre- and post-development conditions for the 1-year 24-hour storm.
- The difference in runoff between pre- and post-development conditions for the 2-year 24-hour storm.

Capture volume is calculated for the contributing drainage areas only. For larger design storms, the pre-development peak flow as calculated by the SET or optionally input by the user is the target, and volume in excess of the extended detention volume is stored and released as quickly as possible while meeting the target.

Peak Only Detention BMPs

These BMPs are designed for peak matching only, and receive no credit for extended detention requirements. For larger design storms, the pre-development peak flow as calculated by the SET or optionally input by the user is the target, and volume in excess of the extended detention volume is stored and released as quickly as possible while meeting the target.

Multiple BMPs

Potential storage volume is calculated separately for every BMP in each drainage area. The total potential capture volume is then summed for each BMP. For instance, if a site has five drainage areas and only three are treated by bioretention, then bioretention capture volume is estimated individually for each of the three drainage areas, and the three volumes are summed to arrive at the total estimated bioretention capture volume. The two drainage areas without bioretention (and their associated runoff volume) do not influence the bioretention capture volume.

The SET adjusts capture volume for Peak and Extended Detention BMPs when multiple BMPs are selected and when the selected volume criterion is for the 1-year or 2-year 24-hour storm. For instance, if both bioretention and extended dry detention are selected, the capture volume from bioretention is subtracted from the capture volume for extended dry detention. It should not be necessary to over-design the extended dry detention, since the bioretention provides some extended detention. Like all of the volume estimation calculations, this adjustment to capture volume is performed separately for each drainage area.

3 Cost Component

The SET Cost Component allows a user to compare the cost of stormwater BMP systems and the cost savings for reducing impervious surfaces within a site design. Once a user enters two or more BMP scenarios, the user can determine which scenario is likely to be least expensive or most cost-effective. The component addresses:

- Construction, design, and engineering costs for BMPs, treatment train connections, additional stormwater conveyance structures, and total site pavement
- Inspection and maintenance costs for BMPs
- Opportunity cost of land devoted solely to BMPs (as a user input).

To estimate BMP costs, SET users enter square feet of surface area, cubic feet of storage volume, or other whole BMP size units and the component reports ranges of costs as a measure of uncertainty.

BMP costs range widely depending on site conditions and design storms, and the use of average costs may lead to inaccurate cost estimates. The SET reports a range of costs so that the user is aware of the uncertainty of BMP cost estimates. As more BMPs are constructed and practices become standardized, more accurate cost data will be available, but BMP cost estimates will continue to vary due to site conditions. SET cost assumptions need to be updated as new cost estimates are available, and local cost data should be used whenever possible. The SET Cost Component contains a number of user-defined options so that a user can tailor the cost estimates to local prices or a particular design. The following sections describe how the initial cost assumptions were compiled and how the SET uses the cost assumptions to estimate site costs.

3.1 CONSTRUCTION COST DATA

3.1.1 General Methods for all BMPs

The SET Cost Component estimates costs with ranges of construction costs from published sources. BMP cost data literature provided construction cost estimates based on watershed area, storage volume, BMP surface area, or BMP length. Tetra Tech used cost data primarily from the NC State Biological and Agricultural Engineering Department (NCSU-BAE), USEPA, the Low Impact Development Center, and the Center for Watershed Protection. Some sources provided regression equations estimated from actual site costs and dimensions; other sources provided approximate cost estimates or ranges by volume, area, or length of the BMP.

Cost ranges were used as quoted in the source and then adjusted for inflation and location. Quoted ranges varied from 25 to 60 percent plus or minus the median of the range. If a source provided a single unit cost without a range, a range was calculated by adding and subtracting 15 percent of the unit cost. The 15 percent error range is the minimum error range that should be considered when using square foot or cubic foot costs (RS Means, 1990).

National and out-of-county costs were adjusted to local prices using RS Means indices (Table 3). For example, if a cost was quoted for Raleigh, the cost was multiplied by the ratio 0.74/0.76, or 0.97, to convert it to Raleigh prices. Conversion from Maryland, Virginia, and Michigan to North Carolina prices was also required for several BMPs. If a unit cost was quoted prior to 2004, an annual rate of 3 percent inflation was used to adjust the unit costs to 2004 dollars. See Appendix C for detailed methods on each BMP or structure.

Table 3. Indices Used to Convert Out of State and National Prices to Local Prices

Location	Ratio of Local Prices to National Prices ¹
MD, VA	0.90
Detroit, MI	1.08
Raleigh, NC	0.76

¹Obtained or estimated from RS Means (2003).

3.1.2 BMPs with Economies of Scale

Several cost regression equations were available that accounted for economies of scale. These equations relate construction cost to watershed area or storage volume. The exponent in the equation controls for economies of scale so that small BMPs cost more per square foot or cubic foot than large BMPs. If the SET Cost Component used these equations alone, the tool would be difficult to update when new information on BMP costs is available but not in the form of a regression equation. Therefore, incremental costs were estimated so that the Cost Component can be updated easily.

As an example of incremental costs, Table 4 lists ranges of cubic foot volume that can be used to estimate wet pond cost. If the volume of a wet pond is greater than 318,000 CF but less than 496,000 CF, then the SET estimates the wet pond cost between \$179,000 and \$241,000. The increments range from about minus 15 percent to plus 15 percent of the mean cost in each interval. To update these costs in the SET, the user would enter a new volume range, a new cost range, or new ranges for both cost and volume based on new information.

The estimates in Table 4 use three equations. With Equation 3-1, watershed area was used to estimate the cost of a wet pond draining a certain watershed area. This equation was estimated in Wossink and Hunt (2003) with data from 13 sample wet ponds. With Equation 3-2, the watershed area was used to estimate the surface area associated with that watershed area. This equation was based on rules of thumb developed by NCSU-BAE (Wossink and Hunt, 2003). The equation assumes that sample wet ponds (those used to estimate the regression equation) required about 1,200 SF per acre of drainage area. With Table 4, Tetra Tech converted the surface areas into volumes by assuming that the sample wet ponds had 6-foot pond depths and 90-degree slopes. Once converted to cubic foot costs, the cost ranges can be used to approximate costs for ponds of varying depths and design storms.

Equation 3-1. Relationship of Wet Pond Construction Cost to Watershed Area (Wossink and Hunt, 2003)

$$C = 14,326x^{0.67}$$

where

C = cost of wet pond construction

x = watershed area draining to wet pond in acres

**Equation 3-2. Relationship of Wet Pond Surface to Watershed Area
(Wossink and Hunt, 2003)**

$$SA = 0.028x$$

where

SA = surface area of wet pond in acres

x = watershed area draining to wet pond in acres

**Equation 3-3. Relationship of Wet Pond Volume to Surface Area
(estimated by Tetra Tech)**

$$V_s = 6SA$$

where

SA = surface area of wet pond in square feet

V_s = permanent pool plus detention volume

Table 4. Example of Wet Pond Surface Area Intervals and Corresponding Construction Costs

Volume of Pond in CF (permanent pool + detention)		Construction Cost	
Min	Max	Min	Max
83,000	131,000	\$73,000	\$98,000
131,000	204,000	\$98,000	\$133,000
204,000	318,000	\$133,000	\$179,000
318,000	496,000	\$179,000	\$241,000
496,000	778,000	\$241,000	\$326,000
778,000	1,222,000	\$326,000	\$442,000
1,222,000	1,888,000	\$442,000	\$592,000

Similar methods described above were used for stormwater wetlands, extended and conventional dry detention, and sand filters. Cost ranges for stormwater wetlands and sand filters were estimated for surface area input using equations from Wossink and Hunt (2003). Costs for extended and conventional dry detention were estimated with an equation relating storage volume to cost from the Center for Watershed Protection (2000). See Appendix C for BMP-specific assumptions and methods.

3.2 ADDITIONAL CONVEYANCE STRUCTURES AND SITE PAVING

The RS Means construction cost data (RS Means, 2003) were used for conveyance structure and site paving unit costs. RS Means (2003) offers costs for a number of pipe types, trenching widths, catch basins, and additional conveyance materials. The SET Cost Component considers types of pipe and trench width that would likely be used for stormwater conveyance but may not cover all types and sizes needed. Catch basin and curb and gutter costs were averaged over several sizes and material types. The user-defined inputs allow additional conveyance structures to be considered.

Most cost ranges in this category were calculated by adding and subtracting 15 percent of each RS Means cost. The sidewalk cost ranges were derived from ranges of thickness in RS Means (2003). The cost ranges do not include mobilization or grading. See Appendix C for more details on how the SET Cost Component uses the RS Means Cost Data for conveyance structures and site paving.

3.3 DESIGN AND ENGINEERING

The Cost Component automatically increases the construction cost of each BMP or structure by 25 percent to account for design and engineering costs. The default rate was set at 25 percent based on Wossink and Hunt (2003). This rate can be adjusted in the Adjust Cost sheet.

3.4 OVERHEAD AND PROFIT

The default rate of overhead and profit was set at 31 percent, based on RS Means (2003). Overhead and profit can be added to each BMP cost with a toggle switch. If the toggle switch is selected, the construction costs are increased by 31 percent. This rate can be adjusted in the Adjust Cost sheet.

3.5 INFLATION

The default cost data are automatically increased by the inflation rate each year according to the current year or project year and the year of the cost data. The default inflation rate is 3 percent. This rate can be adjusted in the Adjust Cost sheet. Equation 3-4 shows how the cost data are adjusted for inflation.

Equation 3-4. Adjusting Cost Data for Inflation

$$C_p = C_d(1 + r)^{(t_p - t_d)}$$

where

C_p = Cost in dollars of the project year

C_d = Cost in dollars of the cost data year

t_p = Year of project

t_d = Year of cost data

r = Inflation rate

3.6 COST EFFECTIVENESS RATIOS

In the cost per load removal formulas, the total load over the project duration is calculated by multiplying the load removed (pounds or tons per year) by the project duration (default is 20 years), as shown in Equation 3-5. Then the cost is divided by the total load over the project duration. These ratios are calculated for the total construction cost, the project duration maintenance cost, and the overall costs (construction plus maintenance).

Equation 3-5. Calculation of Cost Effectiveness Ratio

$$C_e = \frac{C}{(L_y \times t)}$$

where

C_e = cost effectiveness ratio

C = total cost

L_r = load removed per year by BMPs

t = years of project duration

The storage capacity cost-effectiveness ratios report the cost per acre-foot of BMP storage for each design storm; these ratios are based on the BMP storage as reported in the Model Output sheet. The storage capacity ratios are only calculated if the BMP storage volumes are defined in the BMPs sheet. The

storage capacity cost-effectiveness is calculated by dividing the cost by the acre-feet of BMP storage. This cost-effectiveness ratio does not account for the years of project duration. This ratio is calculated for the total construction cost, the project duration maintenance cost, and the overall costs (construction plus maintenance).

3.7 MAINTENANCE COST

The SET Cost Component calculates an inspection and maintenance cost over a total project period. Two types of maintenance cost data are used: 1) percent of base construction cost and 2) annual maintenance costs by BMP size.

NC State University researchers will be publishing unit costs for BMP inspection and maintenance by early 2005. Preliminary maintenance percent rates are being used as placeholders until the maintenance cost estimates from NC State University researchers are available. Dr. Bill Hunt of NC State University recommended 50 percent of construction costs as a preliminary estimate for 20 years of inspection and maintenance.

The percent rate calculates the maintenance cost, over the project duration, in present value terms. The “present value” is the current value of the projected stream of annual maintenance costs. The process of calculating present value is known as “discounting” and works in the following way. The party responsible for maintenance can invest the maintenance fund in another project or fund and earn a return of “r.” Consuming one unit of maintenance in 2006 would have a present value of $1/(1+r)$ in 2005, and one unit consumed in 2007 has a present value of $1/(1+r)^2$ in 2005, etc. The “r” at which future returns are discounted to the present value is called the discount rate (Helfert, 1997; Sugden and Williams, 1981). Discounting reflects the time preference for consumption. Although not synonymous with the interest rate, for private developers and governments it often reflects the rate at which funds can be borrowed and loaned.

A discount rate of 10 percent was used as the default rate for the SET Cost Component. This rate was used by Wossink and Hunt (2003) as the BMP maintenance cost discount rate for private developers. When annual maintenance costs are used, the SET Cost Component will calculate the present value of inspection and maintenance using the discount rate and project duration (default is 20 years), as specified in the Adjust Cost sheet. The project duration and discount rate can be adjusted in the Adjust Cost sheet. Inspection and Maintenance unit costs must be in the same units as the construction costs.

3.8 LAND OPPORTUNITY COST

The SET includes an opportunity cost of land estimate in which the area and cost inputs are user-defined and optional. The opportunity cost of land devoted to BMPs is defined as the value of the foregone development on the BMP land. When estimating this cost, the user would distinguish between BMPs that are incorporated into the landscape and building features and those that require land with sole use as a BMP. For example, bioretention cells are located in yards, parking medians, and landscaped areas. BMPs incorporated into the landscape also include green roofs and underground parking storage. Examples of BMPs that do not share land with other uses include large wet ponds, large bioretention areas, or stormwater wetlands. To estimate the opportunity cost, one estimates the revenue that could have been realized if that land was available for another use.

Land opportunity cost is calculated by estimating the revenue lost per acre by using land solely for stormwater control. Since revenue from land varies by time, location, type of development, and time, it would be difficult to provide an appropriate opportunity cost for every user. Therefore, the SET allows users to enter their estimate of land opportunity cost. User inputs include the total area of land with sole

use as a BMP and the estimated opportunity cost of this land, in dollars per square foot. The output will display the total area devoted solely to BMPs and the total opportunity cost, if specified.

3.9 USER-DEFINED INPUTS

A user can enter user-defined unit costs for each BMP; alternately, a user can enter the total construction cost for up to four user-defined BMPs. The SET uses the same design, engineering, overhead, and profit assumptions for the user-defined costs as for the default cost data. The SET does not adjust the user-defined costs for inflation.

3.10 UPDATING COST DATA

The Adjust Cost worksheet cites the sources used for each BMP cost estimate and allows the user to adjust the cost assumptions based on new data. When using the cost data to estimate costs, the SET increases the cost data by the inflation rate for each year that the cost data is older than the project year, as shown in Equation 3-4.

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Appendix A. Parameters for Hydrology and Pollutant Loading

See references below tables for data sources.

Table A-1. Infiltration Constants

Soil Type	Infiltration (in/yr.)	Data Source
A-Soil Infiltration	18	#1
B-Soil Infiltration	12	#1
C-Soil Infiltration	6	#1
D-Soil Infiltration	3	#1

Land Type	Infiltration Fraction	Data Source
Row Crops	1	#1
Pasture	1	#1
Forest	1	#1
Wetland	1	#1
Meadow	1	#1
Lawn	0.8	#1
Dry BMPs	0.8	#1
Permeable Pavement	0	#9

Table A-2. Regional Rainfall Data

Parameter	Value	Data Source
Annual Rainfall (inches)	44.75	#8
1 inch Design Storm (inches)	1	#9
1-yr 24-hr Design Storm (inches)	2.88	#3
2-yr 24-hr Design Storm (inches)	3.60	#4
10-yr 24-hr Design Storm (inches)	5.38	#4

Table A-3. Event Mean Concentrations

Surface	Event Mean Conc. (mg/L)			Data Source		
	TN	TP	TSS	TN	TP	TSS
Agriculture – Row Crops	2.59	0.4	400	#7	#7	#7
Agriculture – Pasture	2.59	0.4	400	#7	#7	#7
Unmanaged Pervious	1.45	0.25	49.3	#8	#8	#8
Managed Pervious	6.23	1.13	25.0	#8	#8	#8
Normal Traffic Impervious	1.74	0.27	53.6	#8	#8	#8
High Traffic Impervious	3.48	0.49	69.5	#8	#8	#8
Pond/Wetland Surface Area *	1.45	0.25	0	Nutrients assumed to be similar to unmanaged pervious, due to surface inputs from waterfowl and atmospheric deposition. No assumed direct inputs of sediment to pond surface.		
Permeable Pavement	1.74	0.27	53.6	Assumed to be similar to Normal Traffic Impervious		
Green Roof	1.74	0.27	53.6	Assumed to be similar to Normal Traffic Impervious.		
All Other BMP Surface Area	6.23	1.13	25.0	Assumed to be similar to Managed Pervious		

* Represents annual input directly onto surface, not input from runoff. Loading is translated to EMC for consistency.

Table A-4. Curve Numbers *

Land Cover	A Soils	B Soils	C Soils	D Soils
Row Crops	67	78	85	89
Pasture **	49	69	79	84
Forest **	36	60	73	79
Wetland **	36	60	73	79
Meadow ***	30	58	71	78
Lawn ***	39	61	74	80
BMPs (Pervious Area)***	39	61	74	80
Impervious Surface	98	98	98	98
Pond/Wetland Area	98	98	98	98
Permeable Pavement	98	98	98	98
Green Roof	98	98	98	98

* Data Source: #6

** Reflects Fair Hydrologic Condition

*** Reflects Good Hydrologic Condition

Table A-5. IDF Coefficients Used for Rational Method *

Parameter	1-yr	2-yr	10-yr
g	104	132	195
h	18	18	22

* Data Source: 2-yr and 10-yr from #2; 1-yr extrapolated from #2.

Table A-6. Rational Coefficients ****Pervious Land Covers***

	A Soils	B Soils	C Soils	D Soils	
Row Crops	0.20	0.26	0.30	0.35	slope < 2%
	0.25	0.30	0.35	0.40	slope 2%-6%
	0.30	0.34	0.40	0.45	slope > 6%
Pasture	0.07	0.13	0.19	0.22	slope < 2%
	0.12	0.20	0.26	0.32	slope 2%-6%
	0.17	0.27	0.33	0.42	slope > 6%
Forest	0.07	0.10	0.12	0.14	slope < 2%
	0.10	0.13	0.15	0.18	slope 2%-6%
	0.13	0.16	0.18	0.22	slope > 6%
Wetland	0.07	0.10	0.12	0.14	slope < 2%
	0.10	0.13	0.15	0.18	slope 2%-6%
	0.13	0.16	0.18	0.22	slope > 6%
Meadow	0.07	0.11	0.17	0.21	slope < 2%
	0.10	0.14	0.20	0.24	slope 2%-6%
	0.14	0.17	0.23	0.27	slope > 6%
Lawn, Pervious BMP Area	0.15	0.20	0.25	0.28	slope < 2%
	0.20	0.25	0.30	0.35	slope 2%-6%
	0.25	0.30	0.35	0.42	slope > 6%

Impervious Land Covers

Impervious	0.94	slope < 2%
	0.95	slope 2%-6%
	0.96	slope > 6%

Pond/Wetland Surface Area	0.95
Permeable Pavement, Green Roof	

* Data Sources: Synthesis of #2 and #5.

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Appendix B. BMPs and Efficiencies Used in Site Evaluation Tool

Table B-1. BMPs and Efficiencies Used in Site Evaluation Tool

BMP	Efficiency (percent removal)			Hydrology Influence	
	Total Nitrogen	Total Phosphorus	TSS	Annual % Infiltrated ^c	Annual % ET ^c
Wet Pond	25% ⁶	40% ⁶	85% ⁵	0% ^{3, 8}	5% ^{3, 8}
Stormwater Wetland	40% ⁶	35% ⁶	85% ⁵	0% ^{3, 8}	10% ^{3, 8}
Extended Dry Detention ^a	10% ⁶	10% ⁶	25% ²	0% ^{3, 8}	5% ^{3, 8}
Conventional Dry Detention	0% ²	0% ²	0% ²	0% ^{3, 8}	5% ^{3, 8}
Bioretention	35% ⁶	45% ⁶	85% ⁵	7% ^{3, 8}	35% ^{3, 8}
Sand Filter (Delaware Design)	35% ⁶	45% ⁶	85% ⁵	0% ^{3, 8}	0% ^{3, 8}
Infiltration Trench ^b	45% ³	55% ³	85% ⁵	85% ^{3, 8}	5% ^{3, 8}
Grass Swale	20% ⁶	20% ⁶	35% ^{1, 5}	2% ^{3, 8}	3% ^{3, 8}
Water Quality Swale (Maryland Design)	30% ³	40% ³	80% ¹	10% ^{3, 8}	25% ^{3, 8}
Vegetated Filter Strip with Level Spreader	20% ⁶	35% ⁶	57% ^{4, 7}	2% ^{3, 8}	3% ^{3, 8}
Green Roof	0% ³	0% ³	0% ³	0% ^{3, 8}	50% ^{3, 8}
Permeable Pavement	0% ³	0% ³	0% ³	5% ⁸	10% ⁸
Cistern/Rain Barrels	20% ³	35% ³	50% ³	15% ⁸	5% ⁸
50' Restored Buffer with Level Spreader	30% ⁶	30% ⁶	62% ^{4, 7}	5% ^{3, 8}	5% ^{3, 8}

^a Extended Dry Detention provides extended detention (minimum 48 hours) for the water quality capture volume.

^b Infiltration Trench appropriate only for highly permeable soils where entire capture volume can be infiltrated.

^c Fraction of annual runoff that is intercepted by BMP and then infiltrated or lost through evapotranspiration (ET).

Sources

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Appendix C. SET Cost Component Cost Data Sources

Cost Data: Detailed Methods

The following 21 tables contain explanations and sources for each cost range in the SET. The costs reported in the tables represent the costs as they appear in the source, without adjustment for inflation or location. The cost ranges reported here do not contain design and engineering, unless otherwise noted. Please refer to the “Adjust Cost” sheet in the attached SET demonstrations for the final, adjusted cost ranges. Each table contains the following information:

- **Cost Equation, Price or Price Range** quotes the cost information directly from the source, without any adjustment for inflation or location.
- **Explanation** describes how the cost information was used to determine unit costs for the SET.
- **Range** indicates the percent error represented by the cost range and what input thresholds are employed, if any.
- **Location** indicates the location that the cost information represents.
- **Reference** cites the reference for the cost information; the full citation can be found in the references section.

The acronyms used in the tables are defined as:

- **CF** = Cubic Feet
- **SF** = Square Feet
- **LF** = Linear Feet
- **VF** = Vertical Feet
- **EDD**=Extended Dry Detention

BMP Name	Wet Pond	
Cost Equation, Price or Price Range	1. $C = 13,909 * x^{0.67}$ 2. $SA = 0.028x$ 3. $V_s = 6SA$ (Costs in 2003 dollars)	C = cost of wet pond construction x = watershed area draining to wet pond in acres SA = surface area of wet pond in acres V _s = permanent pool plus detention storage
Explanation	Cost ranges were estimated by watershed area with Equation 1, converted to SF costs with Equation 2, and then converted to CF costs with Equation 3. Equation 2 assumes that the sample wet ponds (those used to estimate the regression equation) required about 1,200 SF per acre of drainage area. Equation 3 assumes that the sample wet ponds had 6-foot pond depths and 90-degree slopes. The 6-foot depth represents 3 feet of permanent pool and 3 feet of detention storage.	
Range	Each SET cost range represents plus or minus 15 percent of the midpoint; Wet pond volumes can range from 0.13 to 263 acre-feet.	
Location	Raleigh, North Carolina	
Reference	Wossink and Hunt, 2003	

BMP Name	Stormwater Wetland (including Pocket Wetlands)	
Cost Equation, Price or Price Range	1. $C = 3,852 * x^{0.48}$ 2. $SA = 0.038x$ (Costs in 2003 dollars)	C = cost of wetland construction x = watershed area draining to wet land in acres SA = surface area of wetland in acres
Explanation	<p>In Wossink and Hunt (2003), Equation 1 was estimated with data from 15 stormwater wetlands in North Carolina. With Equation 1, watershed area was used to estimate the cost of a wetland draining a certain watershed area. Equations 2 through 4 were developed by NCSU-BAE and based on typical impervious surface distributions and rules of thumb; the equations relate wetland surface areas to drainage area for three densities of impervious surface. For the SET thresholds, the wetland surface area was calculated from each equation; then the resulting surface areas were averaged to estimate a wetland surface area range for a watershed of average imperviousness.</p> <p>To calculate the stormwater wetland costs in the SET Cost Component, the coefficient in the Equation 1 was multiplied by 2.5 to bring stormwater wetland costs within the range of wet pond costs for similar storage capacities and to reflect professional judgment on the likely costs of stormwater wetland designs.</p>	
Range	Each SET cost range represents plus or minus 15 percent of the midpoint; Wetland surface areas can range from 0.02 to 6 acres.	
Location	Raleigh, North Carolina	
Reference	Wossink and Hunt, 2003	

BMP Name	Extended Dry Detention (EDD)	
Cost Equation, Price or Price Range	1. $C=8.16V_s^{0.69}$ (Costs in 1996 dollars)	C = cost of extended dry detention construction Vs = storage volume up to the emergency spillway
Explanation	This cost equation was originally estimated in 1996 from 18 EDD ponds in Maryland and Virginia. For use in the SET, ranges of cubic foot storage were selected that, when entered into the above equation, calculate a range of costs plus or minus 15 percent of the midpoint.	
Range	Each SET cost range represents plus or minus 15 percent of the midpoint; Storage volumes can range from 0.2 to 53 acre-feet.	
Location	Maryland, Virginia	
Reference	Center for Watershed Protection, 2000	

BMP Name	Cisterns and Rain Barrels, Pre-manufactured	
Cost Equation, Price or Price Range	Various, ranging from \$110 for a 1,800 gallon polyethylene cistern to \$10,000 for a 5,000 gallon fiberglass, steel composite cistern (Costs in 2003 dollars) From \$135.95 for a 65-gallon (9-CF) rain barrel in Raleigh, NC (Costs in 2004 dollars) (Installation, excavation, and downspout costs are not included in the above prices)	
Explanation	<p>The Low Impact Development Center provides approximate costs for the following pre-manufactured cisterns: Galvanized Steel, Polyethylene, Fiberglass, and Fiberglass/Steel Composite.</p> <p>Costs are reported for two sizes per cistern type.</p> <p>Per unit rain barrel costs were available from the Rain Water Solutions website (2004).</p> <p>Cost data were not available for the labor and other installation costs. It was assumed that the cistern installation would take place during the construction of each building's roof drainage system and would not cost more than a conventional gutter and downspout installation.</p> <p>A cubic foot cost was calculated for each type and size of cistern or rain barrel by dividing the cost of one unit by its storage volume. A cost range was estimated by adding and subtracting 15 percent of the cubic foot cost.</p>	
Range	Each SET cost range represents plus or minus 15 percent of the quoted price; No input thresholds have been set.	
Location	National	
Reference	Low Impact Development Center, 2003; Rain Water Solutions, Inc. 2004	

BMP Name	Conventional Dry Detention																			
Cost Equation, Price or Price Range	1. $C_{EDD}=8.16V_s^{0.69}$ 2. $C_{DD}=0.6C_{EDD}$ for lower bound 3. $C_{DD}=1.3C_{EDD}$ for upper bound (Costs in 1996 dollars) 4. \$0.04 to \$0.8 per CF of storage (Costs in 2001 dollars)		C_{EDD} = cost of extended dry detention construction C_{DD} = cost of conventional dry detention construction V_s = storage volume up to the emergency spillway in CF																	
Explanation	<p>Information on the economy of scale for conventional dry detention was not available. A rule of thumb for estimating the cost was developed from conventional dry detention cubic foot costs and the EDD cost equation described above. Conventional dry detention costs were estimated for small storage volumes since these figures were similar to the EDD costs for the same storage volume. The ratio of conventional to EDD costs was calculated for these storage volumes. Then, the ratio was multiplied by each EDD cost range to estimate conventional cost ranges for larger structures.</p> <table><thead><tr><th></th><th>Conventional</th><th>Extended</th><th></th></tr></thead><tbody><tr><td>Storage Volume</td><td>From Rouge River, 2001</td><td>From CWP, 2000</td><td>Ratio</td></tr><tr><td>8,000 CF</td><td>at \$0.30/CF = \$2,460</td><td>\$4,289</td><td>0.6</td></tr><tr><td>12,500 CF</td><td>at \$0.60/CF = \$7,688</td><td>\$5,836</td><td>1.3</td></tr></tbody></table> <p>When estimated in this way, the conventional cost ranges are broader than EDD cost ranges. The broader cost ranges account for the greater uncertainty in estimating the conventional costs.</p>					Conventional	Extended		Storage Volume	From Rouge River, 2001	From CWP, 2000	Ratio	8,000 CF	at \$0.30/CF = \$2,460	\$4,289	0.6	12,500 CF	at \$0.60/CF = \$7,688	\$5,836	1.3
	Conventional	Extended																		
Storage Volume	From Rouge River, 2001	From CWP, 2000	Ratio																	
8,000 CF	at \$0.30/CF = \$2,460	\$4,289	0.6																	
12,500 CF	at \$0.60/CF = \$7,688	\$5,836	1.3																	
Range	Each SET cost range represents plus or minus about 50 percent of the midpoint; Storage volumes can range from 0.2 to 53 acre-feet.																			
Location	Maryland, Virginia, Michigan																			
Reference	Center for Watershed Protection, 2000; Rouge River, 2001																			

BMP Name	Sand Filter	
Cost Equation or Range	1. $C = 47,668x^{0.88}$ 2. $SA = 0.07x$	C = cost of sand filter construction x = watershed area draining to sand filter in acres SA = surface area of sand filter in acres (Costs in 2003 dollars)
Explanation	<p>With Equation 1, watershed area was used to estimate the cost of a sand filter draining a certain watershed area. The watershed area was entered into Equation 2 to estimate the sand filter surface area associated with each watershed area.</p> <p>In Wossink and Hunt (2003), Equation 1 was estimated with data from 12 sand filters in North Carolina. Equation 2 was developed by NCSU-BAE and based on typical impervious surface distributions and rules of thumb; the equation relates filter surface areas to drainage area. Equation 2 assumes that the sample sand filters (those used to estimate the regression equation) drained small, impervious areas and required 720 square feet per acre of drainage area. Although the depths of the sample sand filters were unknown, the depth was assumed to be 18 inches.</p>	
Range	Each SET cost range represents plus or minus 15 percent of the midpoint; Sand filter surface areas can range from 400 to 6,600 SF.	
Location	Raleigh, North Carolina	
Reference	Wossink and Hunt, 2003	

BMP Name	Vegetated Filter Strips
Cost Equation, Price or Price Range	\$0.30 per SF for grass seeded \$0.70 per SF for grass sodded (Costs in 2002 dollars and include design and engineering)
Explanation	A range for each type of filter strip was calculated by adding and subtracting 15 percent of the USEPA quoted price. USEPA based these prices on the cost of seeding or sodding, stating that few actual construction costs were available. USEPA notes that some existing grass areas can be used as filter strips; in that case, the only costs would be for installing a berm and gravel diaphragm. Since the costs included design and engineering, the costs were reduced by 25 percent to be consistent with other costs used in the SET.
Range	Each SET cost range represents plus or minus 15 percent of the USEPA quoted price; No input thresholds have been set.
Location	National
Reference	USEPA, 2002

BMP Name	Level Spreader (not concrete)
Cost Equation, Price or Price Range	\$3 to \$10 per LF for materials and equipment 2-person crew at \$30/hour; estimated 180 hours of labor for a 100-foot channel (Costs in 2001 dollars)
Explanation	A labor cost of \$1.80/LF was added to the reported cost range, based on the 100-foot channel example. The cost range excludes concrete trough level spreaders; cost data were not available for these level spreaders, but they tend to be more expensive than other types.
Range	The published range plus labor was used in the SET, representing plus or minus about 50 percent of the midpoint; No input thresholds have been set.
Location	Raleigh, North Carolina
Reference	Hunt et al., 2001

BMP Name	Forest Buffer, existing and restored
Cost Equation, Price or Price Range	\$70/acre for establishing a forested buffer in the North Carolina Piedmont (Costs in 2001 dollars)
Explanation	A range for restored forest buffers was calculated by adding and subtracting 15 percent of the Wossink and Osmond (2001) quoted price. The cost for preserving an existing forested buffer was assumed to be zero.
Range	Each SET cost range represents plus or minus 15 percent of the quoted price; No input thresholds have been set.
Location	Raleigh, North Carolina
Reference	Wossink and Osmond, 2001

BMP Name	Permeable Pavement
Cost Equation, Price or Price Range	Various, ranging from \$0.50/SF for porous asphalt to \$6.50/SF for porous concrete (Costs in 2002 dollars)
Explanation	<p>The Low Impact Development Center provides approximate cost ranges for the following types of permeable pavement:</p> <ul style="list-style-type: none"> -Grass or gravel parking reinforced with plastic grid -Porous Concrete -Porous Asphalt -Honeycomb Pavers (Interlocking Concrete Paving Blocks) <p>The Low Impact Development Center acquired the cost ranges from a Unilock® representative. The site-specific costs will depend on depth of base and site accessibility. In the SET, the cost ranges were used as quoted, except for routine adjustment for inflation and location.</p>
Range	The SET cost ranges represent plus or minus about 30 to 60 percent of the midpoint; No input thresholds have been set.
Location	Maryland
Reference	Low Impact Development Center, 2003

BMP Name	Green Roofs
Cost Equation, Price or Price Range	<p>\$8 to \$15 per SF for extensive green roofs</p> <p>\$16 to \$30 per SF for intensive green roofs (estimated by Tetra Tech)</p> <p>(Costs in 2004 dollars)</p>
Explanation	<p>Bill Hunt provided the approximate cost range above for extensive green roofs. Reliable cost data for intensive green roofs was not available. The cost range was used as quoted, except for routine adjustment for inflation and location. Tetra Tech estimated that intensive green roofs would cost twice as much as extensive green roofs. This rule of thumb agrees with general green roof costs quoted in Low Impact Development Center (2003).</p>
Range	The SET cost ranges represent plus or minus 30 percent of the midpoint; No input thresholds have been set.
Location	Raleigh, North Carolina
Reference	Hunt, 2004

BMP Name	Bioretention, Ultra Urban and Non-Ultra Urban
Cost Equation, Price or Price Range	\$12 to \$25 per SF for ultra urban sites \$6 to \$12 per SF for non-ultra urban sites (Cost in 2004 dollars)
Explanation	In the SET, the cost ranges were used as quoted, except for routine adjustment for inflation and location. The ultra urban costs should be used for bioretention in highly impervious, downtown areas.
Range	Each SET cost range represents plus or minus about 33 to 35 percent of the quoted price; No input thresholds have been set.
Location	Raleigh, North Carolina
Reference	Hunt, 2004

BMP Name	Water Quality Swale ("dry swale" in MD manual)
Cost Equation, Price or Price Range	\$3 to \$5 per SF (per SF of filter media) (Cost in 2004 dollars)
Explanation	In the SET, the cost ranges were used as quoted, except for routine adjustment for inflation and location.
Range	The SET cost range represents plus or minus about 26 percent of the quoted price; No input thresholds have been set.
Location	Raleigh, NC
Reference	Hunt, 2004

BMP Name	Grass Swale
Cost Equation, Price or Price Range	\$0.50 per SF (Cost in 2002 dollars and includes design and engineering)
Explanation	A cost range for the SET was calculated by adding and subtracting 15 percent of the USEPA quoted price. Since the source included design and engineering, the cost was reduced by 25 percent to be consistent with other costs used in the SET.
Range	The SET cost range represents plus or minus 15 percent of the quoted price; No input thresholds have been set.
Location	National
Reference	USEPA, 2002

BMP Name	Infiltration Trench
Cost Equation, Price or Price Range	\$2 to \$9 per CF for construction (Costs in 1996 dollars)
Explanation	A study of five infiltration trenches in Maryland and Virginia found that the average construction cost for infiltration trenches ranged from \$2 to \$9 per cubic foot of water quality storage. For the SET, the cost range was used as quoted, except for adjustment for inflation and location.
Range	The SET cost range represents plus or minus about 60 percent of the quoted price; No input thresholds have been set.
Location	Maryland, Virginia
Reference	Center for Watershed Protection, 2000

Infrastructure Type	Stormwater Pipes
Cost Equation, Price or Price Range	$C=0.29D^{1.27}$ for corrugated HDPE Type S pipes $C=0.50D^{1.27}$ for corrugated metal pipe, galvanized and coated $C=0.41D^{1.27}$ for corrugated metal pipe, galvanized and uncoated C= Cost per linear foot of pipe; D=Diameter of pipe in inches \$17/LF to \$418/LF for reinforced concrete pipe (depending on diameter) (Costs in 2004 dollars)
Explanation	RS Means (2003) reports pipe costs by length, diameter, and type of pipe. Since RS Means (2003) does not provide continuous cost ranges, pipe cost was regressed on pipe diameter and type to interpolate a continuous cost range. The log-linear regression explained 97 percent of the variability in pipe cost ($R^2 = 97$ percent). A valid relationship could not be estimated between reinforced concrete pipe (RCP) and pipe diameter; approximate ranges of length and diameter were created from RS Means increments for RCP.
Range	Each SET cost range represents plus or minus 15 percent of the midpoint; RCP diameters range from 11.5 to 96.5 inches; other pipe diameters range from 4 to 72 inches.
Location	National
Reference	RS Means, 2003

Infrastructure Type	Trenching
Cost Equation, Price or Price Range	\$2.61 to \$7.75 per LF depending on width and depth (Costs in 2003 dollars)
Explanation	Cost ranges for 2-foot and 4-foot widths were calculated by adding and subtracting 15 percent from the RS Means quoted price. Since prices were quoted for 2, 3, and 4-foot depths, the ranges 1.5 to 2.5, 2.5 to 3.5, and 3.5 to 4.5 were used as input ranges for the SET.
Range	Each SET cost range represents plus or minus 15 percent of the midpoint. Trench depths range from 1.5 to 4.5 feet. Costs for 2-foot and 4-foot wide trenches are available. For wider or deeper trenches, the user can define a length and unit cost.
Location	National
Reference	RS Means, 2003

Infrastructure Type	Curb and Gutter
Cost Equation, Price or Price Range	\$10.25/LF for precast \$14.61 for 24-inch wide, cast-in-place \$15.21 for 6-inch by 18-inch radius, cast-in-place \$16.01 for 30-inch wide, cast-in-place (Costs in 2003 dollars)
Explanation	A cost range for curb and gutter was calculated by adding and subtracting 15 percent from the average of the four curb and gutter types.
Range	The SET cost range represents plus or minus 15 percent of the average linear foot cost of curb and gutter.
Location	National
Reference	RS Means, 2003

Infrastructure Type	Catch Basins
Cost Equation, Price or Price Range	Average of \$936 per unit, ranging from \$543 to \$2,273 depending on type of material, depth, and installation procedure. (Cost is in 2003 dollars)
Explanation	The unit costs of 18 catch basins were averaged. The catch basin depth ranged from 4 to 8 feet, and the materials included brick, concrete blocks, concrete cast-in-place, and precast concrete. A cost range was calculated by adding and subtracting 15 percent from the average catch basin cost.
Range	The SET cost range represents plus or minus 15 percent of the RS Means quoted price; No input thresholds have been set.
Location	National
Reference	RS Means, 2003

Infrastructure Type	Rip Rap
Cost Equation, Price or Price Range	\$31.68 per CY of machine placed rip rap for slope protection (Cost is in 2003 dollars)
Explanation	A cost range for rip rap was calculated by adding and subtracting 15 percent from the RS Means quoted price.
Range	The SET cost range represents plus or minus 15 percent of the RS Means quoted price; No input thresholds have been set.
Location	National
Reference	RS Means, 2003

Infrastructure Type	Total Site Pavement Costs
Cost Equation, Price or Price Range	<p>\$6.33 per SY for bituminous street and parking lot paving, 3 inches thick</p> <p>\$12.94 to \$16.80 per LF for 3-foot wide concrete sidewalks</p> <p>\$16.40 to \$21.90 per LF for 4-foot wide concrete sidewalks</p> <p>\$19.80 to \$27.00 per LF for 5-foot wide concrete sidewalks</p> <p>\$4.35 to \$6.11 per LF for 3-foot wide asphalt walking paths</p> <p>\$5.02 to \$7.31 per LF for 4-foot wide asphalt walking paths</p> <p>\$5.60 to \$8.40 per LF for 5-foot wide asphalt walking paths</p> <p>(Costs are in 2003 dollars)</p>
Explanation	<p>A range for street and parking lot paving was calculated by adding and subtracting 15 percent from the RS Means quoted price.</p> <p>Lower and upper bounds for sidewalk costs represent different thicknesses for pavement and gravel base. Prices for 5-foot wide sidewalk were extrapolated from the 3-foot and 4-foot wide prices. For the SET, the sidewalk cost ranges were used as quoted, except for adjustment for inflation and location.</p>
Range	<p>In the SET, street and parking lot paving cost range represents plus or minus 15 percent of the RS Means quoted price. Sidewalk cost ranges represent plus or minus about 15 percent of the midpoint.</p>
Location	National
Reference	RS Means, 2003