Accounting for Trees in Stormwater Models

August 2018

Produced by the Center for Watershed Protection   *Funded by the USDA Forest Service*

Center for Watershed Protection

Forest Service U.S. Department of Agriculture

This project was made possible through funding from the USDA Forest Service. USDA is an equal opportunity provider, employer and lender.

This paper is intended to help the stormwater engineering community more easily account for trees in runoff and pollutant load calculations so that they can more readily incorporate them into their stormwater management strategies.

1. Introduction

Trees are increasingly being considered as a Best Management Practice (BMP) for meeting state and local stormwater and pollutant load reduction requirements, such as total maximum daily loads (TMDLs), stormwater management requirements for new development and re-development projects, or even the reduction of combined sewer overflows (CSOs). This changing view of trees is based on their ability to improve stream quality and watershed health by decreasing the amount of stormwater runoff and pollutants that reach local waters. The impact of trees on the processes of evapotranspiration, infiltration, and interception are important for providing these benefits and are well-accepted in the scientific community. However, it can be difficult to quantify these benefits, as they are dependent on various factors, such as climate, soils, tree characteristics, and storm event characteristics. Other water quality benefits of trees, such as nutrient uptake, are less well known and even more difficult to quantify for BMP crediting purposes.

Given the complexities of how trees impact the hydrologic cycle, models are an important tool for estimating their benefits under different site conditions, and over different spatial and time scales. Modeling the hydrological benefits of trees can be conducted at various spatial scales, as summarized in Table 1.

Table 1. Scale of Hydrologic Models and Typical Uses

Scale	Uses
Individual project (site) scale	Quantify runoff or pollutant reduction credit associated with tree conservation or planting, for TMDLs or local stormwater regulations.
Catchment/small watershed scale	Quantify runoff or pollutant reduction credit associated with tree conservation or planting, for TMDLs or local stormwater regulations.
City scale	Estimate benefits of trees to support/justify tree canopy program
Regional/watershed scale	Estimate benefits of trees to support/justify watershed protection and restoration program

Site designers and stormwater engineers who incorporate trees into their projects at the site and catchment scales can reduce runoff and therefore reduce the costs associated with structural practices needed to treat site runoff or reduce pollutant loads. However, to realize this cost savings, the runoff reduction associated with trees must be accounted for in stormwater runoff computations. Unfortunately, the necessary data and models to conduct such analyses have not been readily available to the stormwater community. This has hampered the ability to take regulatory credit for tree planting and tree preservation efforts in stormwater permits, long-term CSO plans/consent decrees or TMDL implementation plans.

Due to recent advances in our understanding of the stormwater benefits of trees, some modeling programs have been updated to account for these benefits. Other models, while not explicitly updated to quantify tree benefits, can still be used to account for them by modifying specific model inputs. The purpose of this fact sheet is to summarize this information for site designers and stormwater engineers so that they can more easily account for trees in their runoff and pollutant loading reduction computations. The fact sheet focuses on existing hydrologic and hydraulic models and other tools that can be applied at the site, catchment and watershed scales to account for the stormwater benefits of conserving existing trees and/or planting new trees. With this information, trees can more readily be used for stormwater management purposes.

2. Commonly Used Hydrologic Models

This fact sheet covers nine commonly used models that were selected based, in part, on responses to a 2017 national survey of stormwater engineers administered by Watershed Management Group and The Center for Watershed Protection to identify commonly used models that account for tree benefits and determine data needs. Although all of these models simulate similar processes and include some common inputs such as land cover and rainfall, they also have some key differences that may influence user preference and use (Table 2). Model parameters that vary among the presented models include intended use, complexity, model scale, and model outputs.

2.1 Typical Uses

The models described in this fact sheet include a full range of uses, from stormwater compliance at the individual site scale to large scale basin planning to inform reservoir operations.

2.2 Complexity

Hydrologic models are also quite variable in their complexity. Less complex models such as the Simple Method require only rainfall depth and impervious cover to estimate runoff volumes and corresponding pollutant loads, while more complex models such as the Stormwater Management Model (SWMM) can incorporate detailed rainfall records, and information regarding watershed processes and stormwater conveyance systems. The more complex models are often calibrated or verified with available monitoring data.

2.3 Spatial Scale

Each of the presented hydrologic models is appropriate at a different scale, ranging from an individual site to a large watershed. Typically, models appropriate at larger scales incorporate watershed processes such as groundwater inputs, as well as flow routing through larger stream systems or other water bodies. The scales referred to in Table 2 are from Schueler (2000) and include those listed below. Note that these scales were originally defined for the Mid-Atlantic region, and larger drainage areas may be appropriate in arid regions.

- Site: An individual development site, typically less than 100 acres
- Catchment: First intersection of a site with a stream or very large conveyance
- Subwatershed: 1 to 10 square miles
- Watershed: 10 to 100 square miles

2.4 Temporal Scale

Models also differ with regard to the time scale of the output. Although specific time steps of models may vary, the models covered in the fact sheet can be described as "event based," meaning that they estimate runoff and pollutant loads for a single storm event, or "continuous," meaning the user provides a continuous rainfall record, typically at a daily or hourly time step, and the model provides a corresponding runoff estimate. "Annual" time step models are typically very simple models that estimate annual runoff volumes and pollutant loads based on annual rainfall depths.

2.5 Hydrologic Outputs

Outputs from these models can include runoff volume (for a particular time step), peak flow rates (typically in cubic feet per second), or detailed hydrographs illustrating flow rates at small time intervals over a single storm or continuously over a given time interval. Each of these outputs may be helpful depending on the particular use of the model. For example, peak discharge is often needed to demonstrate compliance with local stormwater management regulations.

Table 2. Commonly-Used Hydrologic Models

Model	Typical Uses	Complexity	Spatial Scale	Temporal Scale	Hydrologic Outputs
Simple Method	General planning, estimate pollutant load; stormwater compliance at the site scale	Low	Site to Subwatershed	Event or Annual	Runoff Volume
Runoff Reduction Method	Estimate pollutant load, BMP sizing	Low	Site to Subwatershed	Event or Annual	Runoff Volume
Rational Method	Calculate peak discharges to size conveyance or storage structures	Low	Catchment	Event	Peak Discharge
WinTR-55	Calculate changes in hydrology, typically to comply with local stormwater regulations	Low/ Medium	Catchment to Subwatershed	Event	Runoff Volume; Peak Discharge

Model	Typical Uses	Complexity	Spatial Scale	Temporal Scale	Hydrologic Outputs
HydroCAD	Similar to TR-55, but also incorporates methods to design hydraulics of channels and stormwater structures	Medium	Catchment to Subwatershed	Event	Runoff Volume; Peak Discharge
SWMM	Wide range of uses; especially used in urban environments where routing through the sewer system is important, such as CSO planning	High	Site to Large Watershed	Event and Continuous	Runoff Volume; Hydrograph; Peak Discharge
HEC-HMS	City wide or regional planning for flooding, water supply or reservoir design	Medium	Subwatershed to Large Watershed	Event and Continuous	Runoff Volume; Hydrograph; Peak Discharge
Flo-2D	Flood routing model used to delineate flood hazards, regulate floodplain zoning and design flood mitigation	High	Subwatershed to Large Watershed	Continuous	Runoff Hydrographs; 2-D Map of Flood Zones
WinSLAMM	Planning tool to evaluate the effectiveness of various stormwater practices	High	Site to Subwatershed	Event and Continuous	Runoff Volume

3. Modeling the Effects of Trees on the Hydrologic Cycle

Trees can impact the hydrologic cycle by altering three processes: interception, evapotranspiration and infiltration. The models shown in Table 2 can be adjusted to account for each of these effects individually, or in combination (Table 3).

3.1 Interception

Interception is the capture of rainfall by leaves and branches of plants and the forest floor before it reaches the soil. Depending on the surface area of their leaves, trees may have much higher interception rates than other plants. The interception rate is significant during smaller precipitation events. In many models, interception can be simulated by reducing the amount of rainfall, or altering the hyetograph. Alternatively, the user can add storage, or abstraction, to account for the capture provided by the leaves.

3.2 Evapotranspiration

Evapotranspiration is the amount of water returned to the atmosphere as water vapor though evaporation from the surfaces of the land and plant surfaces, and by transpiration, or movement of water through the plant to the leaves. Trees, due to their large leaf area, typically provide greater evapotranspiration rates and volumes than other plants. Not every model accounts for evapotranspiration explicitly, but for those that include this component of the hydrologic cycle, adjusting some parameters such as the Leaf Area Index (LAI) can account for the impact of trees.

3.3 Infiltration

Infiltration is the amount of rainfall that permeates into the soil surface. Trees can alter the infiltration rate in two ways. Depending on the management of the understory, dropped leaves that are incorporated into the soil as duff or soil-building amendments can increase the available soil storage volume of water and infiltration rates. In addition, evapotranspiration can create additional capacity in the soil profile between storm events by reducing soil moisture content. As a result, a larger portion of potential runoff volume can be retained or infiltrated. Infiltration can be simulated using many different methods, such as the Green-Ampt technique, the Horton Method, or a Curve Number method. In all of these cases, altering certain parameters can account for the impacts of trees.

3.4 Combination of Effects

The simpler or mid-complexity models in Table 2 typically account for trees by modifying a single parameter such as the Curve Number or runoff coefficient.

Table 3 presents potential methods to modify models to account for the effects of trees on these hydrologic processes. An alternative method for any model is to treat the tree as a stormwater BMP that provides retention equivalent to the volume reduction provided by the tree.

Table 3. Potential Methods to Modify Models to Account for Trees*

**An alternative method for any model is to treat the tree as a stormwater BMP that provides retention equivalent to the volume reduction provided by the tree.*

Model	Runoff Calculation Method	Interception	Infiltration	Evapotranspiration
Simple Method	Volumetric Runoff Coefficient (Rv) based on impervious cover	Modify Rv to account for all tree impacts	Modify Rv to account for all tree impacts	Modify Rv to account for all tree impacts
		Reduce rainfall depth to account for interception	Modify Rv	No specific method
Runoff Reduction Method	Volumetric Runoff Coefficient (Rv) based on land cover and soil; runoff reduction achieved through stormwater practices	Same techniques as the Simple Method or Model trees as a stormwater BMP with a single storage volume	Same techniques as the Simple Method or Model trees as a stormwater BMP with a single storage volume	Same techniques as the Simple Method or Model trees as a stormwater BMP with a single storage volume
Rational Method	Runoff coefficient (C) relates peak discharge to rainfall intensity	Modify C to account for all tree impacts	Modify C to account for all tree impacts	Modify C to account for all tree impacts
WinTR-55	Runoff volume based on a Curve Number (derived from land cover); peak discharge calculated using a unit hydrograph and time of concentration	Reduce the rainfall depth to account for rainfall that is intercepted by leaves	Modify the Curve Number to account for changes to soil infiltration	Curve Number is typically not modeled, but can be adjusted to account for soil moisture
		Modify the Curve Number to account for all effects	Modify the Curve Number to account for all effects	Modify the Curve Number to account for all effects
HydroCAD	Underlying hydrology similar to TR-55 but includes flow routing	Same techniques as Win TR-55	Same techniques as Win TR-55	Same techniques as Win TR-55

Model	Runoff Calculation Method	Interception	Infiltration	Evapotranspiration
SWMM	Several options available to model surface runoff, channel routing, baseflow and stormwater storage	Increase depression storage (Dstore-Perv); increase initial abstraction (Unit hydrograph)	Three infiltration models available in SWMM; parameters to modify can include: 1) Curve Number 2) Soil Conductivity (Green-Ampt) 3) Infiltration Rate (Horton Method)	Model as a thin aquifer; apply a vegetation factor to evaporation data
HEC-HMS	Several methods available to model runoff, infiltration, subsurface flow, evaporation, and capture in structural practices and pipe systems	Increase surface storage (initial abstraction); select canopy loss method to account for tree canopy; use overbank land use (treed)	Similar to SWMM, but does not include the Horton Method	Select the canopy loss method to explicitly account for tree canopy
Flo-2D	Uses hydrologic methods similar to SWMM, but is applied to a grid system, allowing for parameters to vary within a watershed; alternatively, allows the user to input a hydrograph rather than computing within the model	Modify the initial abstraction; alternatively, alter the rainfall hyetograph over the specific locations where trees are located	Similar to SWMM, but Flo-2D does not use the Curve Number approach to account for infiltration	Not explicitly calculated in Flo-2D
WinSLAMM	Uses a runoff coefficient (Rv) method, incorporating detailed land cover data; Rv varies based on rainfall depth	Adjust the rainfall series to account for interception as a function of rainfall depth	Change the following parameters: soil type, porosity, infiltration rate and soil compaction	Change the following parameters: Evapotranspiration rate (in/day by month), or vegetation type

4. Tools and Resources to Better Account for Trees in Hydrologic Models

The methods presented in Table 3 capture a wide range of specific techniques to modify stormwater models to account for urban trees. Although many of the potential model changes highlighted in the table are based on the judgment of the modeler or designer, they can generally be categorized into four different methods:

1. Coefficient Adjustment for Simple Models
2. Curve Number Adjustment (for TR-55 Based Models)
3. Rainfall Adjustment to Account for Interception
4. Representing Trees as a BMP

This section presents some resources and examples for each method to quantify the hydrologic benefits of trees in stormwater models.

4.1 Coefficient Adjustment for Simple Models

Two of the models presented above, the Simple Method and the Rational Method, calculate runoff or peak discharge using a single coefficient. Since these methods do not account for each component of the hydrologic cycle, these models are often adjusted by modifying this coefficient. Although runoff coefficient tables typically do not have an urban forest option, most guidance provides a range of coefficients for both grass and woods/forest. Single urban trees could be assumed to lie somewhere in between these coefficients.

Example: The Rational Method

There are many different manuals or references for the Rational Method, with different tables of runoff coefficients. Table 3.7 in the *Stormwater Hydrology chapter of the Knox County, Tennessee Stormwater Management Manual* provides coefficients for a wide range of land covers, including forest.

Example: The Simple Method

The original version of the Simple Method (Schueler, 1987) treated all pervious land uses the same, and calculated the runoff coefficient solely based on the impervious percentage in a drainage area. Other applications of the Simple Method include different runoff coefficients for each pervious land use. One example is the *Runoff Reduction Method* (Collins et al., 2008). This method uses modified runoff coefficients for grass and forest, based on the soil type. Again, there is no specific runoff coefficient for urban trees, but there are coefficients for both grass and forest and urban trees could be assumed to lie somewhere in between these coefficients.

4.2 Curve Number Adjustment (for TR-55 Based Models)

Many of the methods presented in Table 2 use a curve number, from the TR-55 method, to estimate runoff. The curve number is different from a simple runoff coefficient because, rather than estimating runoff as a simple fraction, the method assumes that storage in the soil and vegetative surfaces creates an “initial abstraction” before runoff begins to occur. Consequently, the fraction of rainfall that is converted to runoff varies depending on the storm depth, with larger storm events having a higher runoff percentage. The example provided below is of a tool for adjusting the curve number to reflect the cumulative effects of interception, infiltration and evapotranspiration.

Example: Stormwater Performance-Based Credit for Tree Planting

The Stormwater Performance-based Credit for Tree Planting is a national credit for urban tree planting developed by the Center for Watershed Protection. The credit includes a spreadsheet calculator that provides a modified curve number, and quantifies the runoff and pollutant load (total nitrogen, total phosphorus and total suspended solids) reduction associated with tree planting for a particular design storm. The credit was derived from a water balance model that uses information from i-Tree Forecast to estimate the mean annual runoff for a single tree at maturity planted over turf or impervious cover, compared to runoff from those same sites without trees. The calculator output is based on several user inputs including the nearest city (from a list of 31 cities nationwide), tree type (including five representative species for each city), surface cover, and soil group, as well as the design storm. The materials associated with this credit are available at the Making Urban Trees Count project summary page and include:

- *Stormwater Performance-Based Credit Overview*
- *Stormwater Performance-Based Credit Calculator*
- *Stormwater Performance-Based Credit Documentation*

Stormwater Performance-Based Credit Example Application

The Performance-Based Credit tool uses a curve number adjustment to calculate the benefits of trees in the landscape for a particular design storm. In this example, however, we will highlight the curve number adjustment reflected by trees planted in the landscape. This method assumes that the modified curve number can be used across all design storms.

The spreadsheet results (Figure 1) illustrate the process for modifying the curve number.

- The site data, entered by the user, are as follows:
- Trees are planted near Syracuse, NY (Box 1)
- They are planted over Grass on C Soils (Box 3)
- Trees are Medium Broadleaf Deciduous (Box 4)
- Ten trees are planted (Box 7)
- The Diameter at Breast Height and Tree Canopy Area are 17.4 inches and 9,457 sf, respectively (Boxes 8 and 9). These values are entered by the user, but the suggested values are provided.

Using data from a continuous water balance model using data from the appropriate site location (in this case Syracuse, NY), the calculator defines a unit volume reduction based on rainfall depth and tree diameter (Box 5), and then defines a “representative storm.” This storm event is estimated based on modeling results to determine the storm event that can be used to adjust the curve number based on the tree’s runoff reduction abilities. The curve number is then adjusted (in cells 10-15) by estimating the base runoff (without trees) for the representative storm, and then computing the expected runoff with trees by subtracting the expected runoff reduction (based on the unit reduction rates and tree size). The resulting modified curve number (from about 71 to about 63) can be used to reflect the land cover under the tree canopy area in hydrologic models that use TR-55 based methods.

Step 1: Enter Tree Type and Site Data	1.Precipitation Station (pull-down menu)	2.Region (from Cell 1)	3. Surface (pull-down menu)	4. Tree Selection	Tree Type	Tree Size
	Syracuse, NY	Northeast	Grass - HSG C	BDM	Broadleaf Deciduous	Medium
Step 2: Calculate Unit Runoff Reduction	5.Unit Reduction (cf/inch rainfall/inch DBH) (based on cells 2-4)					
	0.1573					
Step 3: Identify the Representative Storm for this location	6. Representative Storm (inches)					
	0.6260					
Step 4: Enter the tree DBH, number of trees, canopy area and DBH	7. Number of Trees Planted	Typical DBH (inches) for Guidance)	8. DBH (inches)	Tree Canopy Area (sf) (Suggested)	9. Tree Canopy Area (sf) (Entered)	
	10	17.40	17.4	9457	9457	
Step 5: Calculate the Runoff Reductiion Volume for the Repesentative Storm, and calculate a revised curve number for the treed area.	10. Runoff Reduction for the Representative Storm (cf)	11. Base CN	12. "Base" Runoff in the Area Beneath the Tree Canopy (cf)	13. Runoff for the Representative Storm (cf)	14. Runoff In Inches	15. Adjusted Curve Number
	17.1	70.95	30.97	13.84	0.0176	62.88

Figure 1. Example Application of the Stormwater Performance-Based Credit Calculator

4.3 Rainfall Adjustment to Account for Interception

One conservative estimate of trees' impact on the hydrologic cycle is to account only for the interception provided by the tree canopy. The simplest method to account for the effects of interception is to modify the rainfall hyetograph to subtract the interception volume. This method can be applied to any model, from the simplest to the most complex. The example provided below was applied to the WinSLAMM model in Wisconsin.

Example: WinSLAMM Interception Adjustments

The potential role of urban trees for stormwater design was evaluated at a proof-of-concept level by Montgomery Associates Resources Solutions for a planning study of part of the University of Wisconsin-Madison campus in 2016. The purpose of this project was to demonstrate a simple method of quantifying tree canopy rainfall interception and stormwater volume reduction based on data from published research, which was used to better inform a WinSLAMM model of the benefits of tree canopy cover over a parking lot. The study, Calculating Stormwater Volume and Total Suspended Solids Reduction Under Urban Tree Canopy in Wisconsin Using Available Research (Gaffield et al., 2017), used a California interception dataset that was adjusted for Wisconsin climate and rainfall to create a spreadsheet model to calculate canopy interception depth as a function of rainfall depth. An adjusted rainfall series was created, showing that 13% of 1981 rainfall would be intercepted by trees over the parking lot. This original rainfall data and the new adjusted rainfall data was run in WinSLAMM and volume and pollutant reductions were calculated. This model does not account for soil infiltration, storage or evapotranspiration. This approach could potentially be applied after further research to fill in gaps in the model, and could also potentially be used to modify rainfall inputs to other models.

4.4 Representing Trees as a BMP

The cumulative effect of trees can be represented as a stormwater BMP or Green Infrastructure practice that provides retention equivalent to the volume reduction provided by the tree. In this representation, trees are modeled as though they capture stormwater runoff after it runs off the land surface. One advantage of this technique is that it allows us to directly relate trees to other stormwater practices. For example, regulations in many communities equate tree planting with a specific runoff reduction volume or, alternatively, an equivalent impervious cover reduction. The examples below illustrate how to both quantify the runoff reduction volume of trees and represent this volume in a hydrologic model.

Example: Minnesota's Minimum Impact Design Standards (MIDS) Calculator

The State of Minnesota's MIDS Calculator provides an example of how to calculate the benefits of urban trees in the context of stormwater regulations. This method calculates the potential storage that a tree can provide based on characteristics of the tree, the soil and the tree's location. In addition, it separately accounts for the volume provided by interception, infiltration and evapotranspiration. Both of these characteristics are unique, as most tree crediting systems provide a single credit for tree planting, irrespective of these planting characteristics. Trees are represented in the MIDS Calculator as an engineered tree trench system (i.e., a "tree box") either with or without an underdrain.

In the MIDS Calculator, trees are assumed to treat only the surface area that drains to them. Thus, the total retention volume treated is limited to the volume of runoff directed toward the tree pit for the design storm. At a minimum, this area includes the soil surface of the tree pit or, if representing a tree planted on a pervious surface, the canopy area. In addition, the user can specify additional land area that is sloped in the direction of the tree trench. For example, sidewalks may slope toward a street tree.

The potential storage volume is calculated using the following Equation:

$$V = VI + VET + Vinf$$

Where:

V = Total Volume (cf)

VI = Interception Volume (cf)

V_{inf} = Infiltration Volume (cf)

V_{ET} = Evapotranspiration Volume (cf)

The volume intercepted by canopy (*VI*) is based on the interception capacity of deciduous and coniferous tree species times the canopy projection area. The interception capacity is assumed to be 0.043 inches for a deciduous tree and 0.087 for a coniferous tree, and the canopy projection area is based on the diameter of the tree canopy at maturity, dependent on the tree species.

The evapotranspiration volume (VET) is limited by both the potential evapotranspiration (based on the leaf area and the rate of evaporation), as well as the water available in the soil. Thus, the MIDS calculator calculates ET in two steps, applying the minimum of the two volumes:

1. Volume Available for Evapotranspiration

   The volume available in the soil is calculated by the following:

   $V_{ET\text{-}Soil\ Volume}$ = Volume at Field Capacity – Volume at Permanent Wilting Point

2. Potential Evapotranspiration.

   The Potential ET is calculated by:

   $VET = (CP)(LAI)(Erate)(Eratio)*3$

   Where:

   CP is the canopy projection area (square feet);

   LAI is the Leaf Area Index (equal to the leaf area divided by the canopy area)

   E_{rate} and $_{Eraio}$ are the evaporation rate and ratio, respectively.

   3 = average days between storms in Minnesota.

The evaporation rate is based on city-specific data, but the evaporation ratio (i.e., the fraction of the evaporation rate that can be achieved over a leaf surface, is assumed to be 0.2. The Infiltration Volume (VInf) is based on the porosity of the media (n), the field capacity of the media (FC), and the volume of the media:

$$Vinfb=(n-FC)*\text{volume of media}$$

When calculating the potential volume captured by trees, the evaporation rates included in the MIDS Calculator are specific to Minnesota, so results may not be accurate outside of Minnesota. In addition, the calculator estimates annual volume and pollutant reductions based on weather data specific to the zip code entered, and these estimates will not be accurate in other areas. However, the equations included in the online calculator are available and could easily be applied without using the calculator itself.

For more information, read *Calculating Credits for Tree Trenches and Tree Boxes* or *Download the MIDS Calculator*.

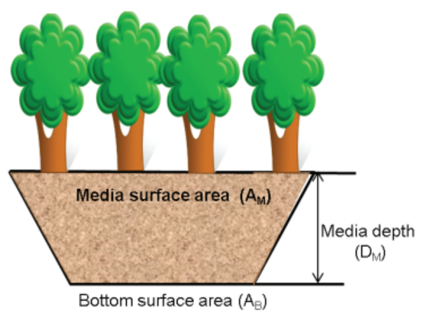
MIDS Calculator Example Application

The MIDS calculator provides a framework for quantifying stormwater reduction volumes and associated annual pollutant reduction across a range of practices. Here, we will present a simple example of quantifying the storage volume of trees planted in tree trenches near Minneapolis, MN. In this example, we assume the following:

- Trees are planted in a media with a 2,000 ft^2 surface area (and equivalent area at the bottom of the trench).
- The media depth is 2.73 ft (this depth corresponds to the depth required to meet the 24-hour draw-down time given the soil infiltration rate specified (0.3 in/hr)
- The water contents at wilting point and field capacity are 0.12 and 0.22, respectively.
- Three medium-size deciduous trees are planted.

The tree and size, combined with the location, are used to generate a canopy area and leaf area index. These data combined with evaporation rates based on the site location, are used to estimate the total storage volume provided by the trees, with a resulting total volume of 72 cubic feet from ET, 5 cubic feet from interception and 1,201 cubic feet from storage in the soil media (i.e., infiltration). The total runoff volume achieved for a particular storm is then simply calculated as the lower value of the total runoff volume directed to the tree trench and the total storage provided by that trench through interception, infiltration and evapotranspiration.

$$V = \left(\frac{A_M + A_B}{2} * n * D_M\right) + V_I + V_{ET}$$



Required treatment volume	100	ft^3
Media surface area [A_M]	2000	ft^2
Bottom surface area [A_B]	2000	ft^2
Media depth [D_M]	2.73	ft
Media field capacity - wilting point [FC - WP](range 0.05-0.17)	0.12	ft^3/ft^3
Media porosity - field capacity [n - FC](range 0.15-0.35)	0.22	ft^3/ft^3
Tree type (most common)	Deciduous	
Tree size (average for all trees)	Medium	
Number of trees	3	
Interception capacity [IC]	0.043	inches
Canopy projection [CP]	490	ft^2
Leaf area index [LAI]	4.1	
Soil volume per tree [S_V]		ft^3
Underlying soil - Hydrologic Soil Group	7 MH (HSG B, 0.3 in/l	
Infiltration rate of underlying soils	0.3	in/hr
User defined infiltration rate		in/hr
Required drawdown time	24	hrs
Volume reduction of BMP from ET [V_{ET}]	72	ft^3
Volume reduction of BMP from interception [V_I]	5	ft^3
Volume reduction stored in soil media	1201	ft^3
Volume reduction capacity of BMP [V]	1279	ft^3

Figure 2. Example Application of the MIDS Calculator

Example: District of Columbia (DC) General Retention Compliance Calculator

The District of Columbia's stormwater guidance accounts for trees much more simply than the MIDS calculator, assuming values of 20 cubic feet for each preserved tree and 10 cubic feet for each newly planted tree. These numbers were derived by applying a commonly-used tree benefit (i.e., 100 square feet of impervious cover reduction) to DC's design storm. Although the credit itself is simple, the accompanying Compliance Calculator allows the user to convert the benefits of trees, and other green infrastructure, to an equivalent curve number reduction in order to calculate the effects of these practices on peak runoff rates. This technique is helpful to understand how these practices can assist with meeting flood reduction requirements, in addition to stormwater retention requirements typically associated with smaller storm events.

DC General Retention Compliance Calculator Example Application

The example below highlights the Curve Number calculation portion of the General Retention Compliance Calculator. This calculator assumes that trees provide the same volume of stormwater reduction, regardless of the storm size. Thus, the calculator assumes that trees provide a given volume of reduction, and then it "back calculates" a curve number for each storm event.

In this example (Figure 3) ten trees are planted on a small drainage area (50% impervious 10,000 square feet). The trees themselves are entered on a separate sheet, and total a runoff reduction of 100 cubic feet. This volume equates to approximately 0.12 inches of runoff over the entire drainage area. The calculator computes the runoff volumes for the 2-,15- and 100-year storm events with the original curve numbers to be 1.84, 3.65 and 6.69 inches. Then, each volume is reduced by 0.12 inches to account for the effect of the trees. Finally, the calculator computes an "Adjusted Curve Number" based on the volume reduction achieved by the trees. Note that the effect is greater for the 2-year storm than for larger storm events (Figure 3).

SDA 1				
Land Area		Soils		
Natural Cover	Area (sf)	0.0		
	CN	70		
Compacted Cover	Area (sf)	5000.0		
	CN	74		
Impervious Cover and BMPs	Area (sf)	5000.0	Weighted CN	S
	CN	98	86	1.63
		2-year storm	15-year storm	100-year storm
	Runoff Volume (in) with no BMPs	1.84	3.65	6.69
	Runoff Volume (in) with BMPs	1.72	3.53	6.57
	Adjusted CN	**84**	**85**	**85**

Figure 3. Example Application of thhe DC General Retention Compliance Calculator

5. Additional Tools and Resources on Stormwater Benefits of Trees

Other resources and tools may also help to estimate the hydrologic benefits of trees in the landscape. Some examples are provided in this section.

5.1 i-Tree Products

The USDA Forest Service's i-Tree suite of products includes a series of tools, some of which provide input to other models, such as leaf area index and other tree characteristics. One of the tools, i-Tree Hydro, acts as a stand-alone watershed model which incorporates trees as a specific land cover. Each of these tools acts at a different time scale and provides different data (Table 5). The tools can be found on the *i-Tree website*.

Table 5. i-Tree Tools, Outputs, and Scale

Tools	Outputs	Scale
i-Tree Canopy	Tree canopy and other land cover percentages and/or area	Site to Watershed
i-Tree Eco	Annual and hourly avoided runoff of trees by species, hourly transpiration, hourly interception	Site to Watershed
i-Tree Streets	Total annual interception by species per tree	Site Scale
i-Tree Hydro	Hydrographs in response to storm events	Watershed, City Scale
i-Tree Design	Stormwater interception	Site Scale
i-Tree Forecast	Provides an estimate of the characteristics as a tree ages. Can provide valuable input to other models estimating the value of trees at various stages of growth.	Individual Tree

5.2 Making Urban Trees Count

In 2017, the Center for Watershed Protection released a national science-based crediting system for urban tree planting, which was funded through a grant from the U.S. Forest Service's National Urban and Community Forestry Advisory Council. The project included an extensive literature review, development of a water balance model to provide an improved method for quantifying the stormwater benefits of urban tree canopy, and credit development. An early version of the water balance model was used by the Chesapeake Bay Program in their Urban Tree Canopy Expansion BMP crediting protocol adopted in 2016.

The water balance model estimates the mean annual runoff for a single tree at maturity planted over grass or impervious cover, compared to runoff from those same sites without trees. The model was run for the four hydrologic soil groups for five tree types at 31 locations in 11 climate zones. The model was reviewed by researchers and practitioners with expertise in stormwater modeling, forestry, engineering, or hydrology and accounts for the effects of tree canopy on rainfall interception, evapotranspiration and infiltration.

The Center used the water balance model results to develop two tree planting credits: one that quantifies the annual nitrogen, phosphorus and sediment load reduction provided by urban trees for total maximum daily load credit, and one that quantifies runoff, nutrient and sediment reductions provided by trees to meet event-based stormwater management requirements. These credits and associated materials (e.g., calculators, design specifications) provide regulators and stormwater practitioners a means to better integrate and account for the effect of trees for stormwater regulatory compliance. The water balance model provides results for all regions of the U.S., so that the crediting framework can be implemented in any state or locality.

The products include:

- Literature Review
- Water Balance Model Documentation
- Design Specifications for Urban Tree Planting
- Pollutant Load Reduction Credit Overview
- Pollutant Load Reduction Credit Tool
- Stormwater Performance-Based Credit Overview
- Stormwater Performance-Based Credit Calculator
- Stormwater Performance-Based Credit Documentation

5.3 Resources from Deeproot

A series of blog articles from Deeproot provides some insight into how calculators and models account for urban trees. Some articles from this series include:

- Shanstrom, N. 2015. *Quantifying Stormwater Benefits of Trees and Soil Part 1: Overview of models and calculators*.
- Shanstrom, N. 2015. *Quantifying Stormwater Benefits of Trees and Soil Part 2: Single-Event Stormwater Models*.
- Shanstrom, N. 2016. *Quantifying Stormwater Benefits of Trees and Soil Part 3: Continuous Stormwater Models*.

5.4 Trees & Stormwater

The *Trees and Stormwater* website was developed through a USDA Forest Service grant by the Ohio Kentucky Indiana Regional Council of Governments and its team of national partners. The site acts as a clearinghouse for information regarding the stormwater benefits of trees. One specific section of the site, called *Stormwater Modeling: It Can Be Done and You Can Do It*, summarizes methods for modeling trees.

6. Summary

Quantifying the effects of urban trees on the hydrologic cycle is an emerging science, and this is particularly true when quantifying these benefits for a particular storm event. While hydrologic models typically account for established forest using a particular land cover, model parameters often need to be adjusted to account for urban trees planted over impervious cover or turf grass. For simpler models, some professional judgment is needed to adjust single parameters, while more complex models may allow the user to modify several parameters to account for the effects of trees on different components of the hydrologic cycle. In recent years, tools have been developed to quantify the characteristics of trees at different stages of development, as well as to adjust specific model parameters. The resources in this paper are intended to help the stormwater engineering community more easily account for trees in runoff and pollutant load calculations so that they can more readily incorporate them into their stormwater management strategies.

7. References

Collins, K., Hirschman, D., Schueler, T. 2008. *The Runoff Reduction Method: Technical Memorandum*. Center for Watershed Protection & Chesapeake Stormwater Network, Ellicott City, MD.

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