The final, edited version of this manuscript will be available on www.VibrantCitiesLab.org in early 2020.

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Urban Forest Systems and Green Stormwater Infrastructure

SUMMARY

Trees provide considerable stormwater volume and pollution control through rainfall interception and intensity reduction, stormwater infiltration and uptake, and nutrient load reduction. The purpose of this document is to focus on the research-based effects of trees on urban stormwater runoff, provide some helpful urban forest management strategies to maximize stormwater benefits, and demonstrate several examples around the United States where the stormwater benefits of urban trees are credited for reducing stormwater volume and pollutant loading. This document is intended to be a resource manual for natural resource professionals to help them better communicate with stormwater managers and engineering professionals about the science and benefits of urban trees in stormwater management. Resources on accounting for the stormwater functions of trees are provided as a starting point for state and local governments interested in providing regulatory credit for the important role of urban forests in green stormwater infrastructure.

INTRODUCTION

Municipalities are increasingly planning for sustainability and improved quality of life for current and future residents as they work toward building healthy and vibrant communities. One method of planning for sustainability involves the consideration of social, environmental and economic impacts of proposed development, known as the triple bottom line. Trees growing in our urban environments provide numerous benefits for humanity that improve quality of life and address this triple bottom line.

Beyond the stormwater benefits covered in this document, more and more scientific evidence shows how urban trees and greenspace positively impact physical, psychological, emotional, and spiritual well-being in humans (USDA Forest Service 2018). Environmental benefits of trees such as improved ambient air quality, carbon sequestration, and reduced stormwater runoff can now be quantified using public domain software found on the internet, such as the USDA Forest Service i-Tree suite of tools. Research has shown that trees provide economic benefits by raising property value, reducing the amount of time rental property goes unrented, and increasing the amount of time customers shop at retail establishments (Wolf 2005).

Strategically planting trees and managing the forest within a city can help to mitigate some of the negative impacts that come with urban development. A properly managed urban forest can help a municipality meet certain environmental regulations and save money through avoided costs, particularly related to stormwater runoff. To better understand how urban trees improve things like human health, economic development, water and air quality, and public safety, visit the Vibrant Cities Lab website.

This document provides a synthesis of the science around how urban trees help mitigate problems associated with stormwater runoff. Several tree crediting tools and case studies are provided to help state and local governments better account for the stormwater benefits of urban forests. A complementary manual for engineering professionals that investigates incorporating forestry into stormwater management programs is available through the Water Research Foundation. For further guidance on the practical implementation of urban forest management,the three-part Urban Watershed Forestry Manual, developed by the Center for Watershed Protection, provides more detail about methods for increasing forest cover in a watershed, conserving and planting trees at a development site, and an urban tree planting guide.

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OVERVIEW OF THE STORMWATER BENEFITS OF URBAN TREES

Green stormwater infrastructure (GSI) is defined as stormwater mitigation practices designed to mimic natural processes that filter and retain rain where it falls. Typical GSI practices include green roofs, urban trees, bioretention, vegetated swales, permeable pavements and water harvesting. GSI includes low impact development (LID) designs and/or engineered systems that manage stormwater runoff at its source in developed landscapes (EPA 2018). An urban forest system includes the trees within an urban area as well as the ground cover and soil. The parts of this system work together as part of a GSI "treatment train" (a series of practices designed to mitigate runoff) to provide considerable stormwater volume and pollution control through rainfall interception and intensity reduction, stormwater infiltration and uptake facilitation, and nutrient load reduction. Recent review articles have explored how the parts of the system work together to provide these benefits (Berland et al. 2017, Center for Watershed Protection 2017, Kuehler et al. 2017).

The canopy formed by urban trees intercepts rain as soon as it starts to fall, with part of that rainfall retained on foliage and branches, remaining in the canopy where it eventually evaporates back into the atmosphere. When the leaf and branch surface area in the upper part of the tree canopy is filled and cannot hold additional rainfall, excess water drips from these surfaces to those lower in the canopy thus helping to reduce rainfall intensity and delaying runoff to storm drains or other stormwater control measures. This, in effect, allows the stormwater control system to work more efficiently and reduces the chances of it becoming overwhelmed, or of water running over the top of drains and other measures.

Soils provide the bulk of stormwater volume control. Macro- and micropores—spaces between soil particles—allow for temporary water storage from which trees acquire water and nutrients. Tree roots condition the soil through mechanical, biological, and chemical means, increasing its ability to store greater volumes of water. Stormwater runoff not retained in the canopy drips off leaf surfaces or flows along the branches and trunk (stemflow) to the soil at the base of a tree, where it can penetrate deep into the soil profile as water moves along the root surfaces.

Once in the soil, water becomes accessible to tree roots. Through the process of transpiration, water is essentially pulled from the soil pore space and used by the tree between storms. This process allows for greater water storage capacity in the soil as water is transpired most days during the growing season.

Soils also filter nutrients and other pollutants from stormwater runoff. Trees need many of the nutrients found in runoff for growth and survival, especially nitrogen and phosphorus which can negatively impact water quality when found in excess. The uptake of these nutrients from the soil by trees reduces the amount leaching into groundwater, helping to retain and improve water quality. However, trees also store many of these nutrients in their leaves; at the end of the growing season, a large amount of these nutrients remain in senesced leaves. When the tree sheds these leaves in fall, significant amounts of nutrients can find their way to receiving waters, especially if leaves fall onto impervious surfaces such as streets.

Precisely quantifying the stormwater benefits of trees is difficult because of many factors, such as species differences in attributes that affect rainfall storage such as crown architecture and leaf structure and surface texture. For example, needle-leafed trees generally store more rainfall than broadleaf trees, and evergreens intercept more rainfall than deciduous trees over the course of a year. Natural systems also vary in relation to regional climate differences (arid vs. tropical) and microclimates, soil conditions, tree size and configuration of planting, not to mention the average frequency, intensity, and volume of local rainfall events.

In an ideal world, stormwater managers and design engineers could calculate the GSI benefits they need for planning by entering information into simple formulas for stormwater runoff mitigation by urban forest systems. Unfortunately, because of all the variables mentioned, it is difficult to calculate "the" numbers for stormwater benefits. However, good estimates can be made based on current available research.

The following sections contain overviews of the various benefits that trees provide in mitigating stormwater runoff as well as urban forest management strategies that maximize stormwater runoff benefits. Basic "rules of thumb" to estimate stormwater benefits are provided where appropriate, but it is important to note that since nature is infinitely variable, these rules may be superseded by local conditions and species variability. For more information about the roles that trees play in stormwater management, visit www.TreesAndStormwater.org.

Rainfall Retention

Tree canopy intercepts rainfall on leaf surfaces, branches, and stems. This intercepted rainfall is either retained on canopy surfaces and evaporates over time (interception loss), flows down branches to stems and eventually to the soil (stemflow), or drips off canopy surfaces to the ground below (throughfall). Maximizing the amount of rainfall retained in tree canopy (interception loss) is a good strategy to help reduce stormwater runoff in urban areas.

A deciduous tree typically retains approximately 20 percent of the annual rainfall that falls on its canopy, while a conifer retains close to 30 percent (Kuehler et al. 2017). The amount of intercepted rainfall retained in the tree canopy depends on climatic variables such as rainfall intensity and duration, ambient air temperature, wind speed, relative humidity, and solar intensity. Tree crown structure attributes such as leaf architecture, morphology, and water repellency as well as leaf surface area and leaf area index (LAI) also contributes to interception loss. Trees with rigid, rough-surfaced leaves generally retain more rainfall than those with flexible, smooth-surfaced leaves (Xiao and McPherson 2016). Trees with greater leaf area or higher LAI contribute positively to interception loss.

The amount of water remaining on canopy surfaces after a rainfall event and after excess water drips off is known as "static storage" (Keim et al. 2006). This water eventually evaporates back to the atmosphere and does not contribute to stormwater runoff. The depth of static water storage has been estimated for various species using rainfall simulation techniques. Table 1 demonstrates the high variability of static storage among species—and even among species within the same genus.

The volume of rainfall retention in tree canopy can be estimated from the leaf area of the tree. The average depth of static water storage for tree foliage is 0.2 mm/unit leaf area (Wang et al. 2008). Using local growth equations to estimate the leaf area of a tree, one could multiply the leaf area by the depth of water storage (equation 1) to estimate the maximum volume of rainfall retention by tree for a rainfall event (Hirabayashi 2013).

Equation 1 $Vol_{max} = LA \text{ x } 0.2 \text{ mm x } (1 \text{ m}/1000 \text{ mm})$

where

Vol_{max} = maximum volume of rainfall retained by tree foliage (m^3)

LA = leaf area (m^2)

For example, a tree with 250 m^2 of leaf area could be expected to retain 0.05 m^3 of rainfall per rainfall event. This is equivalent to about 13 gallons of water (1 m^3 of water = 264 gallons). This volume may not seem like much, but in a city with millions of trees, the impact is multiplied. Therefore, managing the urban forest to maximize leaf surface area can help to reduce stormwater volume.

Urban Forest Management Strategies to Maximize Rainfall Retention

- Where appropriate, increase leaf area by planting smaller, shade-tolerant trees under larger dominant trees.
- Use ground covers (i.e. mulch or vegetation) under tree canopy to increase surface area for interception.
- Encourage the retention and use of conifers and evergreen broadleaf trees, where appropriate and desired, to maximize interception and evapotranspiration year-round.
- Plant trees with rigid and/or rough-surfaced leaves and bark.
- Encourage the use of trees with greater leaf surface area or higher leaf area index (LAI).
- Maximize belowground soil volume to help store stormwater runoff and encourage deep root growth.
- Consider litter accumulation, root growth characteristics, and long-term maintenance in the tree selection process.
- Ensure proper tree maintenance to maximize health and LAI.

Table 1 - Mean depth of water storage on foliage by tree species

Species Botanical name	Species Common name	Mean depth of water storage *(mm)*	Source
Acacia longifolia	Sydney golden wattle	0.08	Aston (1979)
Acer macrophyllum	Bigleaf maple	0.18	Keim et al. (2006)
Acer saccharinum	Silver maple	0.13	Holder (2013)
Acer truncatum	Shantung maple	0.46	Li et al. (2016)
Alnus rubra	Red alder	0.20	Keim et al. (2006)
Catalpa speciosa	Northern catalpa	0.13	Holder (2013)
Eucalyptus cinerea	Silver dollar tree	0.11	Aston (1979)
Eucalyptus dives	Broadleaf peppermint	0.07	Aston (1979)
Eucalyptus maculata	Spotted gum	0.03	Aston (1979)
Eucalyptus mannifera	Brittle gum	0.09	Aston (1979)
Eucalyptus pauciflora	Snow gum	0.18	Aston (1979)
Eucalyptus viminalis	Manna gum	0.03	Aston (1979)
Gleditsia triacanthos	Honey locust	0.18	Holder (2013)
Pinus radiata	Monterey pine	0.08	Aston (1979)
Pinus tabulaeformis	Chinese red pine	0.43	Li et al. (2016)
Platycladus orientalis	Oriental arborvitae	0.38	Li et al. (2016)
Populus deltoides	Eastern cottonwood	0.19	Holder (2013)
Populus tremuloides	Quaking aspen	0.15	Holder (2013)
Pseudotsuga menziesii	Douglas fir	0.26	Keim et al. (2006)
Quercus gambelii	Gambel oak	0.15	Holder (2013)
Quercus variabilis	Chinese cork oak	0.17	Li et al. (2016)
Thuja plicata	Western redcedar	0.26	Keim et al. (2006)
Tsuga heterophylla	Western hemlock	0.48	Keim et al. (2006)
Ulmus pumila	Siberian elm	0.21	Holder (2013)

Rainfall Intensity under Canopy and Stormwater Runoff Timing

Trees help mitigate flooding and potential soil erosion by temporarily storing rainfall in the canopy formed by branches and leaves, reducing the intensity of rainfall below the canopy and delaying peak stormwater runoff rates.

Open-grown trees typically found in urban landscapes tend to have greater crown volume and thus greater leaf surface area available for water storage than forest-grown trees. As tree surfaces in the upper parts of the canopy become saturated with rain, excess water falls through the canopy. Water falling from higher surfaces fills lower surfaces in the crown until the entire canopy is saturated, a process called “dynamic storage” (Keim et al. 2006).

Tree canopy essentially acts as a stormwater *volume* control mechanism. Although the canopy can hold no additional rainfall once saturated, the rain that continues to fall on the crown is intercepted and takes time to pass from one surface to another, slowing its eventual release as stormwater runoff. It is worth noting that the excess water drips off the tree relatively quickly after the rain has stopped, extending the rain event for a time under canopy.

Urban trees also regulate stormwater runoff by moderating rainfall intensity underneath the tree canopy. Urban trees have been shown to reduce rainfall intensity under the canopy by 25 to 70 percent (Zabret et al. 2017) depending on species, rainfall characteristics, and time of year (fig. 1). Stormwater peak flow rate is controlled in part by rainfall intensity (Kuichling 1889, Bedient et al. 2013); rainfall intensity reductions by tree canopy thus reduce the peak flow of runoff leaving a site. Reducing rainfall intensity has also been shown to significantly reduce runoff by increasing soil infiltration (Nassif and Wilson 1975, Guan et al. 2016). Slowing runoff flow rate and increasing stormwater storage in soils helps to reduce incidences of flooding, combined sewer overflows, stormwater runoff volumes, and flows that erode stream channels and bare soil.

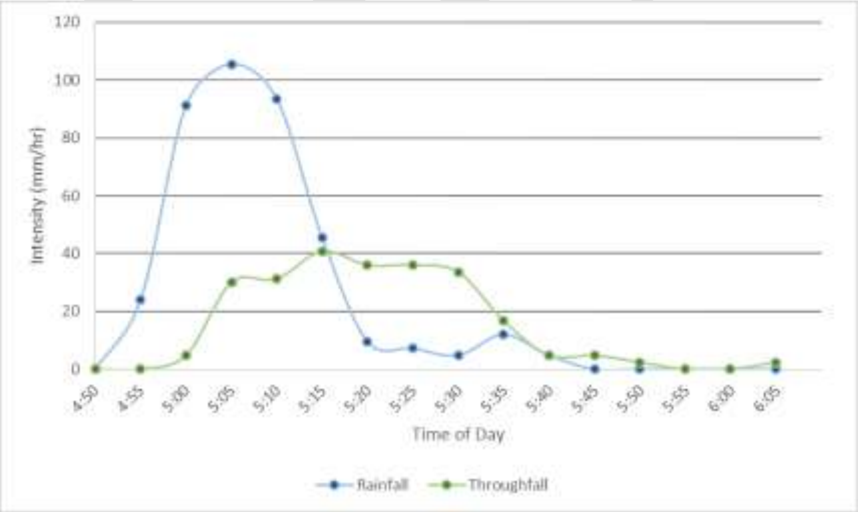


Figure 1—Growing season throughfall intensity under open-grown broadleaf deciduous trees (*Betula pendula*) compared to rainfall intensity above the canopy. Source: Zabret et al. 2017.

Tree canopy has been shown to delay stormwater runoff and increase the time it takes runoff to concentrate at the outlet of a catchment or drainage area (e.g. a storm drain or bioretention practice). Depending on rainfall volume and intensity as well as tree species, this delay can be from 10 minutes to over 3 hours (Xiao et al. 2000, Asadian and Weiler 2009, Gonzalez-Sosa et al. 2017). Growing trees in a catchment with significant impervious surface cover can help delay the runoff hydrograph peak (the maximum stormwater runoff volume reported during a specified time period, displayed graphically). Trees can also reduce the peak flow delivered to the storm drain or GSI practice and help prevent that practice from becoming overwhelmed, thus allowing it to function more efficiently and effectively from a water quality standpoint.

Urban Forest Management Strategies to Reduce Rainfall Intensity

- Where appropriate, retain or plant trees with a high LAI.
- Encourage the use of conifers and evergreen broadleaf trees in the landscape where appropriate.
- Maximize crown volume by pruning only when necessary.
- Plant trees to encourage crown growth over impervious surfaces such as roads, sidewalks, and parking lots.
- When retrofitting a catchment with green stormwater infrastructure practices, retain as much tree canopy in the catchment as possible.

Infiltration of Stormwater into Soils

Soils generally have the capacity to store more water than tree canopies. Infiltration of stormwater into soil delays runoff flow to streams and allows for filtration and adsorption of pollutants. Unfortunately, urban soils tend to be disturbed in some way, either from compaction or loss of structure, which reduces porosity and inhibits water storage. The result is generally diminished infiltration capacity and an increase in stormwater runoff.

Trees help increase infiltration of water into the soil. Tree roots have the ability to condition disturbed soils and loosen compacted soils, thus increasing infiltration and percolation of stormwater runoff (Lange et al. 2009, Hart 2017). In a greenhouse study, Bartens et al. (2008) showed that deciduous trees increased infiltration rates of compacted clay loam subsoil by 150 percent compared to unplanted controls. In a second study under mature urban trees in Iran, Zadeh and Sepaskhah (2016) showed that significantly greater volumes of water infiltrated into soil under tree canopy compared to soils not under tree canopy cover. Depending on soil texture, the cumulative infiltration of water under canopy increased by 69 to 354 percent compared to soil not under the canopy. The rate at which water infiltrated into soil under tree canopy cover also depended on soil texture. The infiltration rate was 800 percent greater under the canopy of trees growing in clay loam soil compared to that in open clay loam soil; however, there was only a 12.5 percent increase in infiltration rates under canopy with loamy sand compared to loamy sand in open areas. In both studies tree roots were reported to cause this increase in infiltration.

Stemflow can also help with infiltration of rainfall through preferential flow along root surfaces. Unless the extent of permeable surface at the base of the tree is very limited (as can be the case with some urban street or parking lot trees), the stemflow infiltrates into the soil macropores along the root surfaces. Quantification of the influence of stemflow on infiltration rates or volumes continues to be studied (Levia and Germer 2015).

Managing urban forests to take advantage of stemflow can help mitigate stormwater runoff. Schooling and Carlyle-Moses (2015) reported that stemflow accounted for 3 percent of rainfall for events greater than 0.4 inches (10 mm). In addition to rainfall intensity and wind speed, stemflow depends on the smoothness of the bark and branch angles. Smooth-barked trees with acute branch angles have been shown to produce greater stemflow than rough-barked trees or trees with more horizontally oriented branches. Staelens et al. (2008) also found that stemflow volume increased from 6.4 to 9.5 percent of total rainfall when leaves were not on the tree (i.e., during the dormant season).

Trees encourage infiltration of rainfall and stormwater runoff into the soil by directing water to a single point at the base of a tree or by slowing water dripping onto permeable surfaces under the canopy. Where appropriate, directing stormwater runoff to open green spaces such as parks, and planting trees in those green spaces can be a useful, efficient, and relatively inexpensive urban stormwater runoff mitigation strategy. Strategically planting smooth-barked trees with acute branch angles near impervious surfaces so that their canopies grow over those surfaces could help direct more rainfall to more permeable surfaces during the winter months.

Urban Forest Management Strategies to Increase Stormwater Infiltration

- Maximize belowground soil volume and quality to enhance infiltration and storage
- Where appropriate, use organic mulch beneath tree canopy to help improve infiltration and retain stormwater runoff.
- Plant trees in large open areas where stormwater is directed.
- Ensure adequate belowground aeration for root growth.
- Plant trees with acute branch angles near impervious surfaces to help direct rainfall to permeable surfaces.
- Ensure adequate permeable soil space directly adjacent to tree stems to allow for infiltration of stemflow.

Transpiration and Stormwater Runoff

Trees need water to function and grow. Water stored belowground in soil is removed and used by trees and eventually returned to the atmosphere through the process of transpiration. Trees influence soil water storage through this process. As water is removed from the soil by trees, soil pore space becomes available to be filled by stormwater runoff from subsequent rainfall events.

Transpiration rates are highly variable by tree species, stem size, and leaf area. Average growing season daily water use has been reported to be as high as 47 gallons for a 23-inch diameter tulip poplar (*Liriodendron tulipifera*) while a 25-inch chestnut oak (*Quercus montana*) transpired 6 gallons (Ford et al. 2011). In a California study, 15- to 22-inch diameter sycamore (*Platanus* spp.) street trees transpired between 27 and 46 gallons of water daily during the growing season, but 24-inch pines only transpired about 13 gallons (Pataki et al. 2011). These differences in the amount of water transpired can be attributed, in part, to the tree's wood architecture or xylem element type (fig. 2). Species with deep sapwood and diffuse-porous xylem (e.g., yellow poplar, blackgum, birch, dogwood, red maple, sycamore) transpire water in greater volumes than species with shallow sapwood and ring-porous xylem (e.g., oak), species with semi-ring-porous xylem (e.g., hickory) or species with tracheid xylem (e.g., conifers).

Data collected on trees in the mountains of western North Carolina to the Gulf Coastal Plain of Georgia show that diffuse-porous species can transpire between 0.6 to 1.5 gallons of water per day per inch of stem diameter during the growing season depending on the size of the tree, while ring-porous species transpire about 0.3 gallons of water per day per inch (fig. 2). Because the trees studied were well-watered and their roots not impeded by urban infrastructure, these rates can be considered an upper limit. See figure 2.

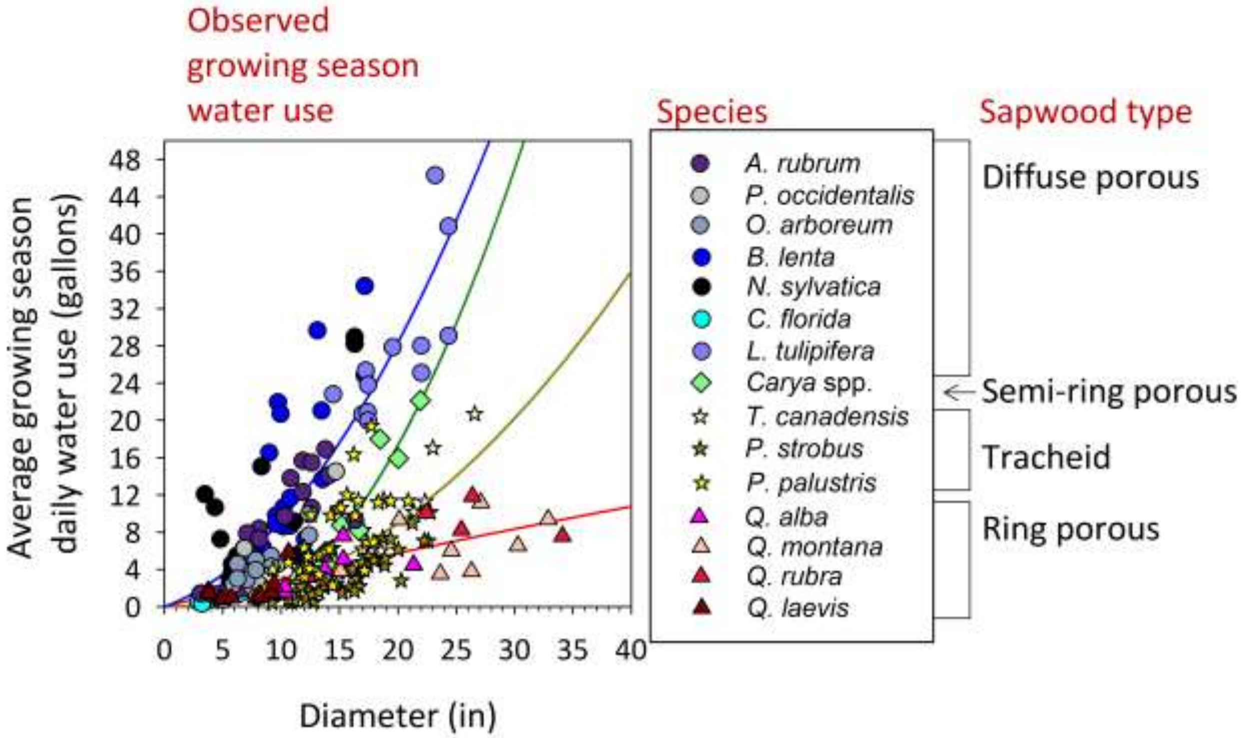


Figure 2—Average growing season daily water use for trees growing in western North Carolina and the Gulf Coastal Plain of Georgia. Sources: Ford et al. 2011; Ford et al. 2008; Ford and Vose 2007; Hawthorne and Miniat, unpublished data; Oishi and Miniat, unpublished data, Vose et al. 2016..

Transpiration rates also depend on many environmental factors. Foliar stomata, the pores in leaves that allow for gas exchange with the atmosphere—thus regulating water flow in the tree through the release of water vapor—open and close depending on light levels, air temperature, humidity, wind, and soil moisture. Using data from multiple urban tree transpiration studies and local meteorological data, Moore et al. (2019) were able to estimate that 5,000 m^2 (53, 820 ft^2) of street tree canopy area in Kansas City, KS could transpire approximately 1,585 to 1,850 gallons of water from the soil each day during the growing season depending on xylem element type and thus allow for additional runoff storage between rainfall events. They warn, however, that this assumes the soil moisture content is not limiting and has enough water for the trees to continue transpiring at these rates.

Regional weather patterns may dictate the best trees to use in urban systems. For example, in regions with a more Mediterranean climate (e.g.., California) where water for irrigation may be limited, it might be best to plant tree species with ring-porous or tracheid xylem types that are able to conserve water through reduced transpiration. In a region that receives abundant rainfall (e.g., the southeastern U.S.), planting diffuse-porous species could help mitigate stormwater runoff by creating increased soil storage capacity through increased transpiration.

Based on this information, it would be advantageous to plant trees with diffuse-porous xylem elements in areas used to store stormwater runoff, where soils are frequently wet, and to plant ring-porous species in drier, upland sites or in bioretention practices that use high infiltration media. To determine the xylem element type of many tree species, search the Wood Finder section of The Wood Database.

Urban Forest Management Strategies to Maximize Transpiration

- Ensure adequate belowground aeration for root respiration and increased water storage capacity.
- Select tree species with greater leaf surface area.
- Retain larger trees in the landscape where appropriate.
- Plant larger-statured trees where appropriate.
- Plant trees having diffuse-porous xylem in large open areas where stormwater is directed.
- Plant ring-porous trees in drier, upland sites and in bioretention practices that use high infiltration media.

Stormwater Nutrient Uptake and Loading

Trees require nutrients to grow and remain healthy (Coder 2013). Urban stormwater runoff contains many of the 19 or so essential elements used by trees. As stormwater infiltrates into the soil profile, filling soil pore space, it becomes the soil solution from which tree roots absorb nutrients. Most of the chemically charged elements in stormwater adsorb to oppositely charged soil particles, holding them as exchangeable ions. When the roots absorb elements from the soil solution, these exchangeable ions are released through chemical processes into the solution, replenishing nutrient levels for plant absorption (Brady and Weil

2002). However, excessive water in the soil can also cause some of the elements in the soil solution, such as nitrate-nitrogen, to be carried or leached by gravity from the root zone to deeper ground water where they are unavailable to plants. Eventually these elements can make their way to receiving waters and can contribute to eutrophication downstream, resulting in overgrowth of plant life and the death of fish and other species from lack of oxygen.

Urban stormwater runoff is usually directed to gutters and pipes that convey the untreated water to a stream and eventually to larger bodies of water or to a treatment facility for combined sewage systems. This is done mainly to prevent flooding in our cities. However, moving large quantities of untreated urban stormwater to downstream water sources can decrease water quality, diminish recreational opportunities deleteriously affect aquatic life and food sources, and increase treatment costs for human use. Green stormwater infrastructure practices are designed to mimic natural hydrological processes by directing stormwater runoff to permeable surfaces that allow soil to remove nutrients and other pollutants from runoff naturally before it reaches receiving waters.

Nitrogen (N) and phosphorus (P) are two of the most essential elements needed by trees. Urban stormwater runoff can have substantial concentrations of N and P due to natural and human causes. Controlling these elements is critical for municipalities to maintain water quality. Research studies in urban areas show how managing urban forest systems can help control N and P from stormwater runoff.

A study in Baltimore, MD, showed that intact forested areas reduced N leaching by 74 to 81 percent compared to areas of maintained, fertilized turf (Groffman et al. 2009) (table 2). Other studies showed that under individual deciduous trees, N leaching was 40 to 56 percent lower than under turf (Amador et al. 2007, Nidzgorski and Hobbie 2016). In a study in Minnesota, Nidzgorski and Hobbie (2016) showed that leaching of phosphates was reduced by 81 percent under deciduous and 55 percent under coniferous trees in municipal parks. Extrapolating their data to an urban watershed, the authors estimated that urban trees reduce P leaching to groundwater by 1175 to 2648 pounds per year (18 to 39 pounds per square mile). They calculated that trees in the watershed saved $2 to $5 million per year in removal costs compared to installing engineered stormwater infrastructure. See table 2.

Table 2—Comparison of groundwater nutrient concentrations of total nitrogen (TN), oxidized nitrogen (NOx), total phosphorus (TP), and orthophosphates (PO_4^{3-}) under turf, deciduous trees, and conifers from three field studies.

	Turf ***(mg / L)***	**Deciduous trees** ***(mg / L)***	**Conifers** ***(mg / L)***	**Source**
TN	7.32 ± 1.08	3.75 ± 0.55	7.07 ± 0.95	Nidzgorski and Hobbie (2016)
NOx	3.0	1.8	1.4	Amador et al. (2007)
	3.1 – 7.3	0.6 – 1.9*		Groffman et al. (2009)
	5.63 ± 1.00	2.46 ± 0.42	5.95 ± 0.97	Nidzgorski and Hobbie (2016)
TP	0.159 ± 0.020	0.050 ± 0.004	0.085 ± 0.013	Nidzgorski and Hobbie (2016)
PO_4^{3-}	0.131 ± 0.020	0.025 ± 0.003	0.059 ± 0.011	Nidzgorski and Hobbie (2016)

*Forested area

Trees in bioretention practices have also shown to help reduce nutrient loading. Bioretention systems with trees reduced nitrates by 58 to 97 percent and phosphates by 47 to 79 percent compared to those without trees (Bratieres et al. 2008, Read et al. 2008, Denman et al. 2016) (table 3). The effects on total N and P, however, were highly variable. Compared to the amount of nutrients coming into these bioretention systems, trees were found to reduce total dissolved N by 46 to 52 percent (Bratieres et al. 2008) and P by 70 to 84 percent (Bratieres et al. 2008, Denman et al. 2016) (table 4). The authors explained that as trees in these systems matured and increased root mass per soil volume, their effectiveness improved. These studies suggest that bioretention practices with greater tree root biomass are better able to reduce N and P from their stormwater effluent (see tables 3 and 4).

Table 3 Water quality data from three bioretention studies comparing effluent concentrations of total nitrogen (TN), oxidized nitrogen (NOx), total phosphorus (TP), and orthophosphates (PO_4^{3-}) from systems with trees (Soil+Tree) and without trees (Soil only).

	Soil only ***(mg L^{-1})***	**Soil+Tree** ***(mg L^{-1})***	**Reduced** ***%***	**Source**
TN	2.2 6.68	1.8 - 2.3 1.19	**-5% – 18%*** **82%**	Read et al. (2008) Bratieres et al. (2008)
NOx	0.38 5.23 7.43	0.01 - 0.16 0.38 1.96	**58 - 97%*** **93%** **74%***	Read et al. (2008) Bratieres et al. (2008) Denman et al. (2016)
TP	0.11 0.083	0.06 - 0.10 0.070	**9 - 45%*** **16%**	Read et al. (2008) Bratieres et al. (2008)
PO_4^{3-}	0.075 0.064 0.85	.020 - .025 0.034 0.18	**67 - 73%*** **47%** **79%***	Read et al. (2008) Bratieres et al. (2008) Denman et al. (2016)

* Averaged over entire study period

Table 4—Water quality data from two bioretention studies comparing effluent concentrations of total nitrogen (TN), oxidized nitrogen (NOx), total phosphorus (TP), and orthophosphates (PO_4^{3-}) from systems with trees (Soil+Tree) and the dose of nutrients of the applied stormwater (Dose).

	Dose ***(mg/L)***	**Soil+Tree** ***(mg/L)***	**Reduced** ***%***	**Source**
TN	2.21	1.19	46%	Bratieres et al. (2008)
NOx	0.79 2.0	0.38 1.96	52% 2% *	Bratieres et al. (2008) Denman et al. (2016)
TP	0.427	0.070	84%	Bratieres et al. (2008)
PO_4^{3-}	0.127 0.6	0.034 0.18	74% 70% *	Bratieres et al. (2008) Denman et al. (2016)

* Averaged over entire study period

Although trees have been shown to take up substantial amounts of nutrients from the soil profile, they can also contribute significantly to pollution loading in receiving waters by contributing nutrients to impervious surfaces. Airborne contaminants, including N and P, deposit on leaf surfaces and can be washed off during rainfall events. Precipitation dripping from tree canopy over impervious surfaces has been shown to contribute to increased pollutant loading (Halverson et al. 1984). Trees have the ability to move nutrients internally from foliage to other plant tissue for storage before leaves fall off during the autumn; however, about half of the N and P content remains in the leaves after they fall (Aerts 1996).

Studies show that approximately 60 percent of the annual P yield in urban streams comes from autumn leaf fall onto streets (Selbig 2016). Research also shows a strong linear relationship between tree canopy cover over streets and mean gutter stormwater runoff N and P concentration in the autumn (Janke et al. 2017) (fig. 3). From this research we can expect to see an increase in runoff concentration of approximately 0.65 mg/L in total organic N and 0.35 mg/L in soluble reactive P in autumn for every 10 percent increase in tree canopy cover over impervious surfaces (see figure 3).

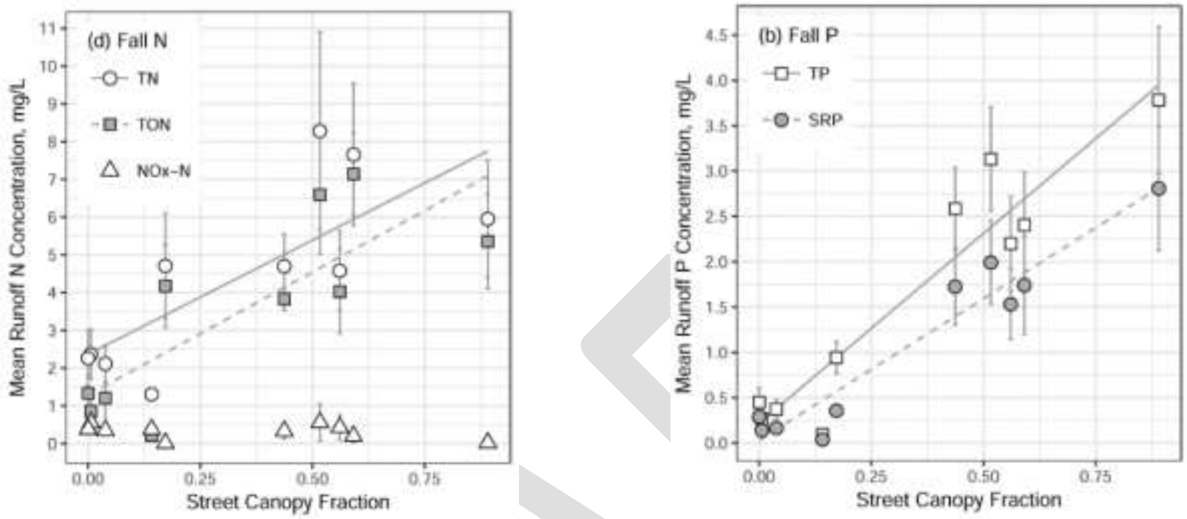


Figure 3—Mean nitrogen (N) and phosphorus (P) concentration in stormwater runoff from street gutters per street tree canopy fraction in the Minneapolis, MN, metropolitan area. Source: Janke et al. 2017.

Litter from urban trees decomposes more rapidly on impervious surfaces than in more natural settings due mainly to increased ambient temperatures and accelerated fragmentation from tires rolling over it (Hobbie et al 2013). Timely and targeted street sweeping, especially in areas with high tree canopy cover, has been shown to reduce nutrient concentrations in urban streams by over 70 percent (Selbig 2016). If tree canopy cover over impervious surfaces is desirable in municipalities to provide co-benefits and improve quality of life, a robust and targeted street sweeping operation is highly recommended to help reduce excessive nutrients in urban streams and lakes.

Urban Forest Management Strategies to Reduce Stormwater Nutrient Loading

- Where appropriate, direct stormwater runoff to areas where it can be infiltrated into the soil or belowground.
- Plant trees in large open areas where runoff is directed and roots can access it.
- Ensure adequate belowground aeration for root respiration.
- Identify those areas of the city where tree canopy cover overhangs impervious surfaces and ensure leaves and debris are removed frequently throughout spring and autumn.

CREDITING TREES IN STORMWATER PROGRAMS

With the growing body of research on the stormwater benefits of urban forest systems, new approaches have been developed in recent years to provide regulatory credit for trees in stormwater management programs. Communities across the nation are seeking cost-effective approaches to meet water quality requirements associated with Municipal Separate Storm Sewer System (MS4) permits, Combined Sewer Overflow (CSO) consent decrees, and Total Maximum Daily Load (TMDL) pollutant load reductions. Urban trees and forests play a central role in a community's green stormwater infrastructure, but they are often not accounted for as stormwater management practices, in part due to variability or uncertainty in quantifying their function relative to engineered practices.

The Center for Watershed Protection led a thorough investigation of crediting approaches for urban trees and published a number of valuable resources on the subject. Their website Making Urban Trees Count provides a comprehensive literature review and modeling documentation; national spreadsheet tools for calculating 1) an event-based Stormwater Performance-Based Credit and 2) an annual Pollutant Load Reduction credit; and sample design specifications for urban tree planting as a Best Management Practice (BMP). Table 5 gives a summary of the two crediting tools. An additional technical guide was developed for stormwater engineers entitled "Accounting for Trees in Stormwater Models," which summarizes available tools and outlines an array of options for incorporating tree values into common stormwater modeling programs (Center for Watershed Protection, 2018a) (**table 5**).

The following case studies provide practical examples of how science-based tree credits have been developed and adopted in three different regulatory contexts: Minnesota, Vermont, and the Chesapeake Bay watershed. They are presented in hopes that other states and localities will learn from and/or adapt these approaches, without needing to reinvent the wheel. While the tree credits are modest relative to other stormwater BMPs, they represent an important step towards better accounting for the watershed benefits of urban forests. One limitation of some of these crediting approaches is that they only provide credit for newly planted trees, not for conserving existing mature trees that generally provide far greater stormwater benefits relative to young trees. Further, the credits described below do not account for potential pollutant loading (e.g. Phosphorus) associated with leaf litter falling on impervious surfaces. As the science and policy strategies around these issues continue to develop, it is anticipated that crediting approaches for trees will be strengthened accordingly.

Having supportive state policies in place, as demonstrated in these case studies, is an important enabling condition to incentivize the conservation and planting of urban trees as a key component of the local stormwater management infrastructure. Ultimately, local governments are the drivers of community tree management and have a variety of policy options to protect and expand the many public values provided by trees, as outlined in "Making your Community Forest-Friendly: A Worksheet for Review of Municipal Codes and Ordinances." (Center for Watershed Protection, 2018b) Incorporating tree-related targets explicitly in permits and policies related to MS4s, CSOs, and TMDLs, as has been done in the District of Columbia and other locations, can do much to bolster the role of urban forest systems in stormwater management.

Table 5— Summary of Tree Planting Credits developed by Center for Watershed Protection.

Characteristic	**Pollutant Load Reduction Credit**	**Stormwater Performance-Based Credit**
Use of Credit	• Compliance with nutrient and sediment TMDLs	• Compliance with site-based stormwater management requirements (volume-based and pollutant-based)
Required Inputs	• Climate region • Number of trees planted	• Nearest city (from drop-down list) • Tree type • Surface over which the tree will be planted • Number of trees planted • A breakdown of HSG soil type/land cover combinations for the entire site • The design storm, in inches
Optional Inputs (default values are provided)	• Tree type • Soil type • Surface over which the tree will be planted • TN, TP and TSS event mean concentrations	• Tree size (DBH) • Tree canopy area • TN, TP and TSS event mean concentrations
Outputs	• Annual reduction in TN, TP and TSS loads (lbs/yr) for an individual tree and for a tree planting scenario	• Runoff (cubic feet), TN (lbs), TP (lbs) and TSS (lbs) reduction for user-defined tree planting scenario for a specific storm event (e.g., design storm)
Key Assumptions*	• TP and TSS load reductions are directly proportional to runoff reduction • TN load reductions are 65% of runoff reduction to account for soluble forms of nitrogen reaching a stream or other waterbody through infiltration and leaching	• The amount of runoff reduction achieved by tree planting is not uniform across all storm events • The annual runoff reduction from the water balance model is translated to an event-based reduction using a unit runoff reduction value
TMDL = total maximum daily load TN = total nitrogen TP = total phosphorus TSS = total suspended sediment DBH = diameter at breast height * Refer to the water balance model documentation for more detailed model assumptions		

Minnesota Case Study

Overview

Minnesota was the first state to develop a robust, science-based approach for crediting engineered tree BMPs within state stormwater regulations. With funding allocated in 2009 from the state legislature, the Minnesota Pollution Control Agency convened the Minimal Impact Design Standards (MIDS) Working Group to develop new standards that would ultimately be adopted into the Minnesota Stormwater Manual (Minnesota Pollution Control Agency 2013). Sub-committees were formed to develop stormwater credits and design specifications for a suite of green infrastructure BMPs, including one focused on trees. The tree BMP sub-committee was interested in and explored credits for retaining existing trees but ultimately adopted the Tree Trench/Box credit, which was easiest to quantify and justify in stormwater standards. One valuable feature of Minnesota's crediting approach is that it encourages well-designed tree BMPs with optimal uncompacted soil volume to maximize tree growth and function in processing stormwater runoff.

Quick Facts

Where: Minnesota Stormwater Program

When: Adopted in 2013 in the online Minnesota Stormwater Manual

What:

- ✓ Volume reduction credit for engineered Tree Trench/Box practices based on interception, evapotranspiration and infiltration.
- ✓ Annual pollutant removal credits for Total Suspended Solids (TSS) and Total Phosphorus (TP) are calculated based on volume reduction.
- ✓ Requires that users enter soil volume, treatment area, tree size, and other inputs into the Minimal Impact Design Standards Calculator.

Key elements of the Minimal Impact Design Standards include the following:

- Stormwater volume performance goal for new development and redevelopment projects with >1 acre of new impervious surface
- Requires post-construction runoff volume to be retained on site for 1.1 inches of runoff from impervious surfaces
- Standardized credit calculations and design specifications for a variety of GSI BMPs, including: green roofs, bioretention basins, infiltration basins, permeable pavement, infiltration trench/tree box, swales, filter strips and sand filters
- A model ordinance package that helps developers and communities implement the new standards

The MIDS approach has received widespread national attention for its innovative and robust crediting approaches. The unique Manual was designed as an online Wiki format so that it could be easily adapted over time with new science, technical and stakeholder input. It has been revisited and updated each year.

The science behind it

The Tree Trench credit methodology was developed by Kestrel Design Group and contract team, with oversight from the tree BMP sub-committee and multiple rounds of stakeholder input (Kestrel Design Group Team 2013). It is based on an extensive literature review of tree interception, evapotranspiration, and infiltration functions. Based on mean values found in Breuer et al. (2003), 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 canopy at maturity, dependent on the tree species. The MIDS calculator provides default tree size options (small/medium/large) that can be used in place of tree species.

The team's report reviews the pros and cons of a variety of methods for quantifying evapotranspiration, recommending use of the Lindsey-Bassuk (1991) single whole tree water use equation. This method relates the total water use of a tree to four measurements: 1) canopy diameter, 2) leaf area index, 3) the evaporation rate per unit time, and 4) the evaporation ratio.

Pollutant removal for infiltrated and evapotranspired water is assumed to be 100% and is calculated by multiplying the volume of water reduced by event mean concentrations for TSS and TP from the International Stormwater Database, version 3.

How the credit works

Minnesota provides a total runoff volume reduction credit for Tree Trench BMPs, by adding together the reductions provided by tree canopy interception, soil storage (infiltration), and evapotranspiration. The interception credit is a function of tree type and projected leaf area at maturity. The storage credit is a direct function of soil volume. The evapotranspiration credit is a function of plant available water and is indirectly related to soil volume (e.g. available pore space). The total runoff volume achieved for a particular storm is 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. The total volume reduction is also translated into annual pollutant removal values for Total Suspended Solids (TSS) and Total Phosphorus (TP). A Tree Trench BMP without an underdrain is assumed to remove 100% of pollutants, while a Tree Trench with an underdrain provides lower volume reduction and pollutant removal credits (**figure 4**).

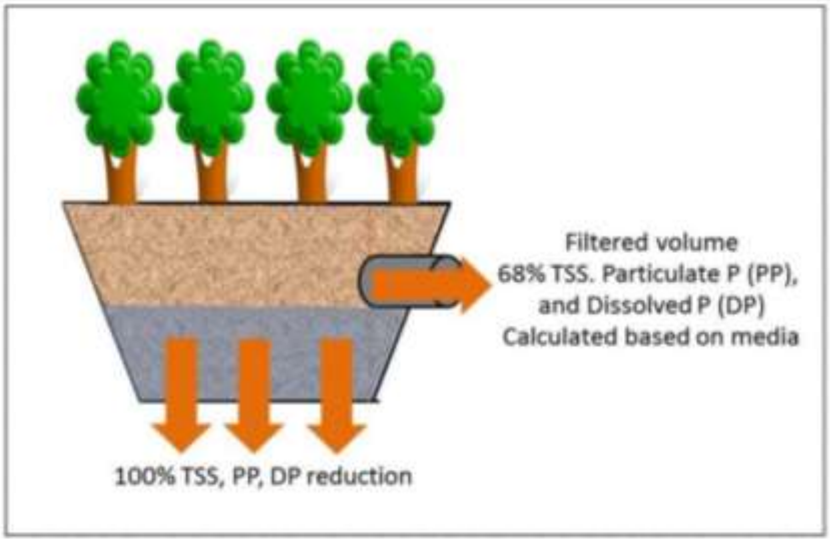


Figure 4—Diagram of a Tree Trench BMP designed with an underdrain, which has a lower volume reduction and pollutant removal credit relative to a Tree Trench with no underdrain.

To calculate the credits, users must enter into the MIDS Calculator a suite of inputs based on the design of the particular Tree Trench BMP such as:

- Site Characteristics
    - watershed area/land cover draining to the Tree Trench BMP
    - downstream/routing BMP

- Soil/Media Characteristics
    - soil volume of the tree box
    - hydrologic characteristics of the soil
- Tree Characteristics
    - number of trees
    - most common tree type (deciduous or coniferous)
    - average tree size at maturity (small/medium/large)

Figure 5 shows one of the input screens for the MIDS calculator, demonstrating how the volume reduction credits are calculated based on the Tree Trench BMP characteristics provided. The figure illustrates how in this crediting approach, the volume reduction based on soil storage (1201 cubic feet) far exceeds the volume reductions for evapotranspiration (72 cubic feet) and interception (5 cubic feet). Thus, the credit incentivizes providing ample soil volume and high quality, uncompacted soil media that will promote infiltration and storage in the short term and enable trees to grow to their optimal size. A helpful summary and example of Tree Trench credits using the MIDS calculator is included in the Center for Watershed Protection's Accounting for Trees in Stormwater Models (Center for Watershed Protection 2018a, p.12). Detailed technical information on the credit equations, input definitions, and other guidance can be found in the online Stormwater Manual section Calculating Credits for Tree Trenches and Tree Boxes.

In developing the credit calculations, it is assumed the tree practice is properly designed, constructed, and maintained in accordance with guidance in the tree section of the Minnesota Stormwater Manual. The Manual website notes that if any of these assumptions is not valid, the BMP may not qualify for full credit. Some of the model inputs used in the MIDS calculator for Tree Trench practices are only applicable to Minnesota and similar climates, so it is not recommended to use the calculator itself beyond those geographic zones. However, the equations and calculations behind the credit could readily be adapted for other climate zones.

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

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 5—A MIDS Calculator Tree Trench BMP input screens showing tree/soil inputs (white boxes) and model outputs (gray).

Vermont Case Study

Overview

Quick Facts
Where: State of Vermont

When: Adopted in 2017 in Vermont Stormwater Management Manual Rule

What:

- ✓ Volume reduction credit in state stormwater permits.
- ✓ Three tree BMPs: Reforestation (active and passive), single tree planting.
- ✓ Companion local crediting framework for smaller sites not covered by state permit.

The effort to include trees and forests as key components of green stormwater infrastructure has been championed by the state forestry agency, Vermont Department of Forests, Parks and Recreation, for a number of years. Starting in 2010, the state's Agency of Natural Resources convened private and public stakeholders in a green infrastructure roundtable that resulted in strategic plans and initiatives to promote low impact development and GSI across state agencies, local governments, and professionals.

As a component of this effort, the state forestry agency secured a federal grant that advanced several strategic actions, including hiring a green infrastructure coordinator within the state's stormwater agency (Department of Environmental Conservation) who helped facilitate the adoption of new policies and practices. Through the grant, a consultant was also hired to complete a comprehensive review and set of recommendations on options to credit trees within the state's stormwater management framework.

During this time, the upcoming revision of the state's stormwater management manual provided a key window of opportunity to advance the green infrastructure recommendations into policy. The initial draft version of the manual included stormwater credits for reforestation (active and passive) but no credit for single tree plantings. In subsequent stakeholder meetings and public comment, support for a single tree credit was voiced; the state worked with partners to incorporate this into the final manual that was officially adopted in 2017. A complementary GSI Toolkit was developed to aid local governments in crediting trees and other GSI practices on smaller development sites that are not covered by the state's permitting process (Vermont League of Cities and Towns 2017).

The science behind it

To establish a sound basis for establishing stormwater credits for trees, the state forestry agency contracted with Stone Environmental, Inc. to review existing research and policy examples and draft recommendations. Stone Environmental, Inc. developed two white papers for the project. The first, describing the stormwater management benefits of trees (Moore et al. 2014a) summarizes scientific knowledge about the tree processes that affect stormwater runoff (interception, transpiration, infiltration, pollutant removal) and reviews considerations for maximizing stormwater benefits at the tree or site scale (soil restoration, engineered tree systems, tree selection, siting, and planting practices).

The second white paper (Moore et al. 2014b) reviews examples from 12 states around the country that illustrate integrating tree retention or planting practices into stormwater programs. It also reviews over a dozen examples of green infrastructure crediting/incentives at the municipal scale, including examples from Seattle, WA, Washington, DC, and Nashville, TN. The findings from these reviews helped inform the credits that were adopted in Vermont, taking into account regulatory concerns and stakeholder input.

How the credits work – state credits

The Vermont Department of Environmental Conservation Stormwater Program issues permits for post-development runoff from impervious surfaces. Permits are required for new development and redevelopment projects that will include more than 1 acre of impervious surfaces after construction.

The 2017 Vermont Stormwater Management Manual Rule sets forth the treatment standards that must be met and the approved methods for calculating treatment volume (Tv) credits for the suite of structural and nonstructural stormwater treatment practices (i.e., BMPs) used onsite (Vermont Agency of Natural Resources 2017). Using the hydrologic condition method set forth in the manual, a suite of practices must be implemented to achieve the “hydrologic condition volume,” which is calculated as the difference between the pre- and post-development site runoff for the 1-year, 24-hour storm.

The three types of state tree credits established under the reforestation nonstructural practice are summarized as follows:

1. **Active reforestation** involves planting a stand or block of trees, or individual trees at a project site with the explicit goal of establishing a mature forest canopy or distributed cover that will intercept rainfall, increase evapotranspiration rates, and enhance soil infiltration rates.

Total volume (Tv) credit = 0.1 inches x reforested area (i.e., 1 acre of reforested area = Tv credit of 363 cubic feet)

2. **Passive reforestation** consists of protecting a portion of a project site from mowing and allowing native vegetation to reestablish.

Total volume (Tv) credit = 0.05 inches x practice area

3. **Single tree planting** involves planting individual trees on a project site.

Total volume (Tv) credit = 5 cubic feet per tree planted

Requirements for state credits

Excerpts from the 2017 Vermont Stormwater Management Manual Rule:

Reforestation Credits

- The minimum contiguous area of active or passive reforestation shall be 2,500 square feet.
- The minimum width for reforested areas shall be 25 feet.
- The entire reforestation area shall be covered with an approved native seed mix covered with mulch to help retain moisture and provide a beneficial environment for the reforestation.
- Active and passive reforestation areas shall not be maintained as landscaped areas. Forest leaf litter, duff, and volunteer sapling and understory growth shall not be removed.
- The manual lists additional requirements regarding tree species selection, soil, slope limitations, planting plans, protection from development, and other design issues.

Single Tree Credit

- Trees planted for the single tree credit shall be at least 2-inch diameter at breast height (dbh) for deciduous trees, or at least 6 feet tall for conifers.

For full details on the state credits, see the 2017 Vermont Stormwater Management Manual, Section 4.2.1 (Vermont Agency of Natural Resources 2017).

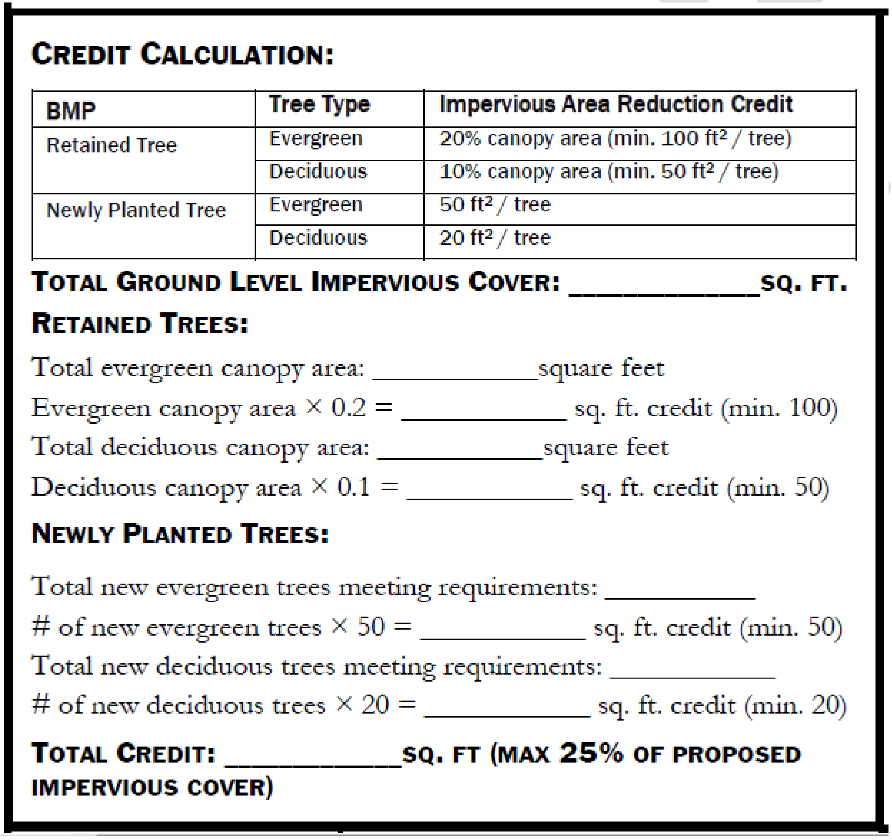
How the credits work – local credits

Many smaller scale development and redevelopment projects do not meet the greater than 1-acre impervious surface threshold, thus do not require a state permit or involve the standard treatment practice requirements and credits described above. Because these smaller projects are governed by local ordinances, the Vermont League of Cities and Towns worked with state agencies and stakeholders to develop a Green Infrastructure Toolkit for local use. The Toolkit features:

- GSI Sizing Tool spreadsheet.
- Set of GSI fact sheets covering credits and criteria for 10 stormwater practices, including trees.
- Low Impact Development and Green Stormwater Infrastructure (GSI) Bylaw Template (i.e., model ordinance) that can be used or adapted into local policy.

The crediting approach for retained and newly planted trees is based on an impervious area reduction credit, which in effect reduces the total volume of runoff that needs to be treated through other practices. **Table 6** shows how the credits are calculated

Table 6—How tree credits are calculated using Vermont's GSI Simplified Sizing Tool. Source: GSI Simplified Sizing Tool Fact Sheet #3, (Vermont League of Cities and Towns 2015)



CREDIT CALCULATION:

BMP	Tree Type	Impervious Area Reduction Credit
Retained Tree	Evergreen	20% canopy area (min. 100 ft² / tree)
	Deciduous	10% canopy area (min. 50 ft² / tree)
Newly Planted Tree	Evergreen	50 ft² / tree
	Deciduous	20 ft² / tree

TOTAL GROUND LEVEL IMPERVIOUS COVER: ____________SQ. FT.

RETAINED TREES:

Total evergreen canopy area: ____________square feet

Evergreen canopy area × 0.2 = ____________ sq. ft. credit (min. 100)

Total deciduous canopy area: ____________square feet

Deciduous canopy area × 0.1 = ____________ sq. ft. credit (min. 50)

NEWLY PLANTED TREES:

Total new evergreen trees meeting requirements: ____________

# of new evergreen trees × 50 = ____________ sq. ft. credit (min. 50)

Total new deciduous trees meeting requirements: ____________

# of new deciduous trees × 20 = ____________ sq. ft. credit (min. 20)

TOTAL CREDIT: ____________SQ. FT (MAX 25% OF PROPOSED IMPERVIOUS COVER)

Requirements for local credits

The Green Infrastructure Toolkit lists a number of requirements for credit, such as:

- The tree(s) must be on the development site and within 20 feet of new and/or replaced ground level impervious surfaces (e.g., driveway, patio, or parking lot).
- Trees must be retained, maintained, and protected on the site after construction and for the life of the development, or until any approved redevelopment occurs.
- Trees that are removed or die must be replaced with like species during the next planting season.
- See additional criteria regarding soil quality and volume and other design requirements.

Retained Trees

- Retained trees must be a minimum 6 inches dbh. For trees smaller than this size that are retained, the newly planted tree credit may be applied instead.
- See additional guidelines for retained trees

Newly Planted Trees

- New deciduous trees must be at least 1.5 inches diameter, measured 6 inches above the ground. New evergreen trees must be at least 4 feet tall.
- See additional tree selection, spacing, planting and maintenance requirements.

For full details, see Fact Sheet #3 (Vermont League of Cities and Towns 2015).

Chesapeake Bay Case Study

Overview

In 2010, the U.S. Environmental Protection Agency (EPA) established the Chesapeake Bay Total Maximum Daily Load (TMDL)—or "pollution diet"—to reduce the amount of nitrogen, phosphorus, and sediment entering the Bay through the region's waterways. The TMDL covers 64,000 square miles that stretch across parts of six states and the District of Columbia. Each of these jurisdictions has committed to reaching ambitious pollutant load reductions by 2025, as documented in phased watershed implementation plans. In order to track and credit progress towards these targets, the states and the District of Columbia must provide detailed reporting of the number and type of approved BMPs implemented on all agricultural and urban lands.

Quick Facts

Where: Chesapeake Bay Watershed
(DC, DE, MD, NY, PA,VA, WV)
When: Adopted in 2016 as approved Total Maximum Daily Load BMP credits by federal and state agencies

What:

- ✓ BMP credits are earned for **urban tree canopy expansion** for dispersed plantings over turf or impervious surface and **urban forest planting** for full reforestation.
- ✓ Tree canopy is mapped and credited as a land use class in the Chesapeake Bay model, with reduced pollutant loading relative to turf or impervious cover.
- ✓ States get credit for newly planted trees for 10 years, after which the tree canopy is tracked directly through high-resolution imagery.

While the Chesapeake Bay TMDL and modeling tools have always assigned low pollutant loading rates to forest land cover, they did not have a way to account for and credit the water quality value of urban tree canopy (individual and small patches of trees in developed areas not large enough to be classified as forest). Thanks to investments by the Chesapeake Bay Program partners in high-resolution land cover data, distinct mapping of forest, urban tree canopy over turf, and urban tree canopy over impervious cover became available in 2016.

A BMP expert panel was convened in 2015 to provide recommendations on how urban tree canopy (including urban tree planting) should be credited in the TMDL context. All documentation of the literature, modeling approaches, and crediting decisions are provided in the report the panel developed (Law and Hanson, 2016). Following review and revision with federal, state and other stakeholders, a new BMP credit for urban tree canopy expansion, as well as a higher credit for urban forest planting (i.e., reforestation of developed/turf areas) were officially adopted in 2016 for use in the TMDL. Having tree BMP credits approved for use in the TMDL has helped incentivize the District of Columbia and other local jurisdictions to include tree planting targets as part of their MS4 permits.

The science behind it

The tree canopy BMP expert panel, with support from the Center for Watershed Protection, completed a thorough literature review on the water quality benefits of urban trees and existing tree crediting approaches. Hynicka and Divers (2016) constructed a water balance modeling approach to estimate pollutant loading rates for tree canopy over turf grass and tree canopy over impervious cover relative to turf and impervious cover without trees. To account for spatial and temporal variation in precipitation, 11 years (2005 to 2015) of daily weather data were used from each of eight regional locations spanning the Chesapeake Bay Watershed. The relative pollutant load reductions are summarized in Table 7.

The expert panel used a variety of tree species, growth, and mortality scenarios in i-Tree Forecast to establish an average canopy acreage credit per tree planted (144 square feet per tree, or approximately 300 trees per acre).

How the credit works

Under the Chesapeake Bay modeling and TMDL framework, every acre of land in the watershed has a designated land use class and associated pollutant loading rate, based on high-resolution land cover mapping, other datasets, and best available science. Like many BMPs in the TMDL framework, the urban tree canopy BMPs are credited based on a *land use change*, or the conversion of a given acreage of land from a higher loading land use (e.g. turf grass or impervious cover) to a lower loading land use (urban tree canopy or forest). For these land use change BMPs, states and local governments track and report the total acreage of each BMP implemented on an annual basis, and the Chesapeake Bay modeling tools calculate the resulting pollutant reductions.

The **urban tree canopy expansion BMP** includes tree planting projects on developed land that increase the tree canopy overlying turf or impervious surfaces but do not create forest-like conditions. Trees do not have to be planted in a single contiguous area. Trees planted in a riparian forest buffer or as part of a structural BMP, such as bioretention practices, are not included; these are tracked under separate BMP credits. Each tree planted is given credit for creating 144 square feet of urban tree canopy (equivalent to 300 trees per acre), which reflects average growth at 10 years after planting. The credit is calculated within the Chesapeake Bay model based on the percentage reduction in nitrogen, phosphorous, and sediment pollutant loads relative to the underlying land use cover. (table 7)

The **urban forest planting BMP** includes projects that create forest-like conditions. Trees must be planted in a contiguous area specified in a documented planting and maintenance plan and conform to the state's planting density and associated standards for forest conditions. Urban forest planting BMPs result in a change of land use from turf grass to forest land. The credit for this BMP is calculated based on the difference between the land use loading rate of turf grass and forest land across the acreage of the urban forest planting.

For both of these BMP credits, the credit expires after 10 years, at which point the canopy coverage is assumed to be tracked and directly credited as a land use through new high-resolution imagery/land use data (see **table 7**).

Table 7—Tree canopy relative land use loading rate reductions in total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) in relation to underlying land use cover. Source: Hynicka and Divers 2016

Land Use	TN Reduction (%)	TP Reduction (%)	TSS Reduction (%)
Canopy Over Turf	23.8	23.8	5.8
Canopy Over Roads	8.5	11.0	7.0
Forest	85.0	90.7	81.6*

*Percent reduction is based on average MS4 land use loading rate for sediment.

CONCLUSION

Urban forest systems (trees, soil, and groundcover) help manage stormwater runoff by reducing stormwater volume, slowing rainfall intensity, delaying runoff, improving infiltration into soil, and increasing water storage capacity in soils. Using trees as part of a stormwater management “treatment train” can increase the efficiency of GSI practices. Larger, mature trees provide greater benefits, and healthy trees appreciate in terms of benefits over time, so managing the entire urban forest to increase leaf surface area is a good strategy to help manage stormwater runoff city-wide. Providing credits in state and local stormwater programs for retaining mature trees and strategically planting new trees is a valuable tool to encourage their use as part of a stormwater management program.

Trees increase the quality of life in our cities for residents, visitors, and business owners. Using them purposefully can help to reduce some of the disservices that come with development and improve the long-term sustainability of urban ecosystems.

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GLOSSARY OF TERMS

Bioretention—A green stormwater infrastructure practice that uses soil or engineered planting media and plants to retain/detain water and filter pollutants from stormwater runoff. Raingardens are a subset of bioretention practices.

Diffuse-porous xylem—water conducting vessel elements in hardwood tree stems having no clear earlywood or latewood arrangement and no discernable difference in pore diameter size.

Dynamic storage—the temporary storage of rainfall on tree canopy surfaces eventually released as throughfall or stemflow to become stormwater runoff.

Green stormwater infrastructure (GSI)—stormwater mitigation practices designed to mimic natural processes that filter and retain rain where it falls. Typical GSI practices include green roofs, urban trees, bioretention, vegetated swales, permeable pavements and water harvesting.

Interception loss—that amount of rainfall that is intercepted on aboveground surfaces and evaporates back to the atmosphere—does not contribute to stormwater runoff.

Leaf area index (LAI)—the total single-side leaf surface area per unit of ground surface area. An LAI of 3 indicates that a plant has three times as much leaf surface area as the ground area under that plant.

Leaf surface area—the areal sum total of all single sides of leaves in a tree.

Macropores—small holes or pores in the soil greater than 75 □m from which water drains relatively quickly by gravity, thus providing adequate oxygen for root growth and playing a role in stormwater infiltration.

Micropores—smaller pores in soil (generally 5 to 30 □m) that tend to hold water in the soil profile where it is available for plant uptake.

Preferential flow—the uneven and rapid movement of water through soil due to cracks or channels in the soil profile caused by the root/soil interface, decayed roots, or other biotic and abiotic activities such as geologic processes

Ring-porous xylem—water conducting tissue in hardwood tree stems that features earlywood pores that clearly form concentric rings.

Runoff hydrograph peak— the maximum stormwater runoff discharge volume reported during a specified time period as related in graphical form (hydrograph). The runoff hydrograph depicts flow (discharge) vs time.

Semi-ring-porous xylem—water conducting tissue in hardwood tree stems where pores do not form discernable rows and sizes of pores gradually decrease from earlywood to latewood.

Static storage—rainfall intercepted by tree canopy tissue after a rainfall event that eventually evaporates into the atmosphere and does not reach the ground surface or become stormwater runoff.

Stemflow—the movement of water intercepted by tree canopy down the stem to the ground.

Throughfall—rain that passes through the tree canopy and drips onto the ground below.

Tracheid xylem – water conducting pores in soft-wooded trees (i.e., pine).

Transpiration—the process where plants take in water from the soil through their roots, passing it to leaves, where it is released as water vapor through pores (stomata) to the atmosphere through evaporation.

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