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Calculating Stormwater Volume and Total Suspended Solids Reduction under Urban Tree Canopy in Wisconsin Using Available Research

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Calculating Stormwater Volume and Total Suspended Solids Reduction under Urban Tree Canopy in Wisconsin Using Available Research

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Abstract

Current research has shown that urban trees can contribute significantly to stormwater volume control by retaining rainfall in the canopy of trees and increasing infiltration. The potential role of urban trees for stormwater design was evaluated at a proof-of-concept level for a planning study of part of the University of Wisconsin (UW)—Madison campus in 2016. There is currently no regulatory stormwater performance credit for trees in Wisconsin, and the effects of urban trees are not simulated by WinSLAMM or other common design models. The purpose of this project is 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 model predicted that tree canopy coverage over a parking lot improved the bioretention performance for both runoff volume and total suspended solids (TSS) load reduction by 15% to 17%, depending on the design of the bioretention facility. Urban forest systems should be considered as one option for sustainable stormwater management, and this model demonstrates that tree canopy interception can have a substantial stormwater runoff reduction benefit.

Introduction

Urban forest systems are a combination of tree canopy cover, ground cover (vegetative or mulch), and belowground water-storage capacity from which tree roots have access to water and nutrients. These systems intercept rainfall (retaining a portion on foliage and stems), help to reduce rainfall intensity and decrease runoff velocity, and increase soil water-holding capacity. Current research has shown that urban trees can contribute significantly to stormwater volume control by retaining on average 20% of annual rainfall in the canopy of trees (depending on rainfall volume and intensity) and increasing infiltration by up to 3.5 times compared to open-space not having tree cover (Teague and Kuehler 2016; Berland et al. 2017; Kuehler et al. 2017). Using urban forest systems with other green stormwater infrastructure practices, such as bioretention, can help to restore predevelopment hydrology and reduce the amount of stormwater needing to be treated. However, quantifying tree canopy benefits using a simple tool that design engineers can understand and have confidence in does not currently exist. The purpose of this

project is to demonstrate a simple method of quantifying tree canopy rainfall interception and stormwater volume reduction based on data from published research.

The potential role of urban trees for site stormwater design was evaluated at a proof-of-concept level for a planning study of part of the UW—Madison campus in 2016. Montgomery Associates: Resource Solutions, LLC (MARS) identified a range of stormwater management options for a portion of campus slated for redevelopment, with an emphasis on green infrastructure approaches. In addition to looking at structural practices like green roofs, bioretention, and rainwater harvesting, UW—Madison asked MARS to evaluate the benefit of tree canopy cover. This led to the development of a screening model of tree canopy interception. The university will use this information in future redevelopment projects on campus, providing site designers with a set of stormwater management options to consider in designing new facilities.

In the state, Wisconsin Administrative Code Chapter NR151 regulates both stormwater runoff volume and TSS. Runoff volume performance standards are based on a comparison

of annual stormwater infiltration volume for pre- and postdevelopment conditions. TSS performance standards specify a percentage reduction in annual TSS load compared to postdevelopment conditions with no stormwater controls.

For new development, state code requires infiltration of up to 90% of the predevelopment infiltration volume (depending on development density) and a reduction in TSS of 80% compared to no controls. Redevelopment sites, such as most of the planning area, are only required to achieve a 40% TSS reduction with no volume control. However, UW—Madison has adopted a much more ambitious, voluntary goal of limiting runoff volume to that which would have occurred under native vegetation cover, inspired by persistent flooding on Lake Mendota adjacent to campus. In addition, the recently established total maximum daily load for the Rock River Basin requires a campus-wide TSS reduction of approximately 72% compared to no controls, and the Division of State Facilities' Sustainable Facilities Standards specifies a voluntary 80% TSS reduction goal.

State code requires a continuous simulation with rainfall-runoff and water quality models for an “average” year. The modeling period specified is the 1981 rainfall series, evaluated from March 12 through December 2 of that year, and is meant to simulate the nonfrozen precipitation period. Although winter precipitation and spring snowmelt are important parts of the annual water budget in Wisconsin, this standard practice recognizes the difficulty in incorporating frozen conditions in stormwater designs. WinSLAMM is one of the models commonly used and accepted by regulators for stormwater design, and it has been used extensively for past stormwater design and compliance on the UW—Madison campus. Thus, UW—Madison asked for WinSLAMM to be used for this planning study as well.

There is currently no regulatory stormwater performance credit for trees in Wisconsin, and the effects of urban trees are not simulated by WinSLAMM or other common design models. Consequently, MARS developed a method to integrate tree canopy interception into the WinSLAMM model and used it to demonstrate potential benefits of canopy interception for stormwater management.

Methodology

A spreadsheet model was developed to simulate the effect of tree canopy interception on the rainfall dataset used as input for WinSLAMM. Because local data on canopy rainfall interception were unavailable, data from a California precipitation study on an evergreen oak species (Xiao et al. 2000) were used as a surrogate for Wisconsin, where deciduous oak species are common. In their study, Xiao et al. (2000) developed a rainfall interception measuring system using tarps under an 8-year-old, open-grown cork oak (*Quercus suber*) with a leaf area index of 3.4. Cork oak is typically found growing in Mediterranean climates and retains foliage throughout the year. Collecting rainfall and runoff over two winter (rainy) seasons, the researchers were able to calculate maximum canopy rainfall interception depth indirectly from throughfall and stemflow water volume data. Based on their data, the maximum tree canopy rainfall interception depth was estimated to be approximately 0.1 inches. The obvious differences in tree species and climatic conditions between Wisconsin and California highlight the need for local data. These differences were partially accounted for by adjusting the published relationship to consider seasonal leaf emergence and senescence, as described below.

A logarithmic regression for tree canopy interception was developed (Figure 1 and Equation 1) that varies with rainfall depth and has a maximum canopy rainfall interception depth of 0.1 inches.

Rainfall Interception (RI): $\%RI = -0.113\ln(x) + 0.1647$, (1)
where x is rainfall depth in inches.

The canopy interception model uses rainfall depth for each event in the 1981 series to compute the interception percentage for each of those events. Seasonal leaf emergence and senescence in the tree canopy and the resulting influence on leaf area is critical to rainfall interception. In southern Wisconsin, tree foliage typically emerges in April and falls in October. This is approximated in the model as a fraction of total leaf coverage in the canopy for each month: 0 for winter months (November to March), 0.5 for April and October, and 1 for May to September. Thus, canopy interception is simulated to be zero in winter and one-half of the full leaf-on value during spring emergence and fall senescence.

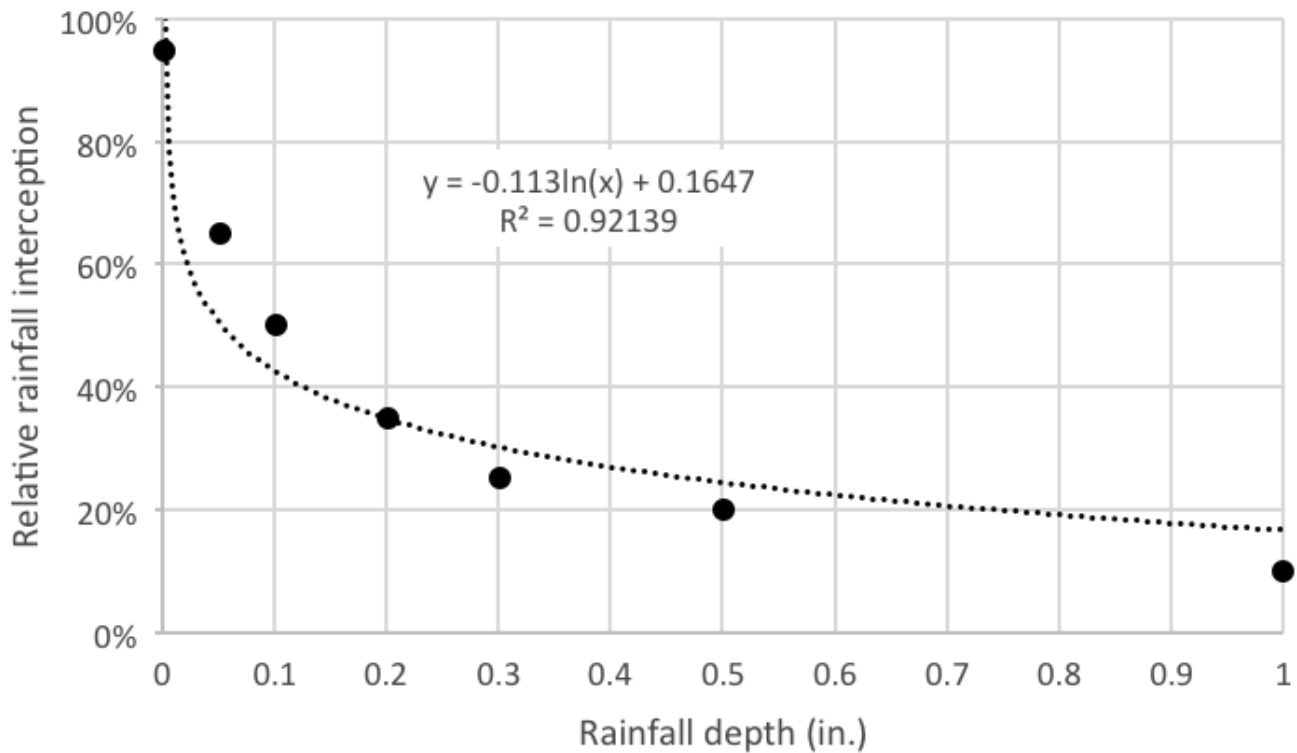


Figure 1. Relationship between relative rainfall interception (compared with throughfall and stemflow percentages) and rainfall depth based on data from Xiao et al. (2000).

Sample Calculation

On April 12, 1981, Madison, Wisconsin, recorded 0.13 inches of rain. Using Equation (1), the percentage of rainfall intercepted is:

$$\%RI = -0.113 \ln(0.13) + 0.1647 = 39.5\%$$

The rainfall interception percentage from equation (1) is then multiplied by the daily rainfall depth (x) to yield the depth of rainfall intercepted, assuming full canopy coverage:

$$39.5\% \times 0.13 \text{ in} = 0.051 \text{ in}$$

During April in Wisconsin, leaves are typically expanding and tree canopies do not have full coverage, so the depth of rainfall intercepted is adjusted by multiplying by 0.5:

$$0.051 \text{ in} \times 0.5 = 0.026 \text{ in}$$

Subtracting the seasonally adjusted tree canopy interception depth from the daily rainfall depth yields the daily precipitation depth adjusted for tree canopy interception:

$$0.13 \text{ in} - 0.026 \text{ in} = 0.104 \text{ in}$$

Results

Summing all adjusted daily precipitation depths over the 1981 simulation period estimates that 13% of rainfall would be intercepted by the tree canopy. The impact of this canopy interception on site stormwater design was examined conceptually with a sensitivity analysis of a hypothetical parking lot draining to a bioretention facility. Simulations were conducted for a parking lot without tree cover using the standard rainfall series in WinSLAMM and for the same parking lot with full canopy coverage using the adjusted rainfall series as input to the model. Bioretention facilities were simulated with areas ranging from 1% to 2% of the parking lot area and engineered soil thickness of 1 to 2 feet. The model predicted that tree canopy coverage over the parking lot improved the bioretention performance, with reductions in both runoff volume and TSS load of 15% to 17%, depending on the design of the bioretention facility (Table 1). With the reduced runoff from each rainfall event, the bioretention system was presumably able to retain and treat a slightly greater fraction of the runoff volume and TSS load from each event, resulting in a substantial performance enhancement on an annual basis.

Table 1. Predicted runoff volume and TSS load for 1-acre parking lot treated with bioretention.

BIOFILTER DETAILS			Runoff volume and TSS Reduction Resulting from Tree Canopy Cover
Area (ft ²)	Engineered Soil Depth (in)	Native Soil Infiltration Rate (in/hr)	
500	24	0.13	15.3%
1,000	24	0.13	17.0%
500	12	0.13	16.4%
1,000	12	0.13	15.9%
500	12	1.60	15.9%
1,000	12	1.60	15.5%
500	24	1.60	15.8%
1,000	24	1.60	15.8%

Discussion

The results from this model estimate a 13% reduction in stormwater volume as a result of tree canopy cover over a parking lot. This volume, although substantial, is conservative compared to the 20% average annual reduction published elsewhere (Kuehler et al. 2017). Even so, the potential improvements in stormwater volume and TSS control described above are significant relative to the regulatory performance standards described above. The lower volume reduction predicted by this model may reflect the fact that it only calculated volume reduction resulting from tree canopy cover for seven months during the growing season, April to October. Very little, if any, research quantifying snowfall interception by tree canopy in urban areas exists. However, snowfall interception in deciduous forests have been estimated to be between 4–12% (Yu et al. 2015).

For a typical site with a mixture of impervious surfaces with and without tree cover, the improvement in stormwater performance would be less than this hypothetical example. WinSLAMM and this interception model cannot simulate a mixture of source areas with and without tree cover in a single model because only one precipitation file can be used per model. Until more sophisticated techniques are available, areas of the site with and without tree cover could be simulated in separate WinSLAMM models, with the canopy interception model used to modify the precipitation input file for the portion of the site with tree cover.

This simple method of quantifying tree canopy rainfall interception and stormwater volume reduction was used to better inform a WinSLAMM model of the benefits of tree canopy cover over a parking lot; however, this method could be used to help estimate benefits of canopy interception for other models that use precipitation as an input variable. This model could likewise be used as a stand-alone tool to better understand how much benefit comes solely from existing tree canopy.

Because trees generally take years to reach maturity and provide substantial canopy cover, it would be best to use this model before development to better understand how construction and removal of the existing tree canopy cover will affect a project.

If growth characteristics of particular trees are known, a design engineer could potentially use this tool to estimate future stormwater benefits of newly planted trees to the project site. This model does not include the effect of trees on soil moisture infiltration and storage or evapotranspiration. These processes are not relevant for a tree canopy over an impervious surface but could be important in other settings. The model also does not simulate the effect of trees on nutrient export, an issue that has received considerable recent attention in Wisconsin (e.g., Selbig 2016).

This model is based on limited rainfall interception data from a wintertime study in California, and additional data specific to the study area would improve predictions and local regulatory acceptance. As a check (data not shown), annual rainfall

interception calculated for the same 1981 rainfall data described above using a relationship developed for the “leafed period” in Ghent, Belgium, using open-grown European beech (*Fagus sylvatica*) (Staelens et al. 2008) yielded essentially the same annual interception depth (3.8 inches based on Xiao et al. versus 4.0 inches based on Staelens et al.). Since a greater proportion of urban tree species in Wisconsin is oak, data from the California study were used.

Acquiring sufficient data to develop confidence intervals for the regression model would also help in development of conservative design standards. Leaf area index varies widely among tree species (Nowak 1996), and this presumably has a significant effect on canopy interception (Livesley et al. 2014). The presence of deciduous or evergreen trees and seasonality of precipitation are also important considerations. Storm intensity is implicit in the dataset used to develop the regression relationship, and data that represent local rainfall distributions would also improve predictions. The maximum canopy interception depth of 0.1 inches does not account for antecedent rainfall remaining on leaf surfaces from back-to-back rainfall events. Climatic variables such as wind speed, relative humidity, and dew point interactions are also likely to affect canopy interception and moisture retention; although difficult to directly simulate, local data would better represent those affects as well. The model assumes full tree canopy coverage over the model domain; methods to include the spatial distribution of the tree canopy across a site would depend on which stormwater model was being used.

Urban forest systems should be considered as one option for sustainable stormwater management. Although this screening analysis could be improved in several ways, it demonstrates that tree canopy interception can have a substantial stormwater runoff reduction benefit. Further quantifying the stormwater quantity and quality effects of urban trees and developing more robust design methods warrant additional research.

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