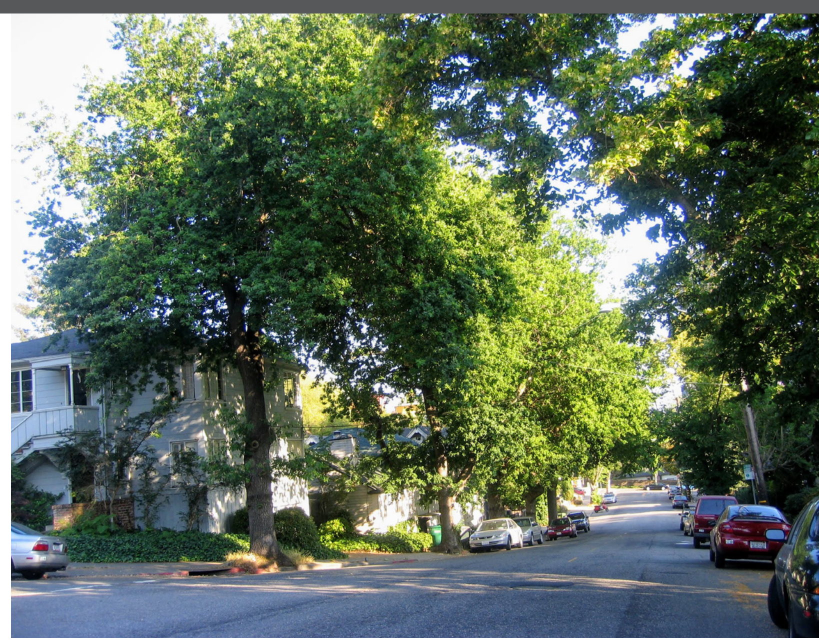
*Toward integrated water quality and ecological benefit evaluation:*

# TREES AND HYDROLOGY IN URBAN LANDSCAPES



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# HIGHLIGHTS

## OVERVIEW

**This effort expands the capacity to evaluate integrated benefits of urban trees within a stormwater modeling framework in the local watersheds of the San Francisco Bay.**

## KEY FINDINGS

- **Both engineered GSI and non-engineered greening activities provide multiple benefits,** but approaches are typically siloed, with engineered GSI used for stormwater management and non-engineered urban greening used to support other ecosystem services. (PAGE 3)
- **Adding a canopy module** to the US Environmental Protection Agency Storm Water Management Model (SWMM) improves quantitative assessments of tree contributions to runoff reduction. (PAGE 5)
- **Evergreen trees in the model intercept more rainfall than deciduous trees** in Northern California climates. (PAGE 12)
- **Increasing the tree well size for street trees** substantially increases runoff reduction benefits. (PAGE 13)
- Due to associated tree well replacement of impervious surface, **street trees have larger runoff benefits compared to park of yard trees** (of the same size). (PAGE 14)
- **Runoff reduction benefits of trees decline slightly with more extreme storm events,** suggesting that **more trees and green stormwater infrastructure (GSI) will be needed in a future climate** to provide the same level of runoff reduction benefits as today. (PAGE 16)
- At the landscape scale, **current trees in the City of Sunnyvale are estimated to reduce runoff by ~5% of annual rainfall.** (PAGE 16)
- **The newly updated SWMM can quantify stormwater benefits of trees** in the same way as green stormwater infrastructure, allowing trees to be evaluated with the sizing criteria for GSI from the Municipal Regional Stormwater Permit. (PAGE 16)

Photograph by Laura Camp, courtesy of Creative Commons.

## CONCLUSIONS

**Urban trees and engineered GSI can be seen as complementary strategies,** where trees can reduce the amount of runoff needing to be treated by engineered GSI. (PAGE 32)

**Trees within the urban landscape could be part of a portfolio approach and multi-benefit assessment framework** to achieve runoff and load-reduction goals, while also providing additional ecosystem services, such as wildlife habitat, healthy soils, heat reduction, air quality improvement, and carbon storage. (PAGE 24, PAGE 33)

# Introduction

Rapid implementation of effective urban greening strategies is needed to address legacies of landscape change and environmental degradation, ongoing development pressures, and the urgency of the climate crisis. With limited space and resources, these challenges will not be met through single-issue or individual-sector management and planning. Increasingly, local governments, regulatory agencies, and other urban planning organizations in the San Francisco Bay Area are expanding  holistic, portfolio-based, and multi-benefit approaches.

**Both engineered GSI and non-engineered greening activities provide multiple benefits, but approaches are typically siloed, with engineered GSI used for stormwater management and non-engineered urban greening used to support other ecosystem services.**

A promising area of integration lies with stormwater management and urban planning, where both engineered green stormwater infrastructure (GSI) and non-engineered greening activities, such as the expansion of and improvements to the urban forest, provide multiple benefits. However, approaches are typically siloed, with engineered GSI used for reducing stormwater pollutant loads and non-engineered urban greening undertaken to support other ecosystem services (e.g., urban heat mitigation, carbon emission reductions, air quality improvements, and human health and well-being). Urban trees are particularly relevant at this intersection. They can play a role similar to GSI in stormwater management, suggesting that trees could be considered an integral part of the watershed-scale green infrastructure network (Berland et al., 2017; Kuehler et al., 2017). Quantified benefits of non-engineered urban greening elements such as trees is still an under-studied component due to complex processes and lack of evaluation and assessment tools that can integrate requirements for stormwater management, forestry hydrology, and benefit evaluation modeling. As a growing area of research, models and tools have been developed that can simulate and evaluate the hydrological benefit of urban trees, with some simplifications (Coville et al., 2020). Overall, improved technical approaches for evaluating the multiple benefits of both engineered and non-engineered urban greening activities are needed to facilitate integrated planning and achieve greater benefits at lower costs.

This project sought to expand the capacity for evaluating engineered GSI and non-engineered urban greening within a modeling and analysis framework, with a primary focus on evaluating the hydrologic benefit of urban trees. The first step was to advance the GreenPlan-IT toolkit (greenplanit.sfei.org), a modeling and optimization framework for analysis of GSI, such that it could represent hydrologic processes within the tree canopy. To explore the role of trees in stormwater runoff, several test case sensitivity analyses were conducted. These examined relative differences between deciduous and evergreen trees, street trees with different tree well sizes compared to impervious surfaces, and relative runoff changes across storm events with differing intensities. Third, a demonstration analysis was performed for the City of Sunnyvale to assess the degree to which trees at the landscape scale affect city-wide runoff. Additional considerations and explorations related to hydrologic impacts of trees are also provided. Finally, we explore a potential technical approach for expanded integrated multi-benefit assessment of urban greening. Overall, as part of the ***Healthy Watersheds, Resilient Baylands*** grant from the US Environmental Protection Agency Region IX Water Quality Improvement Fund, this work supports a watersheds-to-Baylands approach for redesigning urban landscapes for resilience through nature-based solutions.

## *Trees and Stormwater*

Urban stormwater runoff is a major pathway for pollutants to enter waterways, the Bay, and ocean. Rainfall interception by the tree canopy can reduce the magnitude of runoff generated during storm events, which mitigates associated erosion and reduces pollutant loadings to receiving water bodies. Previous research has indicated that the urban forest can substantially contribute to runoff reduction (Xiao et al., 1998). Stormwater benefits of trees results from both canopy interception and change in infiltration at the ground. The leaves and branches of tree canopies intercept and store rainfall, some of which evaporates and some of which drips to the surface below, thus reducing the volume of rainfall reaching the ground and altering stream hydrographs (Carlyle-Moses and Gash, 2011). Tree canopy interception is affected by storm event characteristics (e.g., magnitude, intensity), tree characteristics (e.g., species, age, health), and other weather variables (e.g., temperature, wind; Reid and Lewis, 2009; Li et al., 2017). The root system of trees facilitates the redistribution of water within the soil medium. The roots increase infiltration rates of land surface, allowing more stormwater to infiltrate and be retained in the soil matrix, thus reducing the runoff (Burgess et al., 1998). A recent study shows the root system of trees can increase the soil infiltration rate by more than 89% (Xie et al., 2020). The benefits of trees from increasing infiltration and soil water storage is affected by tree species, tree size/age, soil properties, and urban environmental limitations (Bartens et al., 2008; Wang et al., 2018). The evapotranspiration of trees can also adjust the water balance and thus influence runoff.

Given the stormwater benefits of urban trees, many state and municipal governments have established stormwater credit programs which grant runoff reduction credits for tree conservation and/or newly planted trees. The most common ways to provide credit for urban trees are through recharge volume, water quality volume, and reduction of impervious areas. The state of Minnesota credits via a process-based method where evapotranspiration, interception, and infiltration credits are given to individual trees of certain sizes (MPCA, 2020). The Chesapeake Bay Program considers tree canopy as a type of Best Management Practice (BMP) and gives water quality reduction credit to trees (Forestry Workgroup Chesapeake Bay Program Office, 2018). Pine Lake, GA and Washington, D.C. have applied stormwater volume reduction credit systems for individual trees. Other cities such as Portland, OR, Seattle, WA, Philadelphia, PA, and Indianapolis, IN, apply impervious surface reduction credit systems (Rosenstock et al., 2019). In California, Sacramento and South Placer regions (Sacramento and South Placer Regions, 2007; Sacramento County, 2018) suggest using an impervious surface reduction method to quantify the stormwater benefits of trees. For example, a new deciduous tree can offset the runoff from 100 $ft^2$ of impervious surface and a new evergreen gree can offset the runoff from 200 $ft^2$ of impervious surface. Within the San Francisco Bay Area, the current Municipal Regional Stormwater NPDES Permit does not credit urban trees.

# Tool development

## *Advancing GreenPlan-IT*

Quantifying the impact of urban greening and nature-based solutions for ecosystem resilience in urban landscapes is a growing field in academia and in practice. Including appropriate representation of trees in such assessments is important given the ecosystem functions and services trees provide, such as improving air and water quality, cooling urban heat islands, increasing biodiversity, and enhancing aesthetics, as well as reducing local flooding and associated contaminant loading to waterways. Nature-based solutions to address water quality issues associated with urban stormwater runoff typically center on the modeling, design, and placement of green stormwater infrastructure (GSI). These are typically highly engineered features for capturing and filtering runoff that contain vegetated elements (e.g., tree wells, bioretentions, flow-through planter boxes). Stormwater-focused modeling tools such as the US Environmental Protection Agency's (EPA) Stormwater Management Model (SWMM; Rossman, 2010) have developed detailed modules to represent varied hydrological processes of different design elements of GSI (e.g. drainage, storage, infiltration). While GSI tends to be well-represented in stormwater models, the representation of tree canopy is typically simplified as a type of land use, with the hydrological processes of the tree canopy represented as a fixed value depression storage. This simplification ignores the dynamics of canopy interception, throughfall, and stemflow with different rainfall patterns, intensities, and tree species. Most conventional stormwater models lack the capability to evaluate the hydrological benefits of trees for planning and design, such as representing the hydrological processes of tree species and planting designs, or the hydrologic impact of trees across a range of storm event types. For climates like that of Northern California, the mismatch between the rainy season and tree growing season means that canopy interception processes differ between evergreen trees and deciduous trees, which can affect stormwater budget estimation at different time scales. A more detailed representation of tree canopy processes within stormwater models could help address these environmental factors and help better quantify hydrological benefits of trees.

To better understand the stormwater runoff benefits of trees and support a broader urban greening perspective, the work presented here involved developing 1) a tool that can represent the varied hydrological processes within and under tree canopies, and 2) a method to evaluate the hydrological benefits of urban trees from a storm runoff perspective in a manner similar to evaluating hydrological benefits of GSI. We programmed the canopy interception and evaporation algorithms from the i-Tree software suite (itreetools.org) into SWMM (Rossman, 2010) to allow canopy hydrological processes simulation in SWMM (see the following section for technical details). i-Tree is one of the few tools focused on quantifying ecosystem services of trees, and the i-Tree Hydro tool evaluates individual tree benefits and aggregates them for the tree population. By coding i-Tree algorithms into SWMM, trees with different physical characteristics (e.g., species, size) can be represented under the same framework as GSI, thus the hydrological benefits of trees can be evaluated and compared with GSI. This newly updated SWMM extends the functionality of the GreenPlan-IT toolkit to a more general urban greening planning perspective.

**Adding a canopy module to the US EPA SWMM allows the simulation of vegetation-mediated hydrologic processes in green stormwater infrastructure modeling and analysis, improving quantitative assessments of tree contributions to runoff reduction.**

GreenPlan-IT (greenplanit.sfei.org) is a versatile planning-level toolset to help municipalities place GSI in effective locations within the landscape, evaluate expected runoff and contaminant load reductions, and track the effectiveness of these installations (Wu et al., 2019). GreenPlan-IT was designed to support the cost-effective selection and placement of GSI in urban watersheds through a combination of GIS analysis, watershed modeling, and optimization techniques. GreenPlan-IT comprises four distinct tools: (a) a GIS-based Site Locator Tool (SLT) that combines the physical requirements of different GSI types with local and regional GIS information to identify and rank potential GSI locations, (b) a Modeling Tool built on SWMM to establish baseline conditions and quantify anticipated runoff and pollutant load reductions from GSI sites, (c) an Optimization Tool that uses a cost-benefit analysis to maximize flow or load reduction objectives through combinations of GSI and tree types within the study area, and (d) a Tracker Tool that tracks GSI implementation and reports the cumulative programmatic outcomes for regulatory compliance and other needs (Figure 1). For this effort, the SLT was used to identify potential locations of trees, the updated SWMM was used to evaluate the effect of trees on runoff in a manner similar to GSI evaluation, and the Optimization Tool was used for a Monte Carlo simulation to examine the relationship between the number or cost of trees or GSI and runoff reduction. The Tracker Tool was not used.

In summary, the expansion of the Modeling Tool (SWMM) of the GreenPlan-IT toolkit allows trees of different characteristics and with different planting designs to be represented in SWMM via the new canopy module. We used this to explore how tree characteristics affect hydrological processes and how that changes across different storm event types. We conducted a demonstration analysis using the GreenPlan-IT toolkit for the City of Sunnyvale to assess hydrologic benefits of trees at the landscape scale.

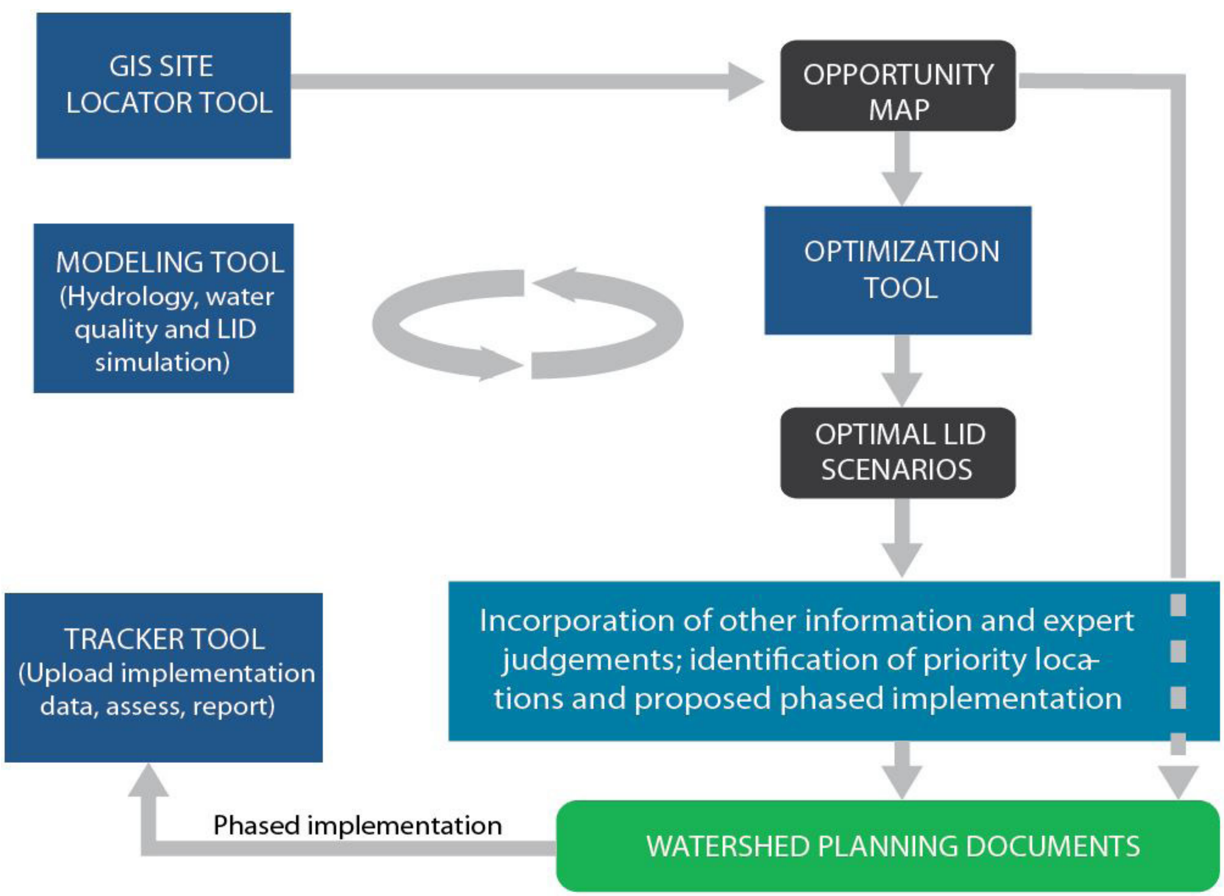



**Figure 1.** Diagram of the GreenPlan-IT toolkit (GSI Site Locator Tool, Modeling Tool, Optimization Tool, and Tracker Tool) and how they relate to one another.

## Tree canopy module for SWMM

The algorithms of the new SWMM canopy module are adopted from iTree-Hydro tool (Hirabayashi, 2013). The representation of hydrological processes within and through the tree canopy is shown in Figure 2 below. The canopy interception process can be divided into three stages as shown in Figure 2. The first stage begins at the onset of precipitation. In this stage, the precipitation reaches the canopy and fills the canopy storage until it is filled up or saturated. The second stage starts when the canopy storage is saturated. The subsequent precipitation falls through the canopy and reaches the ground. The third stage starts when the precipitation ends. The water stored in the tree canopy starts to dry up, gradually increasing available canopy storage to its maximum value.

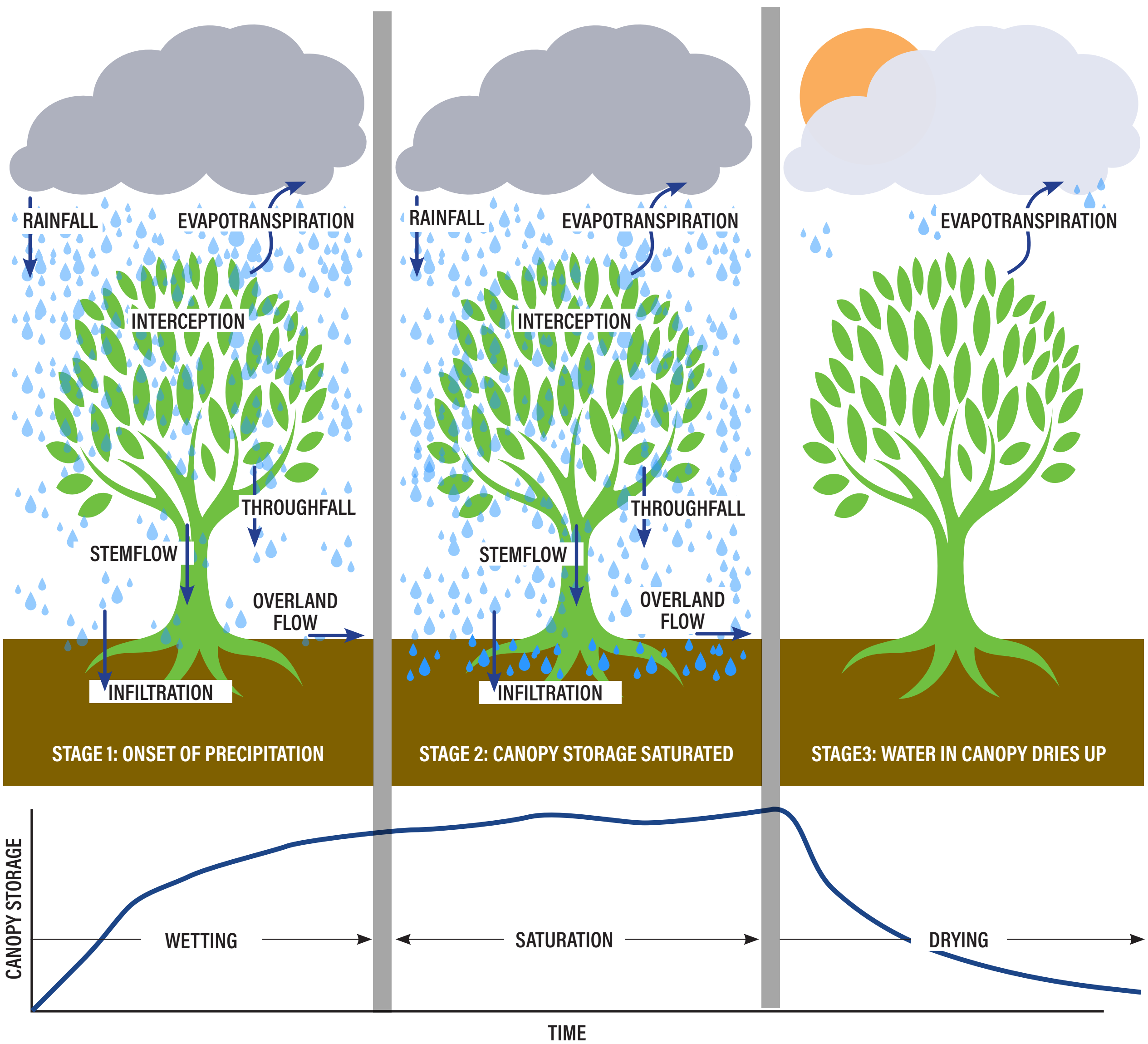



**Figure 2.** Tree canopy hydrological processes represented in the newly added tree canopy module of SWMM. The canopy storage time series follows the pattern of observational data (Modified from Xiao and McPherson, 2016).

During the first stage, the precipitation $(P)$ is divided into canopy precipitation $(P_c)$ and through precipitation $(P_t)$ that falls through the canopy. The water stored in canopy $(S_v)$ in this stage is a function of precipitation and canopy evaporation $(E_v)$

$$S_v(t) = S_v\,(t\text{-}1) + P_c\,(t)\text{ - }E_v\,(t\text{-}1)$$

$$S_v > 0 \text{ and } S_v <= S_{vmax}$$

The maximum canopy storage per unit canopy area is a product of leaf area index $(LAI)$ and specific leaf storage of water ($S_L$), both of which are well-studied tree characteristics that vary substantially depending on whether trees are deciduous or evergreen, the tree species, tree age, and other differences (Wang et al., 2008).

$$S_{vmax} = LAI\ S_L$$

The through precipitation at time $t$ is calculated as

$$P_t(t) = P(t)\ (1 - C)$$

$C$ is canopy cover fraction which is related to density of canopy. It is calculated as

$$C = 1 - e^{-kLAI}$$

$k$ is an extinction coefficient (0.7 for trees, 0.3 for shrubs. 0.7 was used in this project; Wang et al., 2008).

The canopy precipitation at time $t$ is the difference between $P$ and $P_t$

$$P_c(t) = P(t) - P_t(t)$$

Evaporation from canopy is calculated as

$$E_v(t) = PE(t)\ (S_v(t)/S_{vmax})^{2/3}$$

$PE$ is the potential evaporation rate. In the SWMM canopy module, it is represented as the product of the actual evaporation rate $(E)$ and the inverse of the vegetation evaporation coefficient $(V_c)$. The actual evaporation rate $(E)$ value is from the evaporation simulation results of SWMM. Vegetation coefficients are based on a standardized reference and are computed as the ratio of vegetation evapotranspiration to the reference evapotranspiration (Corbari et al., 2017).

$$PE(t) = E(t)/V_c$$

If $S_v$ is equal to $S_{vmax}$, the second stage starts. The canopy storage stays constant if the precipitation is larger than the evaporation. The $P_t$ at the second stage is calculated as

$$P_t(t) = P(t)\ (1 - C) + P_c(t) - E_v\,(t)$$

Once precipitation stops, the third stage starts. The water stored in the canopy is reduced through evaporation until the canopy storage reaches the maximum or the next precipitation event occurs

$$S_v(t) = S_v(t - 1) - Ev(t\text{-}1)$$

## *Tree representations with the canopy module*

The canopy module developed through this project was added as a new feature for the Low Impact Development (LID) modules of SWMM. Different types of GSI are represented in SWMM by different combinations of modules. For example, bioretention with an underdrain could be represented using the combination of surface, soil, storage, and drain modules. With the addition of canopy module in SWMM, individual trees are dynamically represented in a similar way as GSI, with the combination of canopy, surface, and soil modules. The canopy module contains several parameters to distinguish varied canopy structures of different trees (e.g., leaf area index, extinction coefficient, vegetation evaporation coefficient, canopy size). With the combination of the canopy module and the modules representing conditions under the tree canopy, both tree species and planting designs can be distinguished in SWMM. Design features such as tree wells, curbs, and drainage areas that are routed to the tree well can be added into the model by setting the parameters of surface and soil modules. By treating trees in the same way as LID/GSI in SWMM, trees can be modeled as individual treatment features within a subwatershed or modeled as their own specific treatment subwatershed that receives stormwater runoff from other subwatersheds.

Photograph by Robin Grossinger, SFEI.

# Hydrologic evaluation of tree types and storm events

To explore how different characteristics of trees and storm events affect the volume of stormwater runoff and demonstrate the capability of the updated SWMM, evergreen and deciduous trees growing in parks or yards (park tree) and along streets (street tree) were compared at the site scale. This took advantage of the flexibility to represent trees with varied forms and features in the canopy module along with existing surface and soil modules in SWMM. In the Mediterranean climate of Northern California, rains come in winter when deciduous trees have lost their leaves. Evergreen trees thus have greater canopy storage during the rainy season than deciduous trees. These two types of trees were distinguished in this analysis by assigning different canopy storage volumes (based on LAI and specific leaf storage). We used parameters representing typical or average-sized trees, based on trees within the City of Sunnyvale. Another important factor to consider when simulating trees in urban settings is the imperviousness of the land surface under the tree canopy. Unlike trees grown in residential yards and parks, the trees planted in the streets have a large portion of impervious land surface under the canopy. In this study, street trees and park trees were distinguished by different degrees of imperviousness under the canopy. The four major tree types considered were: evergreen park tree, deciduous park tree, evergreen street tree, and deciduous street tree. Some major features of these four types of trees as represented in the canopy module are shown in Table 1 and discussed further in subsequent sections.

A hypothetical one-acre test watershed was used to evaluate the hydrologic response to different tree characteristics. The soil parameters were constant across all scenarios. The slope of the test watershed was set as the average slope value of the City of Sunnyvale. To account for impervious surfaces that are not directly connected to stormwater catch basins, 25% of stormwater runoff from impervious surfaces was routed to pervious surfaces. As a test case to simplify interpretation, the one-acre watershed was assumed to have 100% tree canopy coverage.

**Table 1.** Tree parameters used in the SWMM canopy module demonstration analysis. Canopy storage per unit area was derived from Xiao and McPherson (2016). Canopy area was determined from products based on LiDAR and aerial imagery analysis.

| Tree types | Max canopy storage per unit area (in) | Canopy area (ft$^2$) | Pervious surface area under canopy/ tree well (ft$^2$) | Berm height (in) | Soil depth (in) | Infiltration rate (in/hr) |
|---|---|---|---|---|---|---|
| *Evergreen street tree (S, M, L tree well)* | 0.04 | 450 | 8, 18, 30 | 3 | 21 | 0.06 |
| *Evergreen park tree* | 0.04 | 450 | 450 | 0 | 21 | 0.06 |
| *Deciduous (leaf-off) street tree (S, M, L tree well)* | 0.01 | 450 | 8, 18, 30 | 3 | 21 | 0.06 |
| *Deciduous (leaf-off) park tree* | 0.01 | 450 | 450 | 0 | 21 | 0.06 |

## *Comparing deciduous and evergreen trees*

The major difference between evergreen and deciduous trees in terms of model representation is the maximum canopy storage volume (a function of LAI and specific leaf storage). Average canopy storages per unit canopy area of 20 northern California tree species (both evergreen and deciduous) are 0.030 inches for broadleaf deciduous, 0.031 inches for broadleaf evergreen and 0.049 inches for coniferous evergreen, and stem and branch surface storage for broadleaf deciduous (i.e., leaf-off) is ~0.01 inches (Xiao and McPherson, 2016). In this study, the average canopy storage value of broadleaf evergreen and coniferous evergreen was assigned to evergreen trees (see Table 1). The stem surface storage for broadleaf deciduous was assigned to deciduous trees with the assumption that leaves are off when most storm events occur. Thus, for this analysis, the maximum canopy storage of an evergreen tree is four times larger than a leaf-off deciduous tree of the same size.

A simplified 'big-leaf' model was used to represent the canopy structure. The product of the canopy storage per unit area and the canopy size is the total canopy storage capacity. The average tree canopy size was derived from EarthDefine data (EarthDefine, 2018). The EarthDefine tree canopy dataset, derived from 2006 LiDAR and 2016 NAIP imagery, is the most recent high resolution information found depicting tree canopy for the City of Sunnyvale study area. Total canopy area and individually identified trees were used together to estimate an average individual tree canopy area for all trees in the City of Sunnyvale. The average canopy size of all trees using the EarthDefine data is approximately 450 ft$^2$. The canopy size is the projected area of the canopy.

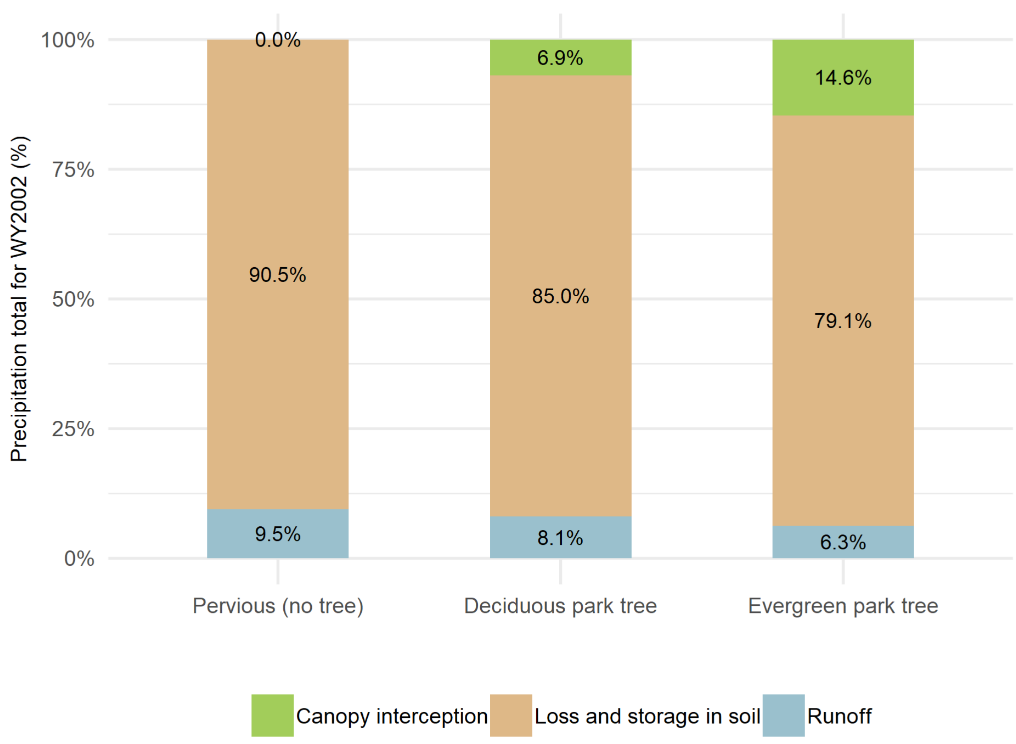
Photograph by Robin Grossinger, SFEI.

For this evaluation, the 2002 water year (WY) total precipitation (11.1 inches) for the City of Sunnyvale was used to drive SWMM to assess the runoff reduction due to evergreen versus deciduous trees for an average year. This year is considered a representative water year for PCBs and mercury stormwater loading which is recommended as a baseline year in the Bay Area Reasonable Assurance Analysis (RRA) Guidance (BASMAA, 2017). Using a water year as opposed to one or more individual larger design storm events is more representative of overall conditions because it includes a range of medium and larger storm sizes as well as low-magnitude, low-intensity rainfall, which is captured more effectively by trees than larger storms.

To highlight the differences in canopy characteristics of deciduous and evergreen trees and show the stormwater runoff benefit via canopy interception, hydrologic simulations of the one-acre test watershed for 100% pervious land surface without trees, with 100% coverage of evergreen trees, and with 100% coverage of deciduous trees were compared. Figure 3 shows the partition of rainfall for WY2002 into loss from canopy (canopy interception), loss and storage in soil, and runoff for the three different land cover scenarios. The canopy interception of evergreen trees is more than twice as large as that of deciduous trees. For this simplified test case, 15% of WY2002 rainfall was intercepted by evergreen tree canopy compared to 7% for deciduous tree canopy. The 15% or 7% less precipitation reaching the ground (throughfall) reduces the stormwater runoff, but not to an equal percentage. This is because the soil infiltration rate determines how much of this throughfall will run off. That is, precipitation lost from the tree canopy through interception would have otherwise gone to either soil infiltration or runoff. The size and intensity of rainfall events are also factors. Stormwater runoff is usually generated during large rainfall events and/or high intensity rainfall events when the soil matrix under the canopy is saturated or the rainfall rate exceeds the infiltration rate. While the tree canopy intercepts some portion of the rainfall, canopy storage is exceeded more quickly with large and high intensity rainfall events such that they are more likely to result in stormwater runoff under the canopy. This analysis shows that runoff reduction due to tree canopies above entirely pervious surface is 2% and 4% of annual rainfall (or, 20% and 40% of total runoff) for deciduous and evergreen trees, respectively.

**Evergreen trees in the model intercept more rainfall than deciduous trees in Northern California climates.**

**Figure 3.** Precipitation partitioning associated with three different land covers: pervious, deciduous park trees, and evergreen park trees. Analysis was conducted for the one-acre test watershed in the City of Sunnyvale for the 2002 water year (11.1 inches).



## *Comparing impervious surface with no trees to street trees*

This section assesses the hydrological benefits of adding street trees (with tree wells) to areas of impervious sidewalk or other surfaces. Trees along streets are usually planted in tree wells, with limited pervious surface under the canopy. The infiltration process is limited within tree wells. The size of tree wells, as well as the permeability of the substrate, influences the volume of stormwater that can infiltrate into the soil matrix. To explore this relationship, a sensitivity analysis was conducted using evergreen trees with three different tree well sizes: small (8 $ft^2$), medium (18 $ft^2$), and large (30 $ft^2$). The percentage of pervious surface area under the tree canopy was 2%, 4%, and 7%, respectively. For this analysis, a 3-in high berm was assumed to surround the tree well (allowing for some ponding and infiltration) and the stormwater runoff from the adjacent impervious surface was not routed into the tree well. A 2-year storm (1.86 inches) with 24-hour duration was selected to drive the simulation process (Schaaf & Wheeler, 2007). The distribution of the storm was derived from a normalized rainfall pattern recommended by the manual for use in Santa Clara County (Schaaf & Wheeler, 2007). The design storm simulation was conducted on the one acre test watershed.

**Increasing the tree well size for street trees substantially increases runoff reduction benefits.**

Simulations with evergreen street trees (450 $ft^2$ canopy size, see Table 1) with small, medium, and large tree wells were compared to a simulation with 100% impervious area. The stormwater runoff generated from 100% impervious area was 1.8 inches per unit area for the 1.86 inch design storm (97%). Tree canopy interception and tree well infiltration for the three different tree settings reduced the runoff from the 100% impervious conditions by 6.9%, 11.2%, and 15.5% of the storm event (Figure 4). Substantial stormwater runoff was generated for all three street tree scenarios due to the large percentage of

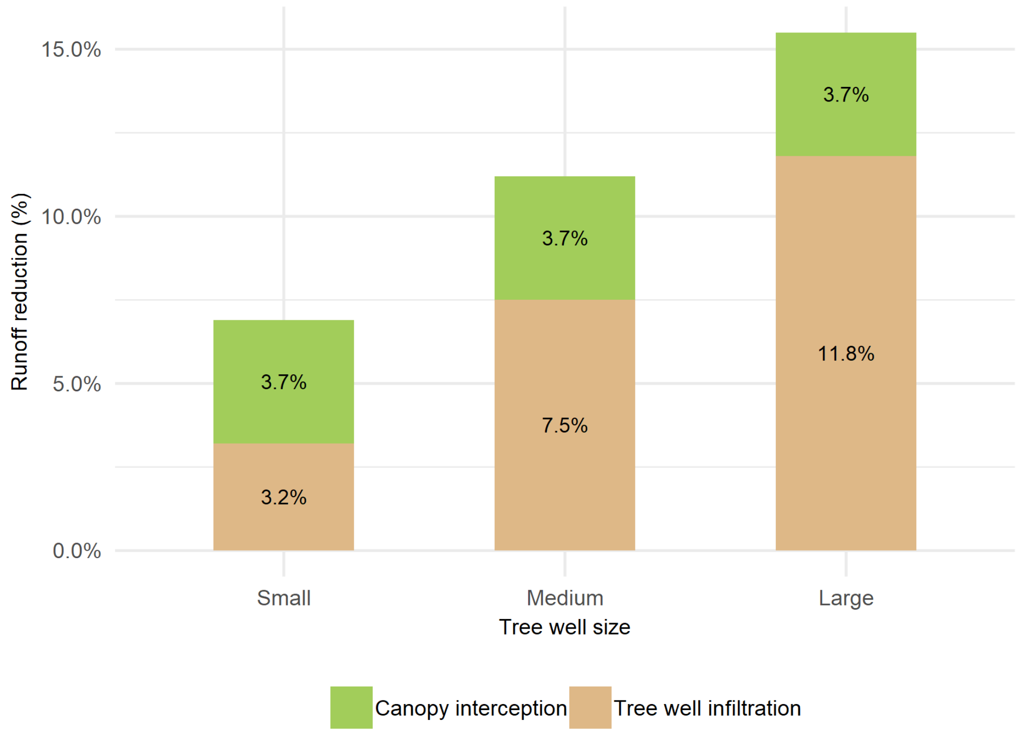


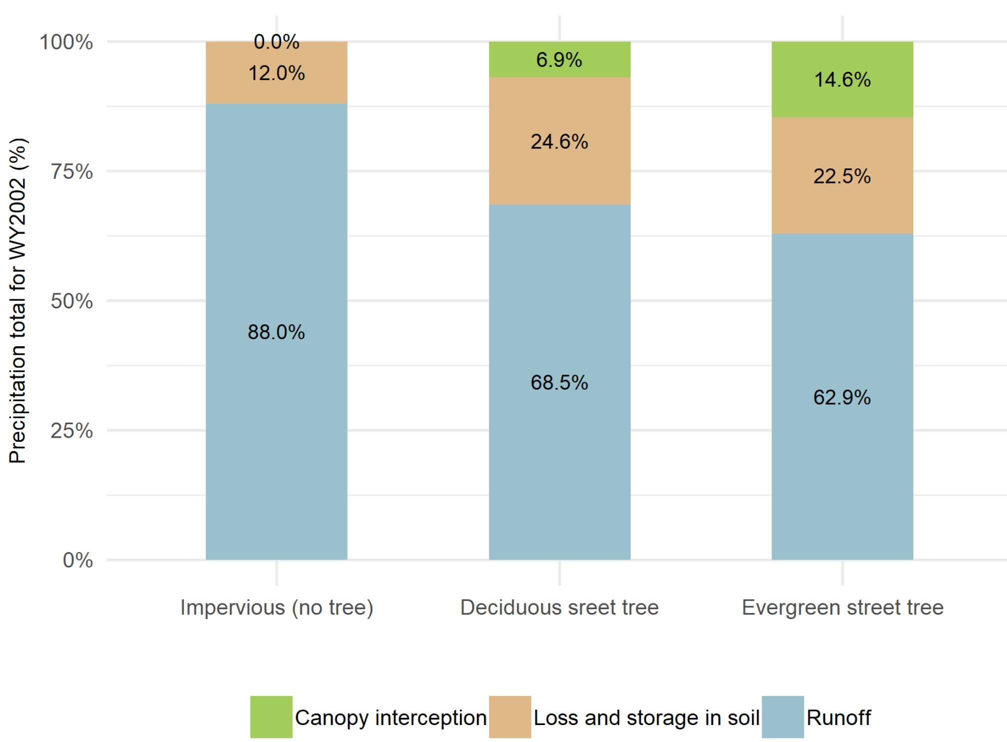

**Figure 4.** Reduced runoff as a percentage of a 2-year 24-hour design storm depth by evergreen trees with three different tree well sizes compared to runoff under 100% impervious land surface conditions (sidewalk or similar with no tree).

impervious area under the street tree canopies. Infiltration through tree wells reduced runoff per unit area by 0.06, 0.14, and 0.22 inches for the small, medium, and large tree well sizes. Runoff reduction increases as the size of the tree wells increases. Also, the 2-year 24-hour storm is a relatively large and intense storm. Thus, relatively more rainfall would be expected to pass through the tree canopy than for a smaller and less intense storm event. This is illustrated by the fact that rainfall intercepted by the tree canopy is 4% of the storm event (0.07 inches per unit area), which is much smaller than the 15% evergreen tree interception of WY2002. This indicates that the impact of canopy interception decreases with more extreme storm events, a logical outcome, which is explored further in the following section.

**Due to associated tree well replacement of impervious surface, street trees have larger runoff benefits compared to park or yard trees (of the same size).**

Similar to the analysis comparing deciduous and evergreen park trees, SWMM simulations were conducted to compare deciduous and evergreen street trees (100% coverage, medium tree well size) against 100% impervious coverage in the one-acre test watershed for WY2002 (note, there is no difference between street and park tree canopy interception in this analysis). Figure 5 shows the rainfall partitioning for the three scenarios. Much less stormwater can infiltrate into the land surface and be stored in the soil matrix in an urban setting with high imperviousness compared to more

**Figure 5.** Precipitation partitioning for three different land covers: impervious (no tree), deciduous street trees, and evergreen street trees. Analysis was conducted for the one-acre test watershed in the City of Sunnyvale for the 2002 water year (11.1 inches).



natural pervious settings. Thus, a large portion of precipitation intercepted by the canopy translates to reduction in stormwater runoff. Compared to the 100% impervious surface conditions where 88.0% of rainfall becomes runoff, an additional 19.5% and 25.1% of annual rainfall is intercepted by tree canopy and infiltrated into the tree well for deciduous and evergreen trees, respectively. The contribution of interception and infiltration are 6.9% and 12.6% for deciduous trees and 14.6% and 10.5% for evergreen trees, respectively. The larger canopy storage of evergreen trees intercepted 7.7% more stormwater and reduced 5.6% more runoff than deciduous trees.

## Relative benefit of trees across different storm events

As indicated by the previous analysis, the portion of rainfall intercepted by the tree canopy varies with storm intensity. A sensitivity analysis was conducted to further examine the impact of storm intensity on canopy interception and resulting runoff. The runoff reduction of street trees with 100% canopy coverage for the one-acre test watershed under six different design storm events were assessed. Four were storm events of current climate conditions (1-yr 24-hr, 2-yr 24-hr, 10-yr 24-hr, and 25-yr 24-hr) and two were future storm events (RCP8.5 2-yr 24-hr and RCP8.5 10-yr 24-hr). The rainfall depths of storm events for current conditions were acquired from NOAA point precipitation frequency estimates for the City of Sunnyvale (Perica et al., 2014), and rainfall depths for future events were derived from the extreme precipitation estimation of Cal-Adapt (cal-adapt.org/tools/extreme-precipitation). Downscaled daily precipitation data (6 km resolution) for the City of Sunnyvale from 10 global climate models (GCMs) of the more extreme RCP 8.5 scenario were analyzed and the average change ratio of the rainfall depths between the historical condition and the end of 21$^{st}$ century conditions were applied to the 2-year 24-hour storm and 10-year 24-hour storm to get the future rainfall depth of the same return periods. The design storm pattern from the Santa Clara Drainage Manual (Schaaf & Wheeler, 2007) was used to disaggregate daily rainfall depths to five minute intervals. Table 2 shows the rainfall depths of the six selected storm events. The change of storm pattern under future climate was not considered in this experiment, which can be further investigated in the future.

**Table 2.** Rainfall depths associated with four 24-hr storm events reflecting the current climate and two 24-hr storm events under future (end of 21st century) climate scenarios for the City of Sunnyvale.

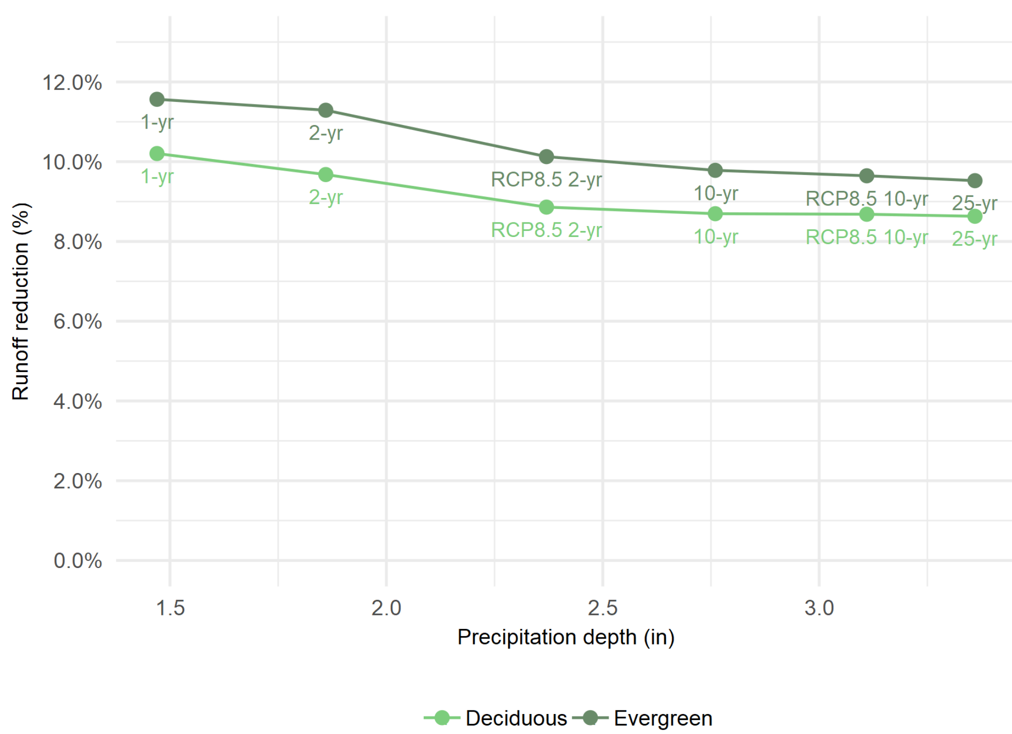
| Recurrence interval | 1-yr | 2-yr | RCP8.5, 2-yr | 10-yr | RCP8.5, 10-yr | 25-yr |
|---|---|---|---|---|---|---|
| *Rainfall depth (in)* | 1.47 | 1.86 | 2.37 | 2.76 | 3.11 | 3.36 |


Photograph by Dileep Eduri, courtesy of Creative Commons.

**Runoff reduction benefits of trees decline slightly with more extreme storm events, suggesting that more trees and GSI will be needed under a future climate to provide the same level of runoff reduction benefits as today.**

Figure 6 shows the percentages of runoff reduction of evergreen and deciduous street trees for the different storm events. As the storm events become more extreme, stormwater runoff reduction due to trees declines. The rate of decline is higher when the storm events are less intense (more frequent) and the changes become negligible for storm events larger than the 10-year recurrence interval. Evergreen trees, with their greater canopy interception compared to deciduous trees, show higher runoff reduction (reducing an additional 1 to 1.6% of total rainfall amount) across all storm events. With the expectation of increasing storm intensity and a greater proportion of rainfall occurring as intense storms in the future under climate change, the effectiveness of street tree runoff reduction would be expected to decline. For example, the runoff reduction declined 1.2% and 0.8% (of rainfall amount) for evergreen and deciduous street trees, respectively, between the current and future 2-year 24-hour storm event. This implies more runoff reduction solutions (more trees and GSI) will be needed in order to achieve the same runoff reduction under more extreme events associated with climate change. Future changes of other meteorological variables such as temperature were not considered in this comparison, by assuming the impacts is negligible at the single storm event scale. Future changes of other meteorological variables such as temperature were not considered in this comparison (by assuming the impacts is negligible at the single storm event scale).

**Figure 6.** The percentage of reduced runoff from different storm events by evergreen and deciduous street trees.



# Trees at the landscape scale

For a demonstration analysis of the tree canopy module for SWMM, a city-wide model in SWMM previously established for the City of Sunnyvale was updated and used to evaluate the hydrologic impact of trees at the landscape scale. The overall approach was to conduct hydrologic modeling representing conditions with and without existing trees within Sunnyvale for a typical water year. The output from the "no-tree" and "tree" modeling scenarios were then compared.

## *The City of Sunnyvale study area*

The City of Sunnyvale is one of the major cities in Santa Clara County and part of Silicon Valley, with an area of 22.8 square miles (14,600 acres) and a population of over 152,000 people. The average annual precipitation of the City of Sunnyvale is ~14 inches. Its land uses are primarily residential, industrial, and commercial. Like many cities in the Bay Area, Sunnyvale has undergone significant growth over time and experienced environmental issues typically associated with urbanization, including increased loadings of sediment, PCBs, mercury, and pathogens. Sunnyvale is regulated by the Municipal Regional Stormwater NPDES Permit (MRP; SFBRWQCB, 2015), and stormwater management is a driver for a number of Sunnyvale plans, activities and area-wide programs. Due to recognized benefits as well as regulatory requirements, cities are increasingly turning to nature-based solutions to address urban challenges such as stormwater runoff and associated contaminant loading. In its recent Green Stormwater Infrastructure Plan (City of Sunnyvale and EOA, Inc., 2019), Sunnyvale articulates its goals for shifting from traditional "gray" stormwater infrastructure to GSI. Beyond stormwater and water quality benefits, the plan recognizes the additional benefits these features offer over traditional stormwater infrastructure, including improved air quality, increased water supply, urban heat reduction, safer streets, and wildlife habitat. Sunnyvale's recent Caribbean Drive Green Street project is an example of urban greening that uses GSI to also provide human safety and recreation as well as ecological benefits.

Like many cities, Sunnyvale is engaged in a wide range of urban greening activities. Its Urban Forest Management Plan was established with the goal of maintaining and enhancing the benefits of Sunnyvale's urban forest, primarily through its Street Tree Program (Bernhardt et al., 2014). Currently, tree canopy covers ~18% of Sunnyvale (both public and private trees) and ~11% of street tree planting spaces (public places only) are vacant. The urban forest plan proposes to increase overall canopy cover to 20.5%, or an additional 15,000 trees in residential areas and 14,000 trees in commercial areas. This plan also recognizes the importance of coordination across departments so that activities provide mutual benefits across programs.

The study area for this analysis covers the majority of the City of Sunnyvale and covers an area of 20.9 square miles (13,386 acres). Within the Sunnyvale boundary, the analysis focused on three major watersheds (Sunnyvale West Channel, Sunnyvale East Channel, and Calabazas Creek) which cover about 27%, 26%, and 33% of the Sunnyvale footprint, respectively (86% combined; Figure 7; Wu et al., 2018). This application built upon prior work that used the SWMM Modeling Tool for the City of Sunnyvale (Wu et al., 2018). All three watersheds in the City of Sunnyvale were delineated and subdivided into a total of 215 subwatersheds based on their connections and flow direction. These subwatersheds range from 4.6 to 173 acres in size.

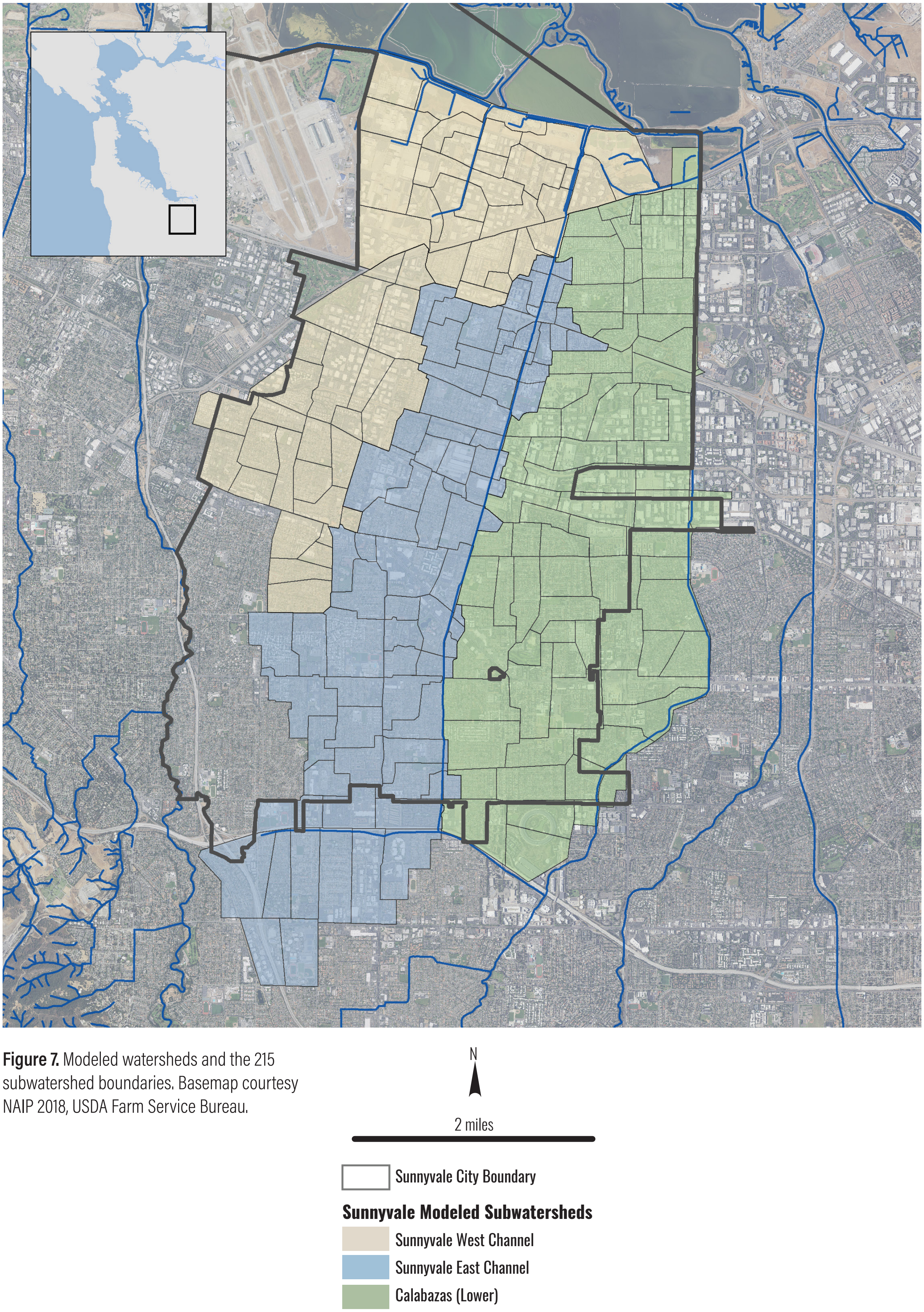



**Figure 7.** Modeled watersheds and the 215 subwatershed boundaries. Basemap courtesy NAIP 2018, USDA Farm Service Bureau.

## SWMM setup

Detailed information describing the input data that were used to set up and calibrate the model in SWMM for the City of Sunnyvale are documented in Wu et al. (2018). The original model was considered as a baseline model to conduct hydrological simulations for WY2002. Hourly rainfall data were obtained for WY2002 from a gauge at the Sunnyvale wastewater treatment plant maintained by Valley Water (Santa Clara Valley Water District, alert.valleywater.org/map). A basic quality assurance assessment was completed for these data that involved checking the data at a monthly time step against other neighboring NOAA rainfall station locations, graphical inspection of the data, and comparison of the data to the frequency depth duration published in the NOAA 14 Atlas (Perica et al., 2014). The total annual rainfall for this station was 11.1 inches in WY2002. The 2002 water year is considered as a reference year for PCBs and Hg TMDLs, and is thus a useful year for stormwater management in terms of water quality.

The baseline model in SWMM is used to provide the stormwater runoff simulation results of WY2002. The current number and types of trees in each subwatershed of Sunnyvale were identified and then the newly updated SWMM with the canopy module was used to add trees into the baseline model. The differences in the simulation results between the baseline and current trees scenarios were used to examine the hydrologic impact of trees at the landscape scale.

## Identifying and characterizing Sunnyvale trees

The number of trees and their primary characteristics (e.g., species, age/size, street or park tree) affect hydrologic processes at the landscape scale. For the SWMM application to Sunnyvale, we determined the existing number of trees per subwatershed (Figure 8), the proportion of deciduous versus evergreen trees, and proportion of park versus street trees (Figure 9).

To identify existing tree locations and determine the number of trees per subwatershed, we used spatial data of tree coverage derived from 2006 LiDAR and 2016 NAIP imagery (EarthDefine, 2018). The proportion of deciduous and evergreen trees was established using existing classified vegetation cover data (USGS, 2016). Though vegetation classes allow for separation of deciduous and evergreen tree coverage, the resolution is relatively coarse (30 m). Given the low resolution of the data, a city-wide ratio of deciduous versus evergreen trees was assessed. Additionally, trees were distinguished as either street trees or park (or yard) trees based on proximity to streets. Specifically, street trees were identified as those trees (from the EarthDefine dataset) within 43 feet of a street centerline, or within 10 feet of the edge of the right of way (defined as the edge of parcel polygons that were merged together). All other tree polygons were defined as park trees (see Figure 9 for an illustration of the outcome from this approach).

This analysis produced an estimated total of 236,335 trees (both public and private) with 18% canopy cover within the modeled subwatersheds of Sunnyvale, which aligns with the 2014 Sunnyvale Urban Forestry Plan's estimate of 231,000 trees (~18% canopy cover) in Sunnyvale (Bernhardt et al., 2014). For the evergreen and deciduous tree assessment, the ratio was found to be 6.7% evergreen, 83.9% deciduous, and 9.4 % mixed evergreen/deciduous. This contrasts with the Sunnyvale street tree inventory (public only), which reported 47% evergreen (8% conifer) and 52% deciduous trees (Bernhardt et al., 2014). However, the street trees in this inventory represent less than 16% of total trees in Sunnyvale and may not be representative of the total population. Given the assessed dominance of deciduous trees, all trees for the city-wide analysis were evaluated as deciduous trees. This is a conservative approach that

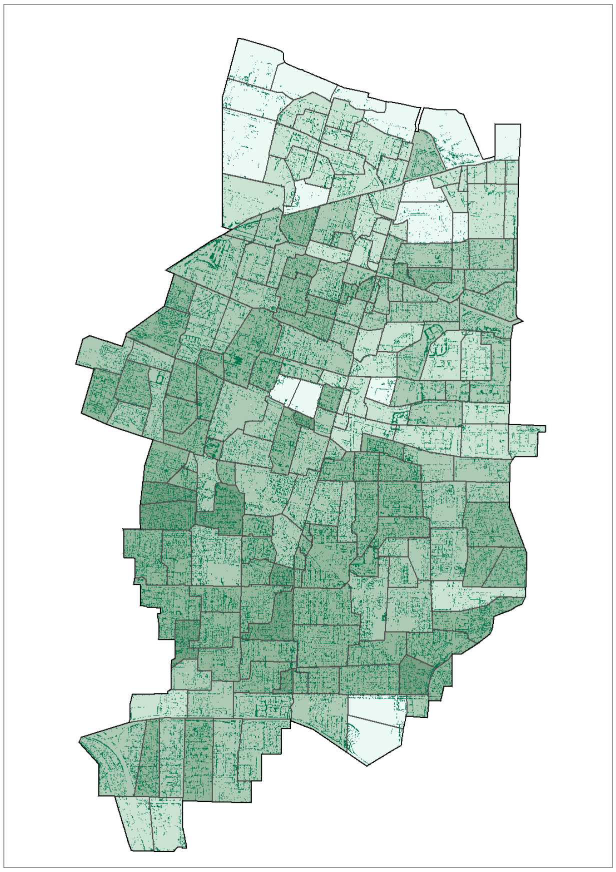



**Figure 8.** Existing trees within the City of Sunnyvale's modeled sub-watersheds. Tree dataset courtesy EarthDefine (2018).


**Figure 9.** Example of how EarthDefine tree polygons were classified as street trees or park trees. Tree dataset courtesy EarthDefine (2018). Basemap courtesy NAIP 2018, USDA Farm Service Bureau.

likely underestimates the runoff reduction impacts of current trees. Across the modeled subwatersheds for Sunnyvale, 48.3% of trees were classified as park trees and 51.7% were classified as street trees. The number of assigned street trees in this analysis is over three times the number of street trees in the Sunnyvale street tree inventory and thus captures trees that may not be maintained by the City of Sunnyvale as street trees, but likely have characteristics of street trees (e.g., impervious surface beneath much of the tree canopy).

## *City-wide runoff results*

Using the tree characterization, the City of Sunnyvale model in SWMM was updated to include the estimated number of street and park trees in each subwatershed. The reference WY2002 was applied to both the baseline model and the model with trees added. Figure 10 shows the runoff depth of each subwatershed under the baseline and current trees scenarios. The majority of runoff is generated in lower elevation areas of the watershed where there are higher proportions of impervious area. The runoff coefficients for subwatersheds range from 0.19 to 0.67.

**(a) Baseline Modeled Runoff (in)** **(b) Modeled Runoff with Trees (in)**

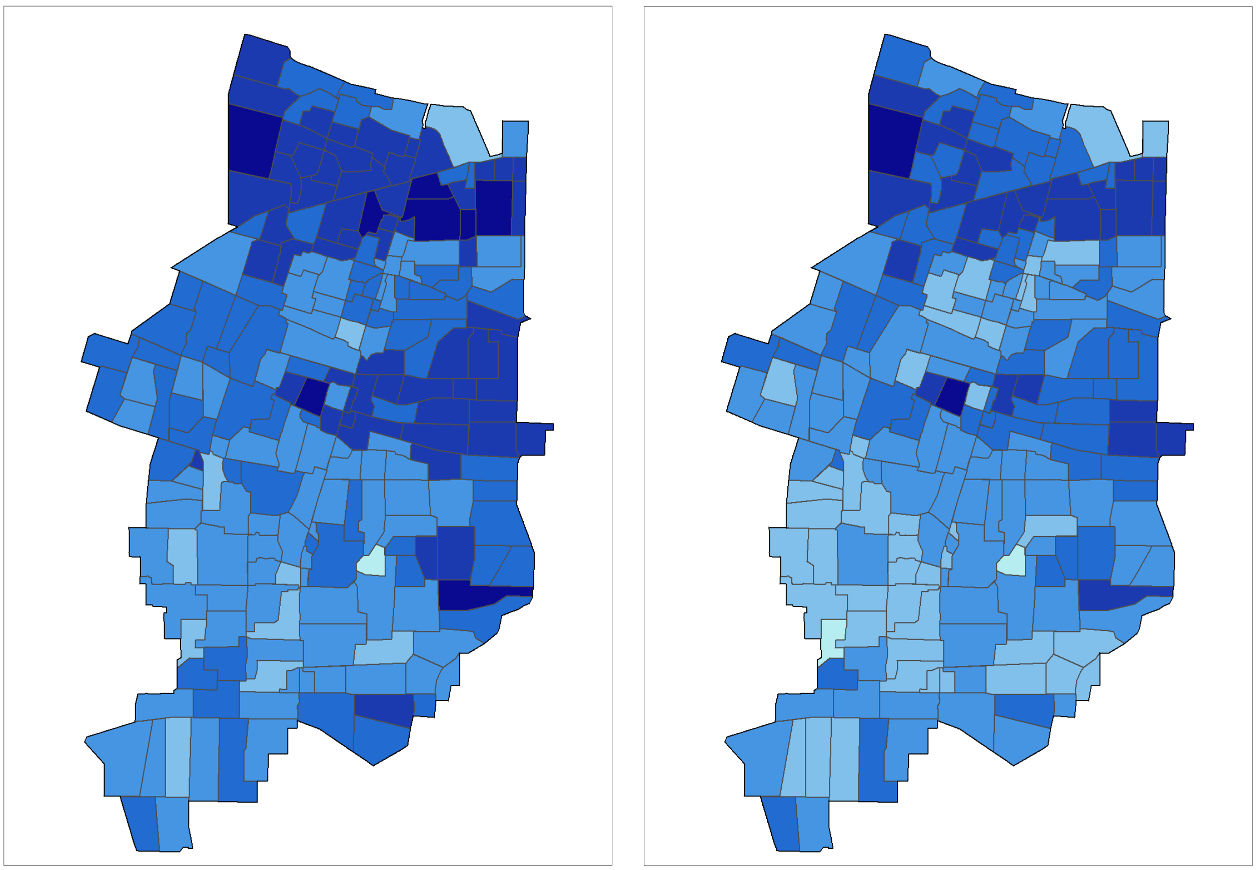
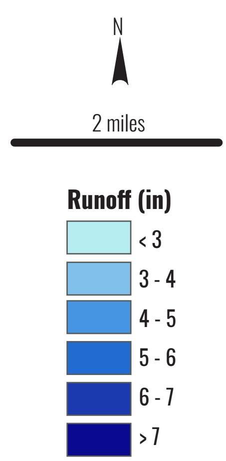


**Figure 10.** Modeled runoff depths for each subwatershed in the City of Sunnyvale study area for (a) baseline conditions and (b) conditions including the explicit hydrologic effects of trees (based on the estimated 236,335 trees currently in Sunnyvale).



The difference in runoff depths between the two scenarios for each subwatershed shows the stormwater runoff reduced due to trees. This is illustrated in Figure 11, where the reduced runoff depth per unit area for each subwatershed is normalized by the WY2002 annual rainfall depth. The reduced runoff ranges from 1.4% to 9.5% of the annual rainfall across the Sunnyvale subwatersheds. The subwatersheds with a higher density of street trees are associated with larger runoff reduction benefits, as shown in the inset plot of Figure 11.

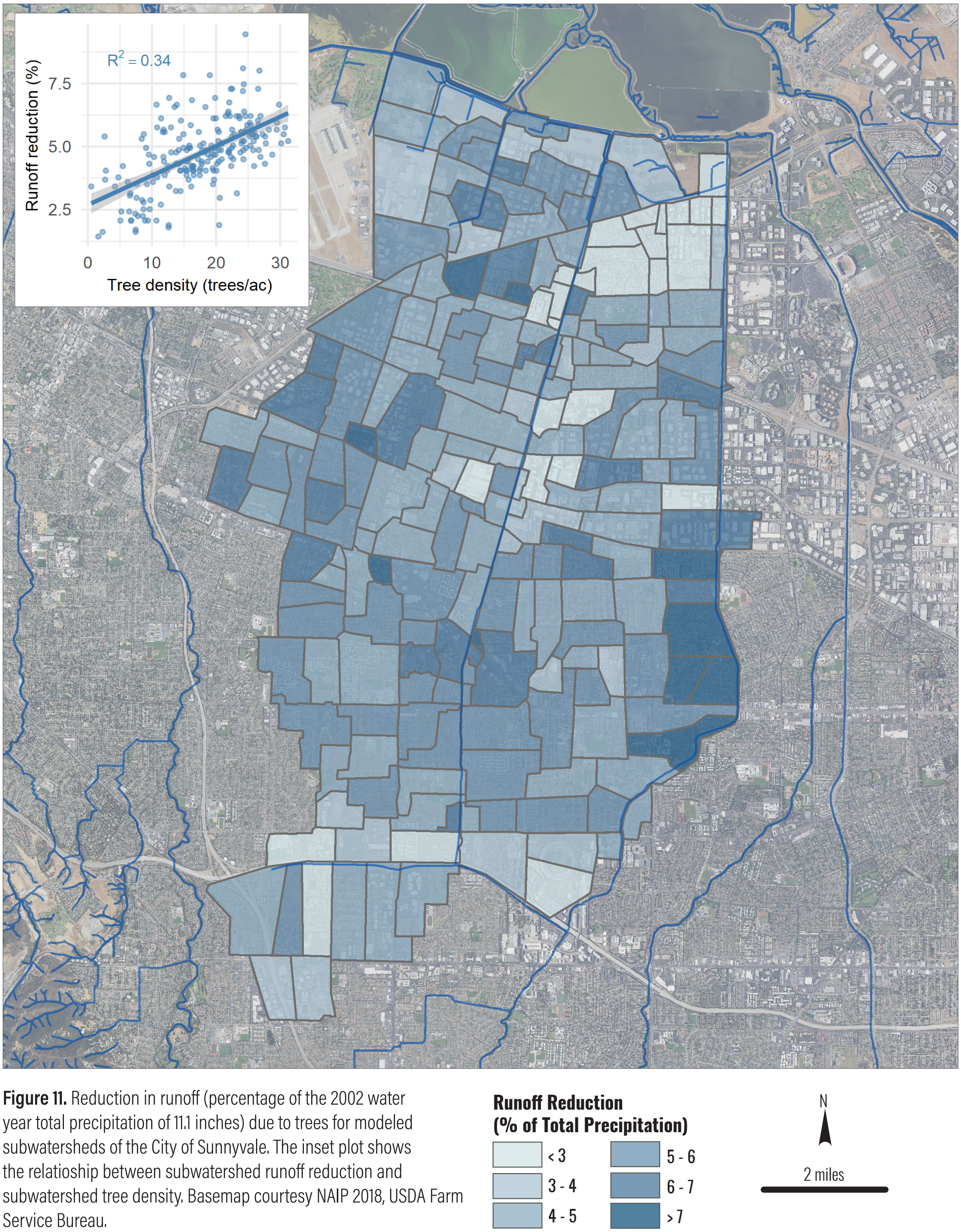
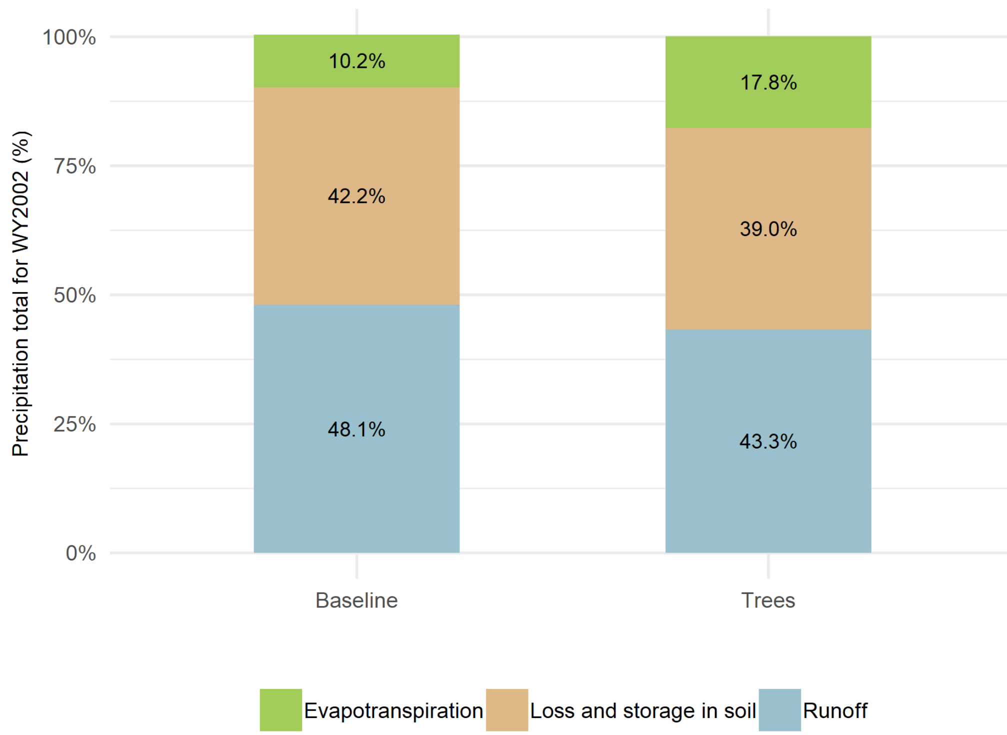



**Figure 11.** Reduction in runoff (percentage of the 2002 water year total precipitation of 11.1 inches) due to trees for modeled subwatersheds of the City of Sunnyvale. The inset plot shows the relatioship between subwatershed runoff reduction and subwatershed tree density. Basemap courtesy NAIP 2018, USDA Farm Service Bureau.

**At the landscape scale, current trees in the City of Sunnyvale are estimated to be reducing runoff by ~5% of annual rainfall.**

The total runoff generated for each scenario was compared to show the overall impact of current trees in Sunnyvale. Figure 12 shows that for WY2002, the current trees in Sunnyvale evaporated 7.7% more of annual rainfall than the baseline scenario. The increase of evaporation is mainly due to interception and evaporation at the canopy layer. This increased evaporation translates to reductions in both infiltration as well as runoff. With 18% mixed coverage of both street and park trees in Sunnyvale, this demonstration analysis suggests that the stormwater runoff reduction benefit is 4.6% of annual rainfall. This number agrees well with previous research results. For example, the avoided runoff due to urban canopy at the landscape scale range from 0.6% to 2.6% with a canopy cover from 5% to 13% (Xiao et al, 1998).

**Figure 12.** Rainfall partitioning of the 2002 water year for the City of Sunnyvale with trees ('Trees') and without trees ('Baseline').



# Exploring future analysis directions

The demonstration analysis described in the previous sections is a proof of concept approach that illustrates the hydrologic significance of trees within urban landscapes and the potential for trees to play an important role in stormwater management as elements of urban greening strategies. Further analysis will be necessary to more fully evaluate the hydrologic role of trees with varying characteristics and to incorporate trees into typical management evaluations for regulatory purposes and site-specific design guidance. The following sections include initial analysis and suggested directions for next steps.

## *Tree characteristics: Growth and age*

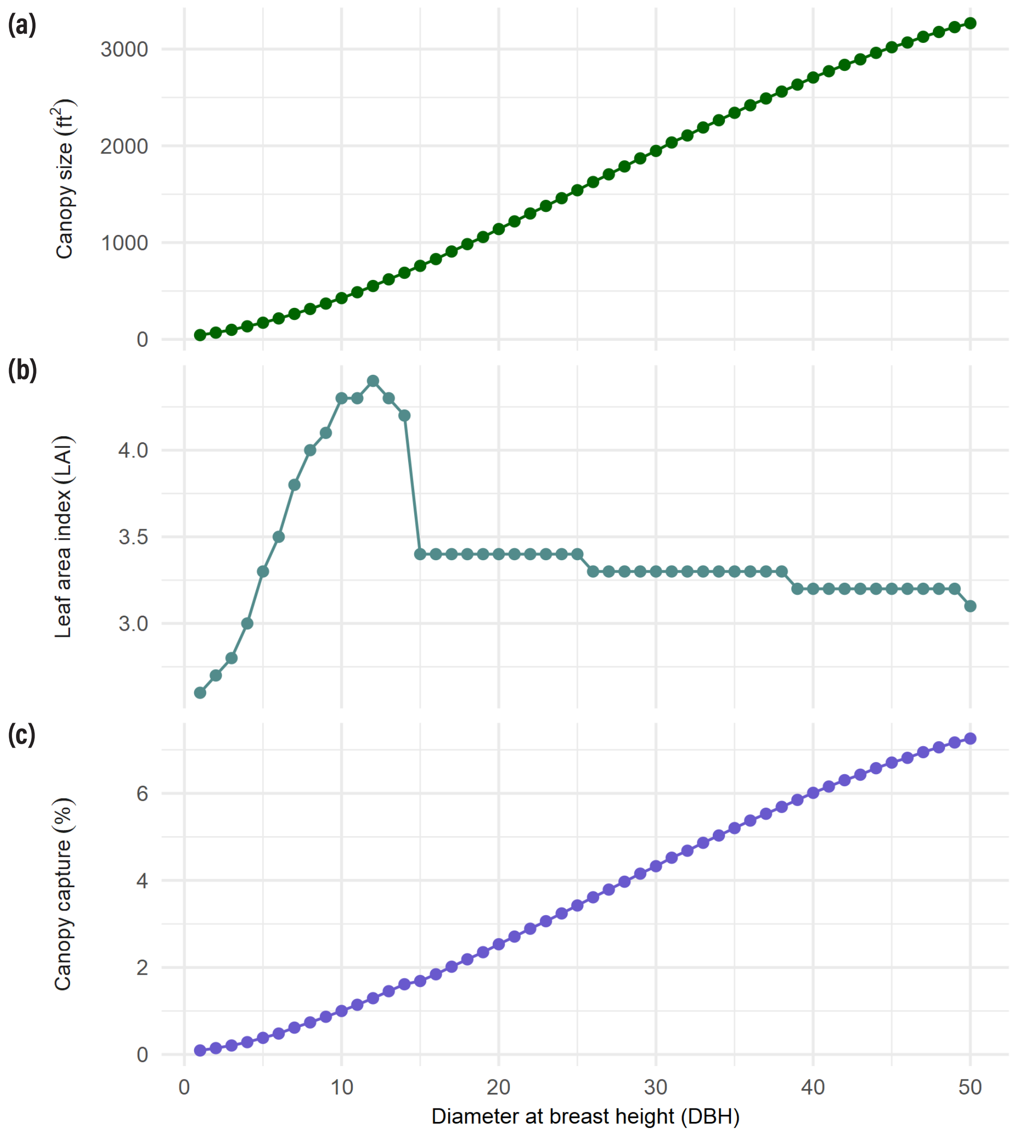
Tree canopy interception and evapotranspiration are closely related to canopy size and structure. These characteristics are highly variable across trees of different ages and species. They also vary over time, seasonally and inter-annually. Tree canopy size and leaf area index (LAI) are two parameters that adjust the interception and evaporation processes in the new canopy module of SWMM. For an initial investigation of the impact of tree sizes on the canopy interception, a common native evergreen species, coast live oak (*Quercus agrifolia*), was selected for a sensitivity analysis.

The canopy size and LAI parameters for coast live oak with a DBH (diameter at breast height) from 1 to 50 inches (1 inch interval) were extracted from the i-Tree database (database.itreetools.org; Figure 13a and 13b). A test watershed of one acre and 100% tree canopy coverage was established in SWMM and run for each of the tree sizes. The 2-year 24-hour storm was used for the canopy interception evaluation. Figure 13c shows the percentage of rainfall volume captured per tree across the different sizes. The percentage ranges from ~0% to ~7% and is nearly directly proportional to canopy size. Given the wide range of canopy size and more limited variation in LAI, canopy size is the primary factor determining capture volume. Similar analyses could be conducted for other common species to provide greater insight into the range of expected canopy capture depending on species and size.

The range in rainfall capture indicates the size of trees and the time for newly planted trees to grow to desired sizes should be considered when planning to use trees as a nature-based solution for stormwater management. The factor of tree size is also relevant to differences between street and park trees as the growth and longevity of street trees is often more limited than park or yard trees due to planting space (volume of soil and tree well size), maintenance, and other environmental factors. Improved understanding of how much these factors influence the hydrologic impact of trees in combination with cost-benefit assessments of planning for and maintaining larger and healthier street trees could help guide planting and management practices.

Photographs by Robin Grossinger, SFEI.

**Figure 13.** Tree size relationships. Tree canopy (a) and leaf area index (LAI; b) of coast live oak are shown as they relate to diameter at breast height (DBH), with values derived from the i-Tree database (database.itreetools.org). In (c), the percentage of rainfall volume captured from a 2-year 24-hour storm event is shown.




Photographs by Shira Bezalel, SFEI.

## *Stormwater management perspective*

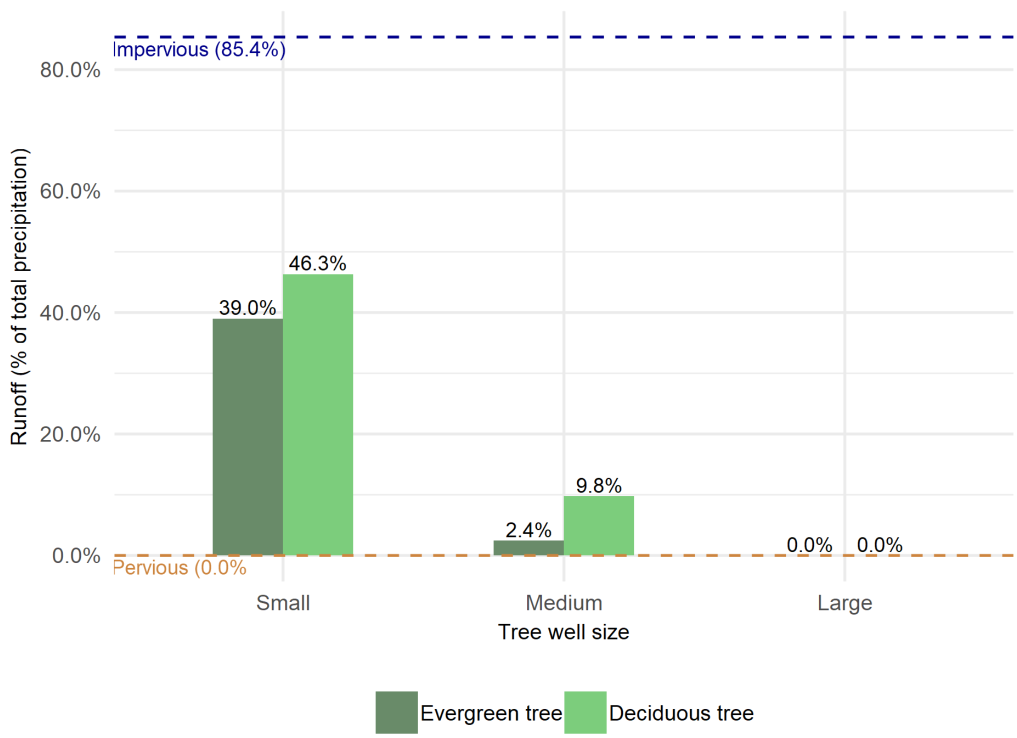
From a stormwater regulatory perspective, urban trees have been credited in various ways across the country (Center for Watershed Protection, 2017). The newly updated SWMM offers an approach for quantifying the stormwater benefit of trees in the same way as GSI. Thus, the tool can be used to evaluate trees with the sizing criteria for GSI from the Municipal Regional Stormwater NPDES Permit (MRP 2.0; SFBRWQCB, 2015). For a demonstration approach here, the hydraulic sizing volume-based criteria for treatment best management practices from MRP 2.0 was selected to evaluate the performance of street trees: "The maximized stormwater capture volume for the area on the basis of historical rainfall records… (e.g. approximately the 85$^{th}$ percentile 24-hour storm runoff event)" (SFBRWQCB, 2015). If a street tree can be considered as a self-treating unit, it should capture all the stormwater from the 85$^{th}$ percentile 24-hour storm event. For this exploratory analysis, an 85$^{th}$ percentile daily rainfall depth of 0.37 inches was determined based on daily rainfall data at Moffett Airport (a NOAA site with long term precipitation records). This was corrected to 0.41 inches using a 1.12 correction factor from the NOAA Atlas 14 (Perica et al., 2014) to account for the difference of the rainfall depths between constrained and unconstrained 24 hours (daily vs. any consecutive 24 hours).

**The newly updated SWMM can quantify stormwater benefits of trees in the same way as GSI, allowing trees to be evaluated with the sizing criteria for GSI from the Municipal Regional Stormwater Permit.**

Photograph by Richard Masoner / Cyclelicious, courtesy of Creative Commons.

This analysis found that street trees with larger tree wells can be considered as self-treated areas. Trees with small (8 $ft^2$) and medium size tree wells (18 $ft^2$) cannot capture all the stormwater of a 85$^{th}$ percentile 24-hour event. However, evergreen street trees with medium size tree wells captured nearly all of the stormwater runoff (97%) and could thus be considered a self-treated area with slightly larger tree wells. To complete the analysis, design storm depth was disaggregated to a five minute interval to run eight simulations for a one acre test watershed with 100% evergreen and deciduous street tree coverage for three tree well sizes and with 100% pervious and 100% impervious land surface. Unlike previous analyses that did not route the runoff from adjacent impervious areas into the tree wells, all stormwater runoff from the impervious surface under the tree canopy was routed into the tree wells, which treated the street tree as a whole self-treating unit (a recommended design to maximize the infiltration of street trees). Figure 14 shows runoff depths of a 85$^{th}$ percentile 24-hour storm event from the different land covers. Street trees with larger tree wells can be considered as self-treating areas. Trees with small (8 $ft^2$) and medium size tree wells (18 $ft^2$) cannot capture all of the stormwater of an 85$^{th}$ percentile 24-hour event. However, evergreen street trees with medium size tree wells captured nearly all of the stormwater runoff (97%) and could thus be considered a self-treating area with slightly larger tree wells. The results detailed above demonstrate that tree wells can treat more stormwater than that derived from their footprints, which has implications for design considerations.

**Figure 14.** Runoff depth from different land surfaces (pervious (P), impervious (IMP), street trees with small (S), medium (M), and large (L) tree wells) after a 85$^{th}$ percentile 24-hour storm event.



## *Design perspective*

There may be adjustments to site design criteria for tree planting that could increase stormwater benefits. The previous analysis showed that a tree well can treat stormwater runoff from a larger surface area than its own well size. This suggests that additional runoff benefits could accrue if stormwater runoff from adjacent areas was routed to the tree well (e.g., via surface grading or curb cuts). The previous analysis suggested that a typical tree size (450 ft²) with a large size well (30 ft²) can capture 100% of stormwater runoff generated under its canopy for a 85$^{th}$ percentile storm event, which is equivalent to a sizing factor of 0.067. This implies there will be additional hydrological benefits of stormwater capture if tree well sizes can be larger than 30 ft² for an average size tree and if surface grading is applied to route stormwater from the adjacent impervious surface into the tree well. Larger tree well sizes and surface grading will therefore allow more stormwater to be captured. Further, volumetrically larger tree wells provide more root space for trees, which help trees be more resilient to drought (and less dependent on irrigation) and overall provide better conditions for more healthy, larger, faster-growing, and longer-lived trees. Such factors could potentially reduce overall maintenance costs of trees.

The tree canopy module update of SWMM adds the flexibility for design specifications to represent more types of GSI with additional detail. For instance, the tree canopy processes can be added to GSI representations, such as flow-through planter and bioretention area. A core advantage of this model update is that it can incorporate broader planning perspectives by allowing urban trees and GSI to be evaluated together, thus facilitating more integrated urban greening planning. For example, a city could choose to represent its urban forest plan in modeling conducted to develop stormwater management plans. The current GSI design and sizing criteria were applied to individual GSI, such as a bulb-out at a street block (Figure 15a). The updated SWMM can evaluate trees and GSI facilities in series, enabling planning using the street block as a whole unit. Like the example illustration in Figure 15b, from runoff reduction point of view, if trees and GSI were designed and evaluated together, the size of GSI within the larger unit could be reduced to achieve the same effect of stormwater capture on the street block level.

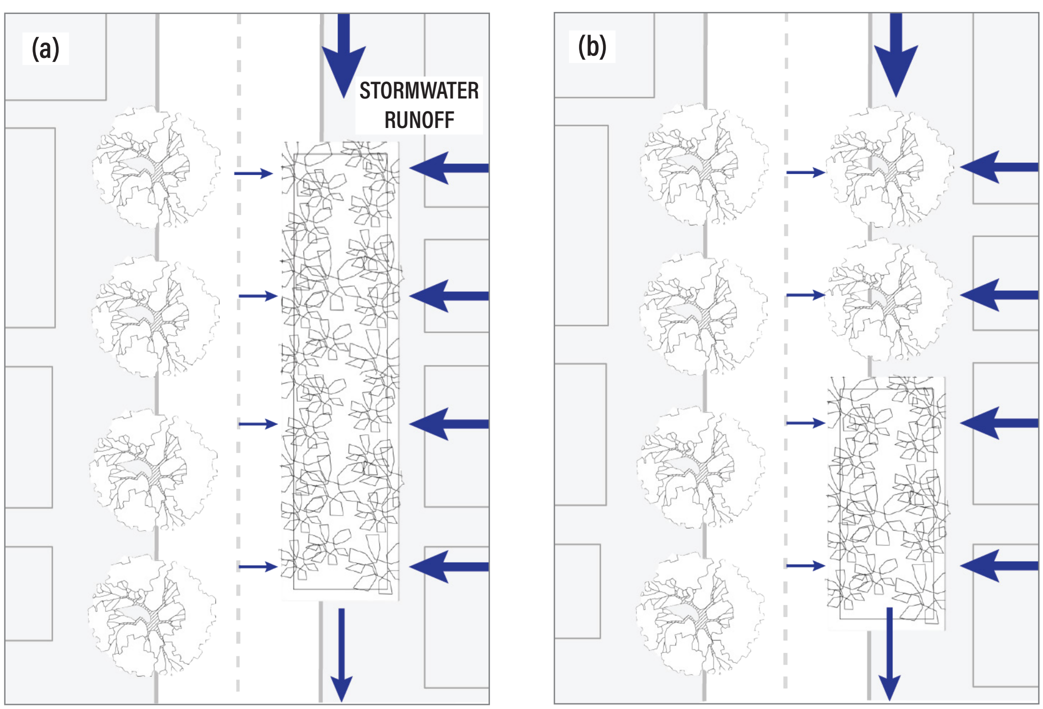



**Figure 15.** A conceptual illustration of how street trees and GSI can be considered together to address stormwater management in terms of runoff reduction. Including runoff reduction from trees in GSI design considerations (e.g. routing runoff through tree wells) may allow smaller engineered GSI (b) compared to when engineered GSI alone is considered (a).

## *Comparing trees to bioretention*

Determining how best to use limited resources and physical space is an important part of urban planning. Comparing stormwater runoff reduction benefits associated with trees versus engineered GSI features can inform such assessments. To explore these ideas, an initial evaluation was conducted for runoff reduction benefits associated with potential future trees and engineered bioretention GSI features. The GreenPlan-IT Site Locator Tool and Optimization Tool were leveraged to assess the effectiveness of street tree and bio-retention installation scenarios. The GreenPlan-IT Site Locator Tool was used to identify potential locations for both types of installations (Figure 16). Locations were identified in parking lots, within on-street parking buffers (where curb bulb-outs could be placed), and from a buffered City of Sunnyvale street tree opportunity layer (the latter layer was only used for potential tree locations; City of Sunnyvale, 2010). Areas not suitable for street trees and bioretention installations were removed, including building footprints, wetlands, golf clubs, and the side of the road with "red" fire truck access curbs. In order to account for spacing between trees and the lost space from driveways and intersections, the total area identified was reduced by 50% evenly across the study area to provide a conservative estimate of total potential locations available for adding trees and bioretention.

The potential locations for street trees and bioretention features provided by the GreenPlan-IT Site Locator Tool was used as boundary conditions (maximum number of street trees or bioretention features that could be installed for each subwatershed) for the Optimization Tool. The Optimization Tool was used for Monte Carlo simulations that generated two sets of scenarios, one for street trees and one for bioretention features. The Optimization Tool process repeatedly and automatically generates SWMM input files with different street trees/bioretention scenarios (numbers of street trees/bioretention features for each subwatershed), calls SWMM, and then summarizes the model output results. Model output results include summarized stormwater runoff reduction for the whole modeling domain and the total cost of each scenario. The 2-year 24-hour design storm was used to drive the hydrological simulation. Evergreen street trees with medium size tree wells were selected to represent street trees. The design and cost specifications for street trees and bioretention features used in this analysis are listed in the Table 3.

**Table 3.** The design specifications of bioretention and street trees in the cost analysis.

| | Surface area ($ft^2$) | Tree well size ($ft^2$) | Berm height (in) | Soil media depth (in) | Storage depth (in) | Infiltration rate (in/hr) | Under drain | Sizing factor* | Area treated (ac) | Cost per unit installation area ($/$ft^2$) |
|---|---|---|---|---|---|---|---|---|---|---|
| *Bioretention* | 500 | - | 9 | 18 | 12 | 5 | Yes | 0.04 | 0.29 | 104 |
| *Evergreen street tree* | 450 | 18 | 3 | 21 | - | 0.06 | No | 1 | 0 | 2 |

* A sizing factor is the percentage ratio between the surface area of the selected GSI facility and the impervious surface area it treats

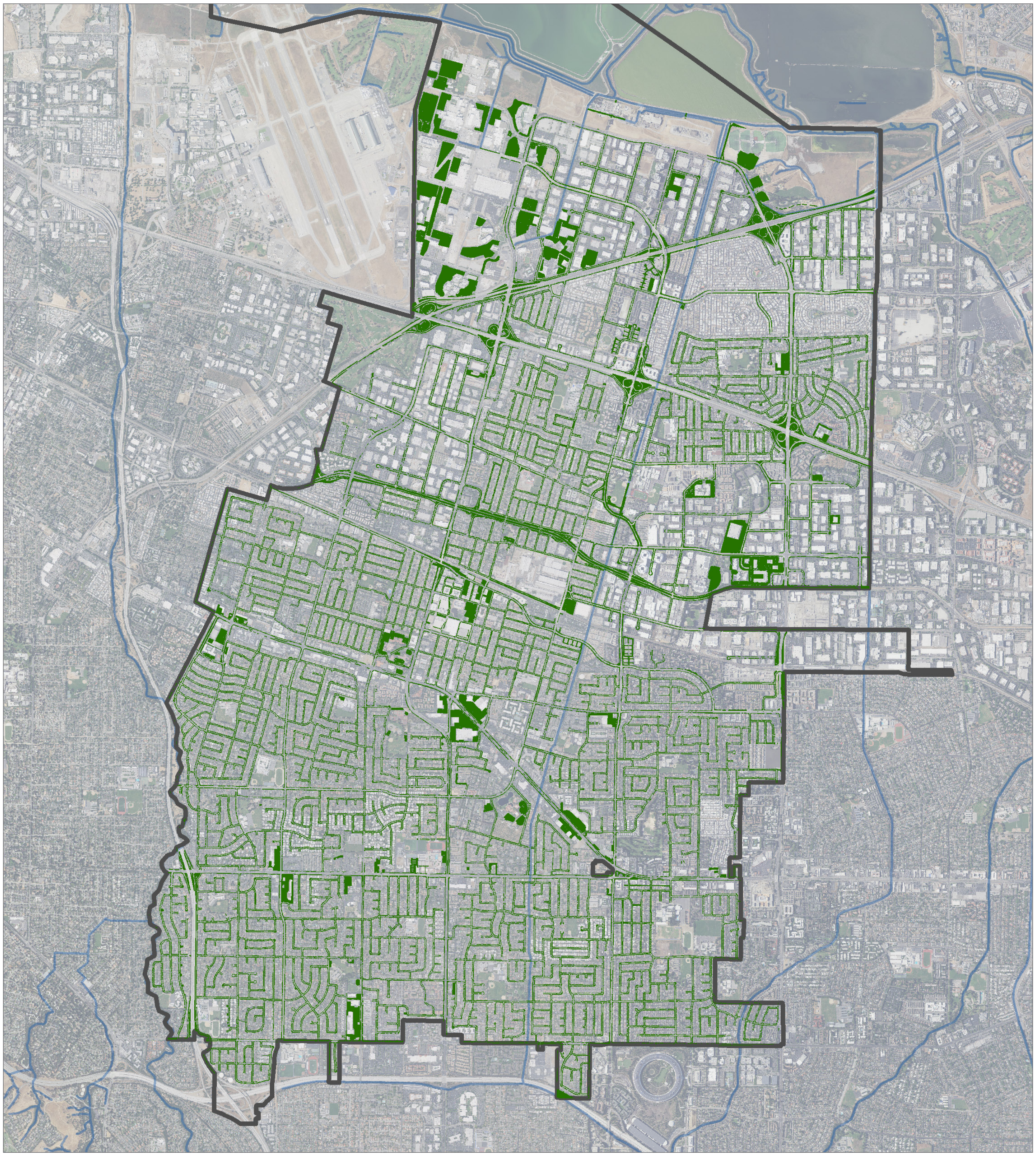


Figure 16. Potential locations for street trees identified using the GreenPlan-IT Site Locator Tool. Basemap courtesy NAIP 2018, USDA Farm Service Bureau.

Preliminary analyses indicate that street trees are a cost effective way to reduce runoff as part of a portfolio approach to runoff reduction. Figure 17 summarizes the two Monte Carlo simulation results. Based on the parameters used in the analysis, this plot indicates that more runoff reduction is achieved per dollar for trees than for bioretention. For example, for an additional 1% reduction in runoff, the cost of doing so using street trees is $3.4 million less than with bioretention. The 1% runoff reduction is equivalent to a volume of 36,094 $ft^3$, which could acheived by ~14,000 trees in this analysis (2.6 $ft^3$ runoff reduction per tree for the 2-year 24-hour storm event). However, this demonstration analysis only considered hydrological benefits and did not include water quality considerations at this time. This illustrates how different urban greening strategies could be evaluated and compared from a stormwater management point of view. However, a more detailed analysis, broader range of considerations, and additional cost factors would be needed before drawing conclusions concerning relative benefits and using in decision-making processes. One important caveat is that the costs of street trees and bioretention features depend on local factors. Also, the current cost analysis does not fully account for operation and maintenance (O&M) costs. For example, O&M costs should account for the maintenance of street trees throughout their life. Furthermore, engineered GSI, such as bioretention features, are designed to reduce runoff and filter contaminants, treating a large volume of stormwater with a relatively small footprint. Street trees have a much smaller stormwater capture capacity than GSI with the same footprint size and are not designed to directly filter contaminants. It is therefore reasonable to consider street trees and engineered GSI as complementary strategies, where cost-effective stormwater runoff reduction benefits offered by trees can reduce the amount of runoff needing to be treated by engineered GSI. The tools and approach presented here can be used to help make the necessary calculations and comparisons for planning and decision-making.

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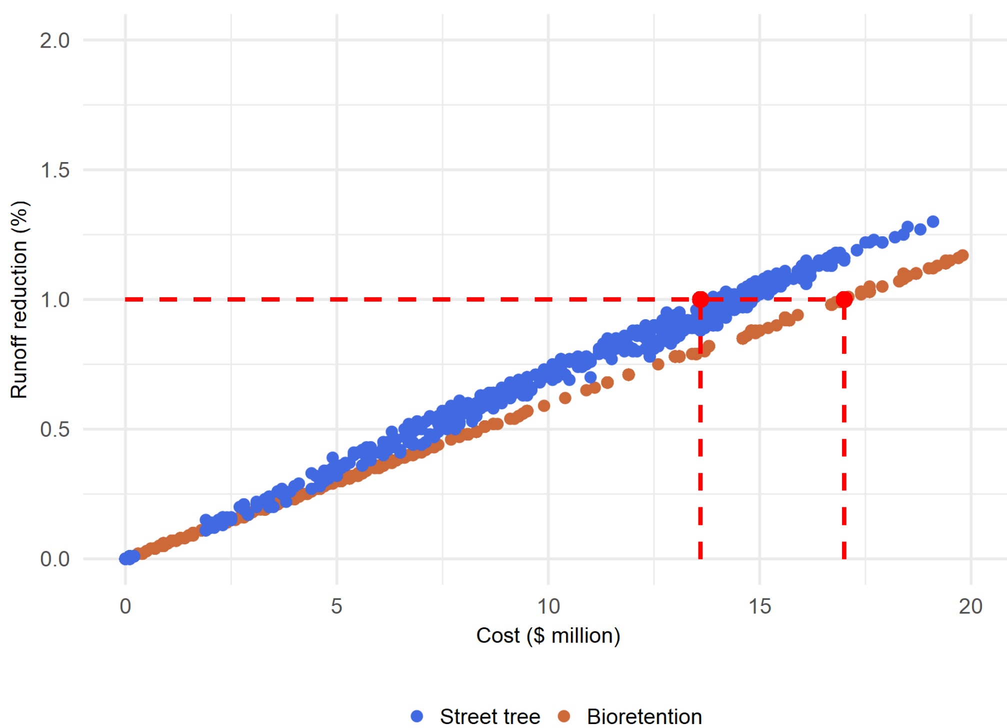
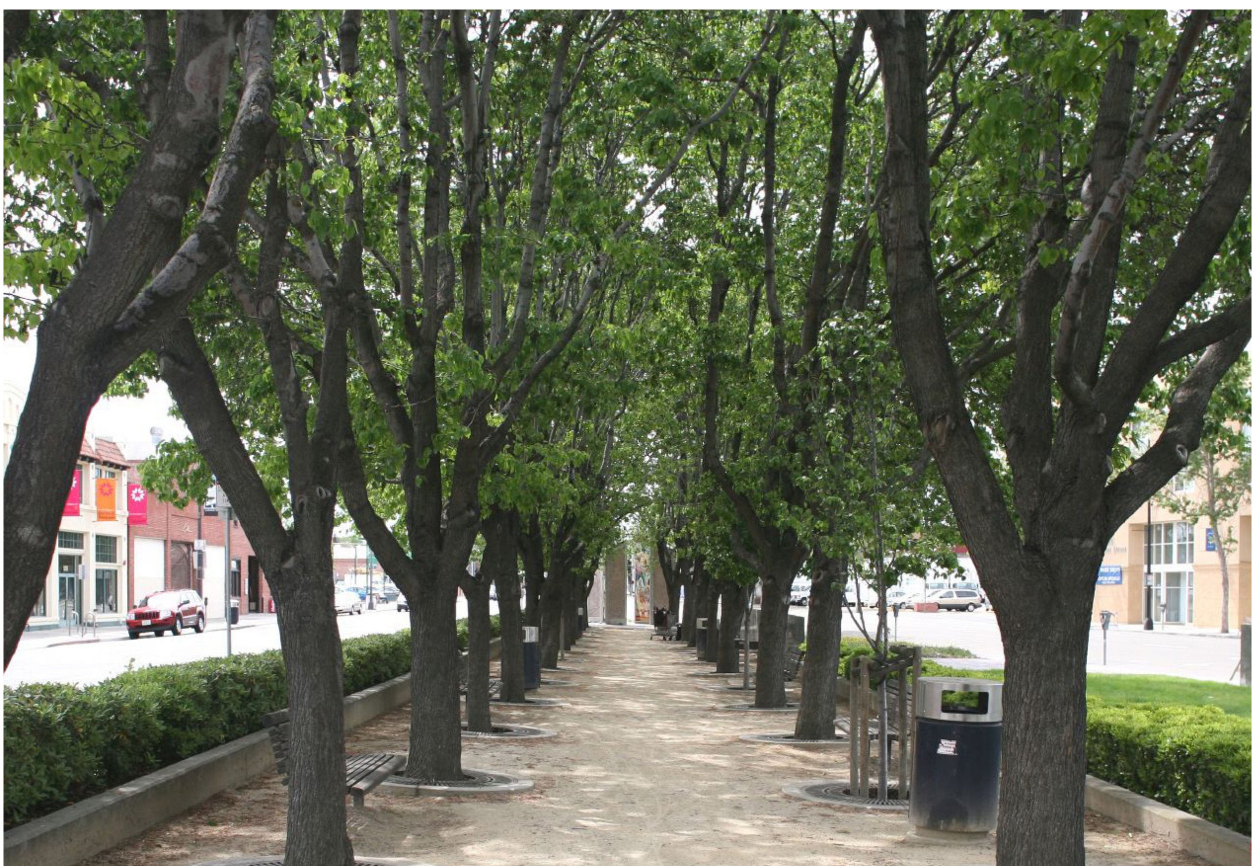
**Figure 17.** Cost-effectiveness in terms of runoff reduction of two scenarios, street trees and bioretention GSI (Zoomed in to 0-2% runoff reduction).



**Urban trees and engineered GSI can be seen as complementary strategies, where trees can reduce the amount of runoff needing to be treated by engineered GSI.**

## *Tool comparison*

The i-Tree software suite (itreetools.org) is a publicly-available and widely applied toolset for evaluating ecosystem services provided by trees. The newly developed SWMM canopy module applies algorithms from the i-Tree Hydro tool. The i-Tree Hydro tool is a component of the i-Tree Hydro+ suite, which focuses on hydrological simulation of the effects of land cover changes on water quantity and quality, and has modules for explicit modeling of vegetation processes. The i-Tree Hydro+ and other i-Tree tools such as i-Tree Eco, i-Tree Landscape, i-Tree Canopy and i-Tree Design, provide a toolset for quantifying ecosystem services and benefit values of trees and forests at multiple scales. By developing the canopy module within the SWMM (hard-coded the canopy storage and evaporation algorithms into existing SWMM structure), this approach takes advantage of the existing SWMM GSI modeling structure as well as a detailed hydrological modeling structure for urban hydrology and water quality. Importantly, SWMM is a commonly used model in urban stormwater management and planning for regulatory purposes. The updated model allows the analysis of integrated design of GSI and trees together, such as GSI and trees in series, drainage area assignments for different GSI and trees, etc. The i-Tree Hydro+ suite is being developed for similar purposes. A comparison between the two different tools would be a useful step to cross-validate the models, show the similarities and differences of the two modeling tools, and better understand the types of applications appropriate for each.



Photograph by Thomas Hawk, courtesey of Creative Commons.

# Towards an integrative multi-benefit approach

While the hydrological benefits of trees is the focus of the modeling and analysis presented in this document, nature-based solutions and urban greening activities provide an array of benefits. These benefits are increasingly recognized, but rarely quantified or seriously considered in a planning context (Filazzola et al., 2019). The solution spectrum includes highly-engineered GSI features to filter contaminants from stormwater that may also contribute to native species diversity, as well as street trees planted for aesthetic reasons that may also reduce runoff and mitigate the urban heat island effect. Benefits are not mutually exclusive. However, though each solution may provide multiple benefits, they are often designed and placed based on a single primary objective. There is increasing emphasis on shifting the urban landscape planning paradigm of individual problems being addressed by individual engineered solutions to one that is more integrative and involves planning across a range of urban greening activities for the multiple benefits that they provide without compromising any individual benefit. This requires alignment across stormwater management, urban development and transportation planning, urban forestry, parks management, and climate action planning to ensure that actions are planned and designed together. With limited resources and space, multi-benefit planning is necessary to meet the challenge of addressing the myriad environmental challenges present in our urban landscapes.

**Trees within the urban landscape could be part of a portfolio approach and multi-benefit assessment framework to achieve runoff and load-reduction goals, while also providing additional ecosystem services, such as wildlife habitat, healthy soils, heat reduction, air quality improvement, and carbon storage.**

This work has focused on the runoff reduction benefit of trees, with the recognition that, through improved understanding and advanced tools, urban trees could be considered alongside more traditional engineered GSI in stormwater management evaluations and plans to address regulatory requirements. This is one of many such intersections, and just as contaminant and runoff benefits of non-engineered urban greening activities could be incorporated into stormwater management evaluations, so too could biodiversity benefits or other ecosystem services be more rigorously considered in the design, selection, and placement of GSI.

To explore this opportunity, a potential technical approach for considering ecological benefits in stormwater management evaluations is described. The approach could be extended to consider other ecosystem services such as carbon sequestration, urban heat mitigation, water supply, and human health factors as well. The potential approach includes four analysis components that could be established to help meet the goal of implementing integrative approaches to assess and plan for multiple benefits across a portfolio of urban greening activities (Figure 18).

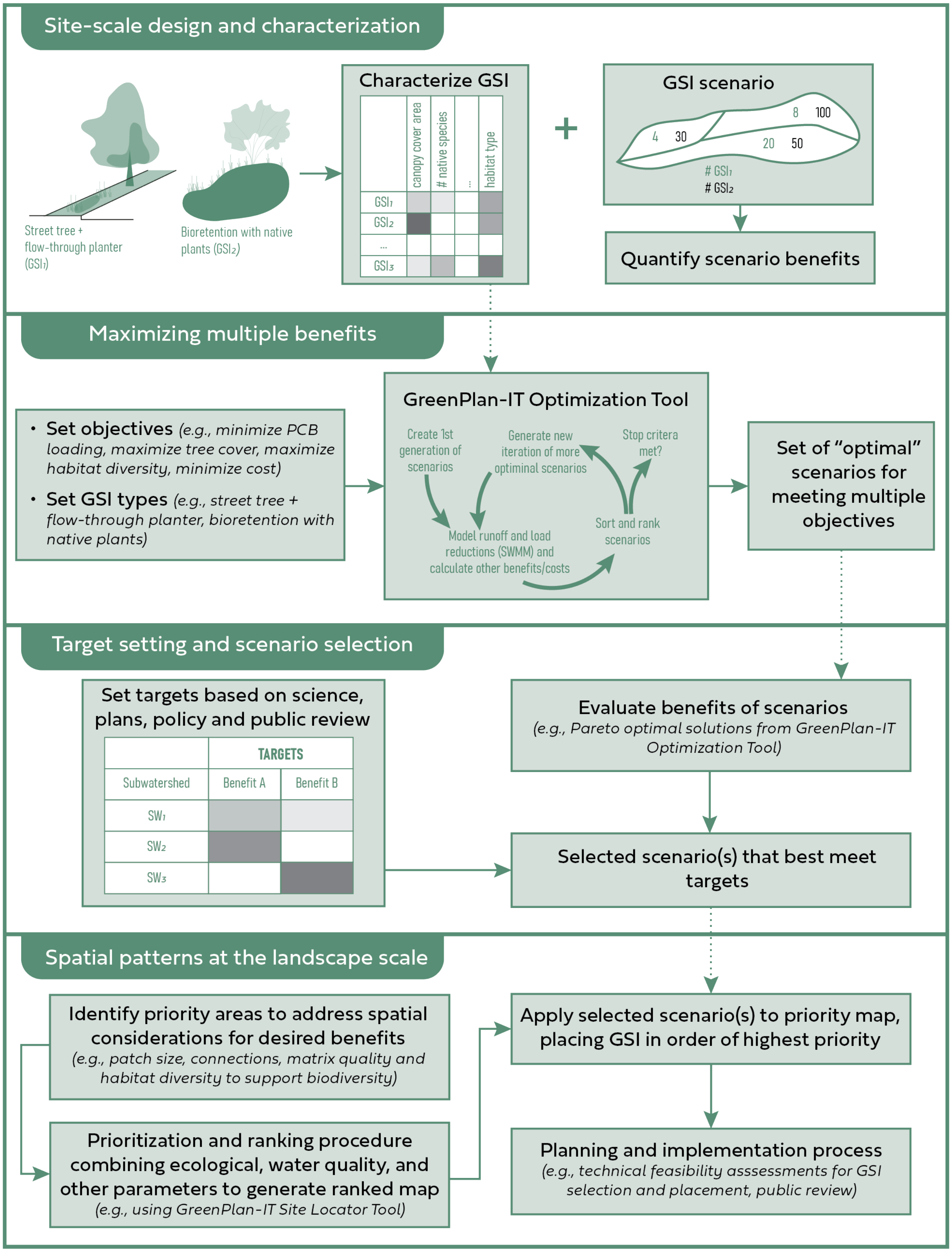



**Figure 18.** Diagram illustrating an integrated multi-benefit approach for urban greening.

## *Site-scale design and characterization*

In the process of establishing Best Management Practices (BMPs) for stormwater management, analysis of GSI benefits typically involves modeling the behavior of GSI types. Performing this quantitative assessment requires that each GSI type be adequately characterized to set model parameters. Expanding assessments to include ecological benefits would therefore involve characterizing GSI types (including non-engineered features such as trees) in ways that their ecological benefits can be quantified based on given numbers and types of planned GSI. For example, GSI types could be characterized by measures such as the expected diversity (or percent cover) of native plants, diversity of native (and non-native) wildlife species supported, habitat or community type area, or annual biomass or net primary productivity. The design characterization offers a pathway to address identified elements to support biodiversity that are manifested at the site scale, such as native vegetation and special resources like large trees or dead wood and undisturbed leaf litter (Spotswood et al., 2019; Figure 19). It may also be important to determine maintenance schedules for engineered soil replacement that ensure biodiversity is not adversely affected by GSI units.

Further, as previously discussed, the tree canopy module update of SWMM allows greater flexibility for GSI design specifications, which could be adjusted for factors that better support biodiversity while also meeting or exceeding runoff and contaminant reduction targets (e.g., adding trees to a bioretention with native grasses and shrubs, expanding soil volume for trees to have adequate growing conditions). Thus, GSI as defined for this analysis approach could include relatively simple non-engineered urban greening elements (e.g., park tree) as well as highly-engineered types. These new or modified ecologically beneficial GSI types could then be used in place of or in addition to more traditional engineered GSI types.

By characterizing GSI using measures of ecological health, ecological benefits could be quantified more readily as part of stormwater planning and therefore offer an approach to quantify multiple benefits for given GSI planning scenarios. The scenarios specifying GSI type and number produced by the Optimization Tool of GreenPlan-IT to achieve contaminant load reduction could be evaluated for associated expected ecological benefits.

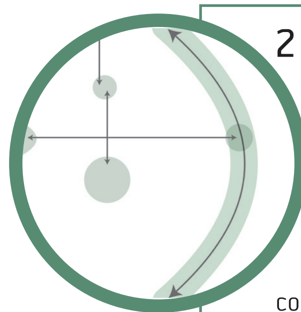
## *Maximizing multiple benefits*

While the previous step would enable the calculation of ecological benefits for a given scenario of GSI type and number, additional analysis would be required to generate scenarios that optimize across multiple objectives, including ecological benefit objectives. One approach could be through modifications to the Optimization Tool of GreenPlan-IT, which employs a multi-objective evolutionary algorithm, NSGA-II (Deb et al., 2002). The current formulation uses objectives of minimizing total stormwater contaminant load or stormwater runoff and minimizing total GSI cost. Alongside stormwater runoff and load reduction benefits, an expanded formulation could include objectives relating to ecological benefits that could be calculated from GSI type and number, such as maximizing tree cover, native vegetation cover, species diversity, and/or habitat diversity (if these characteristics are quantified at the site-scale, as outlined in the previous section). The optimization could also include new or modified ecologically beneficial GSI types developed in the design specification component of the analysis. This analysis component could then result in the identification of a suite of scenarios giving numbers and types of GSI per subwatershed that represent optimal options for maximizing selected multiple objectives. Given tradeoffs between competing objectives, no single solution would be identified. For example, one scenario might have higher percent canopy cover but lower contaminant load reduction and another lower percent canopy cover but higher contaminant load reduction for the same cost.

# ELEMENTS THAT SUPPORT URBAN BIODIVERSITY

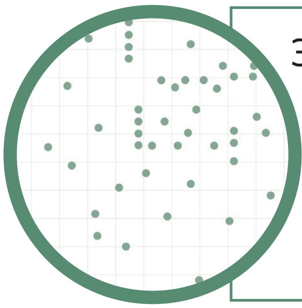
## 1 • PATCH SIZE

The size of a contiguous patch of greenspace in a city. We define patches as contiguous greenspaces of at least 2 acres in size.



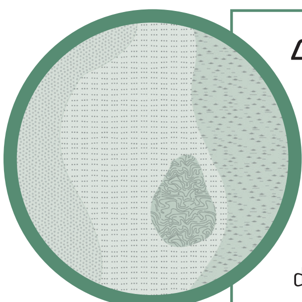
## 2 • CONNECTIONS

Features in the urban landscape that facilitate the movement of plants and animals. Connections include corridors (thin stretches of greenspace that promote linear movement) and stepping stones (sets of discrete but nearby patches that together promote connectivity across the landscape).



## 3 • MATRIX QUALITY

Habitat elements that support ecological process and movement in the urban matrix between patches of greenspace and corridors.



## 4 • HABITAT DIVERSITY

The type, number, and spatial distribution of habitat types within an urban area. Together, mosaics of habitats create diversity in habitat types at the landscape scale.

## 5 • NATIVE PLANT VEGETATION

Plant species long evolved in a specific geography (including nearby species that may be appropriate in the near future, given anticipated range shifts with climate change).

## 6 • SPECIAL RESOURCES

Unique habitat features necessary to support species' life history requirements, including large trees, wetlands, streams, and rivers.

## 7 • MANAGEMENT

Human activities and planning that promote positive biodiversity outcomes.

**Figure 19.** Identified urban landscape elements that support biodiversity. These should be considered in the placement of GSI and in the evaluation of the ecological benefits GSI can provide through their site-scale design as well as placement within the landscape. Source: Spotswood et al. 2019.

## *Target setting and scenario selection*

Once a suite of optimal scenarios are determined, one or more scenarios could be selected for further analysis and potential use in watershed or urban planning. A process for scenario selection could be developed based on setting targets for each of the benefit measures at the watershed (or study area) and/or subwatershed scale and then determining whether scenarios meet or exceed those targets. These targets could be set based on a number of considerations. For ecological benefits, science-based targets should try to address the challenging question of how much is enough to support biodiversity. They can be drawn from guidance in Spotswood et al. (2019) and other synthesis of scientific research. For example, a target tree canopy cover of 40% was recently recommended for urban areas in Santa Clara County to address multiple benefits (Bazo et al., 2020). Canopy coverage or greenspace areas needed to meet targets for spatial metrics relating to biodiversity support, discussed further in the following section, could be folded into subwatershed- or watershed-level targets. Targets developed for urban forest plans could also be considered. For other objectives, contaminant load and runoff reduction targets might be established based on regulatory requirements. Each scenario would subsequently be evaluated and one or more optimal scenarios that meet or exceed set targets would be selected as priority scenarios for use in subsequent planning.

## *Spatial patterns at the landscape scale*

Biodiversity is driven by many physical and biological factors, including the spatial arrangement and patterns of features in the landscape. Quantifying ecological benefits based on the numbers and types of urban greening activities alone cannot address biodiversity benefits accrued via spatial configuration. Accounting for spatial configuration therefore requires a level of planning that places features within the landscape and considers spatial orientation and relationships between features. As described above, results from GSI analysis performed in GreenPlan-IT or other similar modeling and optimization approaches could be used to generate one or more selected scenarios, with recommended suites of GSI (numbers and types) to place per modeled subwatershed (at the neighborhood or multi-block level). The determination of where to best place those GSI to maximize ecological benefits could draw on spatial considerations such as patch size, connections, matrix quality, and habitat diversity, which are elements of urban biodiversity support put forward by Spotswood et al. (2019) in a different component of the *Healthy Watershed Resilient Baylands* project, and summarized in the following text (see Figure 19).

- **Patch Size** For patch size, while there are no hard numbers given the many ecosystem functions different types and sizes of patches can serve in the landscape, it is recommended that patches be a minimum size of 2 acres and be larger than 10 acres to accrue substantial biodiversity benefits. Larger patches offer habitat diversity and protection for species sensitive to urban impacts. They are also more likely to have enough resources to maintain viable populations. Patch shape also matters, with rounder patches having less area associated with edge effects that can be detrimental to sensitive species.

- **Connections** Connectivity between habitat features within landscapes affects the movement of plants and animals, enabling species to satisfy life history requirements and maintain genetic diversity. Given the fragmented nature of urban landscapes, urban biodiversity is heavily dependent on connectivity and stands to be substantially improved by measures that enhance connectivity. Landscape connections include corridors (continuous greenspace) and stepping stones (closely-spaced and readily-accessible patches). Connectivity can occur at different scales (e.g., small features with native plants interspersed between city parks versus city parks and greenways connecting a riverine corridor and upland open space across a city). Specifying areas to improve connections involves identifying existing greenspace corridors or gaps in the landscape between existing habitat areas, from smaller patches to regional biodiversity hubs (e.g., regional parks, riparian corridors). These areas might represent opportunities to expand on existing corridors or add stepping stones in large gaps between existing green spaces. Higher priority should be placed on areas that improve connectivity at the regional scale between different habitat types or for key resources, such as aquatic and riparian habitats.

- **Matrix quality** The urban matrix, or the complex built environment that surrounds patches of greenspace, affects how well the overall landscape supports biodiversity. Alleviating stressors present in the urban environment through added greenspace elements can improve the capacity of existing urban habitat mosaics to support biodiversity and effectively expand the area available for ecological functions and species needs. Improving the quality of the urban matrix can occur through small-scale urban greening activities that add vegetation along streets and in yards, whether through planting trees and shrubs, installing engineered GSI features, or incentivizing rain gardens or pollinator gardens in private yards. Priority locations for such improvements are areas around existing habitat patches, areas between habitat patches to promote connectivity, and areas where clusters of individual improvements could together provide habitat benefits.
- **Habitat diversity** Landscapes composed of diverse habitats are able to serve a broad array of species needs and therefore support greater biodiversity. Both the diversity of habitats and how they are arranged and connected within a landscape affects biodiversity. New urban greening elements should therefore be considered for the habitat type or types they represent and the habitat types they connect to. Different zones within a landscape could be targeted for particular suites of habitat types that promote diversity at the city scale and are aligned with climate, soil, and other physical drivers.

Using available spatial data, existing greenspace and available areas for GSI (including non-engineered greenspace and trees) could be analyzed to identify priority areas that could increase patch size, connectivity, matrix quality and habitat diversity, following guidelines of Spotswood et al. (2019). This could be done through the Site Locator Tool of GreenPlan-IT by ranking the available area for GSI according to its capacity to address spatial considerations. For example, potential GSI locations near an existing high-quality large patch (e.g., park) might be prioritized for their capacity to expand the extent of existing patches, or potential GSI locations within an identified regional connectivity corridor (e.g., between a riparian zone and park) might be prioritized for their capacity to fill connectivity gaps and improve matrix quality.

These prioritized areas could then be incorporated into the ranking and prioritization steps of the Site Locator Tool which would include other location-specific reasons to prioritize GSI (e.g., areas with higher levels of contaminants). This analysis would produce a map showing higher and lower priority areas and what ranking information was used to set those priorities for each GSI type, while still allowing the benefits of individual objectives to be explored individually.

A final map for a selected scenario could then be developed showing the areas where the scenario's numbers and types of GSI per subwatershed could be distributed within the landscape in the order of highest priority. As a modeling and desktop analysis approach, analysis results would provide a general idea of where, how much, and what type of GSI might be needed to meet objectives, but further technical feasibility assessments would be required for ultimate selection, design and implementation of GSI.

Conducting integrated multi-benefit analysis may reveal that meeting multi-benefit objectives within the constraints of existing highly developed urban landscapes may require more ambitious planning than merely fitting urban greening activities in existing available area, such as large-scale redevelopment planning (e.g., establishing high-density housing while creating space for greener streets, greenways, and parks), strategic buyouts in high priority areas (e.g., along riparian corridors), or other changes on public and private property.

**Further research is needed to apply this work within an integrated multi-benefit assessment framework and assess what might be achievable for maximizing benefits within urban landscapes.**

The integrated analysis approach described here would provide planning-level guidance that could be used in common by stormwater managers, urban foresters and planners, watershed managers, as well as regulators in the process of establishing plans and selecting, locating, and designing specific projects. It is intended to help focus efforts on types and locations of urban greening activities that achieve benefits across multiple objectives, provide a method for quantifying those benefits, and mutually support the goals of many entities involved in urban planning and management. This would support an overall desired outcome of more coordinated urban greening efforts that achieve greater overall benefits at lower costs than if each objective was sought individually.

Photograph by Robin Grossinger, SFEI.

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