Puget Sound Urban Tree Canopy and Stormwater Management

A Report Comparing USDA Forest Service i-Tree Hydro and Washington State Department of Ecology Western Washington Hydrology Model

plan-it GEO

HERRERA

KCD King Conservation District

the keystone concept

DEPARTMENT OF ECOLOGY State of Washington

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EXECUTIVE SUMMARY

Purpose of the Project

The Puget Sound region in northwestern Washington State (Figure 1) is a complex system of connected waterways across 12 counties. The population of the region has increased by 13% since 2010, and this growth is expected to continue. By 2050, the population in Puget Sound will grow from 4 million to 6 million people[1]. Land development in the region's most populous counties (King, Pierce, and Snohomish) has led to an expansion of impervious surfaces, which in turn increases stormwater runoff and degrades water quality from pollutant loading. Comprehensive restoration plans and policies have been developed to address water quality degradation associated with urban development and increased stormwater. The Puget Sound Urban Tree Canopy and Stormwater Analysis Project is designed to enhance the discussion around those plans and policies, with information about the role tree canopy plays in managing water quality and quantity in the Puget Sound region.

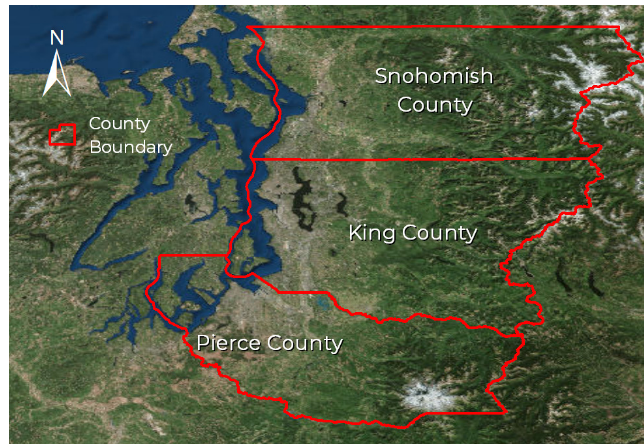


Figure 1. | Watershed Study Counties

Project Details

This project provides resources to fuel productive conversations between the urban forestry and stormwater communities about the role of tree canopy in mitigating stormwater- and runoff-related issues. It accomplishes this by comparing analyses from the modeling tools used by these two communities — the first-ever direct comparison of stormwater models applied to urban forests in the Pacific Northwest.

The two models are:

- i-Tree Hydro, designed to inform forestry managers of the effects of urban tree canopy and impervious cover on changes in streamflow
- The Western Washington Hydrology Model (WWHM), designed to inform planners, engineers, developers and managers on best management practices for meeting stormwater regulatory requirements

The project involves four pilot communities (the cities of Kent, Kirkland, Snohomish, and Tacoma), and four spatial scales (city, drainage basin, neighborhood, and parcel) to demonstrate the practical applications of the two models. The scenarios modeled focus on analyzing increase or decrease (percent change) in stormwater runoff over a six-year period, and based on three variables:

- Loss of tree canopy
- Changes to tree canopy and impervious area resulting from development
- Increases in tree canopy from current canopy levels

i-Tree Hydro	WWHM
i-Tree is a suite of tools developed and supported by the United States Department of Agriculture (USDA) Forest Service and the Davey Institute, and the first vegetation specific hydrology model. Other i-Tree software tools that include stormwater-related benefit analysis are i-Tree Eco and i-Tree Landscape. *https://www.itreetools.org/hydro/* *https://www.itreetools.org/eco/*	The Western Washington Hydrology Model (WWHM) is used to evaluate mitigation practices, primarily stormwater flow control and treatment facilities for runoff generated from development in the western region (west of Cascade Mountain Range) of Washington. *https://ecology.wa.gov/Regulations-Permits/Guidance-technical-assistance/Stormwater-permittee-guidance-resources/Stormwater-manuals/Western-Washington-Hydrology-Model*

[1]*http://archive.kuow.org/post/seattle-region-will-grow-18-million-people-2050*

Key Findings Overall

Key findings from the comparison, presented in further detail in this report include:

1. In nearly all modeled scenarios, i-Tree Hydro yielded lower runoff volumes, and therefore a lower benefit of tree canopy than WWHM.
2. Increase in tree cover over impervious surface results in decreased runoff volumes.
3. Development that includes tree retention results in reduced runoff volume compared with development without tree retention.
4. Scenarios where tree canopy is replaced with any other land cover type, including herbaceous layers or impervious area, result in increased runoff volume.
5. Areas with higher existing tree canopy coverage experience a lower magnitude of runoff volume when tree canopy is reduced.

See Results section on Page 26 for a detailed breakdown.

Key Findings at City Scale

This comparison between i-Tree Hydro and WWHM demonstrates methods, considerations, and results of different modeling scenarios and scales showing increase or decrease in runoff volume. Results vary depending on spatial scale, existing land cover, and other factors such as soil type. In many cases both models simulate changes in total runoff within 1–2% of each other.

Table 1 summarizes a few of the key findings for each pilot community at the city spatial scale. The percent change in total runoff as compared with existing conditions are from two of this project's seven modeling scenarios:

- 1A: All canopy is replaced with herbaceous/grass cover
- 3B: Existing tree canopy cover is increased by 20%.

For results at other spatial scales (drainage basins, neighborhoods, and parcels) and for the other canopy scenarios, see Appendix E on Pages 70-86.

Table 1. | City Scale Results Summary from Scenarios 1A and 3B

County	Pilot Community	Simulated Area – City Scale (sq. miles)	Tree Canopy Coverage (Percent of Simulated Area)	Impervious Area Coverage (Percent of Simulated Area)	Total Precipitation, 10/1/09-09/30/15 (cu. feett)	Change in Total Runoff from Existing Conditions			
						All Tree Canopy Replaced with Herbaceous/ Grass Cover (1A)		*Existing Tree Canopy Increased by 20% (3B)*	
						i-Tree Hydro	*WWHM*	*i-Tree Hydro*	*WWHM*
King	Kent	34.0	28%	40%	14.0B	+ 2%	+ 3%	- 2%	- 5%
King	Kirkland	17.8	37%	38%	7.2B	+ 3%	+ 4%	- 2%	- 9%
Snohomish	Snohomish	3.6	23%	40%	0.8B	+ 1%	+ 9%	- 2%	- 4%
Pierce	Tacoma	62.0	20%	52%	17.0B	+ 0.4%	+ 6%	- 3%	- 3%

While the percent change results presented in Table 1 may seem small, this percent change is calculated based on the runoff volume from the entire city, whereas tree canopy only covers 20–37% of that entire area, resulting in a smaller overall change in runoff. See Appendix G for Sensitivity Results and Discussion on Page 89.

Project Impact

Stormwater engineers and planners use WWHM to design stormwater control facilities in ways that best mitigate the impacts of increases in impervious surface. With expertise from urban forestry program and policy managers, supplemented by analysis from i-Tree Hydro, decision makers can more effectively factor in the impact of a decrease in tree canopy and an increase in impervious surfaces in the planning stages of development projects involving changes to land cover. Including tree canopy in the discussion opens the door for forward-looking strategies, including forest retention and canopy enhancement as a complement to mitigation strategies in a particular jurisdiction.

This technical report is accompanied by a user's handbook designed to help the urban forestry community communicate and collaborate with the stormwater engineering and planning community to integrate canopy management and green stormwater infrastructure into a comprehensive stormwater management approach.

INTRODUCTION

The Benefits of Urban Tree Canopy

The forestry community's understanding of the urban tree canopy and its benefits has grown thanks to decades of research at the site scale (i.e., individual tree level) and landscape scale (e.g., grove, canopy, or forest) conducted by the U.S. Forest Service, the U.S. Environmental Protection Agency, universities, the i-Tree model developers, and others. Tree valuations are becoming more accessible, allowing users to quantify the benefits of adopting tree retention and tree planting policies. And, it's now common for cities and regions to include urban trees as a key performance indicator in canopy cover targets in climate action plans, low impact development (or green stormwater infrastructure) design manuals, and comprehensive plans that go beyond urban forest management.

How urban tree canopy impacts water quality and quantity in the Puget Sound region:

- Rainfall interception
- Evapotranspiration
- Nutrient uptake
- Promotion of healthy soils
- Infiltration to ground water
- Regulation of water temperature from shading that improves habitat
- Reducing the volume of stormwater runoff
- Reducing the flow of pollutants into receiving bodies of water

This project extends the discussion to include stormwater runoff volumes and rates, and improving water quality, which are high-priority issues for all urban areas regardless of climate or weather patterns.

Tree canopy helps to reduce runoff from storm events at the site level and landscape scale by intercepting and evapotranspiring rainfall before it becomes runoff (Figure 2). In Western Washington, tree canopy intercepts an estimated 18–25% of the annual rainfall falling onto it (Herrera 2008), in turn reducing the amount of polluted runoff that makes its way into bodies of water such as Puget Sound. Average annual interception value varies depending on storm intensity. Small storms are characterized by high relative interception, and large storms are characterized by low relative interception. Adding tree canopy can mitigate the impacts of stormwater, such as flooding and degraded water quality. Decreasing tree canopy in favor of impervious surfaces can have the opposite effect, increasing runoff and water-delivered pollutants.

Assessing Tree Canopy's Impact in the Pacific Northwest

The suite of i-Tree tools featured in this project has been used in the Pacific Northwest before — specifically the iTree Eco model in Seattle (see Green Cities Research Alliance on Page 52). However, few if any studies have used i-Tree Hydro in the Pacific Northwest, where a unique set of factors impact efforts to model the ecosystem services of vegetation.

Rainfall patterns create wet winters when deciduous trees have shed their canopy, and dry summers when the canopy is in full leaf out. In addition, the impressive height of tree species such as the Douglas fir, western red cedar, and Pacific madrone results in greater leaf area, which enhances the ecosystem services the canopy provides.

Based on limited data in the Pacific Northwest, a conifer intercepts and transpires an estimated 30% of the precipitation that falls on it, while a deciduous tree intercepts and transpires 15%.

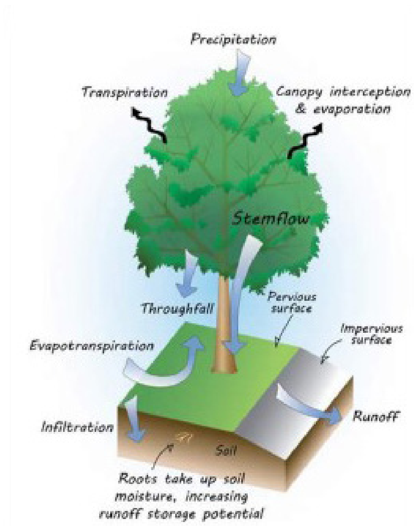


Figure 2. | Trees and the Hydrologic Cycle

i-Tree Reference City

The local reference city through i-Tree Streets for the Pacific Northwest is Longview, Washington. The 16 regions across the nation sample local tree species to predict growth, leaf area, and tree related benefits.

The suite of i-Tree tools is based on research and algorithms that account for seasonal and local variability in precipitation for individual trees, plot-based evaluations of trees, and canopy cover area. This makes i-Tree particularly useful in modeling the nuances and complex variables at play in the Puget Sound region, where an impending increase in population, land development, and impervious surfaces threatens to increase stormwater runoff and degrade water quality from pollutant loading. Modeling the effects of tree canopy in the area requires knowledge and inputs on tree characteristics, local meteorology, land use, soils, and slopes.

Previous efforts to quantify the stormwater benefits of tree canopy coverage (Herrera 2008) resulted in the tree planting and tree retention stormwater flow control credits (BMP T5.16) included in the Washington State Department of Ecology Stormwater Management Manual for Western Washington (Ecology SWMMWW), which allow for the reduction of impervious area when calculating mitigation needed to meet Ecology's stormwater requirements. The tree retention credit included in the Ecology SWMMWW is evaluated at the parcel scale as part of the Western Washington Hydrology Model (WWHM) evaluation performed for this project.

However, Ecology's tree credit is limited to circumstances involving sizing new stormwater facilities. This project gives city managers and project or program managers an alternative pathway to credit trees and tree canopy outside of the development context.

Common Hydrology Models

There are five hydrology models commonly used by stormwater management professionals in the Pacific Northwest. This project is testing and evaluating two of the five models — i-Tree Hydro, which is familiar to forestry professionals and WWHM, which is the model most often used by stormwater management professionals. This project does not address the other models except where specific reference is helpful or needed in relation to discussions about i-Tree Hydro and WWHM.

Hydrology Models Used in the Pacific Northwest

- WWHM and US EPA SWMM – used during development to size flow control and water quality treatment facilities and apply tree-based flow control credits
- i-Tree Hydro – used to quantify urban forest ecosystem services, including stormwater regulation.
- WinSLAMM – planning tool to evaluate the effectiveness of various stormwater practices
- WinTR-55 – used to calculate changes in hydrology, typically to comply with local stormwater regulations
- MGS Flood – another model commonly used in the Pacific Northwest for sizing flow control and water quality treatment facilities and applying tree-based flow control credits

Stormwater Management Benefits of the Puget Sound Urban Tree and Forest Canopy Cover Project

By evaluating the efficacy and productive value of i-Tree Hydro against WWHM, this project is intended to contribute to more robust, inclusive discussions about managing stormwater runoff in the Puget Sound region.

Project deliverables include materials designed to interpret i-Tree Hydro and WWHM results and provide recommendations for future use of these models, creating common ground for urban forestry professionals and stormwater management professionals. With a more accurate, accessible way to link urban forestry and stormwater programs, planners will be better equipped to set meaningful goals, and establish effective policies for development and stormwater management.

Additional Context

- **Primary input:** A high-resolution, 1-meter GIS-based land cover analysis was performed in each of the pilot communities to provide a primary input for the models compared in this project.
- **Calibration:** Calibration of the i-Tree Hydro model has always been available for the Pacific Northwest. Available stream gage and precipitation data for the drainage basin scale were used in Kent and Kirkland for calibration of i-Tree Hydro.
- **Adjustment for small-scale analysis:** At the parcel scale, WWHM was compared with i-Tree Eco instead of i-Tree Hydro, which is not suitable for smaller scale analysis. Six tree species common in the Pacific Northwest were evaluated to assess the benefits of individual trees. Annual stormwater runoff avoided ranged from 60 to 232 gallons for 9-inch diameter trees and 202 to 825 gallons for 36-inch diameter trees (See Appendix K). This project did not model the stormwater benefits of engineered systems for individual trees, e.g., vaults, structural soils, etc.
- **Sensitivity analysis:** The project includes a sensitivity analysis of both models, performed by changing various parameters with a range of high and low values to evaluate the impact each parameter has on model outputs. (See Methods, Page 12)
- **Assessing monetary values:** At this time, neither i-Tree Hydro nor WWHM include monetary values associated with water quantity or quality. Other models in the i-Tree suite of tools do include monetized stormwater benefit values, specifically i-Tree Eco, i-Tree Design, i-Tree Streets, and i-Tree Landscape. In i-Tree Eco, the current value for dollar amount per unit of avoided runoff (default value 2004) is $0.0086/gallon or $0.00115/cubic foot.
- **Vetting and review:** Numerous partner organizations, pilot communities, agencies, and stakeholders participated in workshops over 9 months to contribute to and provide feedback on the modeling approach, outputs, and recommendations.

Project Deliverables

- GIS land cover data
- Comparison of technical parameters
- Summary of limitations or data gaps when using i-Tree Hydro
- Calibrated projects and data for i-Tree Hydro with appropriate inputs and defaults values in the Pacific Northwest
- Numerous scenario results
- Sensitivity analysis
- Presentations and materials

METHODS OF ANALYSIS

Puget Sound hydrology simulation must account for dry summers and wet winters. Winter storm events, accounting for a majority of annual precipitation, occur when deciduous trees are without foliage and conifer transpiration is low. Both i-Tree Hydro and WWHM were developed to simulate complex hydrology, including that experienced in the Puget Sound region. While WWHM was developed specifically for the Puget Sound region, i-Tree Hydro is typically used to simulate hydrology in other U.S. climatic regions. i-Tree Hydro projections have not been previously tested for the Puget Sound region.

In order to compare the models, simulations are conducted with default values ("out of the box" values) for each parameter, for each model. In addition to default parameters, identical input data sources, such as land coverage and precipitation, are used to the maximum extent feasible. Each model has different input data requirements, non-overlapping input data requirements cannot be identical between the models.

Three management scenarios, in addition to an existing conditions scenario, are used to analyze the stormwater effects of tree canopy coverage. The three management scenarios of Tree Canopy Loss, Development, and Tree Canopy Increase are each split into two cases, representing a different level of implementation of the scenario. For example, Tree Canopy Loss (Scenario 1) includes a case with no canopy (100 percent loss, Scenario 1A) and a case with a canopy decrease of 10 percent (Scenario 1B). Each scenario case was evaluated with both models for each of four spatial scales: City, Drainage Basin, Neighborhood, and Parcel. Table 2 shows an in-depth description of each case.

Table 2. | Management Scenario Descriptions

Management Scenario	Cases	Description
Existing Conditions	**Base Case**	Current (existing 2017) land cover percentages of the pilot community spatial scale of interest.
Tree Canopy Loss	1A. **Present Tree Canopy Stormwater Benefit**	What if the area has no tree cover?
		Tree canopy is fully converted to herbaceous (grass) coverage.
	1B. **Partial Tree Canopy Loss**	What if the area loses some tree canopy due to a lack of investment, care, infestation, etc.? 10% of existing tree canopy is converted to herbaceous (grass) coverage.
Development	2A. **Build Out with Tree Preservation**	What if the area has new development (build out) but retains some tree canopy? 5% of tree canopy is converted, half (2.5%) to impervious and half (2.5%) to herbaceous (grass) coverage.
	2B. **Build Out without Tree Preservation**	What if the area has new development (build out) and retains no canopy? 10% of tree canopy is converted, half (5%) to impervious and half (5%) to herbaceous (grass) coverage.
Tree Canopy Increase	3A. **Tree Canopy Increase: Over Pervious Area**	What if the area had a dramatic increase (20%) in tree canopy but 90% of that canopy overhangs pervious area and 10% overhangs impervious area? Tree canopy increases by 20% with 18% coming from existing herbaceous (grass) coverage and 2% coming from existing impervious coverage.
	3B. **Tree Canopy Increase: Over Impervious Area**	What if the area had a dramatic increase (20%) in tree canopy but 50% overhangs impervious area and 50% overhangs pervious area? Tree canopy increases by 20% with 10% coming from existing herbaceous (grass) coverage and 10% coming from existing impervious coverage.

Pilot Community Spatial Scales

Each designated pilot community for the project included four spatial scales: city, drainage basin, neighborhood, and parcel. Each scale was chosen for best representation in differences in trees impact on stormwater at a variety of project area sizes and proper model comparison. Community and stakeholder input were used to select drainage basins, neighborhoods and parcels that would properly represent changes in land cover types for stormwater impact analysis, (e.g., built out, trail restoration, parcels with an appropriate number of trees to inventory). WWHM is typically used for modeling smaller scales (e.g., parcels or neighborhoods) while i-Tree Hydro is used for larger scales (e.g., drainage basin scale using the stream gage data input). The four spatial scales evaluated for this study for each pilot community are shown in the following Tables 4-6.

The City of Kent is located in the middle of the Seattle-Tacoma and Puget Sound region in King County. It is the sixth largest city in Washington with a population of about 129,000 people and an area of about 34 square miles. The city is composed of three main drainage basins, each contributing runoff to Puget Sound. See Appendix D for the full stormwater profile for the City of Kent.

The City of Kirkland is located east of Seattle, along the eastern shore of Lake Washington. It is the sixth largest city in Washington with a population of about 89,000 people and an area of about 18 square miles. The City of Kirkland consists of 15 drainage basins that drain into the Sammamish River and Lake Washington. See Appendix D for the full stormwater profile for the City of Kirkland.

The City of Snohomish is located northeast of Seattle in Snohomish County. The smallest of the pilot communities, it is the 82nd largest city in Washington with a population of about 10,500 people and and area of about 4 square miles. The City of Snohomish consists of eight drainage basins contributing runoff to Snohomish River. See Appendix D for the full stormwater profile for the City of Snohomish.

The City of Tacoma is located southwest of Seattle along Puget Sound in Pierce County. It is the third largest city in Washington with a population of about 222,000 people and has an area of about 62 square miles. The City includes 9 drainage basins draining into Puget Sound. See Appendix D for the full stormwater profile for the City of Tacoma.

Table 3. | Kent

Scale	Drainage Basin	Description of Location	Size (acres)
City	Multiple	Jurisdictional boundary	21,875
Drainage Basin	Upper Mill Creek	In south central Kent	1,619
Neighborhood	Lower Mill Creek	Lower Mill Creek Neighborhood	138
Parcel	Lower Mill Creek	Kensington Heights	1.36

Table 4. | Kirkland

Scale	Drainage Basin	Description of Location	Size (acres)
City	Multiple	Jurisdictional boundary	11,395
Drainage Basin	Juanita Creek	Located in the northern portion of the City of Kirkland. Drainage basin extends north into the City of Bothell.	3,615
Neighborhood	Juanita Creek	Wolff Subdivision	12
Parcel	Champagne Creek	Veridian	0.45

Table 5. | Snohomish

Scale	Drainage Basin	Description of Location	Size (acres)
City	Multiple	Jurisdictional boundary	2,304
Drainage Basin	Swifty Creek	In central Snohomish	330
Neighborhood	Swifty Creek	Historic District	17
Parcel	Swifty Creek	Wetland next to Cady Park	0.88

Table 6. | Tacoma

Scale	Drainage Basin	Description of Location	Size (acres)
City	Multiple	Jurisdictional boundary	31,607
Drainage Basin	Foss Waterway	In south central Tacoma	5,781
Neighborhood	Foss Waterway	Tacoma Mall	589
Parcel	Foss Waterway	Fireman's Park	1.54

Hydrologic Modeling Methods

Since 2001, the Western Washington Hydrology Model (WWHM) has been used to evaluate the effects of tree canopy coverage on stormwater runoff. The version of the model used for this study is WWHM 2012, Version 4.2.13. WWHM is based on the industry standard Hydrology Simulation Program – FORTRAN (HSPF) originally published by the U.S. Environmental Protection Agency. HSPF, and thus WWHM, simulates the hydrologic processes of pervious and impervious land surfaces and of streams and impoundments. WWHM caters HSPF to Western Washington by including meteorological data (e.g., precipitation and evapotranspiration), soil parameters, and land use parameters specific to the region while performing the calculations necessary to evaluate a project area for state and local stormwater regulations.

To represent an application of WWHM in Western Washington at the parcel scale for this project, Ecology's Best Management Practice (BMP) T5.16 from the 2014 Ecology SWMMWW was applied. BMP T5.16 Tree Retention and Tree Planting flow control credits are applied to the existing conditions scenario for each pilot community at the parcel scale, to then be compared to the existing conditions scenario without BMP T5.16 flow control credits. BMP T5.16 allows for the reduction in target impervious surface area when calculating mitigation needs to meet Ecology's flow control requirements. The amount of impervious surface area reduction depends on the tree type (e.g., coniferous or deciduous), canopy area, and proximity of the tree to the impervious surface.

To qualify for tree retention flow control credit per the 2014 Ecology SWMMWW, a retained tree must:

- Have a minimum 6-inch diameter at breast height (DBH),
- Be located within 20 feet of new or replaced ground level impervious surface and,
- Be maintained for the length of the project or replaced in-kind.

To qualify for the tree planting flow control credit per the 2014 Ecology SWMMWW, a new tree must:

- Be included on a jurisdiction's approved species list,
- Deciduous measure at least 1.5 inches in diameter measured 6 inches off the ground at time of planting,
- Confierous measure at least 4 feet tall at time of planting,
- Be located within 20 feet of new or replaced ground level impervious surface,
- Be spaced to accommodate mature tree spread, and
- Be maintained for the length of the project or replaced in-kind.

Neither the retained nor newly planted tree flow control credit is applicable to trees within a native vegetation area or within planter boxes. Jurisdictions may also have specific tree retention and tree planting requirements that differ from the guidance provided in the Ecology SWMMWW. Table 7 details the flow control credits provided by BMP T5.16.

Table 7. | Flow Control Credits for Newly Planted and Retained Trees (BMP T5.16)

Tree Type	Flow Control Credit (as a reduction in project impervious area needing flow control per Ecology requirements)
Retained Coniferous	20% of canopy area, minimum of 100 square feet per tree
Retained Deciduous	10% of canopy area, minimum of 50 square feet per tree
Newly Planted Coniferous	50 square feet per tree
Newly Planted Deciduous	20 square feet per tree

WWHM Resources

- User's Manual - *http://www.clearcreeksolutions.info/ftp/public/downloads/WWHM2012/WWHM2012%20User%20Manual.pdf*
- Workshops - *https://ecology.wa.gov/Regulations-Permits/Guidance-technical-assistance/Stormwater-permittee-guidance-resources/Stormwater-manuals/Western-Washington-Hydrology-Model*

i-Tree Hydro

i-Tree Hydro is a flexible tool for users interested in comparative analyses of different land cover scenarios and their hydrological impacts at various scales. The version of i-Tree Hydro used for this analysis is Version 6 Beta. Version 6 allows each scenario to be paired with a unique parameter set and different land cover data. The underlying hydrology model for i-Tree Hydro is TOPMODEL. TOPMODEL is a physically based, distributed watershed model that simulates hydrologic fluxes of water (infiltration-excess overland flow, saturation overland flow, infiltration, exfiltration, subsurface flow, evapotranspiration, and channel routing) through a watershed. The model simulates explicit groundwater/surfacewater interactions by predicting the movement of the water table, which determines where saturated land-surface areas develop and have the potential to produce saturation overland flow. i-Tree Hydro uses calibrated or non-calibrated streamflow, precipitation, and elevation data specific to the project area to predict changes in streamflow and water quality based on land cover change. For this project, i-Tree Hydro is used to predict the hydrologic impact of land cover changes, specifically tree canopy. Another application in the suite of i-Tree tools (i-Tree Eco) is used at the Parcel spatial scale for each scenario to valuate per tree hydrologic impact using tree inventories conducted by each pilot community. The version of i-Tree Eco used for this analysis is Version 6. Each tree inventory includes diameter at breast height (DBH), proximity to impervious surface, and species.

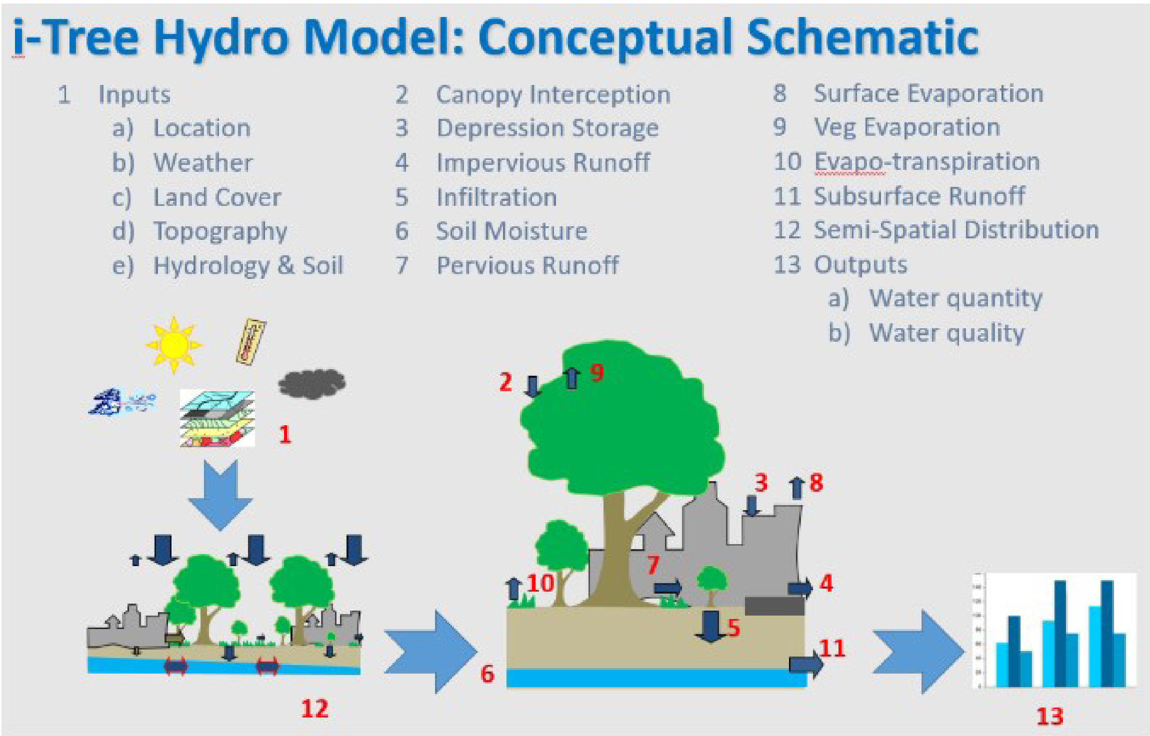


Figure 3. | i-Tree Hydro Model Inputs and Concepts

i-Tree Hydro Resources

User's Manual - *www.itreetools.org/resources/manuals/i-TreeHydroUsersManual.pdf*

i-Tree Hydro Website - *https://www.itreetools.org/hydro/*

Sample Reports - *www.itreetools.org/resources/reports.php*

Workshops - *www.itreetools.org/resources/training/index.php*

Presentation/Webinars - *www.itreetools.org/resources/presentations.php*

TOPMODEL - *https://csdms.colorado.edu/wiki/Model:TOPMODEL*

i-Tree Forecast User's Manual - *https://www.itreetools.org/resources/manuals/Ecov6_ManualsGuides/Ecov6Guide_UsingForecast.pdf*

Accounting for Tree in Stormwater Models - *https://owl.cwp.org/mdocs-posts/accounting-for-trees-in-stormwater-models/*

Model Comparison

The following parameters describe the similarities and differences between the models. See Appendix A for a more detailed comparison.

Table 8. | Summary of i-Tree Hydro and WWHM Comparison

Comparison Metric	i-Tree Hydro	WWHM
Primary Use	Urban tree canopy effect on stormwater runoff, project specific	Sizing flow control and water quality treatment facilities in Western Washington
Underlying Model	TOPMODEL	HSPF
Geographic/Topographic Data Source	DEM or TI file	Analyzed outside of WWHM using any topography data source
Meteorological and Hydrology Data Sources	Weather station data within software, raw NCDC data file, or third-party source. Calibrated stream gage data within software, raw USGS file, or pre-processed gage file.	Precipitation and evaporation data within software or user defined source. No stream gage data used. Calibration step not integrated into the model, but it can be performed independently if calibration data is available.
Tree Vegetation	Tree canopy percent coverage with percent overhanging impervious/pervious, percent deciduous/evergreen, tree leaf area index (LAI).	Input as pervious area classified with flat (less than 5%), moderate (5 to 15%), or steep slope (greater than 15%).
Impervious	Input as percentage of land cover, default value is set at 65% directly connected impervious area.	Input as impervious area classified with flat (less than 5%), moderate (5 to 15%), or steep slope (greater than 15%), impervious area is assumed to be 100% directly connected impervious area.
Soil	5+ types, 8 pre-set parameters	Classified as 3 types (outwash, till, or saturated); each classification is defined by several default parameter values.

See Appendix B for a comparison of the terminology used in i-Tree Hydro and WWHM.

Below is a table describing all i-Tree Hydro inputs used for this study.

Table 9. | Recommended Parameter Inputs for i-Tree Hydro

Parameter	Description
Stream Gage	Hydro, EPA Waters, or USGS – 24-hour, hourly data Gage station closest to the area of interest: Kent - *https://waterwatch.usgs.gov/index.php?id=ww_current* Kirkland - *https://green2.kingcounty.gov/hydrology/GaugeMap.aspx*
Digital Elevation Data	Created with project area boundary in ArcGIS or preloaded TI file when DEM not available
Land Cover	Derived from GIS and remote sensing software or tools such as i-Tree Canopy or i-Tree Landscape
Precipitation Data	After 2005, hourly, from i-Tree Hydro or NCDC: *https://gis.ncdc.noaa.gov/maps/ncei/cdo/hourly*
Tree Leaf Area Index (LAI)	7.4 (based on local literature); LAI is the total leaf area divided by the canopy area.
Evergreen Canopy	Derived from remote sensing classification of aerial or satellite imagery; or estimated through statistical sampling and aerial photo interpretation using a tool such as i-Tree Canopy
Soil Type	Best fit to project area and scale based on data from United States Department of Agriculture (USDA) National Resources Conservation Science (NRCS) Web Soil Survey or local soil data.
Soil Macro pore Percentage	0.1 instead of the current default value of 0.000001 This parameter is under review by the i-Tree development team. Macro pores are large soil pores existing between and within aggregates of soil. Larger the soil macro pore fraction, the more room for air and water to move between soil particles.
Directly Connected Impervious Area (DCIA)	65% default value in i-Tree Hydro; DCIA is the amount drained into the project areas outlet, from connected impervious area.
Shrub Leaf Area	2.2 default value in i-Tree Hydro; can be manipulated by user
Herbaceous Lead Area	1.6 default value in i-Tree Hydro; can be manipulated by user
Shrub Tree Canopy	0 default value in i-Tree Hydro; can be manipulated by user when using GIS land cover data

DATA INPUTS/SOURCES

Each model requires input data to simulate hydrology. Required data inputs vary for each model with some overlap, including land cover, topography, soil and precipitation. i-Tree Hydro also uses streamflow as an input. To ensure accurate comparison of the models, identical data inputs were used for both models for overlapping data needs, while non-overlapping parameters were set at default. Detailed information on selecting inputs for i-Tree Hydro can be found in the i-Tree Hydro manual. "Best fit" parameters, or parameters that best represent the land cover and characteristics of the Pacific Northwest, were found and analyzed per some literary review and discussion with the i-Tree Hydro development team.

Land Cover

Urban tree canopy assessments were conducted for all four pilot communities. Using aerial imagery and LiDAR data in ArcGIS software, an initial land cover data set was produced. After a quality control review to increase land cover identification, accurate land cover percentages were calculated for each community at each spatial scale. The assessments provide existing conditions data for tree canopy, herbaceous/lawn, bare soil/dry vegetation, and impervious coverage area. The methods used are described in Appendix I. Figure 4 shows how i-Tree Hydro inputs and compares the land cover percentages for each case. The results of each community's urban tree canopy assessment are shown on pages 32 -39.

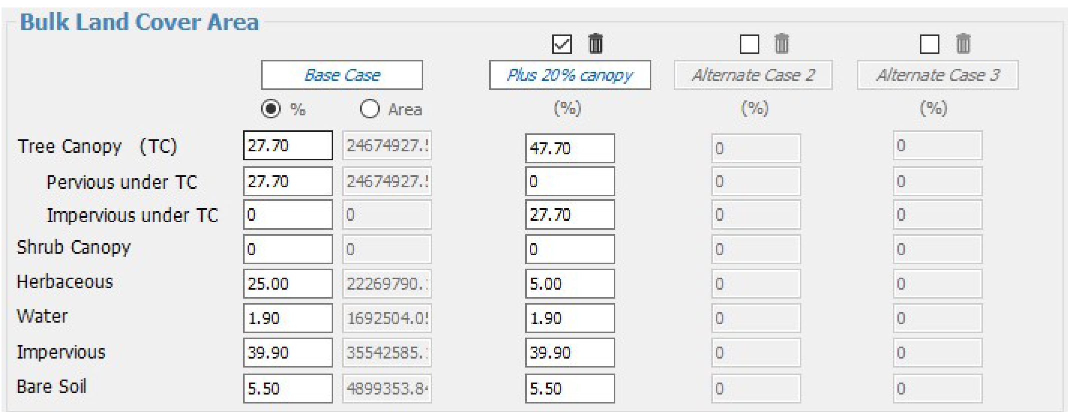


Figure 4. | i-Tree Hydro Land Cover Input Example

i-Tree Hydro land cover is classified by eight types shown in Table 10. i-Tree Hydro averages the effect of different tree species. The tree canopy percentage includes the understory of the tree canopy: percent overhanging impervious and percent overhanging pervious. i-Tree Hydro includes advanced parameters that are automatically populated based on the project area but can be user-defined. One example of an advanced parameter is leaf on and off days; the default value for this parameter is a date range derived from the chosen project area. The Davey Research Institute is currently conducting a review and sensitivity analysis of all of the advanced parameters.

Table 10. | i-Tree Hydro Land Cover Types

Land Cover Type	Description
Tree Canopy	Amount of tree canopy in the project area
Impervious under Tree Canopy	Tree canopy that overhangs impervious surface
Pervious under Tree Canopy	Tree canopy that overhangs pervious surface
Herbaceous	Non-woody, non-tree vegetation such as grass
Shrub Canopy	Woody, non-tree vegetation
Water	Year-round water bodies
Impervious	Roads, buildings, parking lots or other paved areas
Bare Soil	Bare soil or barren areas such as gravel pits or sand

Land cover data input to WWHM is classified by one of four types: forest, pasture, lawn, or impervious. Forest land cover is simulated by parameters derived from a second-growth Douglas fir forest, common to Puget Sound lowlands. Pasture land cover represents land tracts that have been cleared of forest and replaced with shrubs and grasses. Lawn land cover represents urban and suburban vegetation typically found in residential developments and is similar to the herbaceous i-Tree Hydro land cover classification. Impervious land cover represents any hard or compacted surface, including pavement, roofing, compacted bare soil, and water.

Land cover data input to WWHM is classified by one of four types shown in Table 11.

Table 11. | WWHM Land Cover Types

Land Cover Type	Description
Forest	Parameters derived from a second-growth Douglas fir forest, common to Puget Sound lowlands
Pasture	Land tracts that have been cleared of forest and replaced with shrubs and grasses
Lawn	Urban and suburban vegetation typically found in residential developments similar to the herbaceous i-Tree Hydro land cover
Impervious	Any hard or compacted surface, including pavement, roofing, compacted bare soil and water

Topography

A digital elevation model (DEM) was created using ArcGIS software and LiDAR elevation data for each pilot community and spatial scale. LiDAR data for both models was acquired from the Puget Sound LiDAR Consortium for Kent, Kirkland, and Snohomish and from Pierce County for Tacoma. The resolution of the resulting DEM is 10 meters. An example of pilot community DEM is shown in Figure 5.

The DEM created for each pilot community was used to calculate areas of each slope classification.

i-Tree Hydro uses either a digital elevation model (DEM) file or a preprocessed topographic index (TI) to define the topography of the model simulation area. The simulation area is not hand delineated in the program. A drainage basin simulation area may be entered as either a DEM or TI file. A simulation area not defined by a single drainage basin (e.g., a city or a parcel), but rather is entered as a TI file if a DEM is not available.

Topographic data input to WWHM is defined by slope and classified by one of three types:

- Flat (less than 5%)
- Moderate (5 to 15%)
- Steep (greater than 15%)

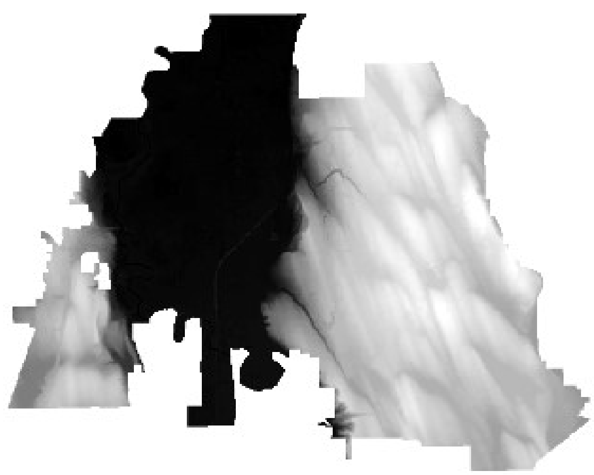


Figure 5. | City of Kent DEM

Soils

Soils input data is derived from the United States Department of Agriculture (USDA) National Resources Conservation Service (NRCS) Web Soil Survey to classify underlying soil type per the requirements of each model.

i-Tree Hydro has 12 predefined soil types. Each soil type is defined by five parameters:

- Wetting Front Suction
- Wetted Moisture Content
- Surface Hydraulic Conductivity
- Depth of Upper Soil Zone
- Initial Soil Saturation

Many other defaulted soil components and factors are represented by default values in i-Tree Hydro. An example of those default values is shown in Figure 6.

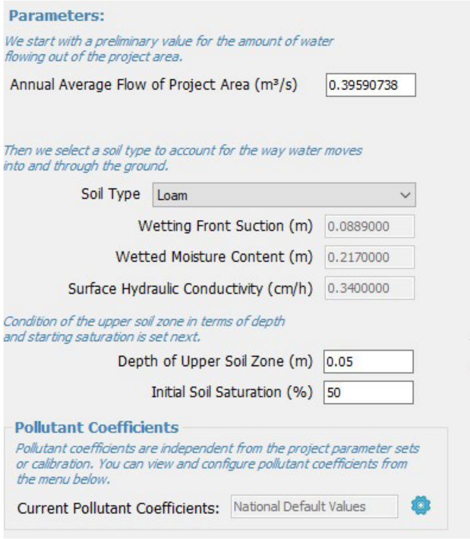


Figure 6. | i-Tree Hydro Soil Default Values

Table 12. | i-Tree Hydro Soil Types

Soil Type	Description
Sand	Course texture, high porosity, low moisture retention
Loamy Sand	Mixture of loam and sand, majority sand
Sandy Loam	Mixture of loam and sand, majority loam
Loam	Half sand, half silt, small amount of clay
Silt Loam	Mixture of loam and silt, majority silt
Sandy Clay Loam	Mixture of sand, clay, and loam
Clay Loam	Mixture of clay and loam, majority clay
Silty Clay Loam	Mixture of silt, clay, and loam
Sandy Clay	Mixture of sand and clay, majority sand
Silty Clay	Mixture of silt and clay, majority silt
Clay	Extremely fine texture, low porosity, high moisture retention
Blended Texture	Combination of all soil types

Soils data input to WWHM is classified by one of three types summarized in Table 13.

Table 13. | WWHM Soil Types

Soil Type	Description
A/B (outwash)	Material transported and deposited by glacial processes, predominantly soil and gravel (Type A) with the possibility of some loamy sands (Type B)
C (till)	Deposited by glacial activity, consolidated and poorly sored with low infiltration rates
D (saturated)	Characterized by high-water content; comparable to wetlands

Precipitation

Precipitation data in i-Tree Hydro may be applied using one of the following three methods:

- Selected from a weather station on a map built into the model software,
- Imported from a National Climatic Data Center (NCDC) weather file,
- Imported from a user-processed weather file.

Precipitation data specific to the project location is built into WWHM and is based on long-term (50 to 70 years) precipitation gage records scaled for project location based on 24-hour, 25-year rainfall intensity isopluvials published in the National Oceanic and Atmospheric Administration Atlas 2 Precipitation-Frequency Atlas of the Western United States, Volume IX-Washington (NOAA, 1973). Precipitation input data may also be uploaded into the model.

For this study, hourly precipitation data from 10/1/09 to 9/30/15 was uploaded from the NCDC website for the Sea-Tac International Airport precipitation gage (727930-24233) and the Snohomish County precipitation gage and uploaded into both models (i-Tree Hydro and WWHM). The procedure for creating and uploading the precipitation input file into i-Tree Hydro is included in Appendix M. The procedure for uploading precipitation input data into WWHM can be found in the WWHM User Manual.

Evaporation

Evaporation data in i-Tree Hydro is standardized in the model for the year 2005. Data required for other years can be acquired in the precipitation data from NCDC. The raw weather from NCDC is used in the i-Tree weather preprocessor to generate processed weather data including potential evaporation variables. i-Tree Hydro uses that processed data to inform the maximum potential evaporation and evapotranspiration from different storages at each timestep. This is a major reason why i-Tree Hydro is generally limited to NCDC weather stations, as NCDC data from U.S. based airports tend to include all the variables needed to estimate potential evaporation & potential evapotranspiration.

Evaporation data is built into WWHM and is based on pan evaporation data collected in the field in Puyallup from 1931-1995. Since evaporation data is not highly variable like rainfall, Puyallup pan evaporation data is used as the default for all 19 counties in western Washington. WWHM scales the evaporation data by 0.72 to 0.82 to convert to potential evapotranspiration. Evaporation data may also be uploaded into the model.

For this study, evaporation data from 10/1/09 to 9/30/15 was downloaded from National Climatic Data Center and uploaded into WWHM and i-Tree Hydro.

Stream Gage

In i-Tree Hydro, a model simulation may be completed using calibration or non-calibration. Calibration simulations use observed streamflow data from a user-defined gaging station to optimize hydrologic parameters to best match simulated streamflow to observed streamflow. Observed streamflow data are included in the software. For non-calibration simulations, the user can use previously calibrated (default) hydrologic parameter values or independently adjust land cover and hydrologic parameter values. Calibrated stream gage data for drainage basins within Kent and Kirkland were downloaded from USGS and King County, respectively. Stream gage data from Upper Mill Creek at Earthworks Parks (USGS 12113347) was used for the City of Kent modeling. Stream gage data from Juanita Creek (12120500) was used for the City of Kirkland modeling. For the drainage basin simulations, the cities of Snohomish and Tacoma did not have available stream gage data for the selected drainage basins for this study. Stream gage data was not used for any of the other spatial scales. Details of the edited stream gage data is described in Appendix M.

WWHM does not use streamflow data for hydrologic simulation. A user may compare WWHM simulation results to measured streamflow external to the WWHM software.

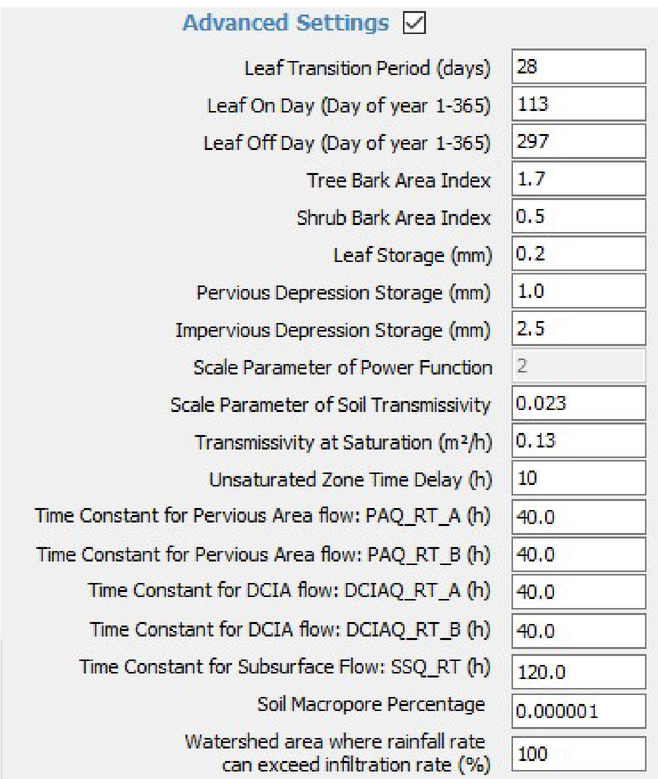
Advanced Parameters

i-Tree Hydro also includes a set of inputs called advanced parameters. These parameters (e.g., leaf on/off days) are auto-populated by the model, depending on location of the project area, but can be adjusted by the user. One example of an advanced parameter that was adjusted for this project was the soil macropore percentage (pMacro). The default value for this parameter in this geographical area was set at 0.000001 percent. pMacro defines the porosity of soils in the model and thus influences infiltration over pervious surface areas. The i-Tree Development Team recommended using a value of 0.1 instead for this project. While this parameter did not change total flow significantly, it does have a large impact on allocation of flow between sub-categories. This is logical as increasing the pore size of soils would increase infiltration and allocation of runoff in pervious areas. Research is underway to determine a new default value. Advanced parameters in WWHM can also be adjusted per the user's need.

WWHM also contains advanced parameters for impervious land categories and pervious land categories called IMPLNDs and PERLNDs, respectively. The default IMPLNDs and PERLNDs in WWHM are based on regional parameter values developed by the U.S. Geological Survey for western Washington (Dinicola 1990) and HSPF modeling conducted by AQUA TERRA Consultants.

Figure 7 shows i-Tree Hydro's list of advanced parameters.

For each impervious land category in WWHM, there are 4 parameters that describe the hydrologic factors that influence runoff summarized in Table 14.


Advanced Settings

Leaf Transition Period (days)	28
Leaf On Day (Day of year 1-365)	113
Leaf Off Day (Day of year 1-365)	297
Tree Bark Area Index	1.7
Shrub Bark Area Index	0.5
Leaf Storage (mm)	0.2
Pervious Depression Storage (mm)	1.0
Impervious Depression Storage (mm)	2.5
Scale Parameter of Power Function	2
Scale Parameter of Soil Transmissivity	0.023
Transmissivity at Saturation (m²/h)	0.13
Unsaturated Zone Time Delay (h)	10
Time Constant for Pervious Area flow: PAQ_RT_A (h)	40.0
Time Constant for Pervious Area flow: PAQ_RT_B (h)	40.0
Time Constant for DCIA flow: DCIAQ_RT_A (h)	40.0
Time Constant for DCIA flow: DCIAQ_RT_B (h)	40.0
Time Constant for Subsurface Flow: SSQ_RT (h)	120.0
Soil Macropore Percentage	0.000001
Watershed area where rainfall rate can exceed infiltration rate (%)	100

Figure 7. | i-Tree Hydro Advanced Parameters

Table 14. | WWHM IMPLNDs

IMPLND Name	Description and Units	Default Value
LSUR	length of surface overland flow plane (feet)	400
SLSUR	slope of surface overland flow plane (feet/feet)	0.01*
NSUR	roughness of surface overland flow plane (Manning's n)	0.1
RETSC	retention storage (inches)	0.10*

* Values for flat slope category, defined as having a land surface slope less than five percent. WWHM also includes moderate (between five and 15 percent) and steep (greater than 15 percent) slope categories. Moderate slope IMPLNDs have default SLSUR and RETSC values of 0.05 and 0.08; steep slope IMPLNDs have default values of 0.1 and 0.05, respectively.

For each pervious land category in WWHM, there are 16 parameters that describe various hydrologic factors that influence runoff summarized in Table 15. The default values vary depending on the vegetation type (e.g., forest, pasture, or lawn) and soil type (e.g., till, outwash, or saturated).

Table 15. | WWHM PERLNDs

PERLND Name	Description and Units	Default Value or Range of Values
LZSN	lower zone storage nominal (inches)	4.0-5.0
INFILT	infiltration capacity (inches/hour)	0.03-2.0
LSUR	length of surface overland flow plane (feet)	100-400
SLSUR	slope of surface overland flow plane (feet/feet)	0.001-0.10
KVARY	groundwater exponent variable (inch-1)	0.3-0.5
AGWRC	active groundwater recession constant (day-1)	0.996
INFEXP	infiltration exponent	2.0-10.0
INFILD	ratio of maximum to mean infiltration	2
BASETP	base flow evapotranspiration (fraction)	0
AGWETP	active groundwater evapotranspiration (fraction)	0.0-0.7
CEPSC	interception storage (inches)	0.10-0.20
UZSN	upper zone storage nominal (inches)	0.25-3.0
NSUR	roughness of surface overland flow plane (Manning's n)	0.25-0.50
INTFW	interflow index	0.0-6.0
IRC	interflow recession constant (day-1)	0.5-0.7
LZETP	lower zone evapotranspiration (fraction)	0.25-0.8
PCW	porosity of cohesion water (soil micropores)	0.12-0.35
PGW	porosity of gravitational water (soil macropores)	0.15-0.38
UPGW	upper zone gravitational water porosity (soil macropores)	0.18-0.45

INTERPRETATION OF RESULTS

i-Tree Hydro

To interpret the results from the i-Tree Hydro analysis, it is necessary to understand the results summary produced by the software with each simulation. The full results summary example for the city of Kirkland, Scenario 1A is included in Appendix J. Each simulation compares two different cases, the Base Case and the Alternative Case. The Base Case represents land cover for existing conditions (see Figure 8). The land cover percentages were derived from the tree canopy assessment.

Land Cover	Base	Alternative
Tree Cover %	37.4	0.0
Shrub Cover %	0.0	0.0
Herbaceous Cover %	20.5	57.9
Water Cover %	2.4	2.4
Impervious Cover %	37.7	37.7
Soil Cover %	2.1	2.1

	Base	Alternative
Tree LAI	7.4	7.4
Shrub LAI	2.2	2.2
Herbaceous LAI	1.6	1.6
Directly Connected Impervious Cover (%)	100.0	100.0

LC beneath Tree Cover	Base	Alternative
Soil Cover %	32.7	0.0
Impervious Cover %	4.6	0.0
Percent Evergreen		
Tree Canopy %	55.0	55.0
Shrub Canopy %	0.0	0.0

Figure 8. | i-Tree Hydro Land Cover Inputs

The Alternative Case describes the land cover percentages for the analyzed management scenario. Each Alternative Case is simulated parallel to the Base Case to produce relative change results to allow for comparison. Relative change and avoided runoff percentages were calculated outside of i-Tree Hydro in a separate results spreadsheet. The four runoff fractions that are reported by i-Tree Hydro include:

- Total Flow
- Base Flow
- Impervious Flow
- Pervious Flow

Streamflow Predictions	Total Flow		Base Flow		Pervious Runoff		Impervious Runoff	
	Base	Alternative	Base	Alternative	Base	Alternative	Base	Alternative
Total Flow (cubic meters)	248,008,301.0	253,162,049.6	140,638.3	152,387.9	125,972,342.2	142,397,250.8	121,894,570.6	110,611,658.3

Figure 9. | i-Tree Hydro Results Outputs

For comparison purposes with the WWHM scenarios, the term "Volume" was used instead of "Flow" in the presentation of results tables in the following sections and appendices. Definitions of each type of volume are described in Table 16. i-Tree Hydro also reports minimum and maximum flow times including the mean and median values shown in Appendix K. Water quality outputs (based on event mean concentrations) are also included in each results summary for the neighborhood, drainage basin, and city scale for each pilot community. Water quality results are included in each results summary for i-Tree Hydro in Appendix F.

Table 16. | Runoff Volume Definitions

Runoff Volume Fraction	Definitions
Total Runoff Volume (TRV)	The predicted streamflow of the base (existing conditions) case, including its components: base flow, pervious flow, and impervious flow
Base Runoff Volume (TBRV)	The primary source of water during periods of low flow. Usually supplied by groundwater, but also by water slowly draining from the shallow subsurface into surface waters (interflow). The portion of surface water supplied by groundwater.
Pervious Runoff Volume (PRV)	The volume of water derived from runoff from pervious surfaces (e.g., bare soil and grass).
Impervious Runoff Volume (IRV)	The volume of water derived from runoff from impervious surface (e.g., roads, sidewalks, and parking lots runoff).

WWHM

The model simulations conducted with WWHM have been configured to output total runoff volume, pervious land surface runoff volume, and impervious land surface runoff volume for consistency with the i-Tree Hydro output (see Table 16). The division of runoff volumes between the land surface type categories allows for better understanding of the effects of tree canopy on stormwater.

A typical WWHM simulation calculates runoff for three depths of the soil column: surface flow (above the soil column), interflow (shallow subsurface flow), and groundwater (deep subsurface flow). Interflow is differentiated from groundwater by its eventual assumed expression into surface water, (e.g., seepage into a stream channel), while groundwater flows downward to a depth preventing eventual expression on the surface or use by vegetation. The WWHM results presented for this study combine the surface and interflow runoff values, but do not include the groundwater flow fraction. This is the standard approach when using WWHM and the related model HSPF.

RESULTS

Results for this study are analyzed with two methods: Direct Modeling Comparison and Management Applications.

The first analysis approach (Direct Modeling Comparison) compares i-Tree Hydro and WWHM simulated runoff with a Directly Connected Impervious Area (DCIA) parameter value of 100 percent in both models. In WWHM, the DCIA parameter is referred to as Effective Impervious Area (EIA) and is typically set at 100 percent; WWHM relies on the user to define effective and ineffective impervious areas prior to entering these values in the model. The default value in i-Tree Hydro is 65 percent DCIA; the i-Tree Hydro developers do not recommend using a DCIA value of 100 percent. The direct modeling comparison is applied to compare results without the effect of the DCIA/EIA parameter. The direct modeling comparison was performed at the neighborhood scale for each pilot community.

The second analysis approach (Management Applications) uses different DCIA parameter values for i-Tree Hydro and WWHM appropriate for each scale and each pilot community. In i-Tree Hydro, the default DCIA parameter value of 65 percent is used for each scale and each pilot community. In WWHM, the default parameter value of 100 percent DCIA (EIA) is used for each scale and each pilot community. This provides the most realistic outputs based on recommended parameters for each model specific to the Pacific Northwest.

For analysis and presentation of comparison results and results from all other simulations, the total runoff volume is used. The results summaries in Appendix J include the total runoff volume divided into impervious and pervious runoff volumes. The divided runoff volumes provide insight into how the runoff from different land uses is allocated within and between the two models.

Pages 31-38 include city scale results for each pilot community for each scenario. Model outputs are represented by total runoff volume and relative change in avoided runoff, compared to the base scenario for each city and scale. Results for each pilot community at the other spatial scales (e.g., drainage basin, neighborhood, and parcel) are included in Appendix E.

Direct Modeling Comparison

Results in Table 17 present relative change in runoff volume from both models for comparison at the neighborhood scale for Scenario 1A only. The percentage change in runoff volume and avoided runoff volume is in comparison to the base case scenario (existing land cover conditions) case for each respective model. These results show the benefit that the existing tree canopy coverage provides: higher percentages of avoided runoff indicate a greater benefit provided by the tree canopy.

Table 17. | Direct Model Comparison for Scenario 1A at the Neighborhood Scale with 100% DCIA

City (Scenario 1A)	Neighborhood	Area (Acres)	i-Tree Hydro (Relative Change, Volume, ft^3)	WWHM (Relative Change, Volume, ft^3)	Avoided Runoff Range (%)
Kent	Lower Mill Creek Neighborhood	138	2.0 million	1.4 million	1-2%
Kirkland	Wolff Subdivision	12.5	0.3 million	0.4 million	4-14%
Tacoma	Tacoma Mall	589	1.0 million	5.0 million	0-2%
Snohomish	Historic District	77	0.4 million	0.2 million	1-5%

Figures 10 through 13 present similar results for direct model comparison (100 percent DCIA) of total runoff volume differences between the base case scenario and Scenario 1A at the neighborhood scale for both models. Results indicate an increase in total runoff volume when all tree canopy is replaced with herbaceous land cover for each pilot community. Without tree canopy coverage, the total runoff volume increases from 2 to approximately 37 million cubic feet over the 6-year simulation period. The large difference in relative change between each pilot community is attributed to the existing land cover of each pilot community. Results consistently showed that higher existing canopy coverage and impervious surface area (as opposed to herbaceous land cover) creates a larger increase in runoff volume when the canopy coverage is converted to impervious land cover. This result indicates the impact tree canopy coverage may have on site runoff volume; greater canopy coverage leads to greater reduction in total runoff volume.

Direct comparison results indicate a larger increase in total runoff volume and impervious runoff volume from the base case scenario than the runoff volumes simulated for the Management Application scenarios. This indicates the importance of the DCIA parameter. The percentage change in total runoff volumes does not increase or decrease widely between the Direct Model Comparison and Management Application analysis approaches. Decreasing DCIA results in decreased in total runoff volume for each management scenario, including the existing conditions scenario, maintaining the same relative change in runoff avoided between the management scenarios and the existing conditions scenario.

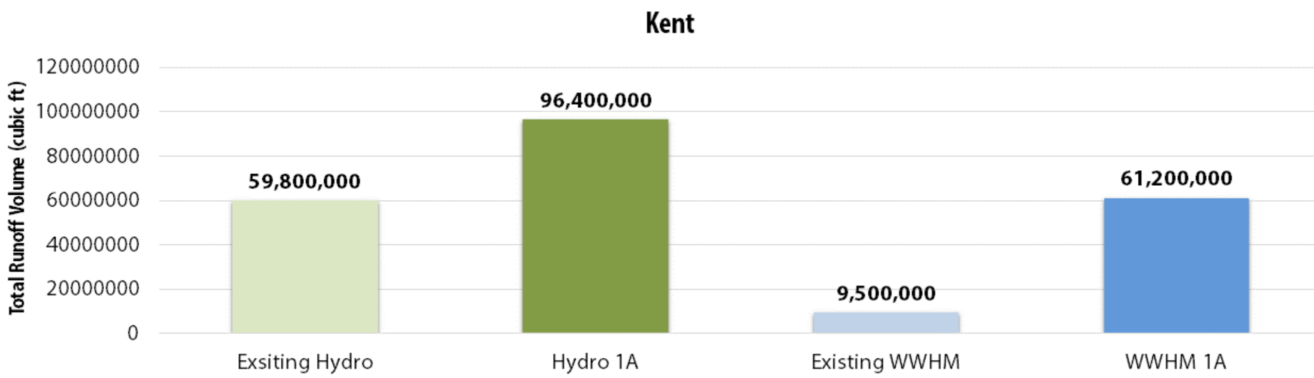


Figure 10. | Kent - Direct Model Comparison Graph for Exiting Land Cover and Scenario 1A over a 6-year period at the Neighbhoord Scale and with 100% DCIA.

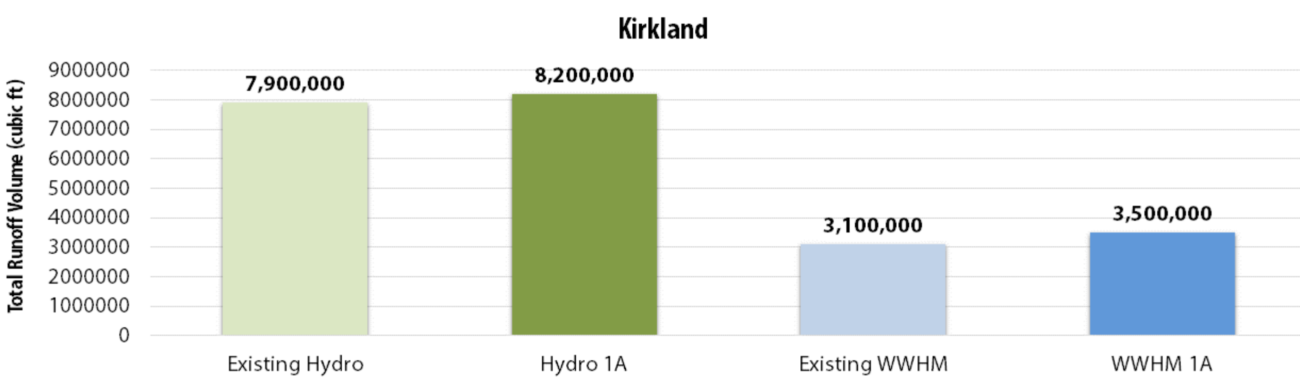


Figure 11. | Kirkland - Direct Model Comparison Graph for Exiting Land Cover and Scenario 1A over a 6-year period at the Neighbhoord Scale and with 100% DCIA.

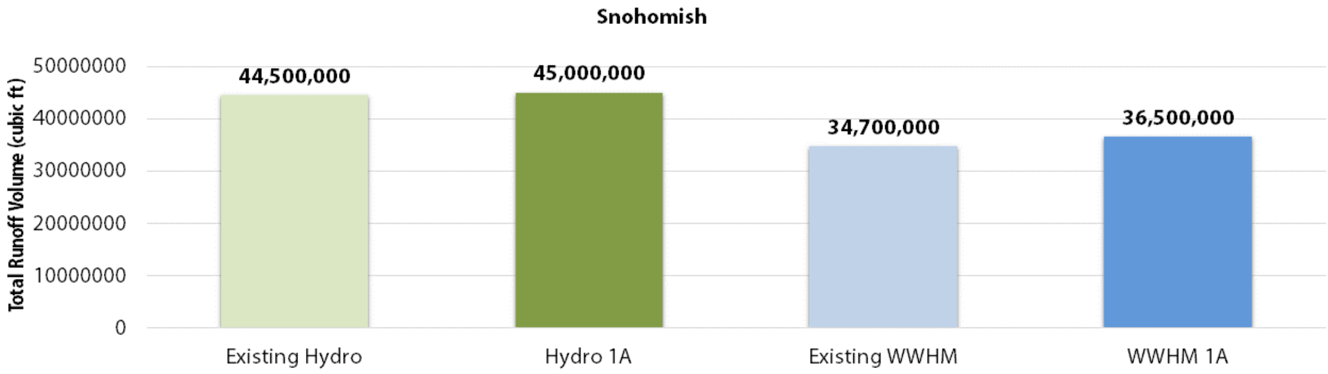


Figure 12. | Snohomish - Direct Model Comparison Graph for Exiting Land Cover and Scenario 1A over a 6-year period at the Neighbhoord Scale and with 100% DCIA.

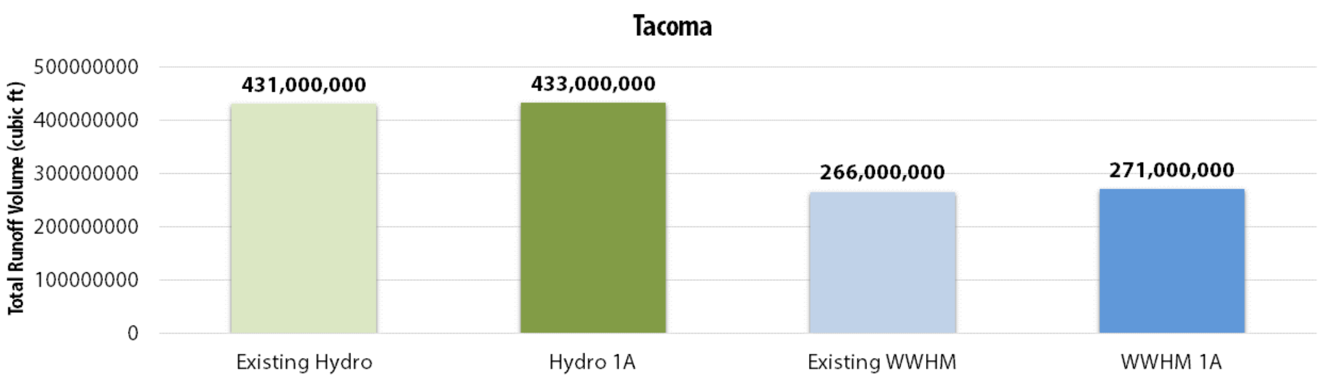


Figure 13. | Tacoma - Direct Model Comparison Graph for Exiting Land Cover and Scenario 1A over a 6-year period at the Neighbhoord Scale and with 100% DCIA.

Management Applications

In addition to the Direct Modeling Comparison analysis approach using the 100 percent DCIA parameter value for both models, results for this study are also analyzed using the model default values for the DCIA parameter (e.g., 65 percent for i-Tree Hydro and 100 percent for WWHM). Model simulations for the Management Applications analysis approach were simulated for each pilot community at each scale for each management scenario; results are shown in Tables 18-20. Consistently, results indicate increased tree canopy coverage reduces stormwater runoff volume. In Scenario 1A (all canopy replaced with herbaceous), there is an increase in total runoff volume. When more tree canopy coverage is retained during development in Scenario 2A (with 5 percent conversion of tree canopy coverage) there is a smaller increase in total runoff volume compared to Scenario 2B (with 10 percent conversion of tree canopy coverage). When tree canopy coverage is increased and is overhanging impervious surfaces (Scenario 3B), there is a larger decrease in total runoff volume compared to increased tree canopy coverage overhanging herbaceous land cover. Results indicate that increasing tree canopy coverage over impervious surface has a greater effect on total runoff volume than increasing canopy coverage over herbaceous land cover.

The amount of change in stormwater runoff volume varies between each spatial scale and pilot community. The differences are attributable to different land surface slopes of the study areas, total area of each scale, and the amount of existing tree canopy coverage. The difference is also attributed to the size and degree of development of each pilot community; the larger and more developed the community, the more runoff is produced. For example, the city of Tacoma is three times larger than the city of Kirkland, and the total runoff volume from Tacoma's existing conditions is 16 times greater than Kirkland's. Another factor in the Puget Sound region is the saturation of soil and pervious land

cover types in the winter months in the Pacific Northwest. The more saturated the soil, grass, and trees are from steady rainfall, the more runoff will occur in that area regardless of a large or small amount of tree canopy coverage.

Some differing trends were found in the results for each scale as well. For example, results for the city and neighborhood scales for Tacoma show a larger decrease in runoff volume when newer canopy is overhanging pervious, rather than impervious. It can be assumed that adding more tree canopy over impervious surface would create a larger decrease in runoff volume. This trend can be attributed to the way that i-Tree Hydro treats the distribution of land cover when there is a low percentage of herbaceous cover to begin with. When this trend occurs, the modeled area has less percentage of herbaceous land than the increase in canopy can allocate. To compensate, i-Tree Hydro converts more area into impervious surface within the model, therefore the simulation will yield lower runoff volumes because more impervious surface is being covered.

Results for each pilot community at the city scale are presented in pages 31-38 individually by pilot community.

Table 18. | City Scale Management Scenario Results

	CITY (Base Case % TC, Base Case % Imp)	Kent (28% TC, 40% Imp)		Kirkland (37% TC, 38% Imp)		Snohomish *(23% TC, 40% Imp)*		Tacoma *(20% TC, 52% Imp)*	
	MODEL	i-Tree Hydro	WWHM	i-Tree Hydro	WWHM	i-Tree Hydro	WWHM	i-Tree Hydro	WWHM
Results for Each Scenario (Percent Change from Base Case)	TC Loss 1A (0%)	2	3	3	4	1	9	0.4	6
	TC Loss 1B (-10%)	1	0.3	1	0.4	0	0.9	-1	0.6
	Develop 2A (-5%)	1	1	0.5	2	2	1	0.5	0.9
	Develop 2B (-10%)	2	3	2	5	3	2	1.7	2
	TC Increase 3A (+20%, 90% over pervious)	-1	-2	-1	-3	-1	-2	-4	-2
	TC Increase 3B (+20%, 50% over pervious)	-2	-5	-2	-9	-2	-4	-3	-3

Table 19. | Drainage Basin Scale Management Scenario Results

	DRAINAGE BASIN (Base Case % TC, Base Case % Imp)	Upper Mill Creek (33% TC, 38% Imp)		Juanita Creek (35% TC, 42% Imp)		Swifty Creek *(18% TC, 54% Imp)*		Foss Creek *(15% TC, 55% Imp)*	
	MODEL	i-Tree Hydro	WWHM	i-Tree Hydro	WWHM	i-Tree Hydro	WWHM	i-Tree Hydro	WWHM
Results for Each Scenario (Percent Change from Base Case)	TC Loss 1A (0%)	2	2	1	5	1	6	0.5	3
	TC Loss 1B (-10%)	1	0.2	0	0.5	1	0.6	0.4	0.3
	Develop 2A (-5%)	1	2	0.5	2	1	0.7	1	0.4
	Develop 2B (-10%)	2	4	2	4	3	2	2	0.9
	TC Increase 3A (+20%, 90% over pervious)	-1	-2	-1	-2	-1	-2	-4	-0.9
	TC Increase 3B (+20%, 50% over pervious)	-2	-8	-2	-8	-2	-3	-2	-2

Table 20. | Neighborhood Scale Management Scenario Results

	NEIGHBORHOOD (Base Case % TC, Base Case % Imp)	Lower Mill Creek Neighborhood (20% TC, 51% Imp)		Wolff Subdivision (51% TC, 25% Imp)		Historic District (16% TC, 66% Imp)		Tacoma Mall (10% TC, 75% Imp)	
	MODEL	i-Tree Hydro	WWHM	i-Tree Hydro	WWHM	i-Tree Hydro	WWHM	i-Tree Hydro	WWHM
Results for Each Scenario (Percent Change from Base Case)	TC Loss 1A (0%)	1	2	4	14	1	5	0	2
	TC Loss 1B (-10%)	1	0.2	1	1	1	0.5	0	0.2
	Develop 2A (-5%)	1	1	1	4	1	0.6	1	0.3
	Develop 2B (-10%)	2	2	2	8	3	1	3	0.7
	TC Increase 3A (+20%, 90% over pervious)	-1	-1	-1	-5	-2	-1	-6	-0.6
	TC Increase 3B (+20%, 50% over pervious)	-2	-3	-2	-16	-2	-2	-3	-1

Parcel Scale Results

For the parcel level evaluation, BMP T5.16 Tree Retention and Tree Planting flow control credits from the 2014 SWMMWW Ecology were applied in WWHM. An existing tree inventory for each parcel site was used to determine if the existing trees met the requirements of tree retention flow control credits to reduce the impervious surface area simulated per Table 7. No credit was applied for newly planted trees, this study evaluated only existing conditions and retained trees. Simulation results are reported as avoided stormwater runoff volume, comparing existing parcel site conditions to existing conditions with BMP T5.16 tree retention credits applied.

- Kensington Heights (City of Kent): No trees are located within 20 feet of ground level impervious areas, so no tree retention credit applies for this parcel.
- Veridian (City of Kirkland): A total of 5 conifers and 8 deciduous trees are 6 inches or greater DBH and located within 20 feet of ground level impervious areas, so a total flow control credit of 73 square feet was applied to the parcel resulting in 11,182 gallons of avoided runoff over the 6-year evaluation period.
- Wetland near Cady Park (City of Snohomish): A total of 2 conifers are 6 inches or greater DBH and located within 20 feet of ground level impervious areas, so a total flow control credit of 33 square feet was applied to the parcel, resulting in 4,445 gallons of avoided runoff over the 6-year evaluation period.
- Fireman's Park (City of Tacoma): All of the trees on the parcel are located within 20 feet of ground level impervious areas; however, only 36 trees were 6 inches or greater DBH. A total of 14 conifers and 22 deciduous trees were used in the flow control credit evaluation, resulting in a reduction of 2,500 square feet and a total of 317,189 gallons of avoided runoff over the 6-year evaluation period.

A separate i-Tree Eco evaluation was used to estimate runoff at the parcel level rather than i-Tree Hydro. Six species common to the Pacific Northwest were chosen and modeled through version 5 of i-Tree Eco at several different DBH values. On-the-ground inventories then provided the necessary characteristics to estimate stormwater mitigation on the parcel. The exact tree species was matched to one of the six modeled in i-Tree Eco that it was most similar to. This reduced the level of effort for modeling as well as data collection in the field for the pilot communities.

- Kensington Heights (City of Kent): 33 trees in total were inventoried and matched to three of the six species. Estimates based on the size and diameter of each tree resulted in a total of 119,722 gallons of stormwater mitigated.
- Veridian (City of Kirkland): 42 trees in total across three different species were inventoried, resulting in a total of 102,818 gallons of stormwater mitigated during the 6-year period.
- Wetland Near Cady Park (City of Snohomish): 44 trees in total across three different species were inventoried, resulting in an estimated 24,686 gallons of stormwater mitigated. Many smaller stature trees were present on this parcel.
- Fireman's Park (City of Tacoma): 49 trees across all six different species were inventoried, resulting in an estimated 58,248 gallons of stormwater mitigated in the 6-year study period.

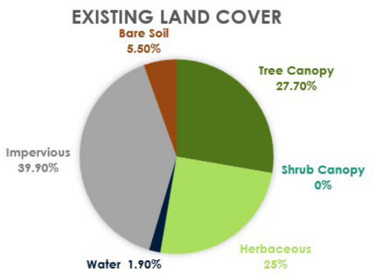
Table 21. | Parcel Scale Results for i-Tree Eco and WWHM

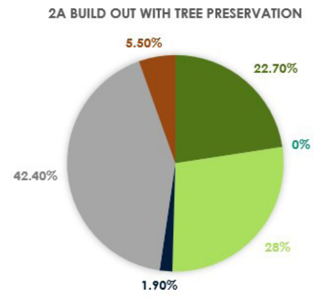
Parcel	Tree Species	Conifer (C) or Deciduous (D)	Number of Trees	Number of Trees Within 20 feet of Impervious and ≥ 6 inches DBH	Avoided Runoff (gallons/6 years)	
					i-Tree Eco	*WWHM*
Kensington Heights (Kent)	Doug Fir	C	23	0	119,722	0
	B Maple	D	9	0		
	W Redcedar	C	1	0		
	Red Maple	D	0	0		
	P Pine	C	0	0		
	L Linden	D	0	0		
Veridian (Kirkland)	Doug Fir	C	4	2	102,818	11,182
	B Maple	D	32	8		
	W Redcedar	C	6	3		
	Red Maple	D	0	0		
	P Pine	C	0	0		
	L Linden	D	0	0		
Wetland Near Cady Park (Snohomish)	Doug Fir	C	0	0	24,686	4,445
	B Maple	D	3	0		
	W Redcedar	C	6	2		
	Red Maple	D	0	0		
	P Pine	C	0	0		
	L Linden	D	35	0		
Fireman's Park (Tacoma)	Doug Fir	C	7	5	58,248	317,189
	B Maple	D	3	3		
	W Redcedar	C	6	5		
	Red Maple	D	21	19		
	P Pine	C	5	4		
	L Linden	D	7	0		

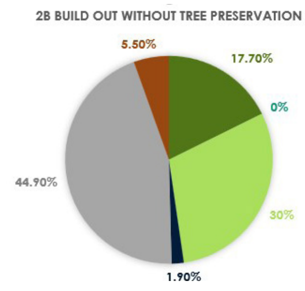
WWHM and i-Tree Eco at the parcel scale showed very different results. Methods and outputs for the two models differ, more research and evaluation are needed.

City Scale Results: Kent

The City of Kent has 27.7% existing tree canopy. Scenarios 2A and 2B represent build out and gain of impervious surface. To show the benefit that the existing tree canopy has on the total runoff volume in the City of Kent, results below show the change in land cover and relative change in flow when impervious surface area is increase and canopy decrease.







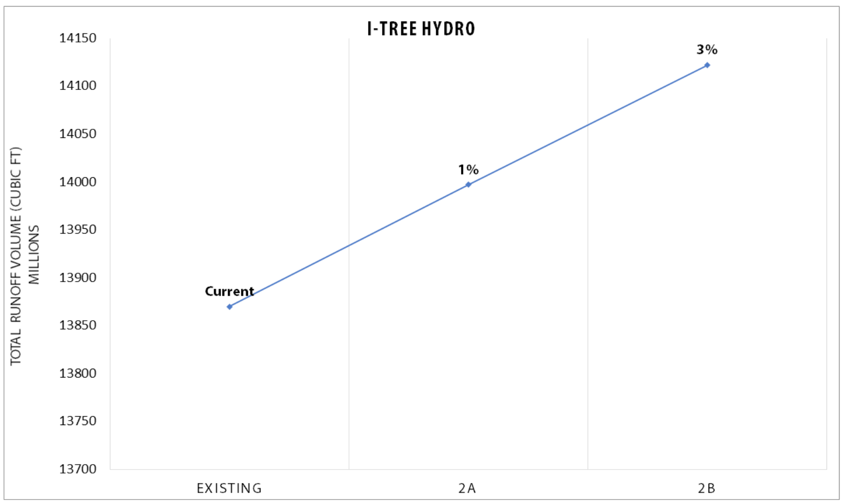


Figure 14. | i-Tree Hydro Results for the City of Kent for the Existing Scenario, Scenario 2A, and Scenario 2B.

As impervious surface increases and tree canopy decreases, total runoff volume increases. Figures 14 and 15 show the increase in total volume with a 5% and 10% decrease in tree canopy and additional impervious area. Scenario 2A retains 5% more tree canopy than Scenario 2B. Relative change in runoff volume ranges from 1 to 3% with the extra 5% decrease of tree canopy concluding that the preservation of tree canopy positively impacts stormwater runoff volume in the City of Kent.

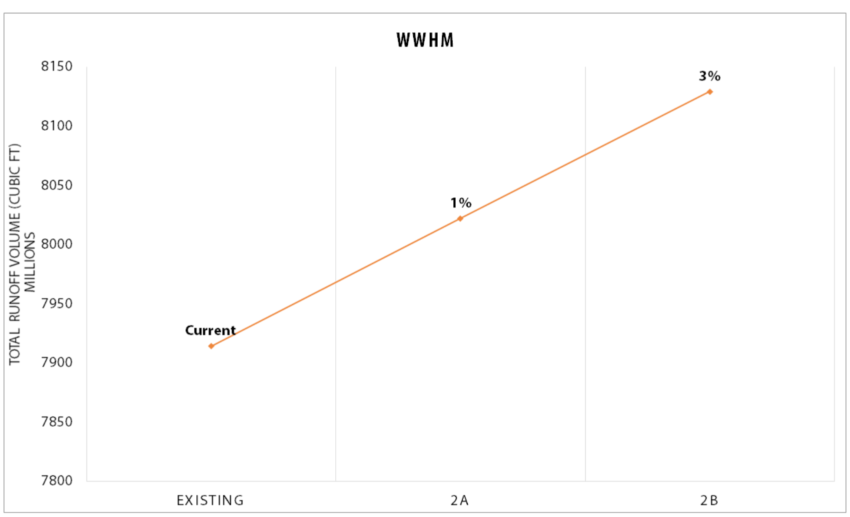


Figure 15. | WHMM Results for the City of Kent for the Existing Scenario, Scenario 2A, and Scenario 2B.

Table 22 on page 32 includes city spatial scale results from the six simulated alternative scenarios. Relative change results are based on the change in volume between the base case and indicated alternative scenario. Relative changes for Scenarios 1A through 2B show that the total runoff volume increases with differing amounts of canopy decrease. Scenarios 3A and 3B show that total runoff volume decreased with a 20 percent increase in tree canopy.

Table 22. | Results for the City of Kent at the City Scale

Scenario	i-Tree Hydro (Relative Change, Volume ft³)	WWHM (Relative Change, Volume ft³)	Avoided Runoff Range (%)
1A. Present Stormwater Canopy Benefit	246 million	257 million	2 to 3%
1B. Partial Tree Canopy Loss	88 million	26 million	0.3 to 1%
2A. Build Out with Tree Preservation	127 million	108 million	0
2B. Build Out without Tree Preservation	252 million	215 million	2 to 3%
3A. Tree Canopy Increase: Over Pervious Area	- 178 million	- 127 million	- 1 to -2%
3B. Tree Canopy Increase: Over Impervious Area	- 253 million	- 429 million	-2 to -5%

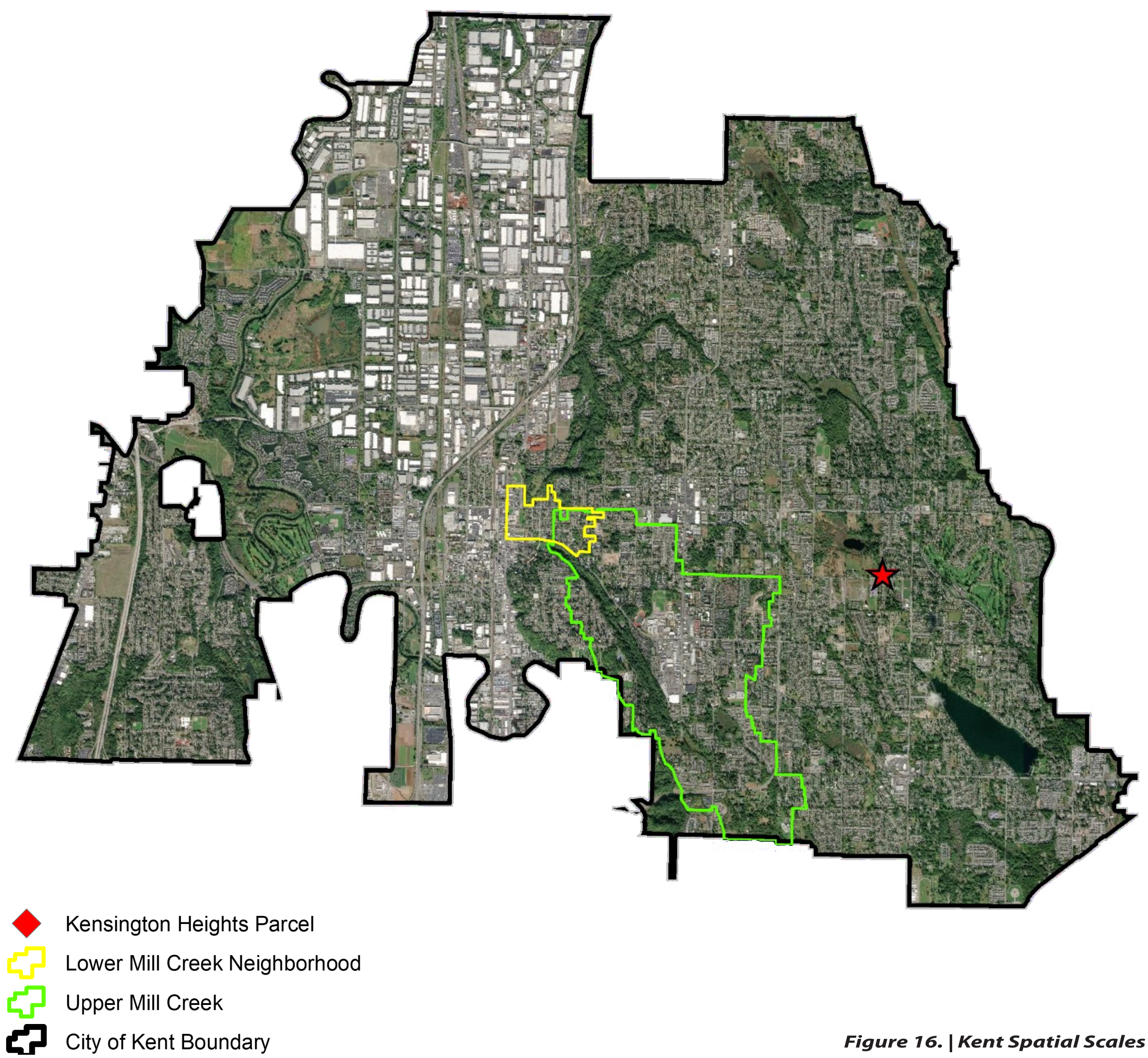
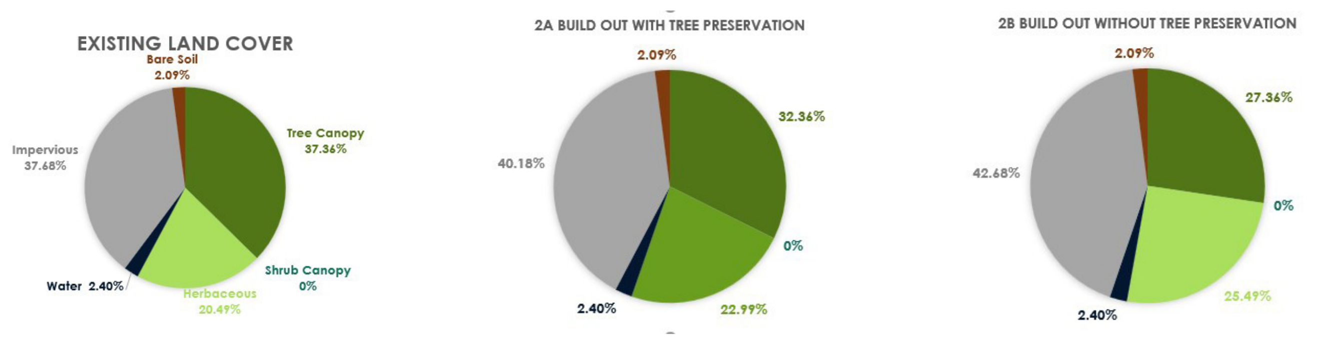


Figure 16. | Kent Spatial Scales

City Scale Results: Kirkland

The City of Kirkland has 37.4% existing tree canopy. Scenarios 2A and 2B represent build out and gain of impervious surface. To show the benefit that the existing tree canopy has on the total runoff volume in the City of Kirkland, results below show the change in land cover and relative change in volume when impervious surface area increases and canopy decreases.



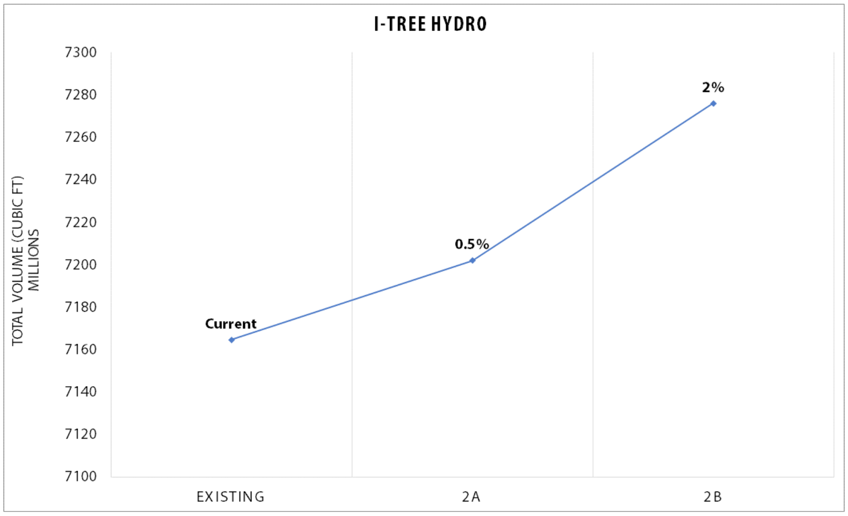


Figure 17. | i-Tree Hydro Results for the City of Kirkland for the Existing Scenario, Scenario 2A, and Scenario 2B

As impervious surface increases and tree canopy decreases, total runoff volume increases. Both Figures 17 and 18 show the increase in total volume with a 5% and 10% decrease in tree canopy and additional impervious area. Scenario 2A retains 5 percent more tree canopy than Scenario 2B. Relative change in runoff volume ranges from 0.5 to 5% with the extra 5% decrease of tree canopy concluding that the preservation of tree canopy positively impacts stormwater runoff volume in the City of Kirkland

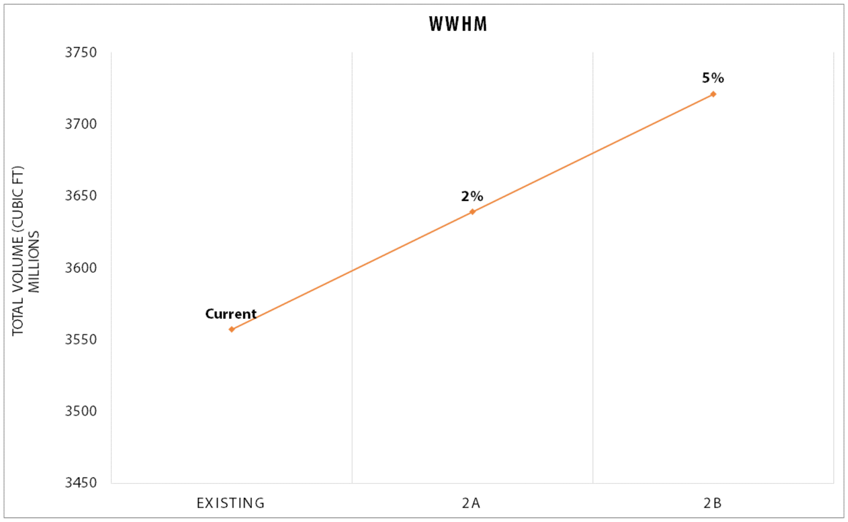


Figure 18. | WHMM Hydro Results for the City of Kirkland for the Existing Scenario, Scenario 2A, and Scenario 2B

Table 23 on page 34 includes city spatial scale results from the six simulated alternative scenarios. Relative change results are based on the change in volume between the base case and indicated alternative scenario. Relative changes for Scenarios 1A through 2B show that the total runoff volume increases with differing amounts of canopy decrease. Scenarios 3A and 3B show that total runoff volume decreased with a 20% increase in tree canopy.

Table 23. | Results for the City of Kirkland at the City Scale

Scenario	i-Tree Hydro (Relative Change, Volume ft^3)	WWHM (Relative Change, Volume ft^3)	Avioded Runoff Range (%)
1A. Present Stormwater Canopy Benefit	182 million	139 million	3 to 4%
1B. Partial Tree Canopy Loss	57 million	14 million	0.4 to 1%
2A. Build Out with Tree Preservation	37 million	82 million	0.5 to 2%
2B. Build Out without Tree Preservation	111 million	164 million	2 to 5%
3A. Tree Canopy Increase: Over Pervious Area	- 93 million	- 88 million	- 1 to -3%
3B. Tree Canopy Increase: Over Impervious Area	- 137 million	- 329 million	-2 to -9%

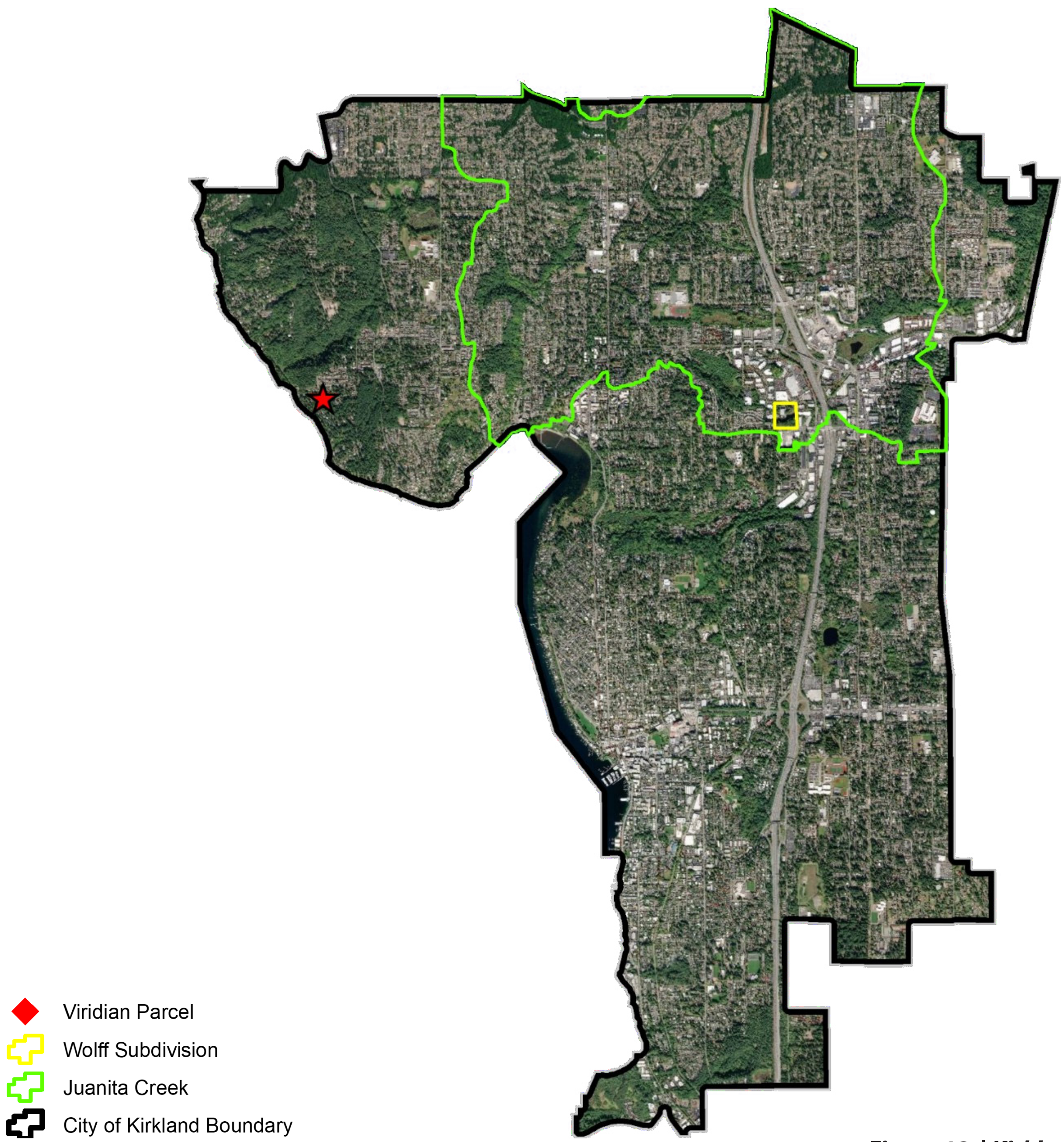
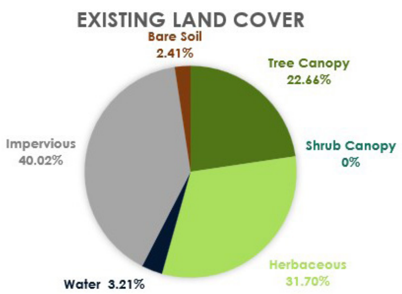
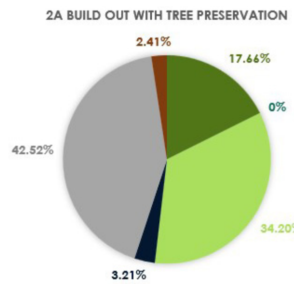


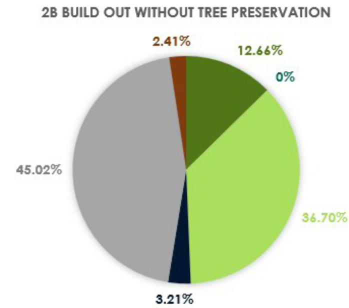
Figure 19. | Kirkland Spatial Scales

City Scale Results: Snohomish

The City of Snohomish has 22.7% existing tree canopy. Scenarios 2A and 2B represent build out and gain of impervious surface. To show the benefit that the existing tree canopy has on the total runoff volume in the City of Snohomish, results below show the change in land cover and relative change in volume when impervious surface area increases and canopy decreases.







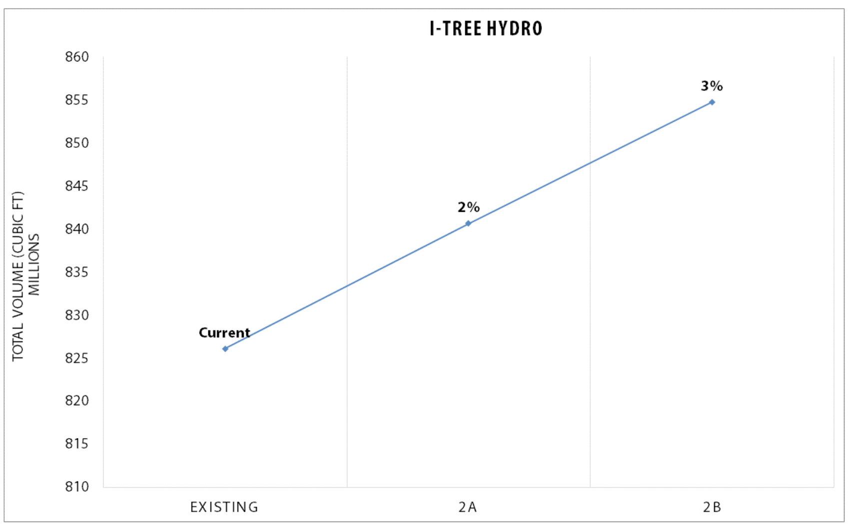


Figure 20. | i-Tree Hydro Results for the City of Snohomish for the Existing Scenario, Scenario 2A, and Scenario 2B

As impervious surface increases and tree canopy decreases, total runoff volume increases. Figures 20 and 21 show the increase in total volume with a 5% and 10% decrease in tree canopy additional impervious area. Scenario 2A retains 5% more tree canopy than Scenario 2B. Relative change in runoff volume ranges from 2 to 3% with the extra 5% decrease of tree canopy concluding that the preservation of tree canopy positively impacts stormwater runoff volume in the City of Snohomish.

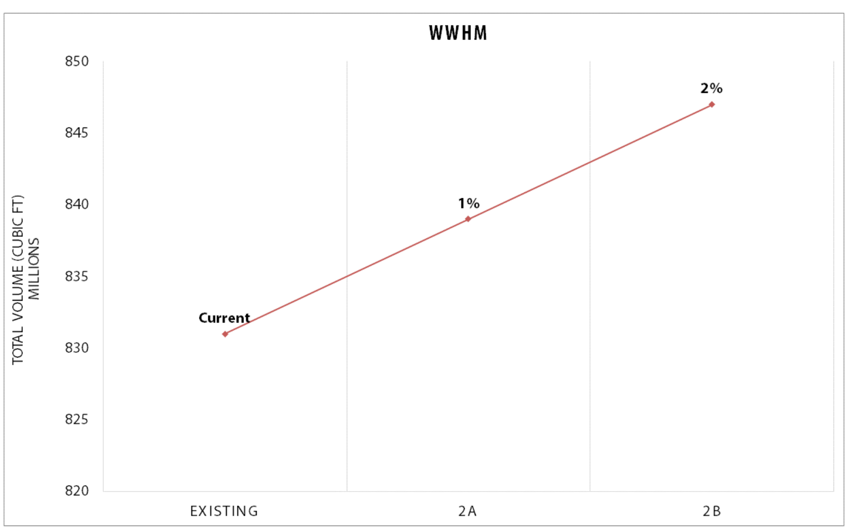


Figure 21. | WHMM Results for the City of Snohomish for the Existing Scenario, Scenario 2A, and Scenario 2B

Table 24 on page 34 includes city spatial scale results from the six simulated alternative scenarios. Relative change results are based on the change in volume between the base case and indicated alternative scenario. Scenarios 1A through 2B show that the total runoff volume increases with differing amounts of canopy decrease. Scenario 3A and 3B show that total runoff volume decreased with a 20 percent increase in tree canopy.

Table 24. | Results for the City of Snohomish at the City Scale

Scenario	i-Tree Hydro (Relative Change, Volume ft³)	WWHM (Relative Change, Volume ft³)	Avioded Runoff Range (%)
1A. Present Stormwater Canopy Benefit	7 million	73 million	1 to 9%
1B. Partial Tree Canopy Loss	3 million	7 million	0 to 1%
2A. Build Out with Tree Preservation	15 million	9 million	1 to 2%
2B. Build Out without Tree Preservation	29 million	17 million	2 to 3%
3A. Tree Canopy Increase: Over Pervious Area	- 6 million	- 18 million	- 1 to -2%
3B. Tree Canopy Increase: Over Impervious Area	- 17 million	- 33 million	-2 to -4%

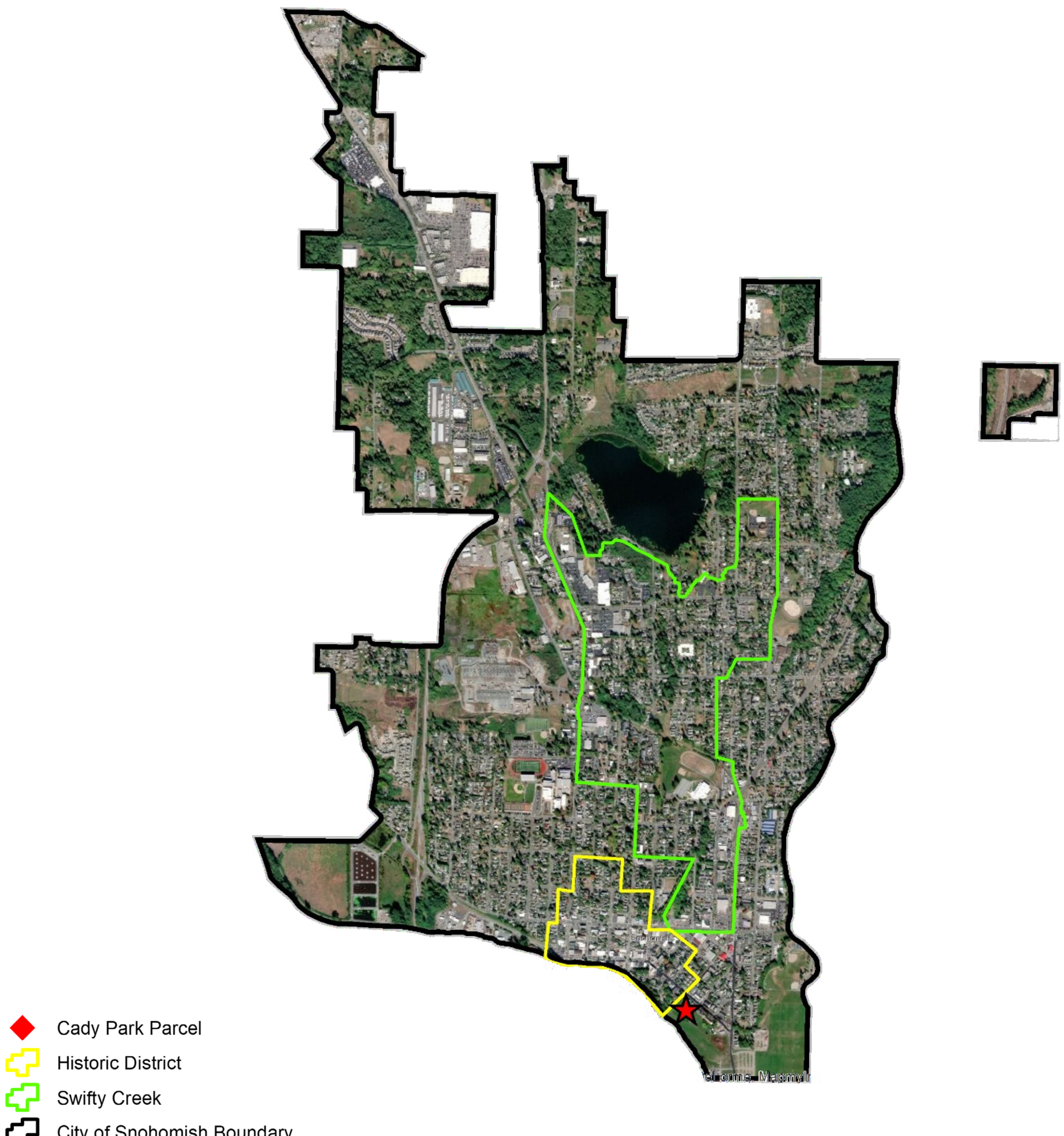
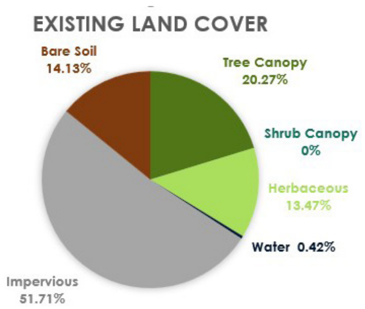
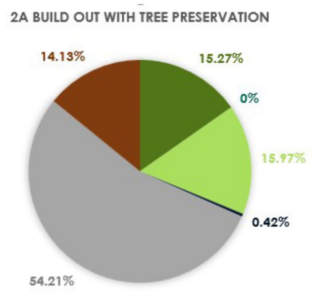


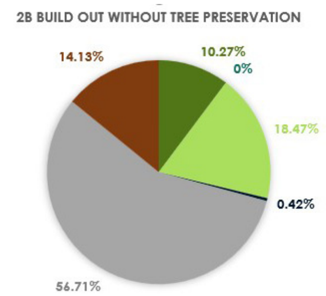
Figure 22. | Snohomish Spatial Scales

City Scale Results: Tacoma

The City of Tacoma has 20.3% existing tree canopy. Scenarios 2A and 2B represent build out and gain of impervious surface. To show the benefit that the existing tree canopy has on the total runoff volume in the City of Tacoma, results below show the change in land cover and relative change in volume when impervious surface area increases and canopy decreases.







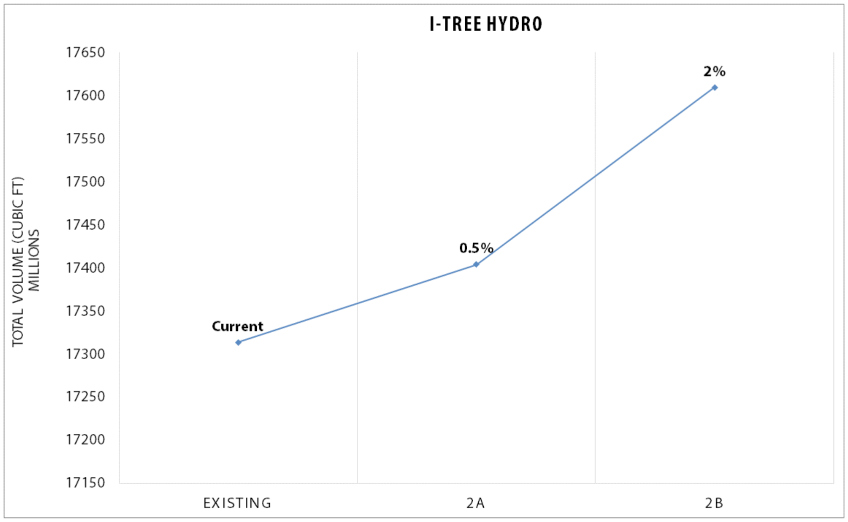


Figure 23. | i-Tree Hydro Results for the City of Tacoma for the Existing Scenario, Scenario 2A, and Scenario 2B

As impervious surface increases and tree canopy decreases, total runoff volume increases. Figures 23 and 24 show the increase in total volume with a 5% and 10% decrease in tree canopy and additional impervious area. Scenario 2A retains 5% more tree canopy than Scenario 2B. Relative change in runoff volume ranges from 0.5 to 2% with the extra 5% decrease of tree canopy concluding that the preservation of tree canopy positively impacts stormwater runoff volume in the City of Tacoma.

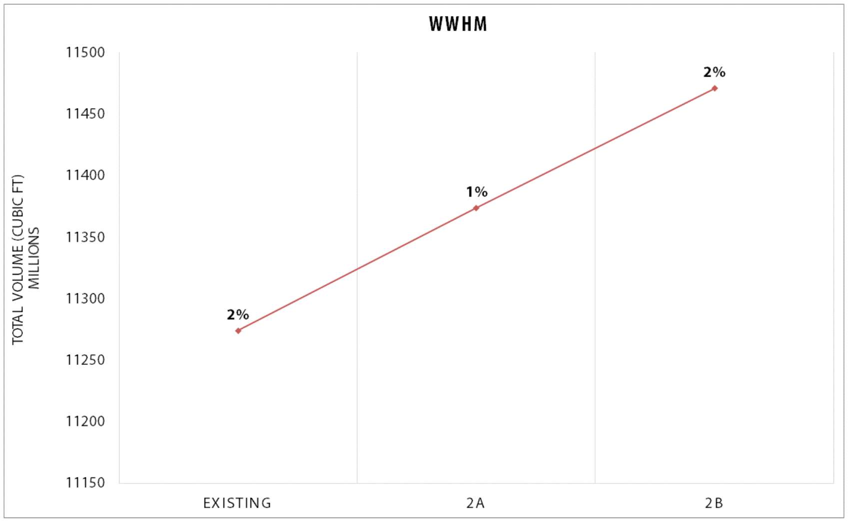


Figure 21. | WHMM Results for the City of Tacoma for the Existing Scenario, Scenario 2A, and Scenario 2B

Table 25 on page 38, includes city spatial scale results from the six simulated alternative scenarios. Relative change results are based on the change in volume between the base case and indicated alternative scenario. Relative changes for Scenarios 1A through 2B show that the total runoff volume increases with differing amounts of canopy decrease. Scenario 3A and 3B show that total runoff volume decreased with a 20% increase in tree canopy.

Table 25. | Results for the City of Tacoma at the City Scale

Scenario	i-Tree Hydro (Relative Change, Volume ft³)	WWHM (Relative Change, Volume ft³)	Avioded Runoff Range (%)
1A. Present Stormwater Canopy Benefit	67 million	674 million	0.4 to 6%
1B. Partial Tree Canopy Loss	- 120 million	67 million	- 1 to +0.6%
2A. Build Out with Tree Preservation	90 million	97 million	0.5 to 0.9%
2B. Build Out without Tree Preservation	296 million	193 million	1.7 to 2%
3A. Tree Canopy Increase: Over Pervious Area	- 705 million	- 185 million	- 2 to -4%
3B. Tree Canopy Increase: Over Impervious Area	- 477 million	- 387 million	- 3%

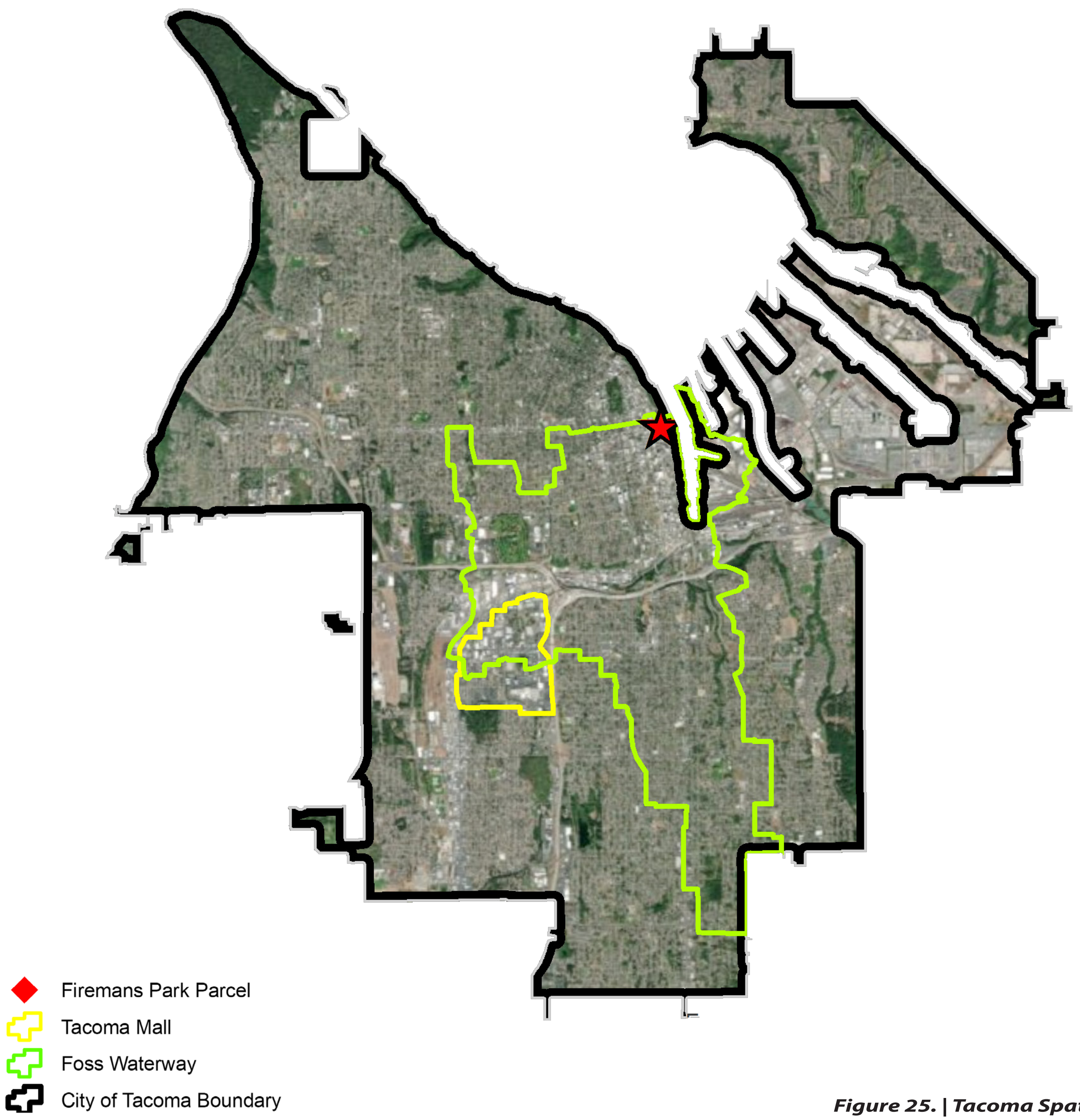


Figure 25. | Tacoma Spatial Scales

Results: Sensitivity Analysis

An analysis was conducted for i-Tree Hydro and WWHM to test the sensitivity of various parameters and their impact on stormwater runoff volume. The City of Kent was selected for the sensitivity analysis.

Base case results for WWHM and i-Tree Hydro were compared to eight sensitivity scenarios simulated in i-Tree Hydro and five in WWHM. For the i-Tree Hydro sensitivity analysis, simulations varying only the target parameter were conducted for high and low values. For example, the low value for directly connected impervious area (DCIA) in i-Tree Hydro is 40 percent and the high value is 100 percent. Results are presented below with a rating of Low, Medium or High based on relative sensitivity of simulation results to the target parameter. A few simulations showed lesser sensitivity to parameters expected to have a greater increase in relative change. For example, i-Tree Hydro had a low sensitivity to leaf area index (LAI) and Low/High herbaceous and percent, while either parameter would be expected to have a larger impact on runoff in any project area. Overall, land use and type had a larger sensitivity than other parameters such as evergreen canopy percent and tree LAI.

A sensitivity analysis was also conducted with WWHM to evaluate land use and soil type parameters and their effect on stormwater runoff volumes. In comparison to the existing conditions scenario, five sensitivity scenarios were simulated in WWHM. Relative change in total runoff volume results, compared to existing conditions, are presented in the table below. Land use coverage changes have a greater relative effect than changes in underlying soil type.

External to this study, the i-Tree Hydro model developer is conducting a sensitivity analysis. Additional sensitivity analysis results are presented in Appendix G.

Table 26. | i-Tree Hydro Sensitivity Analysis Results for the City of Kent at the City Scale.

Parameter Description		i-Tree Hydro				
		Parameter Value		Relative Change		*Model*
		Low	High	Low	High	*Sensitivity (Low, Medium, High)*
Vegetation	Tree LAI	4	10	0.40%	-0.24%	Low
	Evergreen Canopy Percent	10%	80%	0.40%	-0.20%	Low
	Herbaceous Land Percent	0%	52.70%	-0.70%	1.30%	Low
	All Herbaceous/All Canopy	100% Herbaceous	100% Canopy	-10%	-16%	High
	All Herbaceous Under Canopy	100% Herbaceous under Canopy	100% Impervious under canopy	20%	23%	High
Impervious	DCIA	0.4	1	-7%	5%	High
	Herbaceous/ Impervious under tree canopy with +20% canopy	100% impervious under new canopy	100% herbaceous under new canopy	6%	-4%	High
	Herbaceous/ Impervious under tree canopy with +20% canopy	100% impervious under new canopy	100% herbaceous under new canopy	6%	-4%	High
Soil	Soil Porosity	Sand	Clay	20%	-3%	High

Table 27. | WWHM Sensitivity Analysis Results for the City of Kent at the City Scale.

Parameter Description		WWHM	
		Relative Change	Model Sensitivity (Low, Medium, High)
Vegetation	All forested land use with existing underlying soils	-79%	High
	All lawn land use with existing underlying soils	-61%	High
Impervious	All impervious land use with existing underlying soils	101%	High
Soil	Outwash soils underlying existing land use	-13%	Medium
	Till soils underlying existing land use	30%	Medium

KEY FINDINGS AND DISCUSSION

This project provides the first-ever direct comparison of the i-Tree Hydro and WWHM stormwater models applied to urban forests in the Pacific Northwest. Numerous factors influence the hydrological response in i-Tree Hydro and WWHM, the interpretation of results, and the ability to compare results between the two models, as discussed below.

Key Findings

1. In nearly all modeled scenarios, i-Tree Hydro yielded lower relative change in runoff volume outputs, and therefore a lower benefit of tree canopy than WWHM.

i-Tree Hydro model runs yield smaller runoff volume outputs than WWHM model runs for the same geographic locations and scales, as well as lower relative change between current land cover scenarios and management scenarios. This suggests more modest stormwater runoff mitigating benefits of tree canopy in i-Tree Hydro than in WWHM. The difference in total runoff volume outputs between i-Tree Hydro and WWHM is attributed to how flow is allocated between the two models. Difference in infiltration/pervious runoff routines creates a difference between the total amount of runoff volume each model presents.

2. Increase in tree cover over impervious surface results in decreased runoff volumes.

Modeling shows that when tree canopy hangs over impervious surfaces, it provides more effective runoff mitigation than trees over pervious surfaces. Canopy overhanging impervious surfaces intercepts rainfall that would otherwise fall and become runoff because it's not absorbed. Pervious surfaces, including soils and herbaceous and shrub layers, provide absorption benefits on their own, so removing the tree canopy alone results in less overall impact.

3. Development that includes tree retention results in reduced runoff volume compared with development without tree retention.

Tree canopy reduces runoff volume regardless of the percent of area converted from pervious to impervious surface. While specific variables impact the amount of tree-associated runoff mitigation — including tree species, proximity to impervious surface, and ratios of pervious to impervious surface at a particular site — canopy is always correlated with reduced runoff. Other studies have shown that mature trees provide greater stormwater mitigation than replacement trees, suggesting that mature tree and forest retention could be more effective than planting new trees.

4. Scenarios where tree canopy is replaced with any other land cover type, including herbaceous layers or impervious area, result in increased runoff volume.

Across the board, in modeled scenarios where tree canopy is removed and replaced, stormwater runoff increases. This includes modeled scenarios where 100% or only a portion of tree canopy is removed and replaced with an herbaceous layer. Tree canopy associated with pervious area provides the greatest benefit in combination with the associated shrub and herbaceous layers and soils.

5. Areas with higher existing tree canopy coverage experience a lower magnitude of runoff volume when tree canopy is reduced.

A high percentage of canopy cover is associated with multiple types of vegetation (trees, shrubs, herbs) and soils. These elements function together to mitigate stormwater runoff through their combined interception, transpiration, and infiltration functions. When tree canopy is reduced in areas with higher existing canopy coverage, the benefit of these combined functions remains. The resulting increase in stormwater runoff tends to be less than when tree canopy is reduced in areas with lower canopy percentages to begin with.

Discussion of Factors Influencing the Model Comparison

Differences in base case (initial) land cover distribution and land cover types

One of the primary differences between the i-Tree Hydro and WWHM models is the underlying research and source for what a unit of tree canopy (forest) is based on when assessing impact on runoff volumes:

- In WWHM, tree canopy is based on studies from second-generation Douglas fir forest stands.
- In i-Tree Hydro, tree canopy is based on average leaf area index and phenology from reference studies, with further refinement from parameters for percent canopy over impervious, conifer vs deciduous canopy, leaf area, and seasonal variability using leaf-on/leaf-off dates.

It's possible that WWHM overestimates the contribution of trees by assuming leaf-on interception from Douglas fir throughout the year, while i-Tree Hydro accounts for different types of trees and seasonal changes. Forest areas in WWHM may have been developed based on Douglas fir because of available data and studies and also because of its predominance as a forest cover type near new development. New development is often the impetus for stormwater facility design discussions, which may limit tree canopy analysis to the Douglas fir.

The two models also differ significantly in the way they treat pervious surface, or herbaceous areas. Differences in the way pervious areas and flow subcategories are handled (e.g., base or surface flow, impervious flow, etc.) account for significant changes in outputs. For example, WWHM does not include a base flow component, and runoff is not typically broken out into impervious vs pervious flow components. To address the latter, those fractions were modeled in separate model runs in WWHM for comparison to the i-Tree Hydro results.

Implications of scale and runoff allocation

The change in runoff volume across both models, all scales, and all scenarios ranged from as little as 0% to as high as 14%. Some project stakeholders commented that they expected a replacement of all tree canopy with herbaceous cover to result in an annual runoff increase greater than 0 to 4%.

One important consideration when interpreting the results is that the percent is based on all rainfall in an entire area (city, drainage basin, neighborhood), whereas tree canopy only covers and impacts runoff in a portion of the area. For example, the city of Tacoma has 20% average tree canopy and 52% impervious area. A full 80% of the city is not tree covered, which could lead to the assumption that the majority of rainfall never has an opportunity to be mitigated by tree canopy. Yet the results reflect the percent change from total precipitation and all runoff in a given area. On the other end of the range, the city of Kirkland's Wolff subdivision has 51% canopy and just 25% impervious area where replacement of canopy with herbaceous cover resulted in the highest results for both models, at 4% (i-Tree Hydro) and 14% (WWHM).

This suggests two possibilities:

- Percent change in runoff could be presented based on only the precipitation that occurred in tree-covered areas
- The higher the initial tree canopy and lower the initial impervious area, the greater opportunity for trees to mitigate stormwater runoff.

It's also important to remember that i-Tree Hydro does not reflect the impact of individual trees which is best addressed using i-Tree Eco.

Another possibility to consider when looking at lower-than-expected results particularly for the city of Kent, is the potential that i-Tree Hydro does not effectively simulate flat terrain, or DEM in the case of this project. See Figure 5 on Page 18 for the Kent DEM illustrating the City's extensivea look at how flat the terrain is in Kent. This may contribute to the low amount of relative change in runoff, since much of the rainfall will already be infiltrated into the ground or forced into the drainage system because of lack of slope.

Project stakeholders also had questions about the flashiness of storm events and if or how the models account for this given that they use average outputs in calculating annual reduction in runoff. Viewing results on an annual basis may obscure the ephemeral benefits of trees along streams during storm events and their benefits for habitat value and erosion control. i-Tree Hydro allows for event-based modeling, but it is best represented when not using stream gage data. Stream gage data and precipitation data must be set up correctly to accurately calibrate the model for event-based analysis. Event-based data could show different results than the 6-year period used for this project. The precipitation data provided for the city model runs could be used to complete event-based analysis. Rainfall events are shown in Table 1 of the Executive Summary for specific simulations in i-Tree Hydro.

Impact of seasonality

Localized weather patterns affect results for both models — possibly in different ways and at different magnitudes. Because i-Tree Hydro models scenarios based on year-round rainfall, it is easy to predict that Leaf Area Index (LAI) would have a significant impact on sensitivity. In the Pacific Northwest, most precipitation occurs when leaves are absent from deciduous trees, therefore the sensitivity analysis of LAI did not yield a high percent relative change.

Another consideration is the high amounts of rainfall in the Pacific Northwest, possibly resulting in saturation of herbaceous land and canopy areas, which can contribute to low relative change results in total runoff volume. Xiao et al. (1998) found that trees in urban Sacramento, California, intercepted approximately 18% of precipitation during a summer storm event, but only approximately 4% during a winter storm event. This difference is due to the fact that evaporation and antecedent dry periods are greater in the summer than in the winter. More important, it could occur because winter foliage tends to be less dense than summer foliage and winter storms are usually much larger than summer storms. Large storm events overwhelm the capacity of the tree canopy to retain water; therefore, the relative impact of interception on the water balance decreases with storm size.

Sensitivity analysis

Sensitivity analysis results for i-Tree Hydro and WWHM illustrated that certain parameters have much higher impact on results than others. High and low values for each parameter in the analysis were analyzed against the base case (existing conditions) to show relative change, using the city of Kent. i-Tree Hydro parameters such as Directly Connected Impervious Area (DCIA), herbaceous/impervious under canopy, and all herbaceous vs all canopy yielded high sensitivity results, meaning higher relative change in runoff compared with the base case for both low and high values of the parameter.

The results overall show that the parameters directly involving impervious and increase/decrease in impervious have the highest sensitivity in the model. For example, the all herbaceous/all canopy sensitivity parameter changed 100% of the land cover to herbaceous and 100% land cover to canopy, in turn entirely decreasing the amount of impervious area in the project area. Both 100% canopy and 100% herbaceous land cover only decreased the total runoff volume by 10% and 16% respectively. Again, this can be attributed to the way i-Tree Hydro accommodates for herbaceous cover.

i-Tree Hydro version 6 is currently in beta. Future versions are scheduled to include modeling of green infrastructure elements. See *www.itreetools.org* for more information.

Assessing monetary value

Technical and stakeholder committees on this project raised concerns that reporting the percent change in stormwater runoff volume based on scenarios of increasing and decreasing canopy coverage and impervious area may not resonate with decisionmakers. Some stakeholders inquired about the possibility of placing a monetary value on the benefits of urban tree canopy to make the results more meaningful.

One approach to monetize the benefits of urban trees for stormwater management involves multiplying the construction cost per cubic foot of stormwater detained in wet storage facilities (e.g., traditional retention/detention ponds) by the quantity of increased runoff from a scenario with and without tree canopy. As an example, a new development proposes to remove all existing trees from the project site. Runoff model simulations of the proposed site indicate a need for a 5,000 cubic foot detention pond. At $8 per cubic foot, the detention pond cost estimate is $40,000. The same runoff model can be used to simulate the proposed project site with existing trees remaining in the proposed condition. If the runoff model indicates a detention pond size of 3,000 cubic feet in the tree retention scenario, the associated value of the existing tree canopy has a calculated value of $16,000 (5,000 - 3,000 cubic feet) * ($8 per cubic foot). This approach is simplistic and may not be applicable to all scenarios.

At this time, neither i-Tree Hydro (beta) nor WWHM include monetary values associated with water quantity or water quality outputs, and attempting to monetize stormwater quantity and quality benefits is outside the scope of this project. Other models in the i-Tree suite of tools do include monetized stormwater benefit values, specifically i-Tree Eco, i-Tree Design, i-Tree Streets, and i-Tree Landscape.

One recent reference that could be used to look at the typical cost of stormwater facilities in the Pacific Northwest is The Puget Sound Stormwater BMP Cost (Herrera, 2013). Although the cost database focuses on low impact development best management practices (LID BMPs), cost data was also collected for wet ponds. The Puget Sound Stormwater BMP Cost Database includes a total of 23 wet ponds, with costs ranging from $1.26 to $40.86 per cubic foot, and an average cost of $8.26 per cubic foot.

RECOMMENDATIONS AND APPLICATIONS

An overarching goal of this study is to provide recommendations to planners, stormwater engineers, and/or natural resource managers aiming to evaluate or quantity the effects of tree canopy when simulating stormwater runoff in the Puget Sound region. Considerations to assist in this process are outlined below for application, scale, data inputs, and parameters, followed by conclusions.

Application

This project evaluates the stormwater benefit of tree canopy coverage using two models, one specifically designed to model the effects of urban tree canopy and impervious cover on changes in streamflow (i-Tree Hydro), and one created for designing and sizing stormwater BMPs and facilities in Western Washington (WWHM). The results of the evaluation point to tree canopy coverage as a factor influencing stormwater runoff and as a tool available for meeting Ecology's flow control and water quality treatment requirements. Other tools and models included in this section include two additional tools in the suite of i-Tree tools (i-Tree Eco and i-Tree Landscape) and two other models commonly used in Western Washington (MGSFlood and SWMM).

i-Tree Hydro

Based on this evaluation, it is recommended to use i-Tree Hydro when exploring stream or river hydrology responses with detailed urban vegetation inputs and changes in land cover over large areas, possibly where streamflow gage data exists in the drainage basin that is being evaluated. The three primary scenarios used in this study were chosen to demonstrate alternate cases in i-Tree Hydro using typical changes to the urban landscape (i.e., loss in tree cover, increase in impervious surfaces from development, and increase in tree canopy) from policies and programs implemented to protect and expand urban tree canopy. Further detail on i-Tree Hydro is provided in the sections below.

i-Tree Eco

i-Tree Eco provides individual tree and forest analyses that include several components; avoided runoff, pollution removal and human health impacts, species condition and distribution, tree planting inputs, pest risk analysis, and several others. i-Tree Eco is best applied when working with smaller scales such as parcels to gather detailed environmental data, as well as when a tree inventory is already completed for the project area to complete an individual tree analysis.

i-Tree Landscape

i-Tree Landscape is a relatively new tool that includes estimations of stormwater mitigation from trees based on canopy area and a simplified version of i-Tree Hydro. i-Tree Landscape is best applied when looking to explore tree canopy, land cover, and demographic information about a project area, at mostly larger scales including counties and HUC 12 watersheds. i-Tree Landscape provides benefits of trees in a project area as well as help to prioritize planting and show benefit of increase in trees planted. i-Tree Landscape can predict forest risk, health risk, and future climate through land cover data already provided in the application. The GIS-based land cover data produced for the four pilot communities in this project was provided to the i-Tree model developer who uploaded the data into i-Tree Landscape. This is the first time that high-resolution land cover data has been available in the Pacific Northwest for use in i-Tree Landscape. A cursory review indicated similar trends and impacts between i-Tree Hydro and i-Tree Landscape; however, a full evaluation and comparison of results from i-Tree Hydro and i-Tree Landscape was not the focus of this study. There are also fewer and different hydrology related outputs from i-Tree Landscape compared to i-Tree Hydro. Landscape only provides Transpiration (m3/yr), Rainfall Interception (m3/yr), Avoided Runoff (m3/yr), and Avoided Runoff ($/yr). Boundary options for Landscape also differ but are provided within the software for easy access and user's choice. Nonetheless, i-Tree Landscape provides an opportunity to further explore the relationship between land development change on hydrology and other ecosystem services.

WWHM

It is recommended to use WWHM when sizing stormwater BMPs and facilities, or Ecology's flow control credits for tree planting and/or tree retention (BMP T5.16).

MGS FLOOD

MGSFlood is a continuous hydrologic model for stormwater facility design that was developed by MGS Engineering Consultants, Inc. MGSFlood requires similar inputs to WWHM and is also commonly used in the Pacific Northwest for sizing stormwater BMPs and facilities and when applying Ecology's flow control credits for tree planting and/or tree retention (BMP T5.16). The primary difference between MGSFlood and WWHM is that MGSFlood does not require a detailed evaluation of slopes and is best suited to sites with flat (0-5%) or moderate (5-15% slopes). For sites with steeper slopes, the model user would need to modify some of the model default values or use WWHM to more accurately quantify flow volumes and durations.

SWMM

SWMM was first developed in 1971 by the University of Florida; Camp, Dresser, and McKee (CDM); and Metcalf and Eddy. Later versions of SWMM were updated by the by the U.S. Environmental Protection Agency, University of Florida, CDM, and Oregon State University. SWMM is primarily a hydraulic model used to simulate stormwater open channel and pipe networks. However, SWMM includes a hydrologic component capable of simulating rainfall-runoff relationships. The hydrologic simulation in SWMM is typically event-based, compared to continuous simulation, due to the computational demands of calculating pipe flow. SWMM hydrology simplifies subbasins to compute runoff, typically ignoring specific vegetation and topographic effects but instead using generalized assumptions such as surface slope, depressional storage, surface roughness, and percentage pervious and impervious. SWMM may also be used by coupling with another hydrology model to create runoff input to the SWMM-simulated hydraulics.

Scale

While i-Tree Hydro and WWHM can be employed at any scale, it is recommended to use WWHM at smaller sites (e.g., individual parcels and neighborhoods) and to use i-Tree Hydro for larger drainage basins or municipal boundaries (e.g., drainage basin scale and City scale).

i-Tree Hydro

The most appropriate scales for i-Tree Hydro modeling are larger sites (e.g., drainage basin scale and City scale).

The i-Tree Hydro model allows a user to select a project area based on a municipal boundary or a drainage basin boundary. Data sources for these geographic units are available in the i-Tree Hydro model. It is best to use the results from i-Tree Hydro for quantitative purposes when calibrating results to actual streamflow gage data, which can only be done with a drainage basin model. More qualitative results can be interpreted from relative changes in runoff (not quantitative volumes and actual flow amounts) at the city scale which does not allow the user to calibrate results to streamflow but instead uses a topographic index (TI) method. Note that drainage basins can also be run using the TI method when streamflow gage data is unavailable or unable to be formatted correctly. See the i-Tree Hydro manual, Appendix M, and download the software for more details.

i-Tree Eco

The most appropriate scales for i-Tree Eco are smaller sites (e.g., individual parcels). Individual trees, inventories, or randomly located plots can be used in i-Tree Eco to provide the forest or individual tree analyses.

i-Tree Landscape

Appropriate scales into i-Tree Landscape include a range of scales such as states, counties, census block groups, congressional districts, national forests, ranger districts, CFLR boundaries, and HUC 12 watersheds.

WWHM

The most appropriate scales for WWHM modeling are smaller sites (e.g., individual parcels and neighborhoods). WWHM is not commonly used for City scale modeling but can be performed if the sub-basins in the model are an appropriate size.

Data Inputs

As with any model simulation, reliability of the outputs depends on the quality of the data inputs, information on their source, metadata, and currency, and the analyst's in-depth knowledge of how various sources will influence the results. Minimum required data inputs include land cover (e.g., percent cover for tree canopy, impervious surfaces, and herbaceous), elevation, and precipitation. Both WWHM and i-Tree Hydro have built-in data for precipitation and evaporation.

i-Tree Hydro

Calibration of the model for the Pacific Northwest was already possible in i-Tree Hydro. The calibrated method for i-Tree Hydro allows a user to attempt to match observed (actual) streamflow gage data to precipitation within a drainage basin (aka watershed) in order to develop a baseline of hydrologic conditions. It can be challenging to obtain and format stream gage and meteorological data for input into i-Tree Hydro. When obtaining data outside of the pre-processed sets provided within i-Tree Hydro, users can expect to run into several challenges. The first challenge is data availability. Despite an extensive collection of data housed within the tool, it can be difficult to find complete sets of streamflow and weather data that match up temporally. Another challenge is spatial variability. Weather conditions can vary widely across any given area – in an ideal setting a weather station would be located within the same drainage area as the selected stream gage, so that the response in streamflow downstream can be more directly correlated with the amount of precipitation. However, it can prove challenging to locate two stations that are both a) close to each other and b) have extensive, matching records of data.

In the event that there are no data sets available in the desired study area, i-Tree Hydro does allow users to calibrate their own weather and streamflow data, though this process can take time and patience with respect to data formatting. Much of the uncertainty in this process stems from a wide variety of data formats that different weather organizations use – users should be aware of both the potential differences in data formatting and the potential to spend some time converting measurements of rainfall, streamflow, time, and more. That being said, i-Tree provides online resources to aid with data conversion and upload as well as a support team to offer advice.

Running i-Tree Hydro with the calibrated method for drainage areas requires proper formatting of meteorological and streamflow data especially if using raw data from another source outside the model. It can also be challenging to identify sources of precipitation and streamflow data that overlap in time period and correspond to the correct drainage basin. For instance, a weather station may provide precipitation data for a specific location that is outside the drainage area where the streamflow gage is located. Appendix M includes a detailed outline of troubleshooting the process of formatting raw weather and streamflow data for use within i-Tree Hydro.

Once a base case model is developed, it is common with i-Tree Hydro to develop alternate cases by increasing and decreasing various land cover percentages. These scenarios are then compared to the base case (i.e., existing land cover and hydrology). This produces a relative change in flow between scenarios. When creating alternative scenarios in i-Tree Hydro and comparing to base conditions, pay close attention to how the percent of each land cover class is distributed. In particular, any changes that include an increase or decrease in impervious area will yield results that not only illustrate the effects of tree canopy changes but also fundamental hydrology changes.

Anecdotally, for every unit of impervious area increase, approximately 12 units of tree canopy are needed to offset change in runoff due to increase in impervious surface. (Nowak, Kansas City i-Tree Hydro project 2013). Results from this study indicate similar outputs with larger changes in relative flow or volume when impervious area is also modified, not just tree canopy or herbaceous vegetation. In addition, the area of tree canopy with impervious area underneath is an available category for land cover data input to Hydro. It is important to realize that this percentage of the project area is used in both the total tree canopy and total impervious cover. When modifying tree canopy and/or impervious percent inputs, be cautious not to inadvertently add to the total amount of impervious area; this will alter the hydrology response greater than changes in tree canopy cover.

WWHM

Hydrologic simulation with WWHM can be accomplished with minimal effort due to the ease with which data can be input into the software. However, the user must take care to select appropriate input data and needs to understand how that data is interpreted by WWHM.

When selecting the location of a project using the built in WWHM map, in order to load precipitation data, choose the most appropriate location based on the area to be analyzed. This may not be the same as the location of a proposed facility (e.g., detention basin). A large tributary basin may warrant choosing the basin centroid.

Entering land coverage information into WWHM requires categorizing land data into combinations of land use, underlying soil, and slope. The area combinations are typically calculated outside of the WWHM software within a spreadsheet. Be mindful to categorize each data type appropriately. Slope categories (e.g., flat, moderate, and steep) must be accounted for with the correct divisions (e.g., flat is from 0 to less than 5 percent slope, it does not include 5 percent slope). Soils classification is simplified to outwash (Type A/B), till (Type C), and saturated (Type D). The chosen source of soils data may not include the same classifications, requiring the WWHM user to consult appropriate references to determine the soil type for each names soil in the project area. Land use classification is also nuanced. The user must determine how a land use will act hydrologically, which may not be the same as how it looks in typically used aerial photography. For example, a grouping of trees may or may not act hydrologically like a forest depending on adjacent land uses, understory vegetation and land use, and the soil condition beneath and surrounding the trees.

Parameters

i-Tree Hydro

After choosing whether to run i-Tree Hydro with the calibrated (streamflow) method or the simpler TI method, it is recommended to begin using default values for parameters in i-Tree Hydro. If modifying the defaults, use the sensitivity analysis from this report to choose which parameters may be worth modifying. While intriguing from a vegetation and hydrology modeling perspective, parameters such as Leaf Area Index (LAI) and Evergreen Canopy Percent do not have high impact on stormwater runoff results in i-Tree Hydro.

The more characteristics of a tree or forest entered into i-Tree Eco or i-Tree Hydro, the better the model is able to calculate the effects of the tree because species-specific tree parameter equations (e.g., height, crown width, and crown height) do not exist for every tree species. For example, when evaluating benefits for western redcedar in this study, results in gallons of avoided runoff were significantly lower than other species, such as Douglas fir and ponderosa pine. This is because i-Tree Eco is using relative, genus-based equations that do not allow it to grow to its full potential. This can be remedied by entering detailed tree crown measurements into i-Tree Eco for each tree which will drive the leaf area, which in turn drives the benefit calculations. Thus, more reliable estimates will be generated by measuring and entering additional structural parameters on a tree-by-tree basis.

The sensitivity analysis showed that the parameter Directly Connected Impervious Area (DCIA) has a large impact on outputs. While changing the default in i-Tree Hydro from 65 to 100 percent helped better match the WWHM allocation of impervious runoff, it is not recommended by the i-Tree Team and ultimately the primary results in this report are based on a DCIA parameter value of 65 percent.

Late in this study's modeling scenario development, the i-Tree model developers suggested changing the default value in i-Tree Hydro v6 for what is called "pMacro", a value representing the pore size of soils and thus infiltration. The original default value is low (0.000001) and was changed to 0.1 for final modeling. The i-Tree model developers and researchers are undergoing their own sensitivity analysis of this and other parameters at the time of this publication.

WWHM

The version of WWHM used for this project is the same software package available at no cost from Ecology. For forest tree canopy simulation, WWHM uses parameters derived from Western Washington region, second generation, primarily Douglas fir forest runoff. Similarly, tree canopy parameters in i-Tree Hydro are based on regional species composition from reference studies in cities across climate regions of the U.S. and to some degree, species-specific hydrology impacts (e.g., stemflow, bark flow, leaf area). The various parameters used by WWHM to simulate forested land cover are specific to Western Washington, not specific to a given project location and its existing or proposed trees. Calibration of forest land coverage parameters for a WWHM project could include an evaluation of the default parameter values and their reference forest (second growth, primarily Douglas fir forest) in comparison to the project site forest coverage and published values of project specific tree species and proportion.

i-Tree Hydro and WWHM Comparison

The two models break down flow or volume of runoff into sub-categories, and not all are directly comparable, in particular subsurface or base flow and how runoff is allocated onto pervious surfaces. For a more direct comparison, surface runoff estimated in WWHM should only be compared to i-Tree Hydro's estimate of surface runoff (i.e., pervious runoff + impervious runoff which excludes base flow). Even if i-Tree Hydro and WWHM have different estimates of surface runoff, it is more useful to compare equivalent metrics than to compare surface runoff from WWHM versus total flow from i-Tree Hydro (which includes subsurface contribution to outflow).

CONCLUSION AND NEXT STEPS

As urban population and housing density increase, limited space above and below ground requires planning and design that creates multi-benefit landscapes. Each unit of low impact development (or green stormwater infrastructure) should be designed to maximize infiltration, pollutant uptake, air quality, aesthetics, property values, views, and public safety to achieve multiple benefits. This requires establishing policies to protect existing trees during construction and development while also enforcing proper specifications for new tree planting (e.g., minimum soil volume requirements) that allow space for roots, growth (e.g., leaf area), and subsequent benefits to the environment, human health, and community. Understanding the impact of tree canopy on stormwater runoff can help inform such policies.

This project represents a productive step toward bringing urban forestry expertise into the stormwater management conversation. The results of the model comparisons in this project should help urban forestry professionals and stormwater management professionals see where their priorities overlap and how they can help inform each other's perspective. The user's handbook produced in conjunction with this report will help urban foresters analyze and communicate the benefits of tree canopy in stormwater management, using a tool they are already familiar with (i-Tree Hydro).

Moving Forward

The following next steps will help build on the momentum of this project and the cross-industry discussions it's intended to spark.

Model research and refinement

The project team, stakeholders, and King Conservation District expected that the modeling would reveal a greater impact of tree canopy on stormwater runoff than shown in the results. Scenario 1A, for example, places a benefit on existing tree canopy by comparing it with conditions without any trees and with no other modifications to the landscape (e.g., no increase in impervious surfaces). This scenario yielded just a 1 to 9% increase in flow volume across the four pilot communities at all scales.

Studies in other parts of the country have demonstrated a greater impact of citywide canopy on runoff. This may be due to the unique weather patterns in the Pacific Northwest region or it may be an indication that further research and refinement of the models is needed. For example, how do individual tree benefits change when applied to continuous groves of tree stands? How does species makeup affect runoff mitigation, and to what degree can models capture this? And, how will the intensity and frequency of storm events under changing climate conditions impact the urban forest's contribution to water resource protection?

Parameter alignment with new research

The complex hydrologic models used in this project represent real processes and must make a series of simplifications and assumptions to best simulate reality. The land use, soil, and tree parameter values and assumptions within WWHM and additional vegetation parameters within i-Tree Hydro should be compared with the best available research on tree hydrology and effects on stormwater runoff. A literature review may reveal parameter values and assumptions more appropriate for Western Washington than those used in the models for this project, in which case the parameter values and results could be updated as an addendum to this report.

Enhancements to i-Tree models

Finally, results differ from i-Tree models at the individual tree scale vs. landscape. i-Tree Hydro v6 is currently in beta. Work to improve the i-Tree models is ongoing, including a sensitivity analysis and a green infrastructure module planned for a future release.

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http://www.mgsengr.com/mgsfloodhome.html

SWMM
https://www.epa.gov/water-research/storm-water-management-model-swmm

APPENDICES

Appendix A

The Comparison Matrix compares different parameters used to inform modeling the stormwater impacts of tree canopy and other land cover types using i-Tree Hydro and Western Washington Hydrology Model (WWHM).

Comparison Matrix for i-Tree Hydro and WWHM (v4 5.23.18)

Item	i-Tree Hydro	WWHM
Area Size	Drainage basin, Municipality, etc.	User defined
Primary Use(s)	Urban forest effect on stormwater runoff	Sizing flow control and water quality treatment facilities in Western Washington.
Primary Users	Urban Foresters, Municipal Officials	Engineers (public and private), developers, city and county staff reviewing submitted drainage designs, state agency staff
Intended Scales	HUC-12 Drainage basin, City Boundary	All scales
Underlying Model	TOPMODEL	Hydrological Simulation Program - Fortran (HSPF)
Simulation Type	Continuous or Event-Based	Continuous or Event-Based
Spatially Distributed	Lumped, semi-distributed	Lumped, semi-distributed

Geographic/Topographic

Item	i-Tree Hydro	WWHM
Project Area	Drainage basin or non-Drainage basin (i.e., municipality) project area	User defined
Geographic Location of Project Area	Country, state, county, city	Site location selected within a western WA county map (entered to load the appropriate precipitation record)
Topography Source	Digital Elevation Model (DEM) or Topographic Index File	User must segregate land area between flat (0 to <5%), moderate (5 to 15%), and steep (>15%) sloped surfaces; typically analyzed outside of WWHM using survey or LiDAR data

Hydrogology Sources

Item	i-Tree Hydro	WWHM
Weather Station Data	Weather Station data can be found within the i-Tree application, a raw NCDC weather file, or from a third-party source (i.e., universities, airports, etc.). Using weather data from Hydro also includes pre-processed potential evapotranspiration (PET) data.	Precipitation and evaporation data is built into the model and is scaled based on proximity to a gage. Precipitation data can be actual gage data (typically at least a 50-year record) or a synthetic record, depending on location and jurisdiction. External precipitation data can also be imported into WWHM. A minimum of 20 years is required for calculation of accurate flow frequency results, though a 40 to 50-year record is preferred. WWHM does not include snowfall and snowmelt. Potential evapotranspiration (PET) is included in the weather data built into the model.
Calibration Data (Stream Gage Data)	Calibration data can be found within the i-Tree application, a raw USGS data file, or a pre-processed gage file. If not modeling a Drainage basin, stream gage data cannot be used	N/A
Possible Time Steps	Monthly, Weekly, Daily, Hourly	5-, 15-, and 30-minute, hourly, and daily computational time steps. Output may be aggregated to monthly and annually. A 15-minute time step is generally the minimum recommended time step.

Vegetation Categories

Item	i-Tree Hydro	WWHM
Tree Canopy (TC) or Forest	Referred to as Tree Canopy. Input as percent (%) cover in project area. Additional parameters listed below.	Referred to as Forest. Defined with a forest land cover (acres), based on forest coverage at land surface, and does not account for canopy coverage.
Pervious under TC *% of TC over pervious areas*	Yes	N/A
Impervious under TC *% of TC over impervious areas*	Yes	N/A
Tree Leaf Area *Leaf Area Index (LAI) is the total one-sided leaf area divided by the canopy area.*	Yes. Custom LAI can be input to reflect a certain species of tree or an average of many species	N/A
Evergreen or Coniferous Tree Canopy	Yes, % of TC. A default value that can also be estimated using an inventory or a tree canopy assessment	Yes, default forest land cover parameters (PERLND) are based on a second growth Douglas fir forest.
Deciduous Tree Canopy	Yes, % of TC. A default value that can also be estimated using an inventory or a tree canopy assessment	N/A
Leaf Transition Period	Yes, days	N/A
Leaf on Days	Yes, days	N/A
Leaf off Days	Yes, days	N/A
Tree Bark Area Index *This parameter sets the minimum LAI, represented by leafless canopy coverage of deciduous trees in the winter, which is defined as the tree bark area index.*	Yes, LAI	N/A

Item	i-Tree Hydro	WWHM
Leaf Storage *This parameter sets the maximum water depth that a single leaf in the tree canopy can hold.*	Yes, millimeters	The default PERLND value of the interception storage capacity (0.2 inches) may be altered.
Shrub or Pasture	Referred to as Shrub. Input as percent (%) cover in project area. Additional parameters listed below.	Referred to as Pasture. Defined to include non-forested natural areas/scrub/shrub rural vegetation (acres).
Shrub Canopy	Yes, %	Yes, by default pasture land cover parameters (PERLND) account for shrub and pasture coverage, but does not distinguish between shrub and pasture.
Deciduous vs Coniferous Shrub Canopy	The default value is 100% deciduous. A user may modify the % conifer shrub. The value can be estimated using an inventory or a tree canopy assessment.	N/A
Shrub Leaf Area *Leaf Area Index (LAI) is the total one-sided leaf area divided by the canopy area.*	Yes	N/A
Leaf Transition Period	Yes, days	N/A
Leaf on Days	Yes, days	N/A
Leaf off Days	Yes, days	N/A
Scrub Bark Index *This parameter sets the minimum LAI, represented by leafless canopy coverage of deciduous shrubs in the winter, which is defined as the shrub bark area index.*	Yes, LAI	N/A
Leaf Storage *This parameter sets the maximum water depth that a single leaf in the tree canopy can hold.*	Yes, millimeters	The default PERLND value of the interception storage capacity (0.15 inches) may be altered.
Herbaceous or Lawn	Project area covered by non-tree, non-woody vegetation such as grass. Herbaceous canopies are the aboveground portion of herbaceous plants.	Referred to as Lawn. Defined to include sod lawn/grass/ landscaped urban vegetation
Herbaceous Leaf Area *Leaf Area Index (LAI) is the total one-sided leaf area divided by the area of entire leafy canopy coverage.*	Yes, LAI	N/A

Impervious Categories

Impervious land cover represents the amount of the project area covered by roads, buildings, parking lots, and other paved areas that prevent rainfall from naturally infiltrating into the soil.

Item	i-Tree Hydro	WWHM
Impervious Area	Impervious land cover is input as a percentage of the total project area.	Impervious land cover (IMPLND) is categorized by type and associated slope. Each type (road, roof, driveway, sidewalk, parking) is designated for accounting purposes and is simulated the same within the model.
Directly Connected Impervious Area (DCIA) *DCIA represents how much impervious area in the project area drains directly to the project area's outlet(s) over connected impervious surfaces.*	Yes, percentage of impervious area	Yes, only DCIA (also called effective impervious area [EIA]) is categorized as impervious. EIA is the area where there is no opportunity for surface runoff from an impervious site to infiltrate into the soil before it reaches a conveyance system (e.g., pipe, ditch, or stream).

Item	i-Tree Hydro	WWHM
Impervious Depression Storage *This depth is filled before runoff generation from the impervious area begins*	Yes, millimeters	Referred to as surface retention storage. Defined differently for each slope category: • Flat = 0.1 inches • Moderate = 0.08 inches • Steep = 0.05 inches
• Roads • Driveways • Sidewalks • Parking Lots	Yes, included in total impervious area	Yes, with associated slope (flat, moderate, steep)
Roofs	Yes, included in total impervious area	Yes, with associated slope (flat)
Pond	No, not classified as impervious	Yes
Permeable Pavement	No, but will be available in v6, available in 2019	Yes, with associated slope (flat, moderate, steep) or explicitly (e.g., permeable pavement stage-storage-discharge element with parameters for depth, slope, layer thicknesses and porosities, infiltration, etc.)

Stormwater Facilities and Hydraulic Structures

Stormwater facilities are designed to mitigate the impacts of increased surface and stormwater runoff flow rates generated by development (flow control) and/or are designed to remove pollutants from stormwater runoff (treatment). Stormwater facilities can be divided into gray storage (e.g., ponds, vaults) and green storage/filtration (e.g., bioretention, permeable pavement).

Item	i-Tree Hydro	WWHM
Stormwater Facilities	N/A	The acknowledgement and/or addition of various water collecting/runoff reducing infrastructure elements
Gray Storage	N/A	• Ponds • Vaults • Tanks • Gravel Trench Bed
Green Storage/ Filtration	No, but is proposed for v6, available in 2019	• Sand Filter • Bioretention • Green Roof • Permeable Pavement • Compost Amended Vegetated Filter Strip (CAVFS)
Hydraulic Structures (e.g., weirs, tide gates, check valves, etc.)	For the calibration method, a DEM can be modified to clip (remove) areas that are diverted (e.g., drinking water) but the model cannot account for the flow.	User may define any stage-storage-discharge relationship by developing a table with the stage (i.e., height in feet), storage (acre-feet), and discharge (cubic feet per second). Discharge is based on the outlet structure's physical dimensions and characteristics. Surface area (acres) is also required if precipitation and evaporation from the facility are applied.

Soil Categories

Soil properties are important for correctly modeling infiltration and runoff generation processes.

Item	i-Tree Hydro	WWHM
Soil Type(s)	• Sand • Loam • Silt • Clay • Blend	• Ponds • Vaults • Tanks
Bare Soil	Yes, percentage of land cover. • *Soil cover represents the amount of the project area covered by bare soil or barren areas such as gravel pits or sand.*	No, not explicitly included as a land cover type
Additional (Adjustable) Soil Parameters	• Wetting Front Suction (m) • Wetted Moisture Content (m) • Surface Hydraulic Conductivity (cm/h) • Depth of Upper Soil Zone (m) • Initial Soil Saturation (%) • Soil Transmissivity • Transmissivity at Saturation (m2/h) • Soil Macropore Percentage	Soil groups are defined using the following: • USDA texture • NRCS Permeability (in/hr) • Depth from surface • HSG (Runoff potential)

Water Quantity

Water quantity is an important metric for evaluating the changes in forest canopy or other variables being modeled in the base (predeveloped or existing) and alternative (mitigated) scenarios.

Item	i-Tree Hydro	WWHM
Volume of Estimated Runoff	Cubic feet (or cubic meter)	Acre-feet
Types of (Stream)flow or Runoff	• ***Base (groundwater) flow:*** The portion of surface water supplied by groundwater • ***Pervious flow:*** Runoff over vegetation and soil that may drain to streams/lakes/ etc. • ***Impervious flow:*** Runoff over impervious area. Drains into pervious areas or streams/lakes/etc.	• ***Groundwater:*** Typically not used unless there is observed base flow occurring in the drainage basin. • ***Interflow:*** Represents a portion of the flow from pervious areas that is routed to a point of compliance or stormwater facility. • ***Surface Runoff:*** Represents a portion of the flow from pervious areas and all of the flow from impervious areas that is routed to a point of compliance or stormwater facility.
Other Quantity Output(s)	• Total flow • Highest/lowest flow • # of flow events • Length of flow events	• Flow frequency analysis with different statistical methods • Hydrographs • Flood duration analysis between two scenarios • Wetland hydroperiod analysis
Observed vs. Predicted	Graphic comparison output of observed streamflow from provided gage vs. the streamflow predicted by the model	N/A

Water Quantity

Item	i-Tree Hydro	WWHM
Estimation of Pollutant Concentrations	Pollutant loading for a wide range of water quality parameters is calculated based on event mean concentrations (EMCs) and is associated with overland runoff flows in the project area. Specific water quality outputs include: • Total suspended solids (TSS) • Total phosphorus (TP) • Soluble phosphorus (soluble P) • Total Kjeldhal nitrogen (TKN) • Nitrite and nitrate (NO_2 and NO_3) • Copper (Cu) • Lead (Pb) • Zinc (Zn) • Biochemical oxygen demand (BOD) • Chemical oxygen demand (COD)	Pollutant loading based on EMCs can be calculated outside of the model. Pollutants of concern in Western WA typically include: • TSS • TP • Nitrite and nitrate (NO_2 and NO_3) • Dissolved Cu • Dissolved Zn • Fecal coliform bacteria • Total Petroleum Hydrocarbons (TPH)

System Requirements

Item	i-Tree Hydro	WWHM
Hardware	• Pentium or compatible 1600 Mhz or faster processor • 512 MB of available RAM • Hard drive with at least 500 MB free space • Monitor with resolution of at least 800 x 600	• Pentium 3 or faster processor (desirable) • Color monitor (desirable)
Software	• Windows XP service pack 2 or higher OS (including Windows 7 or later) • Microsoft Excel • Microsoft Data Access Component (MDAC) 2.8 or higher (included in installation) .NET 2.0 framework (included in i-Tree Hydro installation) • Adobe Reader 9.0 • ArcGIS (any version) with Spatial Analyst Extension	• Windows 2000/XP/Vista/7/ 8/8.1/10 with 200 MB uncompressed hard drive space • Internet access (only required for downloading WWHM2012, not required for executing WWHM2012)

Appendix B

This document identifies and compares terminology used in i-Tree Hydro and Western Washington Hydrology Model (WWHM) when modeling the stormwater impacts of tree canopy and other land cover types.

Common Terminology for i-Tree Hydro and WWHM (v4 5.23.18)

Terminology	i-Tree Hydro	WWHM
Calibration	Calibration is an optional step where stream gage data and various stormwater parameters can be analyzed to match the predicted (modeled) streamflow with the observed (actual) streamflow. This can be run for catchments (e.g., drainage basins, watersheds), not municipal or other boundaries. Predicted streamflow is the model output and observed streamflow is the actual recorded data (e.g., USGS).	Calibration step not integrated into the model, but it can be performed independently if calibration data is available.
Drainage Basin	Drainage basins are required with the calibration option. Default basins in the model are HUC-8 or 12 watersheds but any catchment or drainage basin can be used as an input. The USGS drainage basin area is provided within the model.	A drainage basin (or land use basin) is user defined. Model documentation states that "a basin can be 1 acre, 100 acres, or 1 million acres, as long as all of the drainage area drains to a single outlet location." A basin can be divided into multiple smaller basins.
Sensitivity Analysis	This is built into the model to see what parameters the auto-calibration step is most sensitive to. This helps a user illustrate the impact of parameter adjustments on the model's goodness-of-fit metrics. It is viewable in a working directory.	Not built into the model but can be performed by the user by varying the range of values entered for a specific parameter and analyzing the associated change in model output.
Precipitation Data	The user can select from the following: • Precipitation data from various weather stations included in the model • Third party precipitation data imported by the user	The user can select from the following: • Actual long-term recorded precipitation data from over 17 gages (primary source is the National Weather Service) • Synthetic precipitation data (158-year time series) generated from actual long-term recorded precipitation data • Third party precipitation data imported by the user
Topography and Slope	Digital elevation model (DEM) values are digested into a Topographic Index (TI) to represent the distribution of wetness likelihood for the area. TI percent is applied to the entire project area, thus distributing all the differences in topography evenly.	The user must segregate land area between flat (0 to <5%), moderate (5 to 15%), and steep (>15%) sloped surfaces; typically analyzed outside of the model using survey or LiDAR data.
Land Cover Distribution	Land cover percentages are applied to the entire project area, distributing all the differences in land cover and topography, based on weighting of each condition.	The user must input lumped land cover data for the project area, which is categorized based on underlying soils and associated slope. Land cover is divided into impervious and pervious (vegetated) categories.
Flow/Runoff Types	• ***Base (groundwater) flow:*** The portion of surface water supplied by groundwater • ***Pervious flow:*** Runoff over vegetation and soil that may drain to streams/lakes/ etc. • ***Impervious flow:*** Runoff over impervious area. Drains into pervious areas or streams/lakes/etc.	• ***Groundwater:*** Typically not used unless there is observed base flow occurring in the drainage basin. • ***Interflow:*** Represents a portion of the flow from pervious areas that is routed to a point of compliance or stormwater facility. • ***Surface Runoff:*** Represents a portion of the flow from pervious areas and all of the flow from impervious areas that is routed to a point of compliance or stormwater facility.
Impervious	Impervious land cover is input as a percentage of the total area of interest (AOI).	Impervious land cover (IMPLNDS) is categorized by type and associated slope. Each type (road, roof, driveway, sidewalk, parking) is designated for accounting purposes and is simulated the same within the model.
Directly Connected Impervious Area	Referred to as DCIA. Input as a percent of the impervious area	Only DCIA (also called effective impervious area [EIA]) is categorized as impervious. EIA is the area where there is no opportunity for surface runoff from an impervious site to infiltrate into the soil before it reaches a conveyance system (e.g., pipe, ditch, or stream). If roof runoff is infiltrated, the roof area is considered ineffective impervious area and can be subtracted from the project area prior to modeling in WWHM.

Terminology	i-Tree Hydro	WWHM
Vegetation: Tree Canopy or Forest	Referred to as Tree Canopy. Input as percent (%) cover in project area.	Referred to as Forest. Defined with a forest land cover (acres), based on forest coverage at land surface, does not account for canopy coverage. Forest land coverage parameters (PERLNDS) are based on a second growth Douglas Fir forest.
Vegetation: Shrub or Pasture	Referred to as Shrub Canopy. This parameter sets the maximum water depth that a single leaf in the tree or shrub canopy can hold.	Referred to as Pasture. Represents non-forested natural areas/scrub/shrub rural vegetation (acres).
Vegetation: Herbaceous or Lawn	Referred to as Herbaceous. Represents project area covered by non-tree, non-woody vegetation such as grass. Herbaceous canopies are the aboveground portion of herbaceous plants.	Referred to as Lawn. Represents sod lawn/grass/ landscaped urban vegetation.
Soil	Two soil types are used in the model: • Bare soil: Compact, dry soil that is considered impervious • Other soil: Spatially distributed throughout the project area by the model and defined for the area by the USDA soil texture triangle (sand, silt, loam, clay blend)	Three soil types are used in the model: • Till: NRCS Type C and some D soils • Outwash: NRCS Type A and B soils • Saturated: Hydric/saturated soils or wetland soils
Flow Duration	N/A	Flow duration analysis shows the percentage of time that flow is likely to equal or exceed some specified value of interest. For flow control in Western Washington, the range evaluated is 50% of the 2-year peak flow up to 100% of the 50-year peak flow. For on-site stormwater management (low impact development) in Western Washington the range evaluated is 8% of the 2-year peak flow up to 50% of the 2-year peak flow. The Low Impact Development (LID) performance standard in Western Washington is: "Stormwater discharges shall match developed discharge durations to predeveloped durations for the range of predeveloped discharge rates from 8% of the 2-year peak flow to 50% of the 2-year peak flow."
Flow Frequency	Not used directly in the model, but a storm of certain frequency could potentially be used as a model or design storm (e.g., 2-year).	Model outputs are based on the Log Pearson III, Weibull, Cunnane, or Gringorten methods and include: • 2-year • 5-year • 10-year • 25-year • 50-year • 100-year
Water Quality	Pollutant loading for a wide range of water quality parameters is calculated based on event mean concentrations (EMCs) and is associated with overland runoff flows in the project area.	The user can compute the target volumes and flows for offline and online water quality facilities and determine if the water quality facility sizing criterion in Western Washington (e.g., 91% infiltration/filtration of the total annual runoff volume) has been met. Pollutant loading for specific water quality parameters must be calculated outside of the model.
Base Case vs. Alternative Case	The base case represents the current conditions of the initial scenario being modeled. This represents current land cover and other parameters in the watershed or project area to allow for running and/or calibrating the model against an alternative scenario with varying inputs or parameters (e.g., changes in land cover, etc.).	• **"Predeveloped"** is similar to i-Tree Hydro's "Base Case," but is formally defined as "the conditions prior to land use development or existing conditions." • **"Mitigated"** is similar to i-Tree Hydro's "Alternative Case," but is formally defined as "the developed land use with mitigation measures (as selected by the user)."

Appendix C: Additional technical details on models, methods and other resources

Additional methods were used outside of the model and model simulations to calculate new land cover scenarios for each case for each scenario for each pilot community at all scales. All calculations were recorded in the excel spreadsheet linked below. A spreadsheet was also kept to record and calculate relative change results for all communities all scales, linked below.

AllScenarioResultsSheet.xlsb.xlsx

Canopy Change Scenarios Calculations.xlsx

Other related resources:

- *http://treesandstormwater.org/*
- *https://www.vibrantcitieslab.com/water-quality/*
- Stormwater Performance-Based Credit for Urban Tree Planting - *https://owl.cwp.org/mdocs-posts/stormwater-performance-based-credit/*

Appendix D: Pilot Community Stormwater and Surface Water Profiles

A profile was developed for pilot community that describes the city's basic characteristics, provides a brief description of the drainage basins, gages, and lists the selected modeling data. Information for each of these profiles was submitted by the pilot communities.

City of Kent

Pilot Community Stormwater and Surface Water Profile

City Population	127,000
City Size (square miles)	34
Tree Canopy Coverage (%)	28
Herbaceous (grass/lawn) Coverage (%)	25
Impervious Coverage (%)	40
Short Description of Surface Water Drainage	The city of Kent's drainage system is composed of three main watersheds. The westernmost portion of the city drains west through creeks in Des Moines to Puget Sound. The center portion includes the Green River valley which receives runoff from the west and east hills. The lower Green River flows north into the Duwamish River and then empties into Elliott Bay in Seattle. The easternmost portion of the city runs off to the southeast into Soos Creek, which flows south and runs into the Green River on the eastern edge of Auburn.

Drainage Basin Descriptions

Basin Name	Basin Area (acres)	Basin Characteristics and Unique Features
Lower Mill Creek	3,282	• Basin A (2016 Surface Drainage Facilities map and the 2008 Drainage Master Plan) • TMDL Implementation Plan in place for temperature • 303(d) list for bioassessment, bacteria, dissolved oxygen, pH
Upper Mill Creek	1,619	• Basin G (2016 Surface Drainage Facilities map and the 2008 Drainage Master Plan) • TMDL Implementation Plan in place for temperature • 303(d) list for bioassessment, bacteria, dissolved oxygen, pH • Earthworks Park is located in this basin and includes stormwater retention
Lower Garrison Creek	1,281	• Basin B (2016 Surface Drainage Facilities map and the 2008 Drainage Master Plan) • Drains to Springbrook Creek
Upper Garrison Creek	2,650	• Basin I (2016 Surface Drainage Facilities map and the 2008 Drainage Master Plan) • Clark Lake is located in the basin
Green River	1,089	• Basin C (2016 Surface Drainage Facilities map and the 2008 Drainage Master Plan) • There are many manmade drainage features, including 350+ public stormwater ponds, 6 dams, and river levees along the Green River through the valley • TMDL Implementation Plan in place for dissolved oxygen • 303(d) list for temperature
Valley Detention	1,638	• Basin Q (2016 Surface Drainage Facilities map) • Drains to Green River and Lower Mill Creek • Includes the Green River Enhancement (Natural Resource) Area
Mullen Slough, Mill Creek (Auburn)	404	• Includes Basins D, E, and F (2016 Surface Drainage Facilities map and the 2008 Drainage Master Plan) • Drains to the Green River
Soos Creek	5,975	• Basin H (2016 Surface Drainage Facilities map and the 2008 Drainage Master Plan)

Drainage Basin Descriptions

Basin Name	Basin Area (acres)	Basin Characteristics and Unique Features
Panther Creek (Eastern)	172	• Basin J (2016 Surface Drainage Facilities map) • Within an area annexed by the City after the 2008 Drainage Master Plan • Drains to Lower Garrison Creek
Panther Creek (Western)	384	• Basin R (2016 Surface Drainage Facilities map) • Within an area annexed by the City after the 2008 Drainage Master Plan • Panther Lake is located in the basin
Westside	3,065	• Basins K, L, M, N, O, and P (2016 Surface Drainage Facilities map and the 2008 Drainage Master Plan) • Bingamon Creek (Basin K), Lake Fenwick (Basin L), Midway Creek (Basin N), McSorely Creek (Basin O), and Johnson Creek (Basin P) are located in these basins

Selected Gages

Type	Source	Gage Name and Location	Length of Available Record	Time Range Selected
Precipitation	National Climatic Data Center (NCDC)	Sea-Tac International Airport (727930-24233)	1948-2018	10/1/05-9/30/15
Streamflow	USGS	12113347 – Mill Creek at Earthworks Park at Kent, WA	1994-2018	2005-2009

Other Modeling Inputs & Data Sources

Type	Source	Notes
Digital Elevation Model (DEM)	Puget Sound LiDAR Consortium	2016 data, ≥ 8.0 points/square meter resolution for LiDAR data, 10-meter resolution for DEM
Soils	National Resources Conservation Service (NRCS)	
Impervious Surface Coverage (%)	39.9%	2017 1m imagery + data layers from city
Tree Canopy Coverage (%)	27.7%	2017 1m imagery + LiDAR

City of Kirkland

Pilot Community Stormwater and Surface Water Profile

City Population	88,000
City Size (square miles)	17.83
Tree Canopy Coverage (%)	37
Herbaceous (grass/lawn) Coverage (%)	21
Impervious Coverage (%)	38
Short Description of Surface Water Drainage	The majority of Kirkland drains west and south into Lake Washington. Small amounts of land on the eastern and north edges of the city flow into the Sammamish River. The City has 15 drainage basins, which contain open stream channels and two small lakes (Forbes Lake and Totem Lake) in addition to many miles of surface water pipes and ditches.

Drainage Basin Descriptions

Basin Name	Basin Area (acres)	Basin Characteristics and Unique Features
Carillon Creek	106	• Water supply to Yarrow Point until ~2003 • 50% single-family residential • 21% multi-family residential • 12% open space • 35% forest cover • 38% impervious (existing)
Champagne Creek	627	• 89% single-family residential • 2% multi-family residential • 9% open space • 43% forest cover • 30% impervious (existing)
Denny Creek	804	• 66% single-family residential • 2% multi-family residential • 56% forest cover • 24% impervious (existing)
Forbes Creek	1,837	• 303(d) list for temperature, dissolved oxygen, pH, ammonia nitrogen, mercury, and bacteria • Includes Forbes Lake (eutrophic) • 67% single-family residential • 8% multi-family residential • 10% open space • 40% forest cover • 37% impervious (existing)
Holmes Point	458	• 85% single-family residential • 3% multi-family residential • 2% commercial • 63% forest cover • 22% impervious (existing)
Houghton Slope A	377	• 55% single-family residential • 2% commercial • 2% open space/park • 27% forest cover (lowest in the City) • 46% impervious (existing)

Drainage Basin Descriptions

Basin Name	Basin Area (acres)	Basin Characteristics and Unique Features
Houghton Slope B	134	• 30 to 40% in a landslide area • 78% single-family residential • 11% multi-family residential • 10% commercial • 36% forest cover • 41% impervious (existing)
Juanita Creek	3,624	• Largest drainage basin in the City • 303(d) list for temperature, dissolved oxygen, and bacteria • 63% single-family residential • 14% multi-family residential • 7% commercial • 39% forest cover • 43% impervious (existing)
Kingsgate Slope	1,616	• Only 563 acres within the City • 67% single-family residential • 1% commercial • 1.5% open space • 43% forest cover • 30% impervious (existing)
Kirkland Slope	211	• Lowest potential for development over the next 20 years • 86% single-family residential • 0.5% commercial • 13% open space/park • 31% forest cover • 39% impervious (existing)
Moss Bay Basin	1,487	• Highest impervious coverage in the City; close to being fully built-out • 56% single-family residential • 6% commercial • 7% open space/park • 32% forest cover • 46% impervious (existing)
South Juanita Slope	287	• 66% single-family residential • 12% commercial • 9% open space/park • 36% forest cover • 44% impervious (existing)
To Redmond	303	• Drains into Redmond and then the Sammamish River • 86% single-family residential • 6% commercial • 2% open space/park • 30% forest cover • 38% impervious (existing)
Yarrow Creek	579	• 51% single-family residential • 8% commercial • 29% open space/park (Yarrow Bay wetland and Watershed Park where limited or no development is allowed) • 51% forest cover • 21% impervious (existing)

Selected Gages

Type	Source	Gage Name and Location	Length of Available Record	Time Range Selected
Precipitation	National Climatic Data Center (NCDC)	Sea-Tac International Airport (727930-24233)	1948-2018	10/1/09 – 9/30/15
Streamflow	King County	Juanita Creek (12120500)	2008-2018	10/1/09 – 9/30/15

Other Modeling Inputs & Data Sources

Type	Source	Notes
Digital Elevation Model (DEM)	Puget Sound LiDAR Consortium	2016 data, ≥ 8.0 points/square meter resolution for LiDAR data, 10-meter resolution for DEM
Soils	National Resources Conservation Service (NRCS)	NRCS (WWHM)
Impervious Surface Coverage (%)	39.9%	2017 1m imagery + data layers from city
Tree Canopy Coverage (%)	27.7%	

City of Snohomish

Pilot Community Stormwater and Surface Water Profile

City Population	10,010
City Size (square miles)	3.6
Tree Canopy Coverage (%)	23
Herbaceous (grass/lawn) Coverage (%)	32
Impervious Coverage (%)	40
Short Description of Surface Water Drainage	The City of Snohomish is bordered by the Snohomish River to the south, the Pilchuck River to the east, and Cemetery Creek to the west. Blackmans Lake sits squarely in the middle of the city. The City's drainage system is composed of 8 drainage basins. One additional drainage basin (North Planning Area) is included in the area located north of the current urban growth area. Each drainage basin ultimately flows into either the Pilchuck River or the Snohomish River.

Drainage Basin Descriptions

Subbasin Name	Basin Area (acres)	Basin Characteristics and Unique Features
Upper Cemetery Creek	875	• The creek runs north-south through the north and west portions of the City • 14 wetlands are physically connected to Cemetery Creek and documented inside the urban growth area • Single-family and rural residential
Lower Cemetery Creek	1,015	• Extensive wetland complex is located at the mouth of the creek outside of the urban growth area • Single-family and rural residential
Blackmans Lake	465	• Undeveloped and rural residential • Contains Blackmans Lake which is approximately 57 acres and has a mean volume of 800 acre-feet • Blackmans Lake is not known to support salmonid species, but is stocked annually with trout
Swifty Creek	330	• Headwaters located at the southern end of Blackmans Lake • Drains the lake to the Snohomish and Pilchuck Rivers • Enclosed in culverts and inaccessible from the rivers; not known to support fish species • Completely developed
Bunk Foss	1,025	• Mostly undeveloped • Developed portion is low density or rural residential
Pilchuck River	466	• City's eastern boundary • Tributary to the Snohomish River southeast of the city • Bunk Foss Creek is a tributary
Snohomish River	445	• The Snohomish River watershed is the second largest watershed draining into Puget Sound • The total Snohomish River watershed area is 1,856 square miles; divided between Snohomish County and King County. • City's southern boundary • Extensive bank armoring and levees • The City owns 19 acres of land in the 100-year floodplain located upstream of the Historic District

Drainage Basin Descriptions

Subbasin Name	Basin Area (acres)	Basin Characteristics and Unique Features
Combined Sewer Area	248	• Downtown commercial and residential
North Planning Area	556	• Future expansion north of the current urban growth area

Selected Gages

Type	Source	Gage Name and Location	Length of Available Record	Time Range Selected
Precipitation	National Climatic Data Center (NCDC)	Paine Field	1948-2018	10/1/09 – 9/30/15
Streamflow	NA	NA	NA	NA

Other Modeling Inputs & Data Sources

Type	Source	Notes
Digital Elevation Model (DEM)	Puget Sound LiDAR Consortium	2005 data, ≥ 8.0 points/square meter resolution
Soils	National Resources Conservation Service (NRCS)	
Impervious Surface Coverage (%)	Tree Canopy Assessment (TCA)	23%
Tree Canopy Coverage (%)	Tree Canopy Assessment (TCA)	40%

City of Tacoma

Pilot Community Stormwater and Surface Water Profile

City Population	211,277
City Size (square miles)	62
Tree Canopy Coverage (%)	20
Herbaceous (grass/lawn) Coverage (%)	13
Impervious Coverage (%)	52
Short Description of Surface Water Drainage	Stormwater discharges from most parcels enter the City of Tacoma's drainage system which is a network of pipes which ultimately flow into Puget Sound. In the Leach and Flett Creek drainage basins, stormwater ultimately flows into Leach and Flett Creek (within Pierce County) with ultimate discharge to Puget Sound. In the Joe's Creek Watershed, stormwater ultimately discharges into Joe's Creek and into the City of Federal Way.

Drainage Basin Descriptions

Subbasin Name	Basin Area (acres)	Basin Characteristics and Unique Features
North Tacoma	4,766	• Part of the Puyallup River and Clover-Chambers Creek watersheds • Primarily residential • Commercial areas include the 6th Ave Proctor District, the Ruston Way commercial areas, and portions of the Westgate Shopping Center • Includes the North End Treatment Plant and the former Asarco smelting site
Foss	5,781	• Part of the Puyallup River watershed • Primarily residential • Industrial areas include the Tideflats and Nalley Valley • The Thea Foss and Wheeler-Osgood waterways became designated Superfund cleanup sites in 1983; cleanup was completed in 2006
Lower Puyallup	2,971	• Part of the Puyallup River watershed • Southern part of the basin is primarily residential with some undeveloped open space and a few small commercial areas • Northern portion of the basin contains industrial and commercial areas • Drains into the Puyallup River, Swan Creek, and T Street Gulch
Tideflats	2,112	• Part of the Puyallup River watershed • Most highly industrial and commercial section of the city • Drains into the Sitcum Waterway, Blair Waterway, and the Hylebos Waterway • The Sitcom and Hylebos waterways have been identified as Superfund cleanup sites
Northeast Tacoma	2,641	• Part of the Commencement Bay watershed • Primarily residential; fastest growing area in the city • Includes many large residential developments and shopping areas to support them
Western Slopes	2,090	• Located in northwest Tacoma • Part of the Clover-Chambers Creek watershed • Primarily residential with steep slopes • Commercial area includes part of the 6th Ave commercial area • Contains Point Defiance Park • Contains underground springs and near surface groundwater • Drains to the Narrows Passage through two small creeks (Gold Creek and Narrows Creek)

Drainage Basin Descriptions

Subbasin Name	Basin Area (acres)	Basin Characteristics and Unique Features
Leach Creek	1,728	• Located in west-central Tacoma • Part of the Clover-Chambers Creek watershed • Contains residential and commercial areas • Includes the Leach Creek holding basin; discharge from this pond forms the headwater of Leach Creek • Discharge from the Leach Creek holding basin is controlled by a gate structure and a pump station • Leach Creek flows into Chambers Creek, which discharges into Chambers Bay, then to the Narrows
Flett Creek	7,153	• Residential with light commercial and industrial areasIncludes Snake Lake and Wapato Lake • Includes the Hosmer holding basin; the holding basin flows to Wards Lake (City of Lakewood) and then to the City's gravel pit • From the gravel pit, the water flows into one of four Flett Creek holding ponds (which also receive water from South Tacoma and Snake Lake) • The discharge from the Flett Creek holding basins is pumped to the headwaters of Flett Creek • Flett Creek flows into Chamber Creek, which discharges into Chambers Bay, then to the Narrows
Joe's Creek	157	• Smallest drainage basin in the city • Primarily single and multi-family homes • Some open space and undeveloped land • Majority of Joe's Creek is in the City of Federal Way • Discharges to Puget Sound at Dumas Bay

Selected Gages

Type	Source	Gage Name and Location	Length of Available Record	Time Range Selected
Precipitation	National Climatic Data Center (NCDC)	Sea-Tac International Airport (727930-24233)	1948-2018	10/1/09 – 9/30/15
Streamflow	NA	NA	NA	NA

Other Modeling Inputs & Data Sources

Type	Source	Notes
Digital Elevation Model (DEM)	Pierce County	2010 data
Soils	National Resources Conservation Service (NRCS)	
Impervious Surface Coverage (%)	Tree Canopy Assessment (TCA)	20%
Tree Canopy Coverage (%)	Tree Canopy Assessment (TCA)	52%

Appendix E: Pilot Community Modeling Results Packets

For each pilot community, all results from all spatial scales and scenarios are listed below. Modeling scenarios as well as flow types are defined below.

Modeling Scenarios

Management Scenario	Cases	Description
Existing Conditions	Base Case	Current land cover percentages ("Current LC" from the Tree Canopy Assessment)
Tree Canopy Loss	1A. Present Canopy Stormwater Benefit (No Canopy)	What if the City, Drainage Basin, Neighborhood, or Parcel had no tree cover? Tree canopy is replaced by all herbaceous (grass/lawn) in this scenario.
	1B. Partial Tree Canopy Loss (- 10% Tree Canopy)	What if the City, Drainage Basin, Neighborhood, or Parcel loses some tree canopy due to a lack of investment, care, infestation, etc.? Modeled as a 10% tree canopy loss; 10% of the tree canopy is replaced by herbaceous (grass/lawn) in this scenario.
Development	2A. Build Out with Tree Preservation (- 5% Tree Canopy)	What if the City, Drainage Basin, Neighborhood, or Parcel has new development (build out), but retains some tree canopy? Scenario removes 5% tree canopy; adds impervious area and herbaceous (grass/lawn) land cover.
	2B. Build Out without Tree Preservation (- 10% Tree Canopy)	What if the City, Drainage Basin, Neighborhood, or Parcel has new development, but retains no canopy? Scenario removes 10% tree canopy; adds impervious area and herbaceous (grass/lawn) land cover.
Tree Canopy Increase	3A. Tree Canopy Increase: Over Pervious Area (+ 20% Tree Canopy; 90/10)	What if the City, Drainage Basin, Neighborhood, or Parcel had a dramatic increase (20%) in tree canopy? Modeling assumes 90% of that tree canopy overhangs pervious area and 10% overhangs impervious area (90/10).
	3B. Tree Canopy Increase: Over Impervious Area (+ 20% Tree Canopy; 50/50)	What if the City, Drainage Basin, Neighborhood, or Parcel had a dramatic increase (20%) in tree canopy? Modeling assumes 50% of that tree canopy overhangs impervious area and 50% overhangs pervious area (50/50).

Definitions

Total Runoff Volume (TRV)	The predicted runoff volume of the base case, including its components: base runoff volume, pervious runoff volume, and impervious runoff volume.
Base Runoff Volume (BRV)	The primary source of water during periods of low flow. Usually groundwater fed, but also fueled by water slowly draining from the subsurface into the river over time. The portion of surface water supplied by groundwater.
Pervious Runoff Volume (PRV)	The measure of water that flows through pervious surfaces such as soil and/or rocks and grass.
Impervious Runoff Volume (IRV)	The measure of water that flows over impervious surfaces such as roads, sidewalks, parking lots, that water cannot penetrate.

Pilot Community: City of Kent

City Scale Results

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (cubic feet)	i-Tree Hydro Volume Change (percent)	WWHM Volume Change (cubic feet)	WWHM Volume Change (percent)
Existing Conditions	**Base Case**	Tree Canopy: 27.7% (1.9% Impervious, 25.8% Pervious) Impervious: 39.9% Herbaceous: 25.0%	TRV: 13,870M BRV: 4,434M PRV: 4,244M IRV: 5,192M	NA	TRV: 7,914M BRV: NA PRV: 1,400M IRV: 6,514M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 39.9% Herbaceous: 52.7%	TRV: 14,116M BRV: 4,592M PRV: 4307M IRV: 5,218M	TRV: +2% BRV: +4% PRV: +1% IRV: +0.5%	TRV: 8,171M BRV: NA PRV: 1,656M IRV: 6,514M	TRV: +3% BRV: NA PRV: +18% IRV: 0%
	1B	Tree Canopy: 17.7% Impervious: 39.9% Herbaceous: 35.0%	TRV: 13,958M BRV: 4,490M PRV: 4,267M IRV: 5,201M	TRV: +1% BRV: +1% PRV: +1% IRV: 0%	TRV: 7,940M BRV: NA PRV: 1,425M IRV: 6,514M	TRV: +0.3% BRV: NA PRV: +2% IRV: 0%
Development	**2A**	Tree Canopy: 22.7% Impervious: 42.4% Herbaceous: 27.5%	TRV: 13,997M BRV: 4,335M PRV: 4,203M IRV: 5,459M	TRV: +1% BRV: -2% PRV: -1% IRV: +5%	TRV: 8,022M BRV: NA PRV: 1,400M IRV: 6,622M	TRV: +1% BRV: NA PRV: 0% IRV: +2%
	2B	Tree Canopy: 17.7% Impervious: 44.9% Herbaceous: 30.0%	TRV: 14,122M BRV: 4,237M PRV: 4,166M IRV: 5,719M	TRV: +2% BRV: -4% PRV: -2% IRV: +10%	TRV: 8,129M BRV: NA PRV: 1,400M IRV: 6,729M	TRV: +3% BRV: NA PRV: 0% IRV: +3%
Tree Canopy Increase	**3A**	Tree Canopy: 47.7% (3.9% Impervious, 43.8% Pervious) Impervious: 37.9% Herbaceous: 7.0%	TRV: 13,692M BRV: 4,327M PRV: 4,199M IRV: 5,166M	TRV: -1% BRV: -2% PRV: -1% IRV: -1%	TRV: 7,787M BRV: NA PRV: 1,359M IRV: 6,429M	TRV: -2% BRV: NA PRV: -3% IRV: -1%
	3B	Tree Canopy: 47.7% (11.9% Impervious, 35.8% Pervious) Impervious: 29.9% Herbaceous: 15.0%	TRV: 13,617M BRV: 4,349M PRV: 4,207M IRV: 5,601M	TRV: -2% BRV: -2% PRV: -1% IRV: -3%	TRV: 7,485M BRV: NA PRV: 1,399M IRV: 6,086M	TRV: -5% BRV: NA PRV: -0.1% IRV: -7%

Drainage Basin Scale Results: Upper Mill Creek

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (cubic feet)	i-Tree Hydro Volume Change (percent)	WWHM Volume Change (cubic feet)	WWHM Volume Change (percent)
Existing Conditions	**Base Case**	Tree Canopy: 32.8% (2.3% Impervious, 30.5% Pervious) Impervious: 38.0% Herbaceous: 23.0%	TRV: 979M BRV: 343M PRV: 287M IRV: 349M	NA	TRV: 504M BRV: NA PRV: 37M IRV: 467M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 38.0% Herbaceous: 55.6%	TRV: 1,000M BRV: 358M PRV: 292M IRV: 351M	TRV: +2% BRV: +4% PRV: +2% IRV: +1%	TRV: 514M BRV: NA PRV: 47M IRV: 467M	TRV: +2% BRV: NA PRV: +27% IRV: 0%
	1B	Tree Canopy: 22.8% Impervious: 38.0% Herbaceous: 33.0%	TRV: 986M BRV: 348M PRV: 289M IRV: 349M	TRV: +1% BRV: +1% PRV: +0.5% IRV: 0%	TRV: 505M BRV: NA PRV: 38M IRV: 467M	TRV: +0.2% BRV: NA PRV: +3% IRV: 0%
Development	**2A**	Tree Canopy: 27.8% Impervious: 40.5% Herbaceous: 25.0%	TRV: 989M BRV: 337M PRV: 284M IRV: 368M	TRV: +1% BRV: -2% PRV: -1% IRV: +5%	TRV: 514M BRV: NA PRV: 37M IRV: 477M	TRV: +2% BRV: NA PRV: +0.1% IRV: +2%
	2B	Tree Canopy: 22.8% Impervious: 43.0% Herbaceous: 28.0%	TRV: 998M BRV: 330M PRV: 281M IRV: 387M	TRV: +2% BRV: -4% PRV: -2% IRV: +11%	TRV: 524M BRV: NA PRV: 37M IRV: 487M	TRV: +4% BRV: NA PRV: +0.1% IRV: +4%
Tree Canopy Increase	**3A**	Tree Canopy: 52.8% (4.3% Impervious, 48.5% Pervious) Impervious: 36.0% Herbaceous: 5.0%	TRV: 966M BRV: 335M PRV: 284M IRV: 347M	TRV: -1% BRV: -2% PRV: -1% IRV: -1%	TRV: 494M BRV: NA PRV: 35M IRV: 459M	TRV: -2% BRV: NA PRV: -4% IRV: -2%
	3B	Tree Canopy: 52.8% (12.3% Impervious, 40.5% Pervious) Impervious: 28.0% Herbaceous: 12.8%	TRV: 961M BRV: 337M PRV: 285M IRV: 339M	TRV: -2% BRV: -2% PRV: -1% IRV: -3%	TRV: 464M BRV: NA PRV: 37M IRV: 427M	TRV: -8% BRV: NA PRV: -0.2% IRV: -9%

Neighborhood Scale Results: Lower Mill Creek Neighborhood for Direct Model Comparison

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (cubic feet)	i-Tree Hydro Volume Change (percent)	WWHM Volume Change (cubic feet)	WWHM Volume Change (percent)
Existing Conditions	**Base Case**	Tree Canopy: 19.7% (3.2% Impervious, 16.5% Pervious) Impervious: 51.1% Herbaceous: 29.1%	TRV: 95M BRV: 18M PRV: 16M IRV: 62M	NA	TRV: 59.8M BRV: NA PRV: 7.3M IRV: 52.6M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 51.1% Herbaceous: 48.8%	TRV: 97M BRV: 18M PRV: 16M IRV: 63M	TRV: +1% BRV: 0% PRV: +1% IRV: +1%	TRV: 61.2M BRV: NA PRV: 8.6M IRV: 52.6M	TRV: +2% BRV: NA PRV: +19% IRV: 0%
	1B	Tree Canopy: 9.7% Impervious: 51.1% Herbaceous: 39.1%	TRV: 96M BRV: 18M PRV: 16M IRV: 63M	TRV: +1% BRV: -2% PRV: +1% IRV: +1%	TRV: 60.0M BRV: NA PRV: 7.4M IRV: 52.6M	TRV: +0.2% BRV: NA PRV: +2% IRV: 0%
Development	**2A**	Tree Canopy: 14.7% Impervious: 53.6% Herbaceous: 31.6%	TRV: 96M BRV: 17M PRV: 16M IRV: 63M	TRV: +1% BRV: -3% PRV: -0.5% IRV: +1%	TRV: 60.4M BRV: NA PRV: 7.3M IRV: 53.1M	TRV: +1% BRV: NA PRV: 0% IRV: +1%
	2B	Tree Canopy: 9.7% Impervious: 56.1% Herbaceous: 34.1%	TRV: 97M BRV: 17M PRV: 15M IRV: 65M	TRV: +2% BRV: -7% PRV: -5% IRV: +5%	TRV: 60.9M BRV: NA PRV: 7.3M IRV: 53.6M	TRV: +2% BRV: NA PRV: 0% IRV: +2%
Tree Canopy Increase	**3A**	Tree Canopy: 39.7% (5.2% Impervious, 34.5% Pervious) Impervious: 49.1% Herbaceous: 11.1%	TRV: 94M BRV: 17M PRV: 16M IRV: 62M	TRV: -1% BRV: -7% PRV: -2% IRV: 0%	TRV: 59.2M BRV: NA PRV: 7.1M IRV: 52.2M	TRV: -1% BRV: NA PRV: -3% IRV: -1%
	3B (+ 20% Tree Canopy; 50/50)	Tree Canopy: 39.7% (13.2% Impervious, 26.5% Pervious) Impervious: 41.1% Herbaceous: 19.1%	TRV: 93M BRV: 17M PRV: 16M IRV: 61M	TRV: -2% BRV: -6% PRV: -1% IRV: -2%	TRV: 57.8M BRV: NA PRV: 7.3M IRV: 50.5M	TRV: -3% BRV: NA PRV: -0.1% IRV: -4%

Neighborhood Scale Results: Lower Mill Creek Neighborhood

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (cubic feet)	i-Tree Hydro Volume Change (percent)	WWHM Volume Change (cubic feet)	WWHM Volume Change (percent)
Existing Conditions	**Base Case**	Tree Canopy: 19.7% (3.2% Impervious, 16.5% Pervious) Impervious: 51.1% Herbaceous: 29.1%	TRV: 88M BRV: 22M PRV: 27M IRV: 40M	NA	TRV: 59.8M BRV: NA PRV: 7.3M IRV: 52.6M	NA

Neighborhood Scale Results: Lower Mill Creek Neighborhood

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (cubic feet)	i-Tree Hydro Volume Change (percent)	WWHM Volume Change (cubic feet)	WWHM Volume Change (percent)
Tree Canopy Loss	1A	Tree Canopy: 0% Impervious: 51.1% Herbaceous: 48.8%	TRV: 89M BRV: 22M PRV: 26M IRV: 41M	TRV: +1% BRV: +3% PRV: +1% IRV: +1%	TRV: 61.2M BRV: NA PRV: 8.6M IRV: 52.6M	TRV: +2% BRV: NA PRV: +19% IRV: 0%
	1B	Tree Canopy: 9.7% Impervious: 51.1% Herbaceous: 39.1%	TRV: 89M BRV: 22M PRV: 26M IRV: 41M	TRV: +1% BRV: +1% PRV: +1% IRV: +1%	TRV: 60.0M BRV: NA PRV: 7.4M IRV: 52.6M	TRV: +0.2% BRV: NA PRV: +2% IRV: 0%
Development	2A	Tree Canopy: 14.7% Impervious: 53.6% Herbaceous: 31.6%	TRV: 88M BRV: 22M PRV: 26M IRV: 41M	TRV: +1% BRV: 0% PRV: 0% IRV: +1%	TRV: 60.4M BRV: NA PRV: 7.3M IRV: 53.1M	TRV: +1% BRV: NA PRV: 0% IRV: +1%
	2B	Tree Canopy: 9.7% Impervious: 56.1% Herbaceous: 34.1%	TRV: 89M BRV: 21M PRV: 26M IRV: 43M	TRV: +2% BRV: -3% PRV: 0% IRV: +5%	TRV: 60.9M BRV: NA PRV: 7.3M IRV: 53.6M	TRV: +2% BRV: NA PRV: 0% IRV: +2%
Tree Canopy Increase	3A	Tree Canopy: 39.7% (5.2% Impervious, 34.5% Pervious) Impervious: 49.1% Herbaceous: 11.1%	TRV: 87M BRV: 21M PRV: 25M IRV: 40M	TRV: -1% BRV: -3% PRV: -2% IRV: 0%	TRV: 59.2M BRV: NA PRV: 7.1M IRV: 52.2M	TRV: -1% BRV: NA PRV: -3% IRV: -1%
	3B	Tree Canopy: 39.7% (13.2% Impervious, 26.5% Pervious) Impervious: 41.1% Herbaceous: 19.1%	TRV: 86M BRV: 21M PRV: 25M IRV: 40M	TRV: -2% BRV: -2% PRV: -1% IRV: -2%	TRV: 57.8M BRV: NA PRV: 7.3M IRV: 50.5M	TRV: -3% BRV: NA PRV: -0.1% IRV: -4%

Parcel Scale Results: Kensington Heights

Cases	Tree Species and Number of Trees	i-Tree Hydro Total Avoided Runoff	WWHM Total Avoided Runoff
Base Inventory/ Count of Trees	Doug Fir: 23 Bigleaf Maple: 9 Western Redcedar: 1 Red Maple: 0 Ponderosa Pine: 0 Littleleaf Linden: 0	119,722/6years	0 Gal/6 years

Pilot Community: City of Kirkland

City Scale Results

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (cubic feet)	i-Tree Hydro Volume Change (percent)	WWHM Volume Change (cubic feet)	WWHM Volume Change (percent)
Existing Conditions	**Base Case**	Tree Canopy: 37.4% (4.6% Impervious, 32.7% Pervious) Impervious: 37.7% Herbaceous: 20.5%	TRV: 7,165M BRV: 2,291M PRV: 2,076M IRV: 2,798M	NA	TRV: 3,557M BRV: NA PRV: 290M IRV: 3,267M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 37.7% Herbaceous: 57.9%	TRV: 7,347M BRV: 2,401M PRV: 2,114M IRV: 2,832M	TRV: +3% BRV: +5% PRV: +2% IRV: +1%	TRV: 3,696M BRV: NA PRV: 429M IRV: 3,267M	TRV: +4% BRV: NA PRV: +48% IRV: 0%
	1B	Tree Canopy: 27.4% Impervious: 37.7% Herbaceous: 30.5%	TRV: 7,222M BRV: 2,318M PRV: 2,087M IRV: 2,818M	TRV: +1% BRV: +1% PRV: +1% IRV: +1%	TRV: 3,571M BRV: NA PRV: 304M IRV: 3,267M	TRV: +0.4% BRV: NA PRV: +5% IRV: 0%
Development	**2A**	Tree Canopy: 32.4% Impervious: 40.2% Herbaceous: 23.0%	TRV: 7,202M BRV: 2,299M PRV: 2,079M IRV: 2,825M	TRV: +0.5% BRV: 0% PRV: 0% IRV: +1%	TRV: 3,639M BRV: NA PRV: 290M IRV: 3,349M	TRV: +2% BRV: NA PRV: 0% IRV: +3%
	2B	Tree Canopy: 27.4% Impervious: 42.7% Herbaceous: 25.5%	TRV: 7,276M BRV: 2,251M PRV: 2,061M IRV: 2,963M	TRV: +2% BRV: -2% PRV: -1% IRV: +6%	TRV: 3,721M BRV: NA PRV: 290M IRV: 3,431M	TRV: +5% BRV: NA PRV: +0.1% IRV: +5%
Tree Canopy Increase	**3A**	Tree Canopy: 57.4% (6.6% Impervious, 50.7% Pervious) Impervious: 35.7% Herbaceous: 2.5%	TRV: 7,072M BRV: 2,236M PRV: 2,053M IRV: 2,784M	TRV: -1% BRV: -2% PRV: -1% IRV: -1%	TRV: 3,469M BRV: NA PRV: 268M IRV: 3,201M	TRV: -3% BRV: NA PRV: -8% IRV: -2%
	3B	Tree Canopy: 57.4% (14.6% Impervious, 42.7% Pervious) Impervious: 27.7% Herbaceous: 10.5%	TRV: 7,028M BRV: 2,245M PRV: 2,056M IRV: 2,727M	TRV: -2% BRV: -2% PRV: -1% IRV: -3%	TRV: 3,228M BRV: NA PRV: 290M IRV: 2,939M	TRV: -9% BRV: NA PRV: -0.1% IRV: -10%

Drainage Basin Scale Results: Juanita Creek

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change		WWHM Volume Change	
			(cubic feet)	(percent)	(cubic feet)	(percent)
Existing Conditions	**Base Case**	Tree Canopy: 35.3% (4.6% Impervious, 30.7% Pervious) Impervious: 42.1% Herbaceous: 20.8%	TRV: 2,269M BRV: 723M PRV: 635M IRV: 911M	NA	TRV: 1,274M BRV: NA PRV: 140M IRV: 1,134M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 42.1% Herbaceous: 56.1%	TRV: 2,750M BRV: 723M PRV: 635M IRV: 911M	TRV: +1% BRV: +10% PRV: +4% IRV: -9%	TRV: 1,339M BRV: NA PRV: 205M IRV: 1,134M	TRV: +5% BRV: NA PRV: +46% IRV: 0%
	1B	Tree Canopy: 25.3% Impervious: 42.1% Herbaceous: 30.8%	TRV: 2,292M BRV: 799M PRV: 662M IRV: 831M	TRV: 0% BRV: +5% PRV: +2% IRV: -5%	TRV: 1,281M BRV: NA PRV: 147M IRV: 1,134M	TRV: +0.5% BRV: NA PRV: +5% IRV: 0%
Development	**2A**	Tree Canopy: 30.3% Impervious: 44.6% Herbaceous: 23.3%	TRV: 2,280M BRV: 727M PRV: 637M IRV: 917M	TRV: +0.5% BRV: +0.5% PRV: 0% IRV: +1%	TRV: 1,298M BRV: NA PRV: 140M IRV: 1,158M	TRV: +2% BRV: NA PRV: 0% IRV: +2%
	2B	Tree Canopy: 25.3% Impervious: 47.1% Herbaceous: 25.8%	TRV: 2,304M BRV: 712M PRV: 632M IRV: 960M	TRV: +2% BRV: -2% PRV: -1% IRV: +5%	TRV: 1,322M BRV: NA PRV: 140M IRV: 1,182M	TRV: +4% BRV: NA PRV: 0% IRV: +4%
Tree Canopy Increase	**3A**	Tree Canopy: 55.3% (6.6% Impervious, 48.7% Pervious) Impervious: 40.1% Herbaceous: 2.8%	TRV: 2,240M BRV: 705M PRV: 628M IRV: 906M	TRV: -1% BRV: -2% PRV: -1% IRV: -0.5%	TRV: 1,244M BRV: NA PRV: 130M IRV: 1,114M	TRV: -2% BRV: NA PRV: -7% IRV: -2%
	3B	Tree Canopy: 55.3% (14.6% Impervious, 40.7% Pervious) Impervious: 32.1% Herbaceous: 10.8%	TRV: 2,226M BRV: 709M PRV: 629M IRV: 889M	TRV: -2% BRV: -2% PRV: -1% IRV: -2%	TRV: 1,177M BRV: NA PRV: 140M IRV: 1,037M	TRV: -8% BRV: NA PRV: 0% IRV: -9%

Neighborhood Scale Results: Wolff Subdivision for Direct Model Comparison

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (100% DCIA for Comparison)		WWHM Volume Change	
			(cubic feet)	(percent)	(cubic feet)	(percent)
Existing Conditions	**Base Case**	Tree Canopy: 51.1% (3.8% Impervious, 47.3% Pervious) Impervious: 25.1% Herbaceous: 23.5%	TRV: 7.9M BRV: 3.1M PRV: 2.0M IRV: 3.0M	NA	TRV: 3.1M BRV: NA PRV: 0.7M IRV: 2.3M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 25.1% Herbaceous: 74.5%	TRV: 8.2M BRV: 3.3M PRV: 2.0M IRV: 3.0M	TRV: +4% BRV: +8% PRV: +1% IRV: -2%	TRV: 3.5M BRV: NA PRV: 1.1M IRV: 2.3M	TRV: +14% BRV: NA PRV: +60% IRV: 0%
	1B	Tree Canopy: 41.1% Impervious: 25.1% Herbaceous: 33.5%	TRV: 8.0M BRV: 3.1M PRV: 2.0M IRV: 3.0M	TRV: +1% BRV: +1% PRV: 0% IRV: 0%	TRV: 3.1M BRV: NA PRV: 0.8M IRV: 2.3M	TRV: +1% BRV: NA PRV: +6% IRV: 0%
Development	**2A**	Tree Canopy: 46.1% Impervious: 27.6% Herbaceous: 26.0%	TRV: 8.0M BRV: 3.0M PRV: 2.0M IRV: 3.2M	TRV: +1% BRV: -2% PRV: -3% IRV: +7%	TRV: 3.2M BRV: NA PRV: 0.7M IRV: 2.5M	TRV: +4% BRV: NA PRV: 0% IRV: +5%
	2B	Tree Canopy: 41.1% Impervious: 30.1% Herbaceous: 28.5%	TRV: 8.1M BRV: 3.0M PRV: 1.8M IRV: 3.4M	TRV: +2% BRV: -5% PRV: -6% IRV: +15%	TRV: 3.3M BRV: NA PRV: 0.7M IRV: 2.6M	TRV: +8% BRV: NA PRV: 0% IRV: +10%
Tree Canopy Increase	**3A**	Tree Canopy: 71.1% (5.8% Impervious, 65.3% Pervious) Impervious: 23.1% Herbaceous: 5.5%	TRV: 7.8M BRV: 3.0M PRV: 2.0M IRV: 2.9M	TRV: -1% BRV: -3% PRV: -1% IRV: -1%	TRV: 2.9M BRV: NA PRV: 0.6M IRV: 2.2M	TRV: -5% BRV: NA PRV: -10% IRV: -4%
	3B	Tree Canopy: 71.1% (13.8% Impervious, 57.3% Pervious) Impervious: 15.1% Herbaceous: 13.5%	TRV: 7.7M BRV: 3.0M PRV: 2.0M IRV: 2.9M	TRV: -2% BRV: -1% PRV: 0% IRV: -4%	TRV: 2.6M BRV: NA PRV: 0.7M IRV: 1.9M	TRV: -16% BRV: NA PRV: 0% IRV: -21%

Neighborhood Scale Results: Wolff Subdivision

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change		WWHM Volume Change	
			(cubic feet)	(percent)	(cubic feet)	(percent)
Existing Conditions	**Base Case**	Tree Canopy: 51.1% (3.8% Impervious, 47.3% Pervious) Impervious: 25.1% Herbaceous: 23.5%	TRV: 7.7M BRV: 3.5M PRV: 2.3M IRV: 1.9M	NA	TRV: 3.1M BRV: NA PRV: 0.7M IRV: 2.3M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 25.1% Herbaceous: 74.5%	TRV: 8M BRV: 3.7M PRV: 2.3M IRV: 2M	TRV: +4% BRV: +6% PRV: +1% IRV: +2%	TRV: 3.5M BRV: NA PRV: 1.1M IRV: 2.3M	TRV: +14% BRV: NA PRV: +60% IRV: 0%
	1B	Tree Canopy: 41.1% Impervious: 25.1% Herbaceous: 33.5%	TRV: 7.8M BRV: 3.6M PRV: 2.3M IRV: 1.9M	TRV: +1% BRV: +1% PRV: 0% IRV: 0%	TRV: 3.1M BRV: NA PRV: 0.8M IRV: 2.3M	TRV: +1% BRV: NA PRV: +6% IRV: 0%
Development	**2A**	Tree Canopy: 46.1% Impervious: 27.6% Herbaceous: 26.0%	TRV: 7.8M BRV: 3.5M PRV: 2.2M IRV: 2.1M	TRV: +1% BRV: -1% PRV: -1% IRV: +7%	TRV: 3.2M BRV: NA PRV: 0.7M IRV: 2.5M	TRV: +4% BRV: NA PRV: 0% IRV: +5%
	2B	Tree Canopy: 41.1% Impervious: 30.1% Herbaceous: 28.5%	TRV: 7.9M BRV: 3.4M PRV: 2.2M IRV: 2.2M	TRV: +2% BRV: -2% PRV: -2% IRV: +15%	TRV: 3.3M BRV: NA PRV: 0.7M IRV: 2.6M	TRV: +8% BRV: NA PRV: 0% IRV: +10%
Tree Canopy Increase	**3A**	Tree Canopy: 71.1% (5.8% Impervious, 65.3% Pervious) Impervious: 23.1% Herbaceous: 5.5%	TRV: 7.6M BRV: 3.4M PRV: 2.2M IRV: 1.9M	TRV: -1% BRV: -2% PRV: -1% IRV: -1%	TRV: 2.9M BRV: NA PRV: 0.6M IRV: 2.2M	TRV: -5% BRV: NA PRV: -10% IRV: -4%
	3B	Tree Canopy: 71.1% (13.8% Impervious, 57.3% Pervious) Impervious: 15.1% Herbaceous: 13.5%	TRV: 7.6M BRV: 3.4M PRV: 2.2M IRV: 1.9M	TRV: -2% BRV: -2% PRV: -0.5% IRV: -4%	TRV: 2.6M BRV: NA PRV: 0.7M IRV: 1.9M	TRV: -16% BRV: NA PRV: 0% IRV: -21%

Parcel Scale Results: Veridian

Cases	Tree Species and Number of Trees	i-Tree Hydro Total Avoided Runoff	WWHM Total Avoided Runoff
Base Inventory/ Count of Trees	Doug Fir: 4 Bigleaf Maple: 32 Western Redcedar: 6 Red Maple: 0 Ponderosa Pine: 0 Littleleaf Linden: 0	102,818 Gal/6years	11,182 Gal/6 years

Pilot Community: City of Snohomish

City Scale Results

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (cubic feet)	i-Tree Hydro Volume Change (percent)	WWHM Volume Change (cubic feet)	WWHM Volume Change (percent)
Existing Conditions	**Base Case**	Tree Canopy: 22.66% (2.26% Impervious, 20.4% Pervious) Impervious: 40.02% Herbaceous: 31.7%	TRV: 826M BRV: 79M PRV: 274M IRV: 474M	NA	TRV: 830M BRV: NA PRV: 282M IRV: 548M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 42.28% Herbaceous: 52.1%	TRV: 833M BRV: 80M PRV: 276M IRV: 477M	TRV: +1% BRV: +1% PRV: +1% IRV: +1%	TRV: 903M BRV: NA PRV: 354M IRV: 548M	TRV: +9% BRV: NA PRV: +26% IRV: 0%
	1B	Tree Canopy: 12.66% Impervious: 41.01% Herbaceous: 40.71%	TRV: 829M BRV: 79M PRV: 275M IRV: 475M	TRV: 0% BRV: +1% PRV: 0% IRV: 0%	TRV: 837M BRV: NA PRV: 289M IRV: 548M	TRV: +0.9% BRV: NA PRV: +3% IRV: 0%
Development	**2A**	Tree Canopy: 17.66% Impervious: 42.52% Herbaceous: 34.2%	TRV: 841M BRV: 76M PRV: 269M IRV: 495M	TRV: +2% BRV: -3% PRV: -2% IRV: +5%	TRV: 839M BRV: NA PRV: 282M IRV: 556M	TRV: +1% BRV: NA PRV: +0.2% IRV: +1%
	2B	Tree Canopy: 12.66% Impervious: 45.02% Herbaceous: 36.7%	TRV: 855M BRV: 74M PRV: 264M IRV: 517M	TRV: +3% BRV: -6% PRV: -4% IRV: +9%	TRV: 847M BRV: NA PRV: 283M IRV: 564M	TRV: +2% BRV: NA PRV: +0.4% IRV: +3%
Tree Canopy Increase	**3A**	Tree Canopy: 42.66% (4.26% Impervious, 38.4% Pervious) Impervious: 38.02% Herbaceous: 13.7%	TRV: 820M BRV: 78M PRV: 272M IRV: 471M	TRV: -1% BRV: -1% PRV: -1% IRV: -1%	TRV: 812M BRV: NA PRV: 270M IRV: 542M	TRV: -2% BRV: NA PRV: -4% IRV: -1%
	3B	Tree Canopy: 42.66% (12.26% Impervious, 30.4% Pervious) Impervious: 30.02% Herbaceous: 21.7%	TRV: 809M BRV: 78M PRV: 272M IRV: 459M	TRV: -2% BRV: -1% PRV: -1% IRV: -3%	TRV: 797M BRV: NA PRV: 280M IRV: 517M	TRV: -4% BRV: NA PRV: -0.8% IRV: -6%

Drainage Basin Scale Results: Swifty Creek

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (cubic feet)	i-Tree Hydro Volume Change (percent)	WWHM Volume Change (cubic feet)	WWHM Volume Change (percent)
Existing Conditions	**Base Case**	Tree Canopy: 18.14% (1.81% Impervious, 16.33% Pervious) Impervious: 53.55% Herbaceous: 26.03%	TRV: 141M BRV: 15M PRV: 45M IRV: 81M	NA	TRV: 130M BRV: NA PRV: 27M IRV: 102M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 55.36% Herbaceous: 42.36%	TRV: 142M BRV: 16M PRV: 45M IRV: 81M	TRV: +1% BRV: +2% PRV: 0% IRV: 0%	TRV: 138M BRV: NA PRV: 35M IRV: 102M	TRV: +6% BRV: NA PRV: +30% IRV: 0%
	1B	Tree Canopy: 13.14% Impervious: 57.84% Herbaceous: 16.84%	TRV: 142M BRV: 16M PRV: 45M IRV: 81M	TRV: +1% BRV: +1% PRV: -1% IRV: 0%	TRV: 131M BRV: NA PRV: 28M IRV: 102M	TRV: +0.6% BRV: NA PRV: +3% IRV: 0%
Development	**2A**	Tree Canopy: 30.3% Impervious: 44.6% Herbaceous: 23.3%	TRV: 143M BRV: 15M PRV: 44M IRV: 84M	TRV: +1% BRV: -3% PRV: -3% IRV: +4%	TRV: 131M BRV: NA PRV: 27M IRV: 103M	TRV: +0.7% BRV: NA PRV: +0.2% IRV: +0.9%
	2B	Tree Canopy: 8.14% Impervious: 60.34% Herbaceous: 19.34%	TRV: 145M BRV: 14M PRV: 44M IRV: 87M	TRV: +3% BRV: -7% PRV: -4% IRV: +8%	TRV: 132M BRV: NA PRV: 27M IRV: 104M	TRV: +2% BRV: NA PRV: +0.5% IRV: +2%
Tree Canopy Increase	**3A**	Tree Canopy: 38.14% (3.81% Impervious, 34.33% Pervious) Impervious: 51.55% Herbaceous: 8.03%	TRV: 139M BRV: 15M PRV: 44M IRV: 80M	TRV: -1% BRV: -2% PRV: -3% IRV: -1%	TRV: 128M BRV: NA PRV: 26M IRV: 102M	TRV: -2% BRV: NA PRV: -5% IRV: -0.7%
	3B	Tree Canopy: 38.14% (11.81% Impervious, 26.33% Pervious) Impervious: 43.55% Herbaceous: 16.03%	TRV: 138M BRV: 15M PRV: 44M IRV: 79M	TRV: -2% BRV: -1% PRV: -3% IRV: -3%	TRV: 126M BRV: NA PRV: 27M IRV: 99M	TRV: -3% BRV: NA PRV: -0.9% IRV: -3%

Neighborhood Scale Results: Historic District for Direct Model Comparison

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (100% DCIA for Comparison)		WWHM Volume Change	
			(cubic feet)	(percent)	(cubic feet)	(percent)
Existing Conditions	**Base Case**	Tree Canopy: 16.02% (1.6% Impervious, 14.42% Pervious) Impervious: 65.98% Herbaceous: 17.47%	TRV: 44.5M BRV: 3.2M PRV: 5.5M IRV: 36M	NA	TRV: 34.7M BRV: NA PRV: 4.7M IRV: 30.0M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 67.58% Herbaceous: 31.89%	TRV: 44.9M BRV: 3.3M PRV: 5.6M IRV: 36M	TRV: +1% BRV: +4% PRV: +3% IRV: 0%	TRV: 36.5M BRV: NA PRV: 6.6M IRV: 30.0M	TRV: +5% BRV: NA PRV: +39% IRV: 0%
	1B	Tree Canopy: 0% Impervious: 66.98% Herbaceous: 26.47%	TRV: 44.8M BRV: 3.2M PRV: 5.6M IRV: 36M	TRV: +1% BRV: +3% PRV: +2% IRV: 0%	TRV: 34.9M BRV: NA PRV: 4.9M IRV: 30.0M	TRV: +0.5% BRV: NA PRV: +4% IRV: 0%
Development	**2A**	Tree Canopy: 11.02% Impervious: 68.48% Herbaceous: 19.97%	TRV: 45.2M BRV: 3M PRV: 5.2M IRV: 37M	TRV: +1% BRV: -5% PRV: -5% IRV: +3%	TRV: 34.9M BRV: NA PRV: 4.7M IRV: 30.1M	TRV: +0.6% BRV: NA PRV: 0.3% IRV: +0.6%
	2B	Tree Canopy: 6.02% Impervious: 70.98% Herbaceous: 22.47%	TRV: 45.8M BRV: 2.8M PRV: 4.9M IRV: 38.1M	TRV: +3% BRV: -10% PRV: -11% IRV: +6%	TRV: 35.1M BRV: NA PRV: 4.8M IRV: 30.3M	TRV: +1% BRV: NA PRV: +0.6% IRV: +1%
Tree Canopy Increase	**3A**	Tree Canopy: 36.02% (3.6% Impervious, 32.42% Pervious) Impervious: 63.98% Herbaceous: 0%	TRV: 43.8M BRV: 3M PRV: 5.4M IRV: 35.4M	TRV: -2% BRV: -4% PRV: -2% IRV: -1%	TRV: 34.2M BRV: NA PRV: 4.4M IRV: 29.8M	TRV: -1% BRV: NA PRV: -6% IRV: -0.5%
	3B	Tree Canopy: 36.02% (11.6% Impervious, 24.42% Pervious) Impervious: 55.98% Herbaceous: 7.47%	TRV: 43.6M BRV: 3.1M PRV: 5.4M IRV: 35.1M	TRV: -2% BRV: -3% PRV: -2% IRV: -2%	TRV: 33.9M BRV: NA PRV: 4.7M IRV: 29.2M	TRV: -2% BRV: NA PRV: -1% IRV: -2%

Neighborhood Scale Results: Historic District

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (65% DCIA for Comparison)		WWHM Volume Change	
			(cubic feet)	(percent)	(cubic feet)	(percent)
Existing Conditions	**Base Case**	Tree Canopy: 65.02% (1.6% Impervious, 14.42% Pervious) Impervious: 65.98% Herbaceous: 17.47%	TRV: 38.5M BRV: 4M PRV: 11.1M IRV: 23.3M	NA	TRV: 34.7M BRV: NA PRV: 4.7M IRV: 30.0M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 67.58% Herbaceous: 31.89%	TRV: 38.9M BRV:4.1M PRV: 11.4M IRV: 23.4M	TRV: +1% BRV: +2% PRV: +2% IRV: 0%	TRV: 36.5M BRV: NA PRV: 6.6M IRV: 30.0M	TRV: +5% BRV: NA PRV: +39% IRV: 0%
	1B	Tree Canopy: 6.02% Impervious: 66.98% Herbaceous: 26.47%	TRV: 38.7M BRV: 4.1M PRV: 11.3M IRV: 23.4M	TRV: 0% BRV: +5% PRV: +1% IRV: -1%	TRV: 34.9M BRV: NA PRV: 4.9M IRV: 30.0M	TRV: +0.5% BRV: NA PRV: +4% IRV: 0%
Development	**2A**	Tree Canopy: 11.02% Impervious: 68.48% Herbaceous: 19.97%	TRV: 39M BRV: 3.9M PRV: 11.1M IRV: 24M	TRV: +1% BRV: -5% PRV: 0% IRV: +3%	TRV: 34.9M BRV: NA PRV: 4.7M IRV: 30.1M	TRV: +0.6% BRV: NA PRV: 0.3% IRV: +0.6%
	2B	Tree Canopy: 6.02% Impervious: 70.98% Herbaceous: 22.47%	TRV: 39.5M BRV: 3.7M PRV: 11.1M IRV: 24.8M	TRV: +3% BRV: -10% PRV: 0% IRV: +6%	TRV: 35.1M BRV: NA PRV: 4.8M IRV: 30.3M	TRV: +1% BRV: NA PRV: +0.6% IRV: +1%
Tree Canopy Increase	**3A**	Tree Canopy: 36.02% (3.6% Impervious, 32.42% Pervious) Impervious: 63.98% Herbaceous: 0%	TRV: 37.9M BRV: 4M PRV: 10.8M IRV: 23M	TRV: -2% BRV: -1% PRV: -3% IRV: -1%	TRV: 34.2M BRV: NA PRV: 4.4M IRV: 29.8M	TRV: -1% BRV: NA PRV: -6% IRV: -0.5%
	3B	Tree Canopy: 36.02% (11.6% Impervious, 24.42% Pervious) Impervious: 55.98% Herbaceous: 7.47%	TRV: 37.7M BRV: 4M PRV: 10.9M IRV: 22.8M	TRV: -2% BRV: -2% PRV: -2% IRV: -2%	TRV: 33.9M BRV: NA PRV: 4.7M IRV: 29.2M	TRV: -2% BRV: NA PRV: -1% IRV: -2%

Parcel Scale Results: Wetland Near Cady Park

Cases	Tree Species and Number of Trees	i-Tree Hydro Total Avoided Runoff	WWHM Total Avoided Runoff
Base Inventory/ Count of Trees	Doug Fir: 0 Bigleaf Maple: 3 Western Redcedar: 6 Red Maple: 0 Ponderosa Pine: 0 Littleleaf Linden: 35	24,688/6years	4,445 Gal/6 years

Pilot Community: City of Tacoma

City Scale Results

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (cubic feet)	i-Tree Hydro Volume Change (percent)	WWHM Volume Change (cubic feet)	WWHM Volume Change (percent)
Existing Conditions	**Base Case**	Tree Canopy: 20.27% (.94% Impervious, 19.33% Pervious) Impervious: 51.71% Herbaceous: 13.47%	TRV: 17,314M BRV: 2,468M PRV: 5,768M IRV: 9,078M	NA	TRV: 11,274M BRV: NA PRV: 2,166M IRV: 9,112M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 52.65% Herbaceous: 32.8%	TRV: 17,381M BRV: 2,556M PRV: 5,890M IRV: 8,935M	TRV: +.4% BRV: +4% PRV: +2% IRV: -2%	TRV: 11,951M BRV: NA PRV: 2,839M IRV: 9,112M	TRV: +6% BRV: NA PRV: +31% IRV: 0%
	1B	Tree Canopy: 10.27% Impervious: 51.71% Herbaceous: 23.47%	TRV: 17,194M BRV: 2,418M PRV: 5,684M IRV: 9,092M	TRV: -1% BRV: -2% PRV: -1% IRV: 0%	TRV: 11,345M BRV: NA PRV: 2,233M IRV: 9,112M	TRV: +0.6% BRV: NA PRV: +3% IRV: 0%
Development	**2A**	Tree Canopy: 15.27% Impervious: 54.21% Herbaceous: 15.97%	TRV: 17,404M BRV: 2,277M PRV: 5,530M IRV: 9,597M	TRV: +0.5% BRV: -8% PRV: -4% IRV: +6%	TRV: 11,374M BRV: NA PRV: 2,171M IRV: 9,203M	TRV: +0.9% BRV: NA PRV: 0.3% IRV: +1%
	2B	Tree Canopy: 10.27% Impervious: 56.71% Herbaceous: 18.47%	TRV: 17,610M BRV: 2,198M PRV: 5,463M IRV: 9,949M	TRV: +1.7% BRV: -11% PRV: -5% IRV: +10%	TRV: 11,471M BRV: NA PRV: 2,177M IRV: 9,294M	TRV: +2% BRV: NA PRV: +0.5% IRV: +2%
Tree Canopy Increase	**3A**	Tree Canopy: 40.27% (2.94% Impervious, 37.33% Pervious) Impervious: 49.71% Herbaceous: 0%	TRV: 16,609M BRV: 2,539M PRV: 5,799M IRV: 8,271M	TRV: -4% BRV: +3% PRV: +1% IRV: -9%	TRV: 11,092M BRV: NA PRV: 2,054M IRV: 9,039M	TRV: -2% BRV: NA PRV: -5% IRV: -0.8%
	3B	Tree Canopy: 40.27% (10.94% Impervious, 29.33% Pervious) Impervious: 41.71% Herbaceous: 3.47%	TRV: 16,837M BRV: 2,356M PRV: 5,592M IRV: 8,889M	TRV: -3% BRV: -5% PRV: -3% IRV: -2%	TRV: 10,891M BRV: NA PRV: 2,144M IRV: 8,747M	TRV: -3% BRV: NA PRV: -1% IRV: -4%

Drainage Basin Scale Results: Foss Creek

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (cubic feet)	i-Tree Hydro Volume Change (percent)	WWHM Volume Change (cubic feet)	WWHM Volume Change (percent)
Existing Conditions	**Base Case**	Tree Canopy: 12.94% (1.29% Impervious, 11.65% Pervious) Impervious: 58.66% Herbaceous: 16.13%	TRV: 3,253M BRV: 378M PRV: 978M IRV: 1,896M	NA	TRV: 2,969M BRV: NA PRV: 589M IRV: 2,380M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 59.95% Herbaceous: 23.85%	TRV: 3,271M BRV: 382M PRV: 987M IRV: 1,902M	TRV: +0.5% BRV: +1% PRV: +1% IRV: +0.3%	TRV: 3,067M BRV: NA PRV: 687M IRV: 2,380M	TRV: +3% BRV: NA PRV: +17% IRV: 0%
Tree Canopy Loss	**1B**	Tree Canopy: 2.94% Impervious: 59.66% Herbaceous: 21.20%	TRV: 3,267M BRV: 381M PRV: 985M IRV: 1,900M	TRV: +0.4% BRV: +1% PRV: +1% IRV: +0.2%	TRV: 2,979M BRV: NA PRV: 599M IRV: 2,380M	TRV: +0.3% BRV: NA PRV: +2% IRV: 0%
Development	**2A**	Tree Canopy: 7.94% Impervious: 61.16% Herbaceous: 14.70%	TRV: 3,291M BRV: 363M PRV: 966M IRV: 1,962M	TRV: +1% BRV: -4% PRV: -1% IRV: +4%	TRV: 2,982M BRV: NA PRV: 589M IRV: 2,393M	TRV: +0.4% BRV: NA PRV: 0% IRV: +0.6%
Development	**2B**	Tree Canopy: 2.94% Impervious: 63.66% Herbaceous: 17.20%	TRV: 3,327M BRV: 348M PRV: 952M IRV: 2,027M	TRV: +2% BRV: -8% PRV: -3% IRV: +7%	TRV: 2,996M BRV: NA PRV: 589M IRV: 2,407M	TRV: +0.9% BRV: NA PRV: -0.1% IRV: +1%
Tree Canopy Increase	**3A**	Tree Canopy: 32.94% (3.29% Impervious, 29.65% Pervious) Impervious: 50.93% Herbaceous: 0%	TRV: 3,137M BRV: 416M PRV: 1,014M IRV: 1,707M	TRV: -4% BRV: +10% PRV: +4% IRV: -10%	TRV: 2,943M BRV: NA PRV: 574M IRV: 2,369M	TRV: -0.9% BRV: NA PRV: -3% IRV: -0.4%
Tree Canopy Increase	**3B**	Tree Canopy: 32.94% (11.29% Impervious, 21.65% Pervious) Impervious: 48.66% Herbaceous: 2.20%	TRV: 3,202M BRV: 372M PRV: 968M IRV: 1,862M	TRV: -2% BRV: -1% PRV: -1% IRV: -2%	TRV: 2,917M BRV: NA PRV: 590M IRV: 2,327M	TRV: -2% BRV: NA PRV: +0.1% IRV: -2%

Neighborhood Scale Results: Tacoma Mall for Direct Model Comparison

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (100% DCIA for Comparison)		WWHM Volume Change	
			(cubic feet)	(percent)	(cubic feet)	(percent)
Existing Conditions	**Base Case**	Tree Canopy: 9.87% (0.99% Impervious, 8.88% Pervious) Impervious: 6.88% Herbaceous: 75.18%	TRV: 431M BRV: 20M PRV: 37M IRV: 374M	NA	TRV: 266M BRV: NA PRV: 15M IRV: 251M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 76.17% Herbaceous: 15.76%	TRV: 433M BRV: 20M PRV: 38M IRV: 374M	TRV: +0.4% BRV: +2% PRV: +1% IRV: 0%	TRV: 271M BRV: NA PRV: 20M IRV: 251M	TRV: +2% BRV: NA PRV: +31% IRV: 0%
	1B	Tree Canopy: 0% Impervious: 75.31% Herbaceous: 16.75%	TRV: 430M BRV: 21M PRV: 40M IRV: 370M	TRV: 0% BRV: +7% PRV: +6% IRV: -1%	TRV: 266M BRV: NA PRV: 16M IRV: 251M	TRV: +0.2% BRV: NA PRV: +3% IRV: 0%
Development	**2A**	Tree Canopy: 4.87% Impervious: 77.68% Herbaceous: 9.38%	TRV: 437M BRV: 18M PRV: 35M IRV: 384M	TRV: +1% BRV: -7% PRV: -8% IRV: +3%	TRV: 267M BRV: NA PRV: 15M IRV: 252M	TRV: +0.3% BRV: NA PRV: +0.3% IRV: +0.3%
	2B	Tree Canopy: 0% Impervious: 80.18% Herbaceous: 11.75%	TRV: 443M BRV: 17M PRV: 32M IRV: 394M	TRV: +3% BRV: -15% PRV: -15% IRV: +5%	TRV: 268M BRV: NA PRV: 15M IRV: 252M	TRV: +0.7% BRV: NA PRV: +0.5% IRV: +0.7%
Tree Canopy Increase	**3A**	Tree Canopy: 29.87% (2.99% Impervious, 26.88% Pervious) Impervious: 62.06% Herbaceous: 0%	TRV: 400M BRV: 28M PRV: 54M IRV: 318M	TRV: -7% BRV: 42% PRV: 44% IRV: -15%	TRV: 264M BRV: NA PRV: 14M IRV: 250M	TRV: -0.6% BRV: NA PRV: -5% IRV: -0.3%
	3B	Tree Canopy: 29.87% (10.99% Impervious, 18.88% Pervious) Impervious: 62.06% Herbaceous: 0%	TRV: 417M BRV: 22M PRV: 42M IRV: 353M	TRV: -3% BRV: +11% PRV: +11% IRV: -6%	TRV: 262M BRV: NA PRV: 15M IRV: 247M	TRV: -1% BRV: NA PRV: -1% IRV: -1%

Neighborhood Scale Results: Tacoma Mall

Management Scenario	Cases	Land Cover %	i-Tree Hydro Volume Change (65% DCIA for Comparison)		WWHM Volume Change	
			(cubic feet)	(percent)	(cubic feet)	(percent)
Existing Conditions	**Base Case**	Tree Canopy: 9.87% (0.99% Impervious, 8.88% Pervious) Impervious: 6.88% Herbaceous: 75.18%	TRV: 360M BRV: 25M PRV: 92M IRV: 243M	NA	TRV: 266M BRV: NA PRV: 15M IRV: 251M	NA
Tree Canopy Loss	**1A**	Tree Canopy: 0% Impervious: 76.17% Herbaceous: 15.76%	TRV: 361M BRV:25M PRV: 93M IRV: 243M	TRV: 0% BRV: +1% PRV: +1% IRV: 0%	TRV: 271M BRV: NA PRV: 20M IRV: 251M	TRV: +2% BRV: NA PRV: +31% IRV: 0%
	1B	Tree Canopy: 0% Impervious: 75.31% Herbaceous: 16.75%	TRV: 360M BRV: 26M PRV: 93M IRV: 240M	TRV: 0% BRV: +5% PRV: +1% IRV: -1%	TRV: 266M BRV: NA PRV: 16M IRV: 251M	TRV: +0.2% BRV: NA PRV: +3% IRV: 0%
Development	**2A**	Tree Canopy: 4.87% Impervious: 77.68% Herbaceous: 9.38%	TRV: 365M BRV: 23M PRV: 92M IRV: 250M	TRV: +1% BRV: -7% PRV: 0% IRV: +3%	TRV: 267M BRV: NA PRV: 15M IRV: 252M	TRV: +0.3% BRV: NA PRV: +0.3% IRV: +0.3%
	2B	Tree Canopy: 0% Impervious: 80.18% Herbaceous: 11.75%	TRV: 370M BRV: 22M PRV: 92M IRV: 256M	TRV: +3% BRV: -13% PRV: 0% IRV: +5%	TRV: 268M BRV: NA PRV: 15M IRV: 252M	TRV: +0.7% BRV: NA PRV: +0.5% IRV: +0.7%
Tree Canopy Increase	**3A**	Tree Canopy: 29.87% (2.99% Impervious, 26.88% Pervious) Impervious: 62.06% Herbaceous: 0%	TRV: 338M BRV: 34M PRV: 97M IRV: 207M	TRV: -6% BRV: +36% PRV: +6% IRV: -15%	TRV: 264M BRV: NA PRV: 14M IRV: 250M	TRV: -0.6% BRV: NA PRV: -5% IRV: -0.3%
	3B	Tree Canopy: 29.87% (10.99% Impervious, 18.88% Pervious) Impervious: 62.06% Herbaceous: 0%	TRV: 349M BRV: 27M PRV: 92M IRV: 230M	TRV: -3% BRV: +9% PRV: 0% IRV: -6%	TRV: 262M BRV: NA PRV: 15M IRV: 247M	TRV: -1% BRV: NA PRV: -1% IRV: -1%

Parcel Scale Results: Fireman's Park

Cases	Tree Species and Number of Trees	i-Tree Hydro Total Avoided Runoff	WWHM Total Avoided Runoff
Base Inventory/Count of Trees	Doug Fir: 7 Bigleaf Maple: 3 Western Redcedar: 6 Red Maple: 21 Ponderosa Pine: 5 Littleleaf Linden: 7	58,249 Gal/6years	317,189 Gal/6 years

Appendix F: Water Quality Results

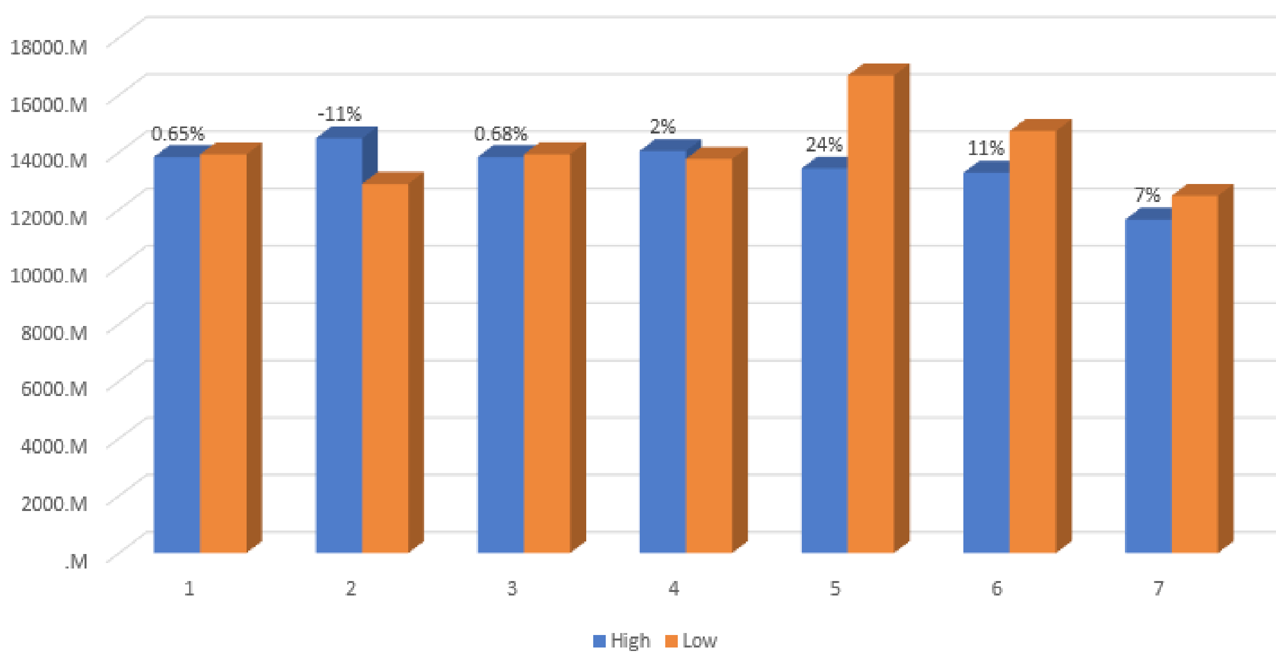
Listed below are tables with complete water quality results for each pilot community at the city spatial scale from i-Tree Hydro. After analysis, it was concluded that relative change in pollutants were parallel with relative change in total flow for each scenario.

Kent: Relative Change Percent						
Pollutant (Event Mean Concentrations)	**1A**	**1B**	**2A**	**2B**	**3A**	**3B**
TSS	1.0%	0.34%	2.0%	5.0%	-1.0%	-2.0%
Copper (dissolved)	1.0%	0.0%	2.0%	5.0%	-1.0%	-2.0%
Zinc (dissolved)	1.0%	0.3%	1.0%	5.0%	-1.0%	-2.0%
Kirkland: Relative Change Percent						
Pollutant (Event Mean Concentrations)	**1A**	**1B**	**2A**	**2B**	**3A**	**3B**
TSS	1.0%	0.62%	1.0%	3.0%	-1.0%	-2.0%
Copper (dissolved)	1.0%	1.0%	1.0%	3.0%	-1.0%	-2.0%
Zinc (dissolved)	1.0%	0.6%	-1.0%	3.0%	-1.0%	-2.0%
Total Phosphorus	1.0%	0.6%	-1.0%	3.0%	-1.0%	-2.0%
TKN	1.0%	0.6%	1.0%	3.0%	-1.0%	-2.0%
Snohomish: Relative Change Percent						
Pollutant (Event Mean Concentrations)	**1A**	**1B**	**2A**	**2B**	**3A**	**3B**
TSS	1.0%	0.4%	2.0%	4.0%	-1.0%	-2.0%
Copper (dissolved)	1.0%	0.0%	2.0%	4.0%	-1.0%	-2.0%
Zinc (dissolved)	1.0%	0.4%	1.0%	4.0%	-1.0%	-2.0%
Total Phosphorus	1.0%	0.4%	1.0%	4.0%	-1.0%	-2.0%
TKN	1.0%	0.4%	2.0%	4.0%	-1.0%	-2.0%
Tacoma: Relative Change Percent						
Pollutant (Event Mean Concentrations)	**1A**	**1B**	**2A**	**2B**	**3A**	**3B**
TSS	- O.14%	-0.5%	2.0%	4.0%	-5.0%	-2.0%
Copper (dissolved)	- O.14%	-0.5%	2.0%	4.0%	-5.0%	-2.0%
Zinc (dissolved)	- O.14%	-0.5%	2.0%	4.0%	-5.0%	-2.0%
Total Phosphorus	- O.14%	-0.5%	2.0%	4.0%	-5.0%	-2.0%
TKN	- O.14%	-0.5%	2.0%	4.0%	-5.0%	-2.0%

Appendix G: Sensitivity Analysis Matrix

Descriptions of each sensitivity parameter and high to low sensitivity (model sensitivity) results are listed below. The graph shows relative change percent and total flow in ft3 per hour in high to low parameter changes.

Parameter	Description (high value used, low value used)	i-Tree Hydro Sensitivity
1. Leaf Area Index (LAI)	Leaf Area Index is the total leaf area divided by the canopy area. High – 10 Used – 7.4 Low – 4.	Low
2. DCIA	Directly Connected Impervious Area, how much impervious area drains directly to the project area's outlet over connected impervious area. High – 100% Used – 65% Low – 40%	Low
3. Evergreen Canopy %	What percent of the existing tree canopy coverage is evergreen canopy. High – 80%, Used – 65%, Low – 10%.	Low
4. Herbaceous Land %	High - 0% Canopy and 52.7% Herbaceous Used – 25% Herbaceous and 27.7% Canopy Low – 0% Herbaceous and 52.7% Canopy	Low
5. Soil Texture	Changing the amount of saturation in the soil. High – Sand Low - Clay	High
6. Herbaceous/Impervious under Tree Canopy	Amount of herbaceous vs impervious understory of the existing tree canopy. High – All new canopy over pervious surface Low – All new canopy over impervious surface	High
7. All Herbaceous vs All Canopy	High – 100% land coverage as canopy Low – 100% land coverage as herbaceous	High



Appendix H: Future for i-Tree Hydro

The most current version of i-Tree Hydro being used and that was used in the project is version V6 beta. This version allowed for more than 2 land cover scenarios to be saved in one project, each scenario to have its own unique set of land cover parameters and allowing pollutant coefficients to be applied to the project as a basis for water quality predictions. All new features of i-Tree Hydro version V6 beta were used in the Puget Sound Urban Tree Canopy and Stormwater Analysis project.

Several planned future updates for i-Tree Hydro V6 are being developed by Davey Institute and i-Tree developers. These include:

- Green infrastructure land cover types are included with unique parameterization for tree pits, rain gardens, green roofs, rain barrels, and porous pavement. Through those classes, other types of green infrastructure can also be simulated, including bioswales, bioretention basins, and green corridors.
- Design Rain tool for simulating storms using regional NOAA data and Intensity-Duration-Frequency (IDF) curves for the United States.
- Curve Number tool for simple runoff prediction using the NRCS TR-55 method based on small-catchment hydrology studies, and built-in comparison of Curve Number model & Hydro model results.
- Climate-based simulations to assess the impact of land cover changes within 25-year past and projected-future climate conditions, based on the international, high-resolution NARCCAP model.
- Preloaded localized soil parameters from NRCS SSURGO data for the entire United States.
- Preloaded localized pollutant coefficients based on recent research from the USDA Agricultural Research Service and Hydro model developers.

Changes in i-Tree Hydro development team have caused some delays in new features for Hydro V6. The development period for a new updated V6 has been extended, additional months of development are needed to bring V6 out of beta status. Green infrastructure needs further peer-review and may be the longest extended update to V6 beta.

Appendix I: Tree Canopy Assessment – City of Kirkland Example

Purpose of the Tree Canopy Assessment

In addition to the hydrologic modeling performed using i-Tree Hydro, a Tree Canopy Assessment (TCA) was also performed in Kirkland as a part of this project. Kirkland's urban forest, which consists of trees along streets and in parks, yards, and natural areas, is a valuable resource that provides the City with many environmental, economic, and aesthetic benefits beyond stormwater management alone. The goal of this assessment was to assess the City's urban tree canopy (UTC), possible planting areas (PPA), and canopy change since 2010. The results were interpreted across a range of geographic boundaries in order to best inform all of Kirkland's various stakeholders and provide actionable information to a diverse range of audiences. The results of this analysis can be used to develop a continued strategy to protect and expand Kirkland's tree canopy. The UTC, PPA, and change metrics should be used as a guide to determine where the city has succeeded in protecting and expanding its urban forest resource, while also targeting the best areas to concentrate future efforts based on needs, benefits, and available planting space.

Tree Canopy Assessment Methodology

This assessment utilized 2017 high-resolution (1-meter) multispectral imagery from the U.S. Department of Agriculture's National Agriculture Imagery Program (NAIP) and 2016 LiDAR data from King County, Washington to derive the land cover data set. Additional GIS layers provided by the City of Kirkland were also incorporated into the analysis, such as the impervious surfaces layers and the 2010 urban tree canopy data which provided the basis of the change analysis.

First, an initial land cover dataset was created using an object-based image analysis (OBIA) software program called Feature Analyst. This process classifies features through an iterative approach in which objects' spectral signatures across four bands (blue, green, red, and near-infrared), textures, pattern relationships, and object height are considered. This remote sensing process used the NAIP imagery and LiDAR to derive five initial land cover classes: tree canopy, non-canopy vegetation, soil & dry vegetation, impervious surfaces, and water. Then, manual classification improvement and quality control were performed on the remote sensing products, additional impervious data layers from the City were utilized to capture finer feature detail and further categorize the land cover dataset, and the amount of urban tree canopy overhanging impervious surfaces was quantified to assist with hydrologic modeling.

Next, the land cover data set and data layers from the City were used to quantify areas where tree canopy could be expanded in the future. All land area in Kirkland that was not existing tree canopy was classified as either possible planting area (PPA) or unsuitable for planting. Possible planting areas were derived from the non-canopy vegetation and impervious classes. Unsuitable areas, or areas where it was not feasible to plant trees due to biophysical or land use restraints (e.g., airport runways, recreation fields, etc.), were manually delineated and overlaid with the existing land cover data set. The final results were reported as PPA Vegetation, PPA Impervious, Total PPA (vegetation and impervious), Unsuitable Vegetation, Unsuitable Impervious, Unsuitable Soil, and Total Unsuitable. Note that while the land cover metrics are based on Kirkland's total acres, the UTC and PPA metrics are based on land acres only. Water bodies are excluded from land area because they are typically unsuitable for planting new trees without significant modification.

Once the land cover map was derived and unsuitable areas were delineated, Kirkland's UTC, PPA, and change metrics were tabulated across the following geographic boundaries:

- The full citywide boundary
- The city boundary prior to the annexation of several neighborhoods in 2011
- HUC-12 watersheds (2)
- King County comprehensive plan land use classes (10)
- Neighborhoods (14)
- Drainage basins (15)
- U.S. census block groups (80)
- Holmes Point region
- Right-of-way
- Critical areas (100' buffer)
- Parks and open space classes (4)
- Shoreline jurisdiction areas (48)

Tree Canopy Assessment Results

Results of this study indicate that in 2017, the city of Kirkland contained 37 percent urban tree canopy (or 4,361 of the city's 11,671 total acres); 20 percent non-canopy vegetation (2,392 acres); 2 percent soil/dry vegetation (244 acres); 38 percent impervious surfaces (4,398 acres); and 2 percent water (277 acres). In further subdividing the impervious areas, 12 percent (1,421 acres) of Kirkland's total area were buildings, 8 percent (973 acres) were roads, 5 percent (585 acres) were parking lots, 3 percent (326 acres) were driveways, 1 percent (159 acres) were sidewalks, and 8 percent (933 acres) were "other impervious" areas such as trails, medians, etc.

Existing urban tree canopy covered 38 percent of Kirkland's land area (4,361 of the city's 11,394 land acres). Of the city's 62 percent of land area not presently occupied by tree canopy, 30 percent (3,421 acres) was suitable for future tree plantings, and 32 percent (3,612 acres) was unsuitable due to its current land use or other restraint. In further dividing the city's urban tree canopy, 12 percent was overhanging impervious surfaces.

A change analysis shows that the city's canopy has decreased by approximately 2 percent, down from 41 percent when it was last assessed based on 2010 imagery.

Reference Data

Classification Data	Tree Canopy	Vegetation	Impervious	Soil / Dry Veg.	Water	Total Reference Pixels
Tree Canopy	82	6	0	0	0	88
Vegetation	1	35	6	1	0	43
Impervious	1	1	101	0	0	103
Soil / Dry Veg.	0	0	4	3	0	7
Water	0	0	0	0	9	9
Total	84	42	111	4	9	250

Overall Accuracy = 92%

Producer's Accuracy	
Tree Canopy	98%
Veg. / Open Space	83%
Impervious	91%
Bare Ground / Soil	75%
Water	100%

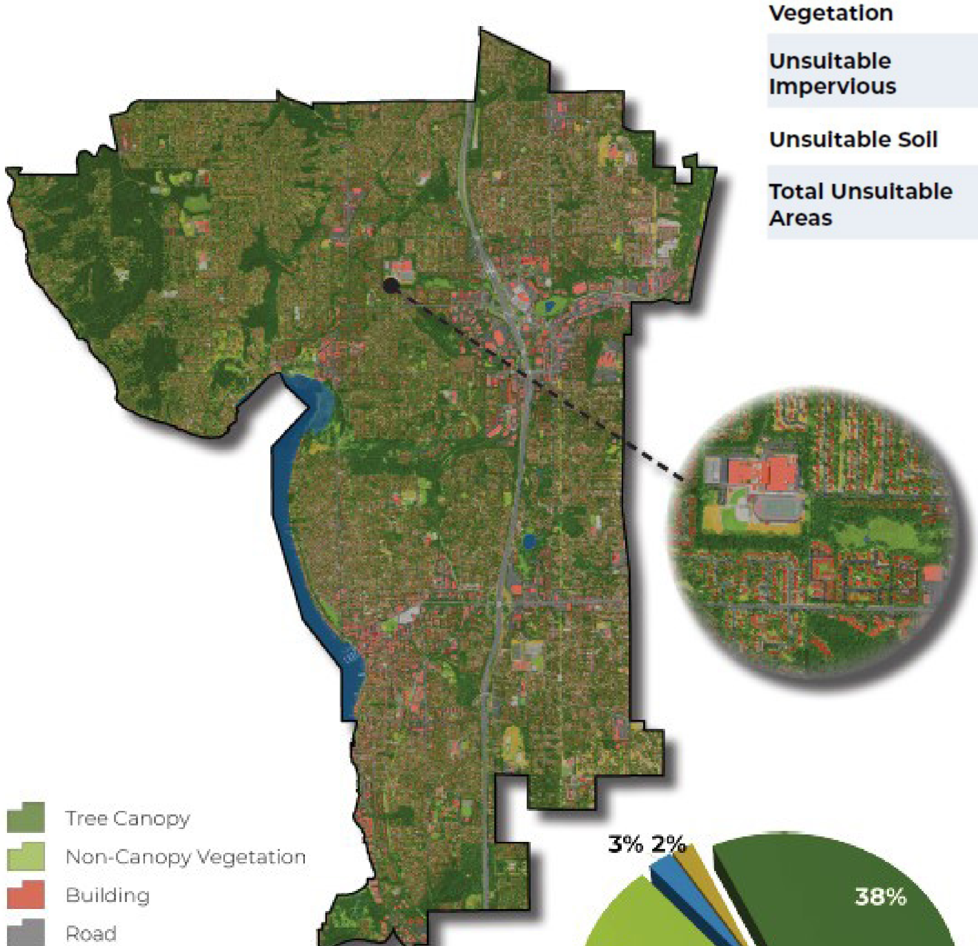
User's Accuracy	
Tree Canopy	93%
Veg. / Open Space	81%
Impervious	98%
Bare Ground / Soil	43%
Water	100%

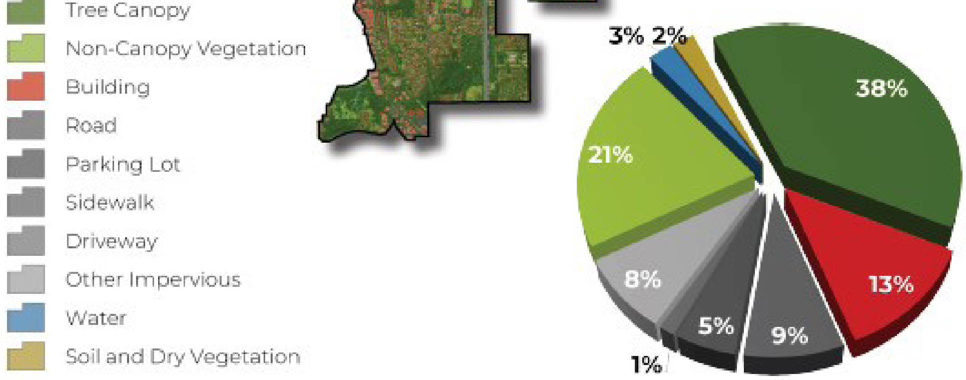
An accuracy assessment of the derived land cover classifications was performed using a sample error matrix and determined that the overall classification accuracy was 92%.

For the complete UTC, PPA, and change results, including by other geographies, refer to the Tree Canopy Assessment report (link). To view Kirkland's tree canopy assessment data in an interactive, weighted priority planning tool, visit the King County Canopy Planner web applcation (link).

City of Kirkland	Land Area		UTC 2010		UTC 2017		UTC Change	
	Acres	Dist.	Acres	%	Acres	%	Acres	%
City Boundary	11,394	100%	4,632	41%	4,361	38%	-272	-2%

City of Kirkland	Acres	%
Total Area	11,671	100%
Land Area	11,394	98%
Urban Tree Canopy	4,361	38%
Possible Planting Area - Vegetation	2,351	21%
Possible Planting Area - Impervious	1,070	9%
Total Possible Planting Area	3,421	30%
Unsuitable Vegetation	40	<1%
Unsuitable Impervious	3,330	29%
Unsuitable Soil	242	2%
Total Unsuitable Areas	3,612	32%





Appendix J: i-Tree Hydro Executive Summary – City of Kirkland Example

For each model simulation in i-Tree Hydro, an Executive Summary is available for viewing and analyzing results. The following sample Executive Summary is for the City of Kirkland, scenario 1A.

i-Tree Hydro Executive Summary

Project Location: Kirkland, Washington
Project Time Span: 10/01/2009 - 09/30/2015

Model Parameters

Watershed Area (square kilometers)	Rainfall (millimeters)	Total Flow (cubic meters)	Stream Gage	Weather Station
47.23	6,476.75	248,008,300.99	N/A	N/A

Land Cover	Base	Alternative		Base	Alternative	LC beneath Tree Cover	Base	Alternative
Tree Cover %	37.4	0.0	Tree LAI	7.4	7.4	Soil Cover %	32.7	0.0
Shrub Cover %	0.0	0.0	Shrub LAI	2.2	2.2	Impervious Cover %	4.6	0.0
Herbaceous Cover %	20.5	57.9	Herbaceous LAI	1.6	1.6	**Percent Evergreen**		
Water Cover %	2.4	2.4	Directly Connected Impervious Cover (%)	100.0	100.0	Tree Canopy %	55.0	55.0
Impervious Cover %	37.7	37.7				Shrub Canopy %	0.0	0.0
Soil Cover %	2.1	2.1						

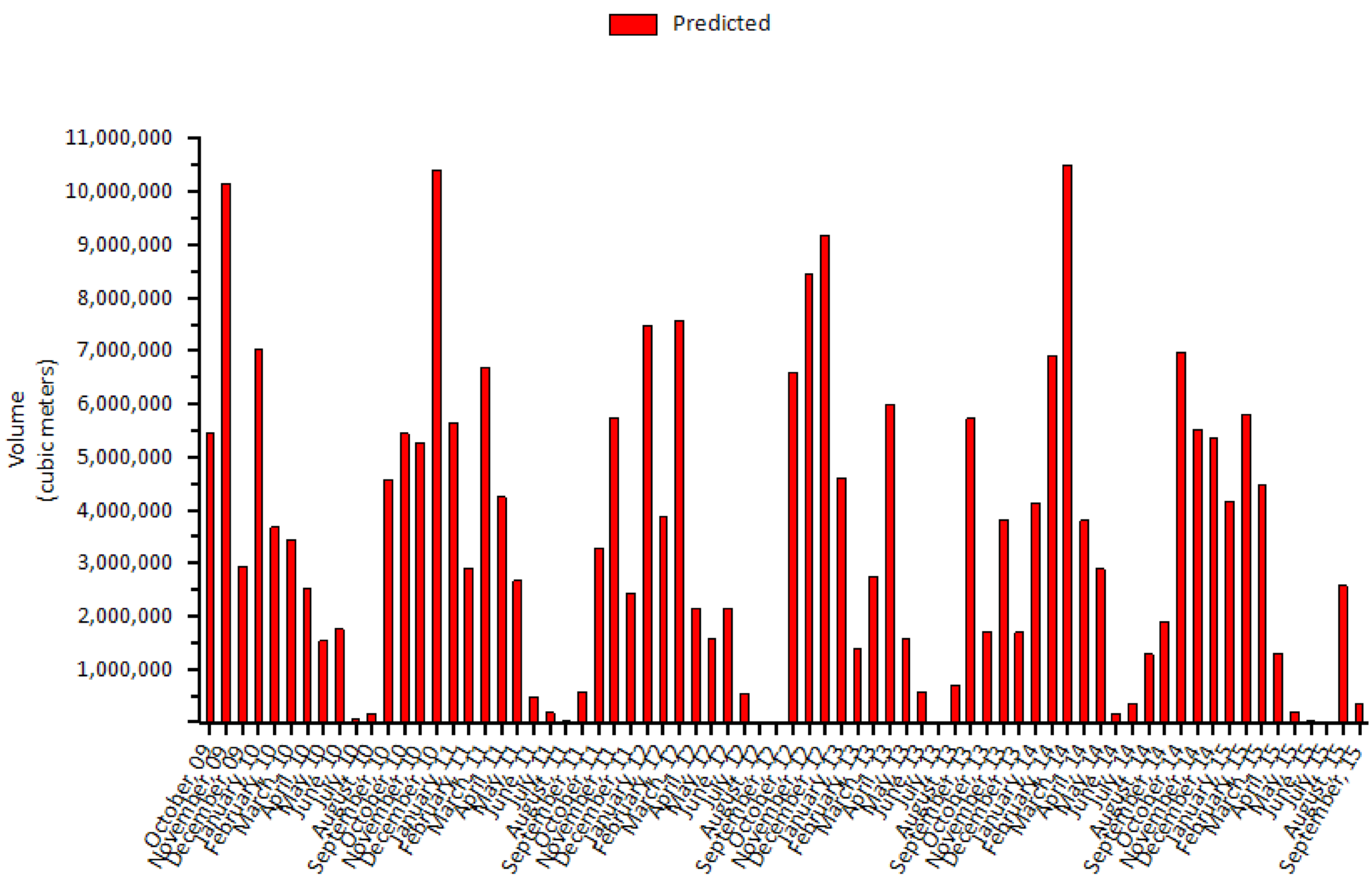
Streamflow Predictions

	Total Flow		Base Flow		Pervious Runoff		Impervious Runoff	
	Base	Alternative	Base	Alternative	Base	Alternative	Base	Alternative
Total Flow (cubic meters)	248,008,301.0	253,162,049.6	140,638.3	152,387.9	125,972,342.2	142,397,250.8	121,894,570.6	110,611,658.3
Highest Flow (cubic meters / hour)	181,111.5	181,162.9	131.5	142.5	100,019.9	108,428.4	81,090.7	72,734.1
Lowest Flow (cubic meters / hour)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Highest Flow Date	12/12/10	12/12/10	10/07/09	10/07/09	12/12/10	12/12/10	12/12/10	12/12/10
Lowest Flow Date	10/01/09	10/01/09	10/01/09	10/01/09	10/01/09	10/01/09	10/01/09	10/01/09
Median Flow (cubic meters / hour)	52.6	62.4	0.1	0.1	2.2	7.0	28.6	30.0
Number of flow events ABOVE median flow	195.0	197.0	1.0	1.0	110.0	136.0	196.0	199.0
Average length of flow events with flow ABOVE median (hours)	134.8	133.5	26,292.0	26,292.0	239.0	193.3	134.1	132.1
High Flow: Number of flow events ABOVE 1 standard deviation	120.0	120.0	1.0	1.0	86.0	98.0	136.0	137.0
Average length of flow events ABOVE 1 standard deviation (hours)	185.5	184.4	26,292.0	26,292.0	282.0	239.6	168.0	166.6
Number of flow events BELOW median flow	195.0	197.0	2.0	2.0	111.0	137.0	197.0	200.0
Average length of events BELOW median (hours)	134.5	133.5	5.0	5.0	234.3	189.5	133.2	131.5

i-Tree Hydro Executive Summary

Project Location: Kirkland, Washington
Project Time Span: 10/01/2009 - 09/30/2015

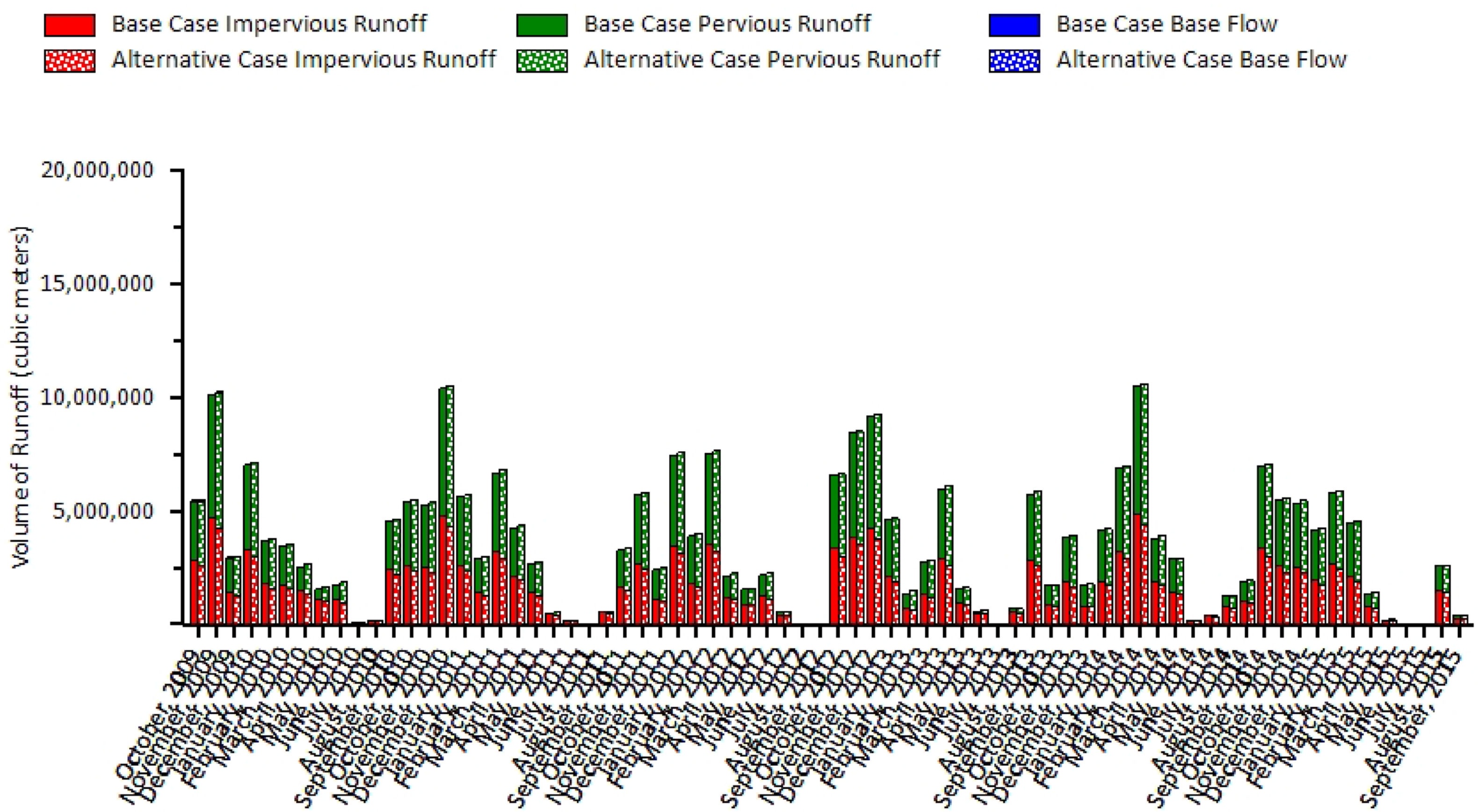
Water Volume: Predicted Streamflow



i-Tree Hydro Executive Summary

Project Location: Kirkland, Washington
Project Time Span: 10/01/2009 - 09/30/2015

Base Case vs. Alternative Case Predicted Streamflow Components

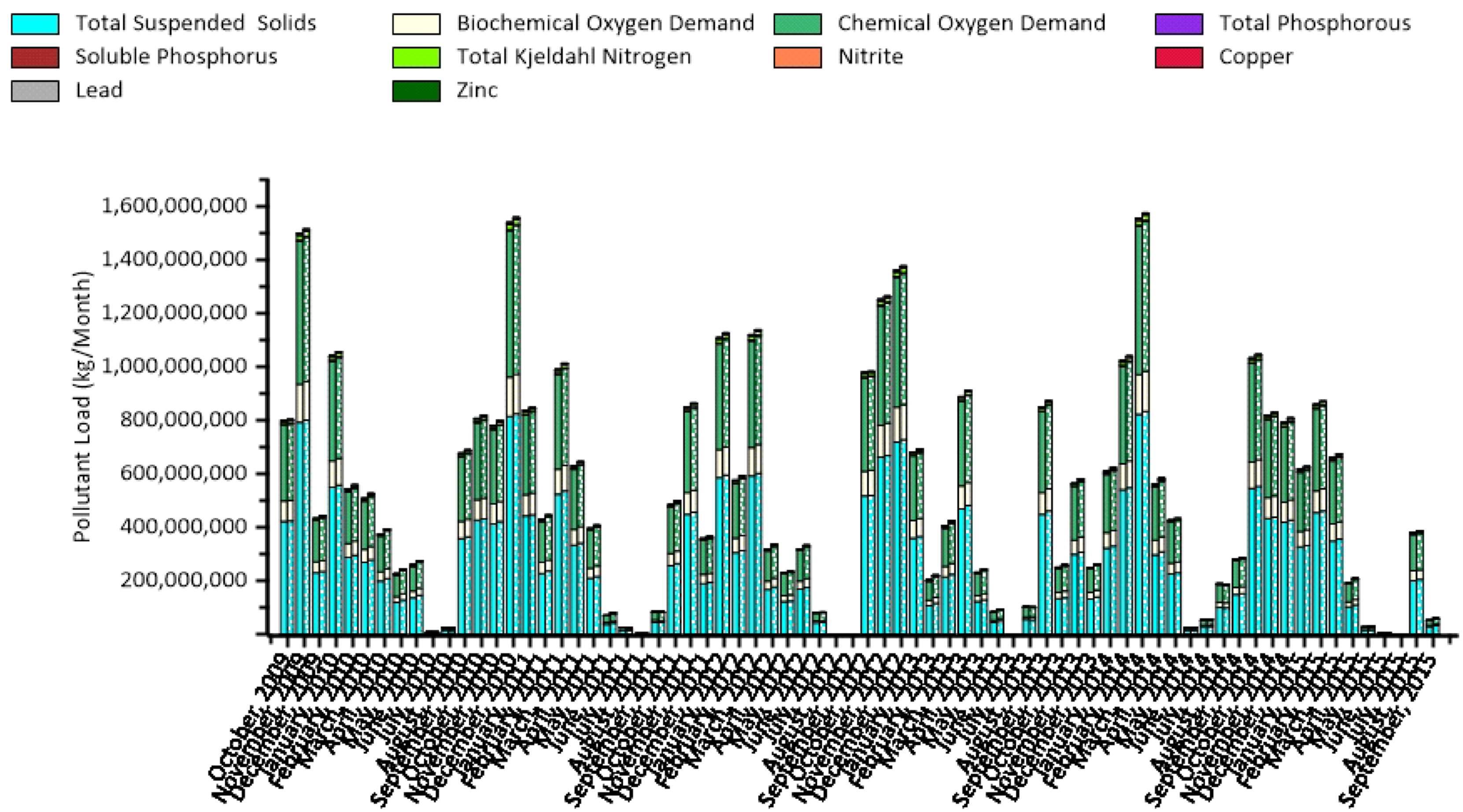


Note: Solid colors represent Base Case values while the hatched pattern indicates Alternative Case values

i-Tree Hydro Executive Summary

Project Location: Kirkland, Washington
Project Time Span: 10/01/2009 - 09/30/2015

Pollutants: Base Case vs. Alternative Case Event Mean Concentration



Note: Solid colors represent Base Case values while the hatched pattern indicates Alternative Case values

i-Tree Hydro Executive Summary

Project Location: Kirkland, Washington
Project Time Span: 10/01/2009 - 09/30/2015

Glossary of Key Terms

Base Case – The original modeled scenario defined by the initial land cover values (e.g. tree cover, herbaceous cover, impervious cover, etc.).

Alternative Case – The modeled scenario contrasted with the base case. It is defined by changes in the initial land cover values representing an increase in development (e.g. increase in impervious cover or decrease in vegetative cover) or an increase in vegetative cover (e.g. increase in tree cover or herbaceous cover).

Base Flow – The stream flow from groundwater and no recent storm runoff. Base flow is generated from the saturated soil zone within i-Tree Hydro.

Impervious Runoff – The predicted overland surface runoff generated from impervious cover areas, which may be impervious cover with or without vegetative canopies. The model first checks that impervious cover specific depression storage is filled and evaporation from this storage is accounted for, before generating impervious flow. Impervious flow either passes directly to the outlet through directly connected impervious cover area (DCIA) or runs on to neighboring pervious cover areas where infiltration may occur.

Pervious Runoff – The predicted overland surface runoff generated from pervious cover areas, which include bare soil and soil areas under herbaceous cover and vegetative canopies. The model uses first checks that pervious cover specific depression storage is filled and evaporation from this storage is accounted for, then uses saturation excess and infiltration excess routines to calculate the total amount of pervious flow. Pervious cover surface runoff generates run-on to neighboring impervious areas, where DCIA transports a portion of the runoff to the outlet, or onto neighboring pervious cover areas where infiltration may occur.

Total Flow volume (cubic meters) – This is the total amount of streamflow (base flow plus pervious and impervious surface runoff) for the modeled time period. To arrive at this number, the predicted total streamflow rate for each timestep (typically m/hr) is multiplied by the watershed area represented by each landcover type and the total number of modeled timesteps (typically hr).

Highest Flow rate (cubic meters / hour) – The largest predicted peak streamflow rate during the modeled period.

Lowest Flow rate (cubic meters / hour) – The lowest predicted peak streamflow rate during the modeled period.

Highest Flow Date – The date of the largest predicted peak streamflow rate.

Lowest Flow Date – The date of the lowest predicted peak streamflow rate.

Average Flow rate (cubic meters/hour) – The average predicted streamflow rate during the modeled period.

Number of flow events ABOVE average flow – The number of continuous periods (timesteps) where the predicted streamflow rate is above the average streamflow rate.

Average length of flow events ABOVE average (hours) – The average length in hours of the continuous periods (timesteps) where the predicted streamflow rate is above the average streamflow rate.

Appendix K: Eco/Parcel Results

Parcel Scale i-Tree Methods

In contrast to the WWHM model, where methodology remained constant across all scales, i-Tree Eco was used for the parcel level in place of Hydro. This is due in part to i-Tree Hydro being used typically for larger areas of interest. For this smaller parcel scale, pilot communities provided a simple tree inventory for all trees on a specified parcel. These inventories included the species of the tree, diameter, and whether the tree was within 20 feet of a ground-level impervious surface (sidewalk, parking lot, etc.).

Species Common Name

- Red Maple
- Ponderosa Pine
- Douglas Fir
- Bigleaf Maple
- Littleleaf Linden
- Western Redcedar

Six species common to the area were then selected in order to create a generalized representation of ecosystem benefits provided on each parcel. These species were then added to i-Tree Eco at varying sizes: from 3 inches to 60 inches, increasing by 3 inches incrementally (3, 6, 9, etc.) for a total of 20 size classes.

Each species inventoried on the selected parcel was mapped to one of the six above species above. Estimations of stormwater runoff mitigation were then applied to each tree based on the diameter of the inventoried tree. Results are reported in both cubic feet and gallons of stormwater runoff mitigated across the entire six-year period*.

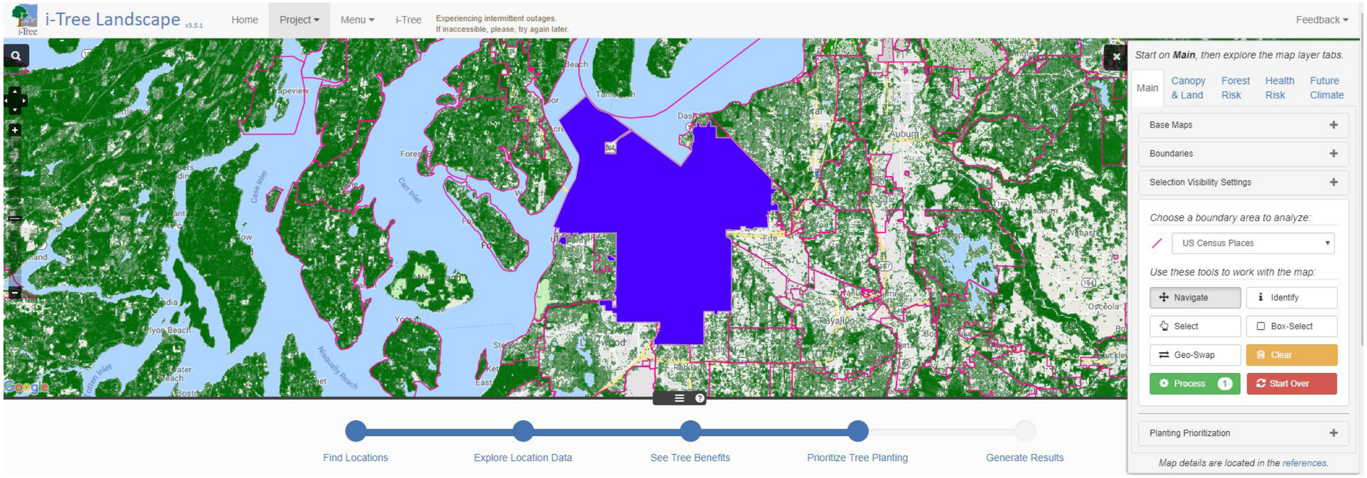
Parcel (City)	Tree Species	Number of Trees	DBH Range (Inches)						Avoided Runoff (gallons/6 years)
			0 to 6	6 to 12	12 to 18	18 to 24	24 to 30	Over 30	i-Tree Hydro
Kensington Heights (Kent)	Doug Fir	23	0	0	0	0	14	9	92,033
	B Maple	9	0	0	6	3	0	0	26,360
	W Redcedar	1	0	0	1	0	0	0	1,329
	Red Maple	0	0	0	0	0	0	0	0
	P Pine	0	0	0	0	0	0	0	0
	L Linden	0	0	0	0	0	0	0	0
Total Avoided Runoff (gallons/6 years)									119,722
Veridian (Kirkland)	Doug Fir	4	0	2	0	2	0	0	8,734
	B Maple	32	0	6	16	8	0	1	88,837
	W Redcedar	6	0	2	3	1	0	0	5,247
	Red Maple	0	0	0	0	0	0	0	0
	P Pine	0	0	0	0	0	0	0	0
	L Linden	0	0	0	0	0	0	0	0
Total Avoided Runoff (gallons/6 years)									102,818
Wetland Near Cady Park (Snohomish)	Doug Fir	0	0	0	0	0	0	0	0
	B Maple	3	1	2	0	0	0	0	2,195
	W Redcedar	6	0	1	2	1	1	1	6,940
	Red Maple	0	0	0	0	0	0	0	0
	P Pine	0	0	0	0	0	0	0	0
	L Linden	35	35	0	0	0	0	0	15,553
Total Avoided Runoff (gallons/6 years)									24,688
Firemen's Park (Tacoma)	Doug Fir	7	2	0	1	2	1	1	16,185
	B Maple	3	0	0	1	1	1	0	9,551
	W Redcedar	6	1	1	2	1	1	0	5,040
	Red Maple	21	4	14	3	0	0	0	24,681
	P Pine	5	2	3	0	0	0	0	2,383
	L Linden	7	7	0	0	0	0	0	408
Total Avoided Runoff (gallons/6 years)									58,248

*i-Tree Eco results were annual – these estimations were then multiplied by 6 to represent the study duration.

Appendix L: Landscape Results – City-wide Tacoma Example

For accurate project area results because of scale limitations, City of Tacoma was used as the example in i-Tree Landscape. Land cover derived by Plan It Geo was uploaded to Landscape for this example and future use. Below are results created by Landscape to show tree benefits of current canopy and prioritize tree planting for the City of Tacoma. All results can be generated by Landscape for other King County cities See *https://landscape.itreetools.org*

Figure AL. | i-Tree Landscape Example Screenshot



Tree Benefits

Carbon

Carbon Storage		Carbon Sequestration		CO_2 *Equivalent Storage*		CO_2 *Equivalent Sequestration*	
$	Tons	$/yr	t/yr	$	Tons	$/yr	t/yr
27,019,472	208,279	443,541	3,419	27,019,472	763, 689	443,541	12,536.4

Air Pollution Removal

$/yr	lb/yr
1, 624	2, 435.2

Hydrology

Transpiration	Rainfall Interception	Avoided Runoff	Avoided Runoff
MG/yr	MG/yr	MG/yr	$/yr
426	820	225	2,012,228

Appendix M: Technical Help

Gathering and customizing data for i-Tree Hydro input, such as stream gage data or precipitation data, is an important first step to Hydro simulations. This Appendix includes technical help for customizing data for input to i-Tree Hydro, including stream gage and precipitation.

How to input custom stream gage data into i-Tree Hydro V6 -

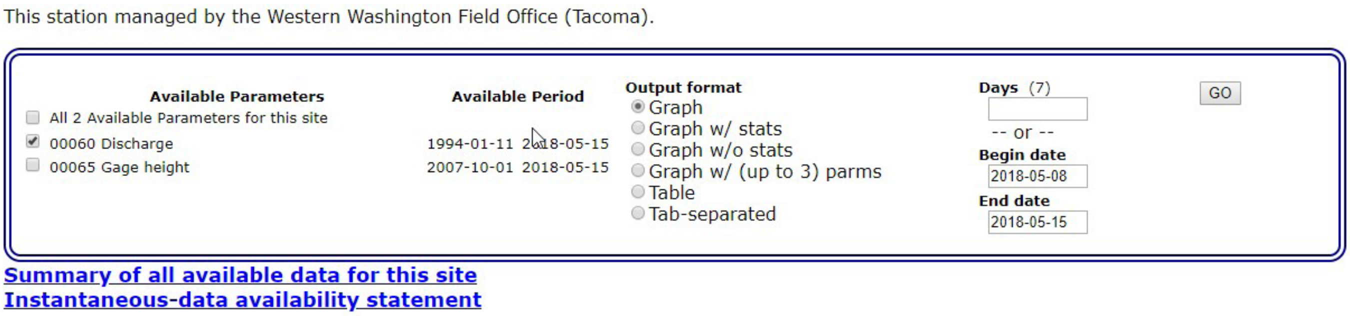
- Necessary Applications/Software
  - i-Tree Hydro V6
  - Microsoft Excel
  - Notepad++
- Obtain custom streamflow data with the following variables
  - Hourly stream flow (cubic feet per second or cubic meters per hour)
  - Time and Date of each reading (a stream gage that collects on the hour is optimal)
- Convert the hourly streamflow data from cubic feet per second to meters per hour
  - "Processed discharge data (m/h) is the specific discharge of your project area at each timestep. This can be calculated by dividing your raw volumetric discharge (measured by a stream gage) by the area of the corresponding drainage basin. For example: USGS stream gage discharge data is often reported in ft3 /s; to process a raw streamflow record of 200 ft3 /s, multiply by 0.028316846592 m3 /ft3 then multiply by 3600 s/hr to get the raw streamflow record of 20,388.1 m3 /hr (note the change in units), then divide that by the watershed area in meters (e.g., 161,44,000 m2) to get the processed discharge value of 1.26289E-4 for that record's timestep." (i-Tree Hydro V6 Manual, 51)
    - Each value should have 5 decimal places (e.g., 1.26289E-4)
- Save the calculated custom stream flow data (only this variable, nothing else) as a Text (tab delimited) file (Save as ProjectArea_CalcCustomFlowData)
- Open "ProjectArea_CalcCustomFlowData" text file in notepad++
  - Insert a zero into each value as shown; 1.26289E-04 ->1.26289E-004
    - This can be done using the column selector tool (ctrl+alt+shift)
- Save the file
- Download a raw stream gage data file from USGS: *https://waterwatch.usgs.gov/index.php?id=ww_current*
  - Data must fit the timeframe of the custom stream gage data that you have already collected
  - Raw stream gage data must be from the same time zone as custom data
- Input the raw stream gage data into i-Tree Hydro V6
  - After you complete the "Project Information" and "Land Cover Inputs" steps; click "File" -> "Save Weather and Gage Data" -> "Save Processed Stream Gage Data"
    - **Make sure the timeframe under "Project Information" matches the timeframe of the custom stream gage data
- Open the processed stream gage file in Notepad++
- Open "ProjectArea_CalcCustomFlowData" in Notepad++
- Press Control F, open the Find tab, type ",0:00:00," Find. Replace with ",0:00:00,*" do this for 0:00:00-9:00:00. This will even out all of the columns for copying and pasting.
- Select and copy all of the calculated custom stream flow data in Notepad++
- Select all of the stream flow data (not the time steps, only the flow measurements) of the processed stream gage file in Notepad++
- RIGHT CLICK +Paste the calculated custom stream flow data to the selected processed stream flow measurements
- Save the new text file in Notepad++ as a .dat file under a new, descriptive name
- When the custom stream gage data has been input into a processed stream gage file, open Hydro and when prompted to input Calibration data, select "Select processed data file" and select the appropriate .dat file containing your newly made custom stream flow data.

Time Frame Change Procedure

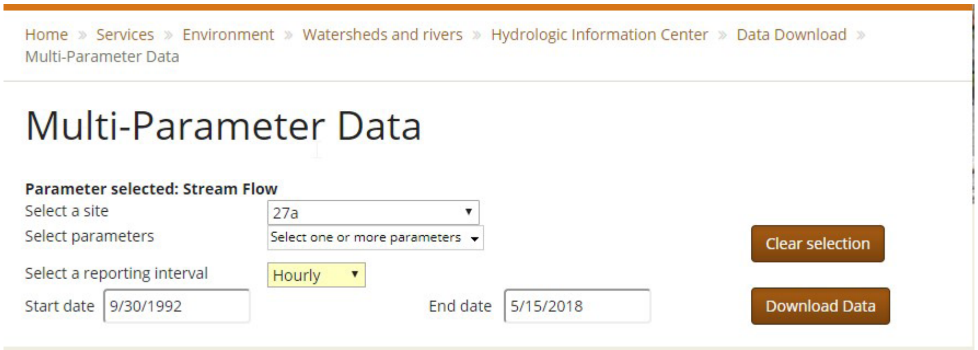
If the timeframe of the project changes for any of the pilot communities follow these steps;

1. Collect weather data within the new timeframe from the appropriate station listed below at the provided link: https://gis.ncdc.noaa.gov/maps/ncei/cdo/hourly
   a. Kent: SeaTac International Airport (727930-24233)
   b. Kirkland: SeaTac International Airport (727930-24233)
   c. Tacoma: SeaTac International Airport (727930-24233)
   d. Snohomish: Snohomish Co (Paine FD) AP (727937-24222)
   e. The collected data files from this site are RAW and can be input into i-Tree Hydro as is.

2. Collect stream gage data within the new timeframe
   a. NOTE: There are different procedures for collecting stream gage data depending on which watershed/drainage basin is being modelled.



   b. KENT -> Mill Creek Drainage Basin
      i. The stream gage data associated with this watershed can be found here; *https://waterdata.usgs.gov/wa/nwis/uv/?site_no=12113347&PARAmeter_cd=00060,00065*
      ii. Only "Discharge" needs to be selected
      iii. Output format should be "Tab-separated"
         • Copy and paste this data into Notepad++ to save it as a text file
      iv. Once saved as a text file, this data can be input directly into i-Tree Hydro as a Raw USGS data file
   c. KIRKLAND ->Juanita Creek Drainage Basin
      i. The stream gage data associated with this watershed can be found here; *https://green2.kingcounty.gov/hydrology/DataDownload.aspx?G_ID=34&Parameter=Stream%20Flow*



      ii. Be sure to select "Hourly" under "Select a reporting interval"
      iii. Open the downloaded data in excel then follow the steps found in the "Creating Custom Stream Gage Data" document
   d. TACOMA->Foss Waterway
      • No Stream Gage data available
   e. SNOHOMISH->Swifty Creek Drainage Basin OR Blackmans Lake Drainage Basin
      • No Stream Gage data available

3. All parameters, including the DEMs, will not change with the timeframe.

Appendix N: i-Tree Hydro Fact Sheet

i-Tree Hydro in 2018

State-of-the-Art, Peer-Reviewed, Public-Domain

Process-Based Hydrological Model

Assessing How Changes in **Tree and Impervious Cover** Affect **Water Quantity & Quality**

Based on *Cutting-Edge U.S. Forest Service Science*

What Hydro Can Inform Us About

- How management practices & urbanization affect water resources.
- How land cover changes impact water quality & quantity in watersheds, municipalities, and user-defined places nation-wide.
- Hourly & total results available in tabular & graphical form, including an automatically-generated Executive Summary report.

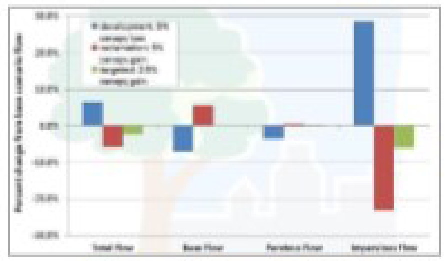


Figure 1: i-Tree Hydro simulation of alternative management scenarios as compared to initial conditions

How It Works

- **Data needs:** location; topography; weather; optional stream flow for calibration; land cover for initial case & optional alternatives.
- **Users inputs:** location, simulation period, and land cover information derived from i-Tree Canopy, NLCD data, and/or local knowledge.
- **Pre-loaded & increasing automated data inputs** with vast coverage in the U.S. for topography, weather data, and hydrological parameters.

What's New in 2018: i-Tree Hydro version 6.0

- **Increased functionality & accessibility**, e.g. 4 scenarios can be paired with different parameter sets & canopy properties in a single project.
- **Easier-to-edit weather & streamflow file formats** enable users to customize their weather and streamflow inputs.
- **Detailed output graphs** for specific hydrologic processes including interception, infiltration, evapotranspiration, and more.
- **Customizable pollutant coefficient** (Event Mean Concentration) values can be set, instead of using the national U.S. average.

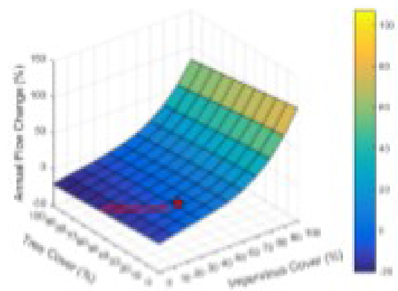


Figure 2: i-Tree Hydro simulated effects of incremental changes to Tree Cover and Impervious Cover in 161km^2 Rock Creek watershed near Washington, DC.

How Can Hydro Help

- **By supporting decision-making** to **reduce stormwater damage** and improve urban forests, environmental quality, and human health.

What's Planned for the Future – Projects, Partnerships, & Research

- **Green infrastructure**: tree pits; rain barrels; green roofs; rain gardens; and pervious pavement – each uniquely parameterized.
- **Design Rain tool** for simulating storms using regional NOAA data and Intensity-Duration-Frequency (IDF) curves for the U.S.
- **Improved water quality modeling**, including tool to identify pollution build-up & buffering hotspots, and database of pollutant coefficients specific to project location and effects of current land cover.
- **Localized soil & hydrology parameters** informed by the NRCS SSURGO database for users all over the U.S.
- **Spatially-distribution of model**, providing advanced users with localized land use decision-making support.

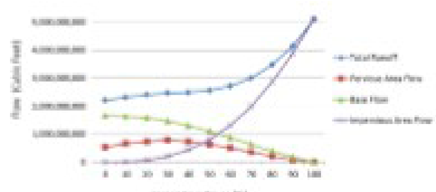


Figure 3: i-Tree Hydro simulation scaling Impervious Cover, with constant Tree Cover, in Rock Creek watershed near Washington, DC.

Puget Sound Urban Tree Canopy and Stormwater Management

A Report Comparing USDA Forest Service i-Tree Hydro and
Washington State Department of Ecology Western Washington Hydrology Model

www.kingcd.org