Western Washington Stormwater Effectiveness Studies

Detailed Study Design Proposal & Quality Assurance Project Plan (QAPP)

The effectiveness of trees in mitigating stormwater runoff in Western Washington

Prepared For:

Stormwater Action Monitoring
Washington State, Department of Ecology
300 Desmond Dr. SE (FedEx)
P.O. Box 47600 (USPS)
Olympia, Washington, 98504-7600
(360) 407-6158

Prepared By:

Washington State University
Puyallup Research and Extension Center
2606 W Pioneer Ave
Puyallup, Washington, 98371
(253) 445-4500

August 2019

Publication Information

Proposal will be stored and accessible to the public at www.ecology.wa.gov/SAM

QAPP Authors and Contact Information

Anand Jayakaran[1], Ph.D., P.E. and Benjamin Leonard[2]
Washington State University
Puyallup Research and Extension Center
[1]Associate Professor and [2]PhD Student
2606 W Pioneer Ave, Puyallup, Washington, 98371
anand.jayakaran@wsu.edu, (253) 445-4523

Project Manager and Contact Information

Linden Lampman
Urban & Community Forestry Program Manager
Washington State Department of Natural Resources
linden.lampman@dnr.wa.gov, 360-902-1703

Signature Page

Approved by:

____ Date ____________
Anand Jayakaran PhD PE, Primary Author, Washington State University

____ Date ____________
Linden Lampman, Lead Entity, Department of Natural Resources – Urban Forestry

____ Date ____________
Abby Barnes, Partner Entity, Department of Natural Resources - Aquatics

____ Date ____________
Keunyea Song, Ecology SAM Project manager

____ Date ____________
Brandi Lubliner, Ecology WQP QA Coordinator

Signatures are not available on the Internet version.

1.0 Table of Contents

List of Figures

2.0 Executive Summary

Quantifying the amount of water native trees in the Pacific Northwest intercept and transpire will enable us to develop a tree water budget. Typical developmental practices in the region involve clear cutting forested tracts of land, preparing the development site by scraping off the surface soil layer and contouring the area, then planting developed sites with saplings. Greater knowledge of how much rainfall (equivalent) is emitted through leaves of mature trees can be used to incentivize developers and planners to retain larger mature trees during site preparation, mitigating the amount of runoff generated from those site. This study aims to quantify a mature individual tree's water budgets and in-particular the amount of rainfall that does not manifest as runoff. The final goal of this study is to measure how interception and transpiration associated with 65 trees belonging to 4 native tree species, vary with climatic and soil conditions over a two-year study therefore quantifying stormwater mitigation impacts by mature trees. Two evergreen and two deciduous species were chosen with trees located at two sites in the Olympia-Tumwater area of western Washington, both with typical weather patterns associated with the Pacific Northwest (PNW) of the United States. Specific project objectives are: A) quantify annual transpiration rates for two mature species of evergreen trees, and two mature species of deciduous trees native to the PNW; and, B) quantify annual canopy interception rates for two species of evergreen trees, and two species of deciduous trees native to the PNW in order to quantify stormwater mitigation impacts by mature trees. Anticipated study outcomes are tree water budgets for four common species of PNW trees divided into four compartments – transpiration, interception, runoff, and stem flow.

3.0 Introduction and Background

3.1 Introduction

The goal of this project is to accurately measure and develop defensible median values for runoff reduction of retained trees in the PNW by direct measurement of interception and transpiration. The work is relevant for stormwater management in the entire western Cascades region. The study will be based on instrumenting a total of 64 trees in two locations in Olympia, WA - 32 individual trees at the Webster Nursery Farm and 32 at the Evergreen State College campus (Figures 1-4). These 64 trees will include two evergreen species (Douglas Fir and Western Redcedar) and two deciduous species (Bigleaf Maple and Red Alder). Each tree will be instrumented with sensors that measure interception, stemflow, transpiration, and localized soil moisture (Figure 5). When combined, data from these sensors will provide a complete view of how much rainfall is managed by an individual tree, or in simple terms, the rainfall that does NOT end up as runoff. Data will be collected over 24 months to include seasonal variability that is typical of the region.

Specific project objectives are: A) quantify annual transpiration rates for two species of evergreen trees, and two species of deciduous trees native to the PNW; B) quantify annual canopy interception rates for two species of evergreen trees, and two species of deciduous trees native to the PNW, and 3) quantify stormwater mitigation benefit by mature individual trees. While it is well known the runoff mitigation potential of forest or large tree stands, there have been very few reports of the use of species-specific estimates for the hydrologic water-budget benefits for common trees in the Pacific Northwest. There is therefore still the need to quantify stormwater mitigation values associated with individual trees.

WSU followed Ecology's Guidelines for Preparing Quality Assurance Project Plans for Environmental Studies, July 2004 (Ecology Publication No. 04-03-030) in developing this QAPP.

3.2 Problem Description

Managing stormwater is a serious challenge in urban areas, particularly for rapidly growing urban communities in Western Washington. Urban trees in parks, natural areas, street-side, and on private lands combined with other green stormwater control elements provide excellent opportunities to reduce stormwater runoff into the Puget Sound.

The importance of quantifying annual canopy interception and transpiration is critical since these processes can delay peak runoff timing and reduce runoff quantity. Unlike deciduous trees, evergreens provide important canopy buffering capacity during the winter months when storms bring large amounts of precipitation in the PNW. Tree crown size is important because large trees provide the greatest capacity for interception. Different species have different forms and canopies, and additional features that influence interception and transpiration (e.g., water-shedding or water-focusing canopies and bark). Therefore, separate species need to be investigated to properly quantify how well each tree species manages incoming precipitation.

3.3 Results of Prior Studies

Results from previous studies established the current system of credits as outlined in "Tree Retention and Tree Planting" BMP in Ecology's SWMMWW (Washington State Department of Ecology, 2014, BMP T5.16). These credits are based on an averaged transpiration rate of 10% of annual precipitation derived from two studies. The first study by Heal et al. (2004) estimated transpiration in Sitka spruce in Scotland, UK, to be about 12% of annual precipitation in turn derived from three lysimeter studies conducted in the 1950's (Law, 1957; Calder et al., 1982). Unsworth et al. (2004) measured total vapor flux above a forest canopy in Wind River, WA between 1998 and 1999 and estimated that transpiration ranged between 66% and 68% of the total water vapor flux above the forest canopy.

Recently, WSU calculated transpiration rate as a function of annual precipitation or impervious surface equivalent using more recent study results measured in Minnesota (Peters et al., 2010). This study measured transpiration rates more directly through sap flux in evergreen and deciduous trees over two growing seasons. The result shows that transpiration (per canopy area) could capture as much as 53% of annual rainfall and 23% for evergreen trees deciduous trees. This effect is equivalent to reducing over 160 ft^2 of impervious surface area.

These are however only estimated values based on data derived from other parts of the country and represent only mathematical efforts and gross approximations of tree canopy area. There is therefore a critical need to measure transpiration directly through sap flux here in Western WA given our unique tree species and distinctive rainfall patterns.

Table 3.3.1: Direct transpiration measurements made by Peters et al. (2010) in Minnesota. Rows highlighted in green are values reported in the study. Rows highlighted in blue were derived by WSU.

Peters et al., 2010 – Minnesota	**Units**	**Evergreen**	**Deciduous**
Transpiration (per unit canopy area)	kg $H_2O/m^2/yr$	307	153
Ave. Canopy Area	m^2	31.1	73.6
Annual Transpiration (whole tree)	kg H_2O/yr	9,548	11,261
Annual Transpiration (whole tree)	ft^3 H_2O/yr	337.1	397.6
Annual Rainfall (average 2007 & 2008)	in/yr	22.8	22.8
Impervious Area Equivalent (assuming 95% runoff)	ft^2	168.5	198.7
Transpiration (per unit canopy area)	In	12.1	6.0
Transpiration as a fraction of rainfall (per unit canopy area)	%	53.0	26.4

4.0 Project Overview

The purpose of this study is to determine the ability of mature native evergreen and deciduous trees to limit the amount of rainfall that is transformed into stormwater runoff. The project aims to quantify how much rainfall trees in the PNW intercept and transpire. These two processes are essential to how trees can mitigate the amount of rainfall that manifests as runoff. Two types of native deciduous and two types of native evergreen trees will be instrumented to capture this information. In total, 64 trees have been identified for instrumentation at two locations in the Olympia, WA area.

This study will offer valuable insight on how to hydrologically value existing trees. We believe that direct measurement of interception and transpiration of individual trees will give us a much-improved picture of how native trees in Western Washington can limit stormwater runoff into Puget Sound. Lastly, directly measuring interception and transpiration from deciduous and evergreen trees will allow for the direct comparison of which species are more effective with regard to stormwater management in the region.

4.1 Study Goal

The study goal is to evaluate the potential of existing native evergreen and deciduous trees to manage stormwater in Western Washington. The results of this study may be used by stormwater managers and landscape developers to apportion greater value to existing trees and may bolster the argument that native trees growing in a lot scheduled for development must be conserved to the greatest extent possible.

4.2 Study Description and Objectives:

The purpose of this proposed work is to develop a rigorously derived hydrologic budget for common evergreen and deciduous trees, based on soil, topographic, and climatic conditions seen in the Pacific Northwest. Douglas Fir, Western Redcedar evergreen trees and Red Alder and Big Leaf Maple deciduous trees were selected due to the conventional roles they have to the PNW region. These trees are frequently found in residential neighborhoods and on vacant sites within community growth management areas.

Specific project objectives are:

1. Quantify annual transpiration rates for two species of evergreen trees (Douglas Fir, Western Redcedar), and two species of deciduous trees (Red Alder, Big Leaf Maple) native to the PNW.
2. Quantify annual canopy interception and stem flow rates for the same trees.
3. Quantify associated environmental conditions such as microclimate and soil moisture to help explain interception, stemflow, and transpiration information.

4.3 Study Location

The two study locations in the south Puget Sound region near Olympia, WA are:

1. The Evergreen State College (TESC) located at approximately 47° 4'14"N by 122°59'7"W.
2. Webster Forest Nursery (WFN) located at approximately 46°56'53"N by 122°57'54"W.

The sites are 8.7 miles apart from each other (Euclidean distance), or approximately 15 minutes (11.9 miles) by vehicle. Both locations offer power and security, which were primary considerations for this work. Both sites are considered forested, but better described as managed forest stands interspersed with agricultural practices, buildings, and a parking lot. Sites represent locations that would typically face development in a rural-urban interface, the interface that is seeing the greatest land use changes in western Washington.

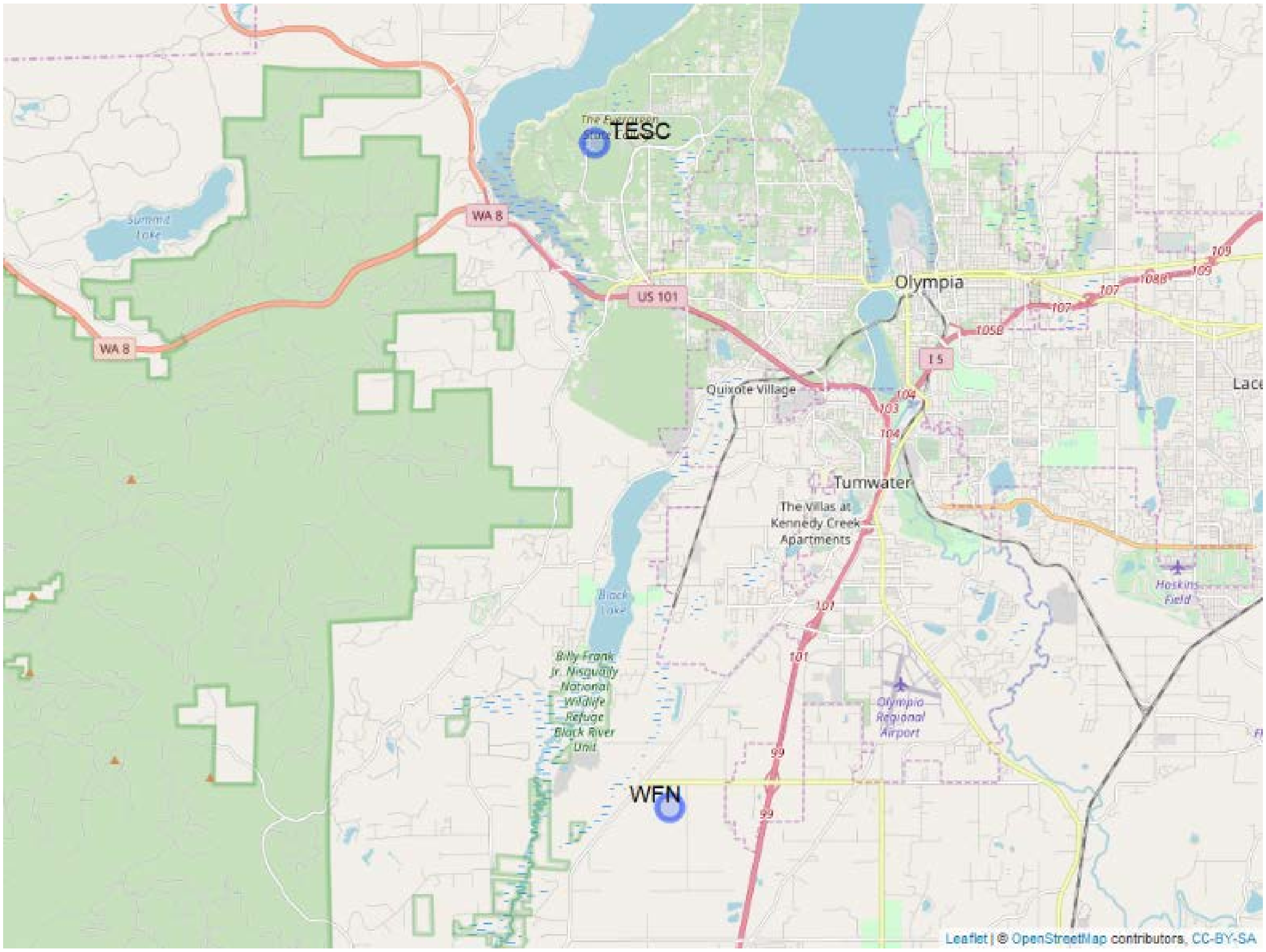


Figure 1: Map of study locations showing The Evergreen State College (TESC) and Webster Nursery Farm (WNF) around the Olympia-Tumwater area of western Washington

4.4 Data Needed to Meet Objectives

Data needed to meet the study objectives are:

1. Climatic data at both locations using research-grade weather stations located in open canopy spaces that will measure climatic data at 15-minute intervals. Data will be collected using a datalogger (RX3000, Onset Inc.) that will transmit the data via cellular modem to a central database that will be housed at WSU – Puyallup
2. Throughfall rates: Throughfall will be measured by installing two 4-inch slotted pipes under every study tree.
3. Canopy Interception: Canopy interception will be estimated by total rainfall from total rainfall.

   Stemflow. Totalized storm event stemflow measurements for 16 evergreen and 16 deciduous trees at two sites.
4. Sap flux: Sap flux measurements will be carried for 32 evergreen trees and 32 deciduous trees located at two study sites

5. Soil moisture. 5 soils sensors at each site in order to capture an average soil moisture conditions at each station.

4.5 Tasks Required to Conduct Study

- Task 1 – Project Administration

  DNR will facilitate project administration by ensuring that project deadlines are met, completing purchasing needs, and ensuring timely communications with SAM.

- Task 2 – Quality Assurance and Project Protocol (QAPP) development

  Prepare a Quality Assurance Protocol Plan (QAPP) for approval by Dept. of Ecology.

- Task 3 – Instrument purchase

  DNR will purchase and own equipment and supplies necessary to complete 64 individual tree monitoring.

- Task 4 – Instrument installation and test

  Sensors will be installed at both site locations with effort provided by all parties involved, including personnel from WSU, WA DNR, Webster Nursery Farm, and The Evergreen State College (TESC).

- Task 5 – Instrument Maintenance and Data Downloads

  All sensors and datalogging systems will be checked on a weekly basis, and data downloaded on a bi-weekly basis.

- Task 6 – Data Analysis, Quality Assurance and Quality Control (QA/QC) check, and Data delivered to ECY

  Data will be analyzed using open source statistical and graphing software.

- Task 7 – Final Report

- Task 8 – Outreach/communication

4.6 Potential Constraints

Vandalism of instrumentation at TESC is a potential constraint, as is the potential for sensor failure at both sites. Adequate rainfall events are needed to quantify interception, and transpiration. The lack of a wide range of rainfall totals and intensities could lead to a lack of storm variability, a key ingredient for a statistically robust dataset. Climatic conditions, availability of staff, equipment malfunction, and study funding sources are all possible conditions that may impact the project schedule, budget, or scope. If potential constraints do arise, they will be reflected in the project audits and reports (see Section 12.0 Audits) and any necessary corrective actions will be taken. Possible corrective actions are summarized in Section 10.0 Quality Control.

5.0 Organization and Schedule

5.1 Key Project Team Members: Roles and Responsibilities

Key Team Members	Role	Responsibility
Linden Lampman, WDNR 360-902-1703, Linden.Lampman@dnr.wa.gov	Project Manager	Project Administration
Ani Jayakaran, WSU 253-445-4523, anand.jayakaran@wsu.edu	Project Technical Lead	Oversight of research, documentation, and data analyses including writing of proposal and QAPP
Jamie Duberstein Clemson University jamieduberstein@gmail.com	Sap Flow Study Lead	Oversight of transpiration study
Dylan Fischer, TESC fischerd@evergreen.edu	Project Technical co-lead	Oversight of research at TESC
Abby Barnes, WDNR Abby.Barnes@dnr.wa.gov	Project coordination	Coordinates TAC review, project team, meetings, equipment purchases. Assists Project manager as needed.
Brandi Lubliner SAM Coordinator, Ecology brandi.lubliner@ecy.wa.gov	Ecology QA Review	Reviews the draft QAPP and provides Ecology QA approval of the QAPP. Interim TAC member.
Benjamin Leonard, WSU Benjamin.leonard@wsu.edu	QAPP Co-author, data analyst	Graduate Student, data collection and analyses
Keunyea Song, Ecology keunyea.song@ecy.wa.gov	Ecology Project Manager	Reviews the project scope and budget, tracks progress, reviews the draft QAPP, and approves the final QAPP. approves deliverables and tracks progress on SAM project website

Table 5.2 TAC - Effectiveness of Trees in Mitigating Stormwater Runoff Members

Name	Title	Roles
Kevin Hansen, LHg, LG, LEED AP	County Hydrogeologist Thurston County Water Resources	Review QAPP Available for study review Review Final Report
Mark Maurer, PE, PLA	Thurston County Water Resources	Review QAPP Available for study review Review Final Report
Brandy Reed	Director of Strategic Partnerships King Conservation District	Review QAPP Available for study review Review Final Report
Joe Roush	Environmental Services Supervisor Waste Resources, Public Works City of Olympia	Review QAPP Available for study review Review Final Report
Juli Hartwig	Roadside and Site Development Manager Washington State Department of Transportation	Review QAPP Available for study review Review Final Report
Foroozan Labib	Water Quality Program Washington State Department of Ecology	Review QAPP Review Final Report

5.2 Project Schedule

Task 1. Project Administration	D 1.1. Quarterly Report 1	12/31/2018
	D 1.2. Quarterly Report 2	3/31/2019
	D 1.3. Quarterly Report 3	6/30/2019
	D 1.4. Quarterly Report 4	9/30/2019
	D 1.5. Quarterly Report 5	12/31/2019
	D 1.6. Quarterly Report 6	3/31/2020
	D 1.7. Quarterly Report 7	6/30/2020
	D 1.8. Quarterly Report 8	9/30/2020
	D 1.9. Quarterly Report 9	12/31/2020
	D 1.10. Quarterly Report 10	3/31/2021
	D 1.11. Quarterly Report 11	6/30/2021
Task 2. QAPP development	D 2.1. Draft QAPP	7/8/2019
	D 2.2. Final approved QAPP	9/1/2018
Task 3. Instrument purchase	D 3.1. List of equipment/supplies ordered and procured by DNR in support of this study	8/1/2019
Task 4. Instrument installation and test	D 4.1 Email confirming successful installation of instruments with photos	9/1/2019
	D 4.2. Email confirming successful readings of instruments	10/15/2019

Task 5. Instrument Maintenance and data downloads	D 5.Quarterly status update in the quarterly reports	
Task 6. Data analysis, QA and QC check, Data delivered to Ecology	D 6.1 Copy of data in excel format	8/1/2021
Task 7. Final report	D 7.1 Draft report to Ecology for comment	10/1/2021
	D 7.2. Final report	11/31/2021
Task 8. outreach/communication	D 8.1 Copy of presentation with stormwater managers and SWG	11/15/2021
	D 8.2. Electronic copy of Fact sheet draft	11/30/2021

6.0 Quality Objectives

The primary data quality objectives for this project are to ensure that the measured data adequately represent sap flux, throughfall, stemflow, soil moisture, and climatic conditions in and around the 64 instrumented trees. Data will be generated according to procedures outlined in Section 8.0. Data will be deemed acceptable in terms of data quality as outlined this section and only those data that meet and exceed our data quality requirements will be used for additional analyses.

6.1 Bias

Bias is the systematic error that results in sample values that are consistently distorted in one direction from the "true" or known value (EPA, 2006; Erickson, 2013). Bias can result from improper data collection, poorly calibrated analytical or sampling equipment, or limitations or errors in analytical methods and techniques (Ecology, 2011).

Table 6.1.1: Summary of the Data Quality Indicator (DQI) "Bias".

Sensor	**Approaches for Addressing Bias**
Soil moisture	Soil moisture sensors are factory calibrated but will be analyzed over the course of the study for sensor drift. Sensor drift over 15% during comparable dry conditions will signal sensor drift and will require a replacement or re-installment of sensor.
Weather station	Weather station sensors are factory calibrated but will be analyzed over the course of the study for sensor drift. Sensor drift over 15% during comparable climatic conditions will signal sensor drift and will require a replacement or re-installment of sensor.
Sap flux sensors	Sap flux sensors are factory calibrated but will be analyzed over the course of the study for sensor drift. Sensor drift over 15% during comparable climatic conditions will signal sensor drift and will require a replacement or re-installment of sensor.
Through fall gage	Interception gages will be calibrated annually using a rain-gage calibration kit. Minimum acceptable limits for calibration checks is 5%.
Stem flow collector	Collection unit will always be dried thoroughly after measurement, and only one type of graduated beaker will be used to measure collected stemflow.

6.2 Precision

Precision is the measure of agreement among repeated measurements of the same property taken under identical or substantially similar conditions (EPA, 2002 and 2006; Erickson, 2013). Data is considered precise when the measured values are consistently the same and imprecise when the measured values are consistently different (Erickson, 2013). Random error is a common cause of imprecise data and is always present because of normal variability in the many factors that affect measurement results. For example, variability in sampling or data collection procedures and/or variations of the actual concentrations in the media being sampled (Ecology, 2011).

Table 6.2.1: Summary of the Data Quality Indicators (DQI) “Precision” and Measurement Performance Criteria (MPC) for quantifying Precision

Sensor	Approaches for Addressing Precision
Soil moisture	No single soil moisture sensor measures the same volume of soil as another sensor, so precision will not be assessed.
Weather station	No single weather station sensor measures the same microclimate as another sensor, so precision will not be assessed.
Sap flux sensors	No single sap flux sensor measures sap flux in the same section of sap wood as another sensor, so precision will not be assessed.
Through fall gage	No single throughfall sensor measures throughfall under the same section of tree canopy as another sensor, so precision will not be assessed.
Stem flow collector	There will only be one stem flow collector at each studied tree, therefore the precision of stemflow measurement cannot be addressed.

6.3 Representativeness

Representativeness is a qualitative term that expresses the degree to which the data accurately and precisely represents the conditions being evaluated (EPA, 2002). Common variables considered when determining the degree of representativeness include the selected sampling locations, sampling frequency and duration, and sampling methods (Ecology, 2011). While all environmental sensors used in this study will be deployed to measure data on a continuous basis, all sensors are prone to failure and erroneous measurements. For this study we aim to collect data that is representative of the range of climatic events that occur over 24-months in the region. At a minimum, we seek to quantify data from ALL sensors for at least 12 storm events that are above 0.2 inches in 24 hours, and 12 inter-storm (dry) events. With these data, we expect to capture how four species of trees manage rainfall during and between precipitation events.

Table 6.3.1: Summary of the Data Quality Indicators (DQI) “Representativeness”

Sensor	Approaches for Addressing Representativeness
Soil moisture	Data will be measured at 15-minute intervals over the entire 24-month period of the study. Five soil moisture sensors will be placed at equidistant positions at each of the four tree plots. The five plots will represent average soil moisture conditions at a plot of trees. 12 storm events, and 12 inter-storm (dry) events will be considered representative.
Weather station	Data will be recorded at 15-minute intervals over the entire 24-month period of the study. Two weather stations, one at each of the study locations will be installed in an open canopy area to measure climatic conditions at that location. 12 storm events, and 12 inter-storm (dry) events will be considered representative.
Sap flux sensors	Data will be measured at 15-minute intervals over the entire 24-month period of the study. Sap flux sensors will be installed at each study tree with the objective of measuring sap flux at least three depths in the sapwood, thereby enabling the development of an attenuation function that allows for the estimation of transpiration within the entire sap wood cross section for that particular tree. A total of 32 evergreen and 32 deciduous trees will be instrumented, distributed across 4 native tree species. 12 storm events, and 12 inter-storm (dry) events will be considered representative.

Through fall gage	Data will be recorded at 15-minute intervals over the entire 24-month period of the study. A single throughfall gage will be installed in a manner that it accepts throughfall from two slotted collector pipes installed below the tree canopy. The two collector pipes will be oriented in a manner that ensures that the slots are exposed to the most representative regions of that tree's canopy. Canopy structure and orientation are not accounted for when arranging interceptor pipes primary because there are overlapping canopies around the trees, therefore best on our best judgement, areas of canopy that are most representative of the tree being studied will be chosen for locating interceptor pipes. A total of 24 evergreen and 24 deciduous trees, will be instrumented, equally partitioned across 4 native tree species. A smaller number of trees will be instrumented for throughfall compared to sap flux due to the greater accuracy of throughfall instrumentation. 12 storm events, and 12 inter-storm (dry) events will be considered representative.
Stem flow collector	Stem flow will be collected at a tree by creating a collar around the study tree and diverting all water flowing down the tree trunk into a container. The stem flow collar will be installed in a manner that sap flux instrumentation also installed on the tree does not interfere with stem flow collection. If collecting stem flow from a tree is impeded by sap flux instrumentation, an alternative tree of similar species, age, and structure, will be chosen. A total of 12 evergreen and 12 deciduous trees will be instrumented for stem flow. The smaller number of trees is due to low stemflow volumes expected and due to the high accuracy since stemflow is measured directly. 12 storm events, and 12 inter-storm (dry) events will be considered representative.

6.4 Completeness

Completeness is the amount of valid data needed to be obtained during the study to meet the project objectives (Lombard and Kirchmer, 2004).

Table 6.4.1: Summary of the Data Quality Indicator (DQI) "Completeness"

Sensor	**Approaches for Addressing Completeness**
Soil moisture	Data will be recorded at 15-minute intervals over the entire 24-month period of the study with the aim of capturing at least 12 storm events and 12 inter-storm (dry) periods. Five soil moisture sensors will be placed at equidistant positions at each of the four tree plots. The five plots will represent average soil moisture conditions at a plot of trees over two years. Obtaining 95% of continuous data that pass QAQC requirements over the 12 storm and 12 inter-storm events will be considered acceptable to meet the Completeness DQI.
Weather station	Data will be recorded at 15-minute intervals over the entire 24-month period of the study with the aim of capturing at least 12 storm events and 12 inter-storm (dry) periods. Two weather stations, one at each of the study locations will be installed in an open canopy area to measure climatic conditions at that location. Obtaining 95% of continuous data that pass QAQC requirements over the 12 storm and 12 inter-storm events will be considered acceptable to meet the Completeness DQI.
Sap flux sensors	Data will be recorded at 15-minute intervals over the entire 24-month period of the study with the aim of capturing at least 12 storm events and 12 inter-storm (dry) periods. Sap flux sensors will be installed at each study tree with the objective of measuring sap flux at least three depth in the sapwood, thereby enabling the development of an attenuation function that allows for the estimation of

	transpiration within the entire sap wood cross section for that tree. Obtaining 95% of continuous data that pass QAQC requirements over the 12 storm and 12 inter-storm events will be considered acceptable to meet the Completeness DQI.
Through fall gage	Data will be recorded at 15-minute intervals over the entire 24-month period of the study with the aim of capturing at least 12 storm events and 12 inter-storm (dry) periods. A single throughfall gage will be installed in a manner that it accepts throughfall from two slotted collector pipes installed below the tree canopy. The two collector pipes will be oriented in a manner that ensures that the slots are exposed to the most representative regions of that tree's canopy. Obtaining 95% of continuous data that pass QAQC requirements over the 12 storm and 12 inter-storm events will be considered acceptable to meet the Completeness DQI.
Stem flow collector	Stem flow will be collected at a tree by creating a collar around the study tree and diverting all water flowing down the tree trunk into a container. The stem flow collar will be installed in a manner that sap flux instrumentation also installed on the tree does not interfere with stem flow collection. If collecting stem flow from a tree is impeded by sap flux instrumentation, an alternative tree of similar species, age, and structure, will be chosen.

6.5 Comparability

Comparability is a qualitative term that expresses the measure of confidence that one dataset can be compared to another and can be combined or contrasted for the decision(s) to be made. Data are comparable if sample collection techniques, measurement procedures, analytical methods, and reporting are equivalent for samples within a sample set and meet acceptance criteria between sample sets.

Table 6.5.1: Summary of the Data Quality Indicator (DQI) "Comparability"

Sensor	**Approaches for Addressing Comparability**
Soil moisture	There are no numeric measurement quality objectives for this data quality indicator; however, standard installment, standard sampling frequencies, units of measurement, and reporting conventions will be applied in this study to meet the goal of data comparability.
Weather station	There are no numeric measurement quality objectives for this data quality indicator; however, standard installment, standard sampling frequencies, units of measurement, and reporting conventions will be applied in this study to meet the goal of data comparability.
Sap flux sensors	There are no numeric measurement quality objectives for this data quality indicator; however, standard installment, standard sampling frequencies, units of measurement, and reporting conventions will be applied in this study to meet the goal of data comparability.
Through fall gage	There are no numeric measurement quality objectives for this data quality indicator; however, standard installment, standard sampling frequencies, units of measurement, and reporting conventions will be applied in this study to meet the goal of data comparability.
Stem flow collector	There are no numeric measurement quality objectives for this data quality indicator; however, standard installment, standard sampling frequencies, units of measurement, and reporting conventions will be applied in this study to meet the goal of data comparability.

6.6 Sensitivity

Sensitivity denotes the rate at which the analytical response (e.g., absorbance, volume, meter reading) varies with the concentration of the parameter being determined. In a specialized sense, it has the same meaning as the detection limit (EPA, 2002). The capability of a method or instrument to discriminate between measurement responses representing different levels of the variable of interest.

Table 6.6.1: Summary of the Data Quality Indicator (DQI) "Sensitivity"

Sensor	**Approaches for Addressing Sensitivity**
Soil moisture	10HS soil moisture sensors (±3.1%)
Weather station	Climatic sensors a. Temperature (± 0.21°C) b. Humidity (2.5 % RH) c. Photosynthetic Active Radiation (PAR) (±5 µmol/m^2/sec) d. Solar Radiation (±10 W/m^2) e. Barometric pressure (±3 mbar) f. Wind speed and direction (±1.1 m/s & ±1.4 degrees)
Sap flux sensors	Sap flux Thermal Dissipation Probe (TDP) sensors (0.1 Ω)
Through fall gage	Hobo Rain Gages (±4%)
Stem flow collector	± 50 ml

7.0 Experimental Design

7.1 Study Design Overview

The study involves instrumenting 64 trees at two locations in the Olympia area to determine transpiration rates of four species of large (>12” DBH) native trees, comprising two evergreen and two deciduous tree species. Of these 64 trees, all will be instrumented to measure sap flux and canopy interception, and 24 instrumented for stemflow.

The two locations are TESC and the Webster Nursery Farm. At each of the two locations, a weather station will be installed to measure microclimatic variability. At each location, four plots of trees have been targeted for instrumentation giving a total of 8 plots between the two sites. Amongst these 8 plots, 32 deciduous and 32 evergreen trees have been identified for further instrumentation and comprise 15 Red Alder, 17 Bigleaf Maple, 22 Douglas Fir, and 11 Western Redcedar. Each of the 8 tree plots will be monitored for variation in soil moisture over the period of study. The work will be carried out over two years, starting in August 2019 and ending in August 2021.

7.2 Sampling-Site(s) Selection Process

The Evergreen State College (TESC) and Webster Forest Nursery (WFN) were selected as sampling-sites for this study. The locations of these sites are presented in Figure 1.

In total, 7 sampling-sites in the south Puget Sound region were evaluated and 2 were selected. Criteria for selection of trees included tree health, abundance and species diversity. In addition, site accessibility, power availability, and security were important considerations. The following sites did not meet criteria: Tacoma landfill, Tacoma Narrows Bridge, Mason Gulch, and WSU Puyallup Research and Extension Center. Only TESC and WFN were able to meet the criteria of site accessibility, power availability, and security while also offering at least 8 healthy replicates of four identified native tree species.

During the site selection process 7 native tree species were considered and 4 were selected. This included the selected species: bigleaf maple (*Acer macrophylum*), douglas fir (*Pseudotsuga menziesii*), red alder (*Alnus rubra*), and western redcedar (*Thuja plicata*) in addition to black cottonwood (*Populus trichocarpa*), Garry oak (*Quercus garryana*), and grand fir (*Abies grandis*). The 4 species selected are very prominent in the region and include two evergreen species (douglas fir and western redcedar) and two deciduous species (bigleaf maple and red alder). The 3 species not selected were consistently not present or present in low abundance or health across all proposed sampling-sites.

The Evergreen State College (TESC) was surveyed on September 18th, 2018 by Ani Jayakaran, Jamie Duberstein, Carly Thompson, Dylan Fischer, Ben Leonard, and Ryan Bartlett. Site access was granted by Dylan Fischer. Four plots on campus were chosen and 32 trees were tagged as candidates. These areas are northeast of the organic farm (Figure 2) and northeast of parking lot C (Figure 3). Within each area, two sap flow stations were marked with 8 trees within a 50 ft. perimeter assigned to each station.

Webster Forest Nursery (WFN) was surveyed on October 26th, 2018 by Ani Jayakaran and Ben Leonard. Candidate trees were then tagged on January 14th, 2019 by Anand Jayakaran, Carly Thompson, and Ben Leonard. Site access was granted by John Trobaugh. An area in the southwest corner of WFN was identified as a secure location with multiple groves of diverse tree species and access to power. Four plots with 33 trees were identified for instrumentation (Figure 4).

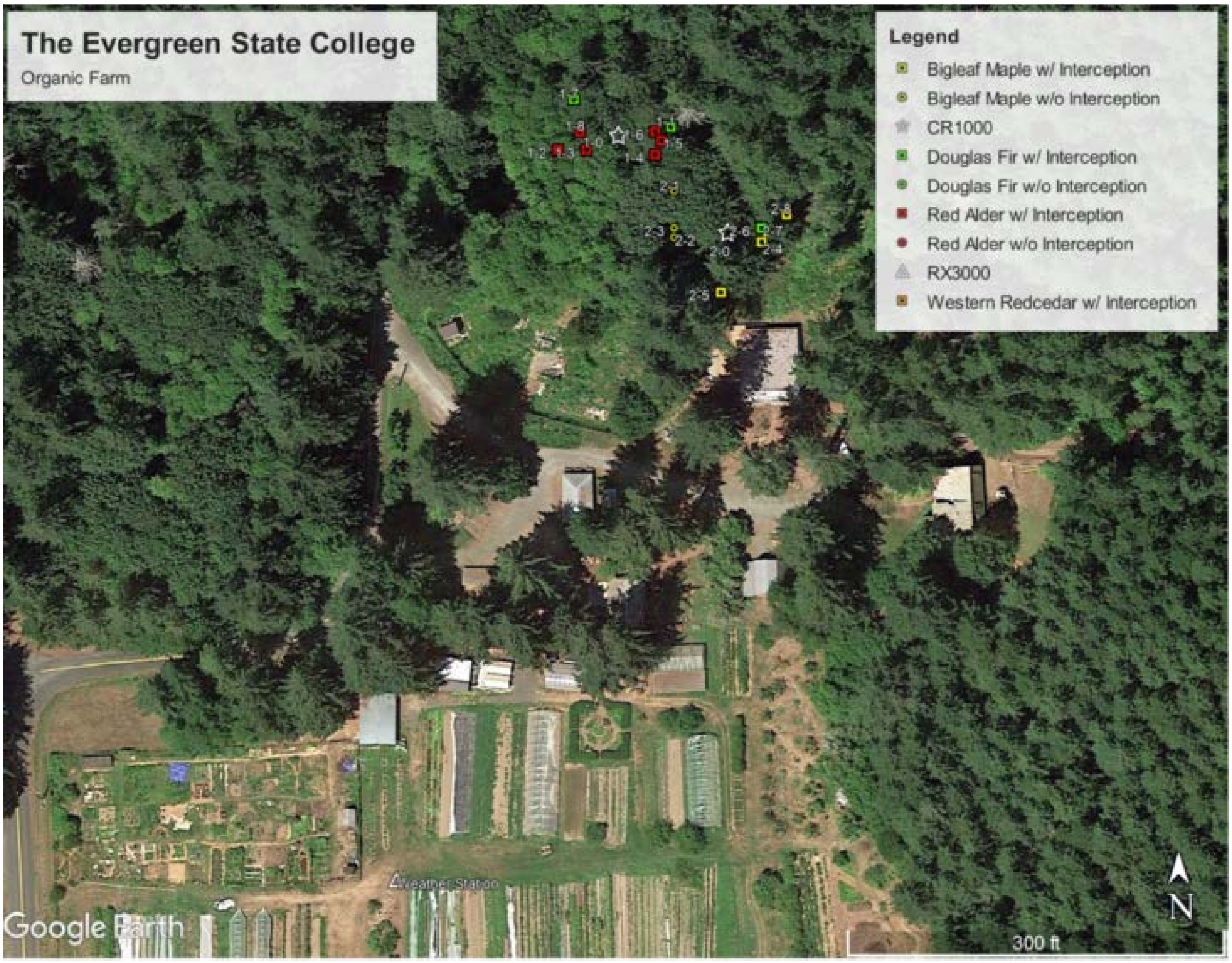


Figure 2: Two plots in the organic farm area of TESC. CR1000 depicts one sap flux datalogger. RX3000 denotes one interception-soil moisture datalogger.

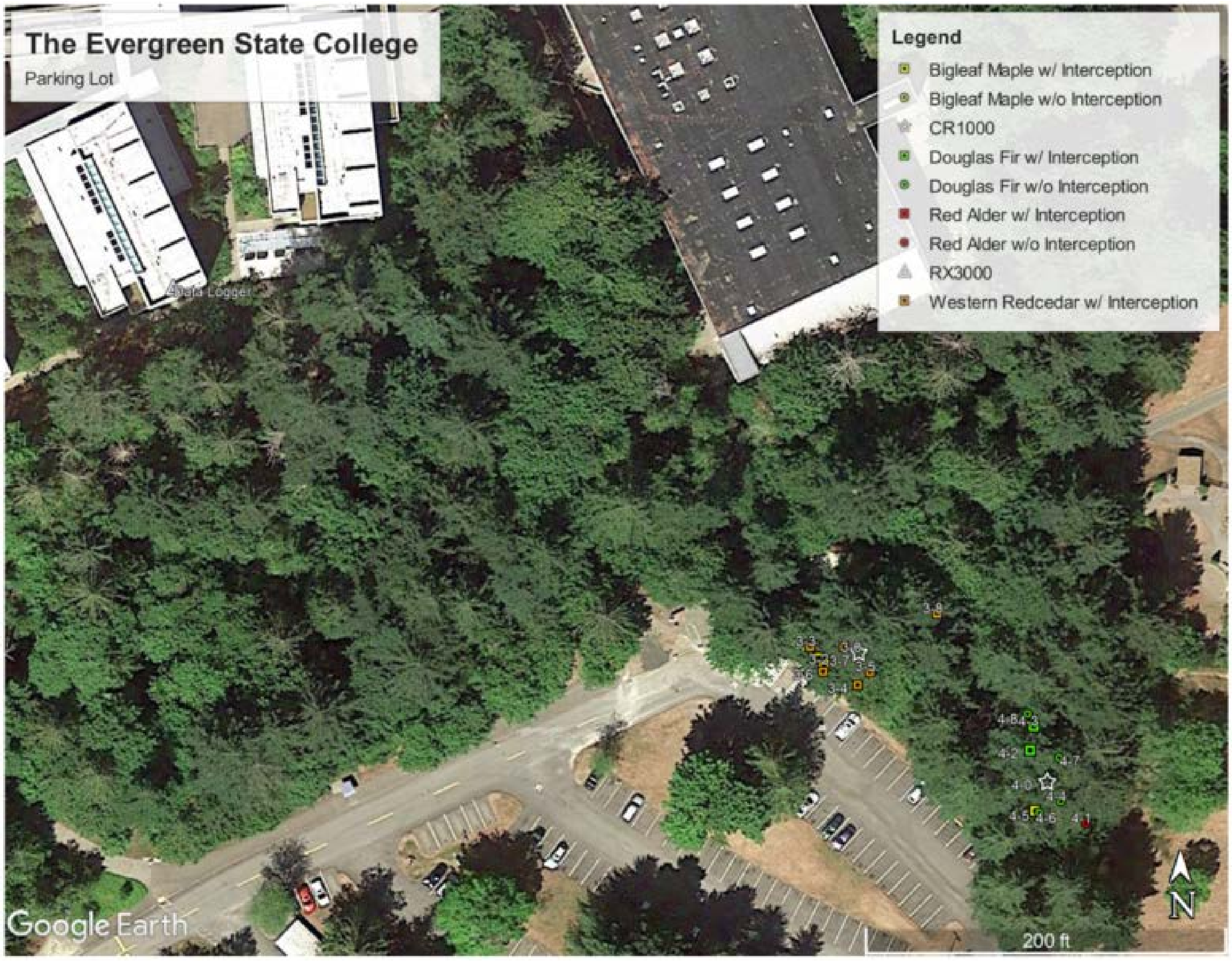


Figure 3: Two plots in the Parking Lot C area of TESC. CR1000 depicts one sap flux datalogger. RX3000 denotes one interception-soil moisture datalogger.

Figure 4: Four plots at the Webster Forest Nursery. CR1000 depicts one sap flux datalogger. RX3000 denotes one interception-soil moisture datalogger.

7.3 Tree selection process

Only larger trees with well-developed canopies and trunks will be chosen, however, there is likely to be overlapping canopies as tree proximity is an important consideration when instrumenting for sap flux. Overlapping canopies can impact throughfall measurements. To circumvent this issue, collector pipes will only be placed under the part of the canopy not affected by canopy overlap.

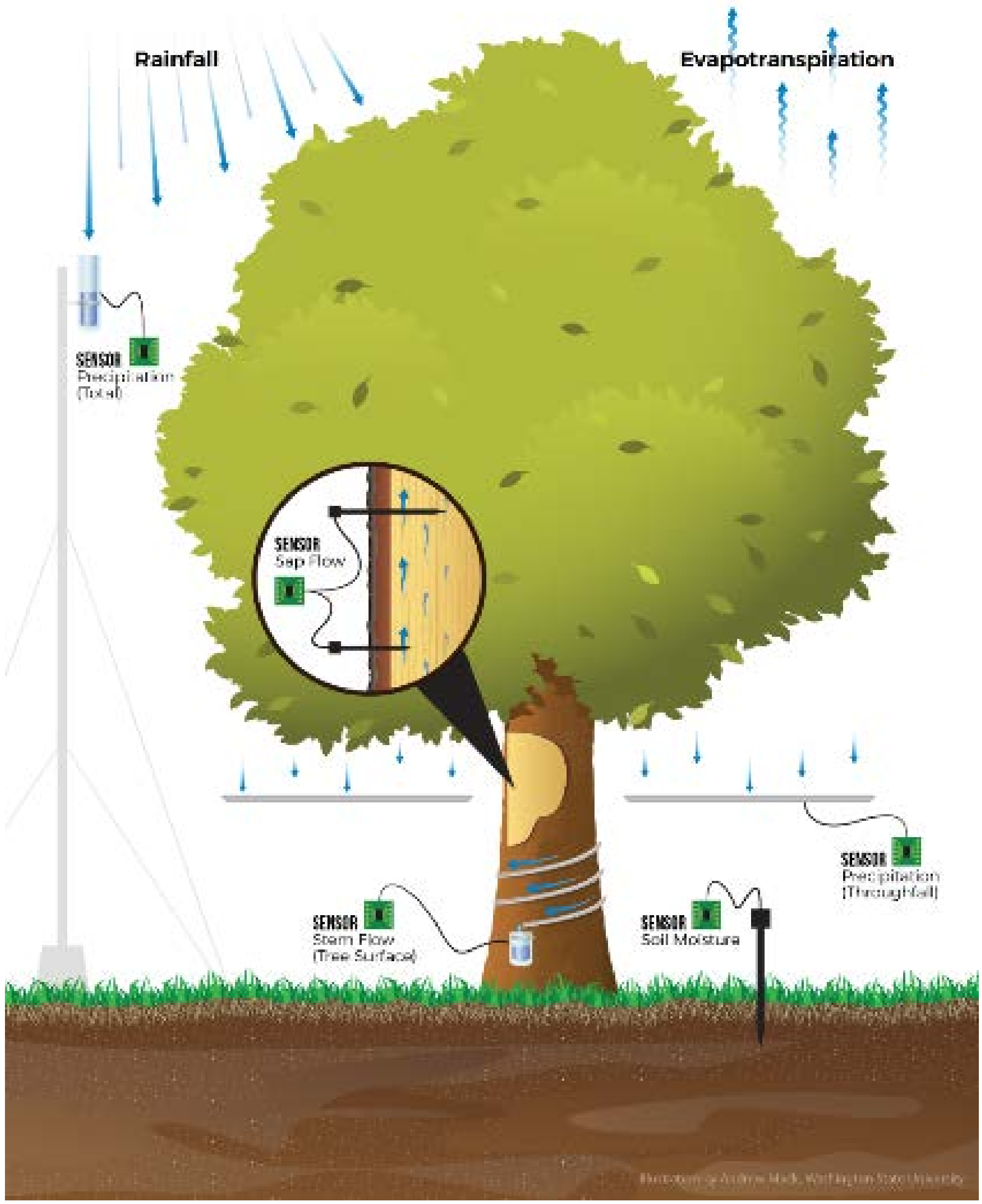


Figure 5: Sensor deployment strategy designed to quantify interception and transpiration

7.4 Type of Data Being Collected

Types of data that will be collected through this study comprise:

1. Continuously measured climatic data recorded at 15-minute intervals at two locations. Open canopy rainfall, temperature, humidity, photosynthetically available radiation, and atmospheric pressure, wind speed, and wind direction.
2. Continuously measured canopy throughfall recorded continuously and the data will be presented in 15-min intervals at 64 trees. The 64 trees will be distributed amongst locations,

tree plots, and tree species as best as possible. Based on initial investigations at both sites, 15 Big Leaf Maple, 17 Red Alder, 21 Douglas Fir, and 11 Western Redcedar have been identified for instrumentation of canopy throughfall.

3. Discretely measured per storm event totalized stemflow at 24 trees. Stemflow volumes will be measured by collecting stemflow associated with a storm event (or a series of storm events) in a container at the base of each study tree. Collected water will be measured using a graduated beaker. Once measurement is completed, the collection container will be emptied in preparation for subsequent storm event(s).
4. Continuously measured soil moisture data recorded at 15-minute intervals at 8 tree plots. At each tree plot, an array of 5 soil moisture sensors will be deployed within the root zone. Soil moisture data aggregated to represent averaged soil moisture conditions per tree plot.
5. Continuously measured sap flux data recorded at 15-minute intervals at 64 trees that are distributed across the 8 study plots. There are 8 trees that have been identified per tree plot. Based on initial investigations at both sites, 15 Big Leaf Maple, 17 Red Alder, 21 Douglas Fir, and 11 Western Redcedar have been identified for sap flux instrumentation.
6. Discretely measured tree metrics such as canopy area, leaf area index, tree diameter at breast height, will be measured for every one of the 64 instrumented trees.

The number of individual trees, species, and sampling locations were chosen to provide enough statistical power to determine how well four types of native trees manage rainfall given variability in climatic events over a two-year period.

Table 7.4.1: Summary of locations, number of sensors installed per each tree type

Location			**The Evergreen State College (TESC)**				**Webster Forest Nursery (WFN)**				**TESC total**	**WFN total**	**Total**
Area			Organic Farm		Parking Lot		North Field		South Field				
Site (Plot)			1	2	3	4	5	6	7	8			
Weather Station Installed (Y/N)			Y	Y	N	N	Y	Y	N	N	-	-	-
# of Soil Moist Sensor			5	5	5	5	5	5	5	5	20	20	40
Tree type	Bigleaf Maple		# of trees										
		Canopy throughfall		6	2	1		1	2	3	9	6	15
		Sap flow	-	6	2	1	-	1	2	3	9	6	15
		Stem flow	-	1	1	1	-	1	1	1	3	3	6
	Red Alder		# of trees										
		Canopy throughfall	6	-	-	1	6	2	-	2	7	10	17
		Sap flow	6	-	-	1	6	2	-	2	7	10	17
		Stem flow	2	-	-	1	1	1	-	1	3	3	6
	Douglas Fir		# of trees										
		Canopy throughfall	2	2	-	6	2	5	1	3	10	11	21
		Sap flow	2	2	-	6	2	5	1	3	10	11	21
		Stem flow	1	1	-	1	1	1	-	1	3	3	6
	Western Redcedar		# of trees										
		Canopy throughfall	-	-	6		-	-	5	-	6	5	11
		Sap flow	-	-	6		-	-	5	-	6	5	11
		Stem flow	-	-	3		-	-	3	-	3	3	6
Total			# of trees										
		Canopy throughfall	8	8	8	8	8	8	8	8	32	32	64
		Sap flow	8	8	8	8	8	8	8	8	32	32	64
		Stem flow	3	2	4	3	2	3	4	3	12	12	24

8.0 Sampling & Monitoring Procedures

8.1 Standard Operating Procedures

1. Climatic data will be measured using two weather stations (HOBO-Onset) installed at the two sites – one at TESC and one at Webster. Weather stations will be installed per the instruction manuals provided. Recorded data will be transmitted to WSU Puyallup on an hourly basis. Sensor calibration and maintenance will be carried out on a monthly basis. A rain gage calibration kit will be used to ensure the rain gage is appropriately calibrated. Maintenance will ensure that batteries are adequately charged and that sensors are not obscured by debris.

2. Canopy throughfall instrumentation will comprise two slotted sections per tree of 4-inch schedule 40 pipe, with 64 trees chosen for throughfall instrumentation. Both pipes will be arranged so that they empty into a HOBO-Onset rain gage. Slots will be cut in the PVC pipes in order to maximize exposed surface area while maintaining the structural resilience of the pipe. This design was based upon a technique used by Asadian (2010) who cut three 31.5 in. (0.85 m) by 1.1 in. (0.028 m) slits in 9.8 ft. (3 m) for collecting throughfall. Slit area was expanded after correspondence with the author of this study. Three 33.3 in. by 1.5 in. slits were cut to provide a surface area of ~150 in^2 per trough. This results in a total surface area of 300 in^2 per tree. This arrangement is illustrated in the schematic below and conforms with methodology also used by Asadian and Weiler (2009). The schematic below shows the arrangement of pipes and rain gage in profile (left) and in plan (right). Rain

gages will automatically log and transmit data to a central datalogger, which in turn will transmit data to WSU-Puyallup on an hourly basis

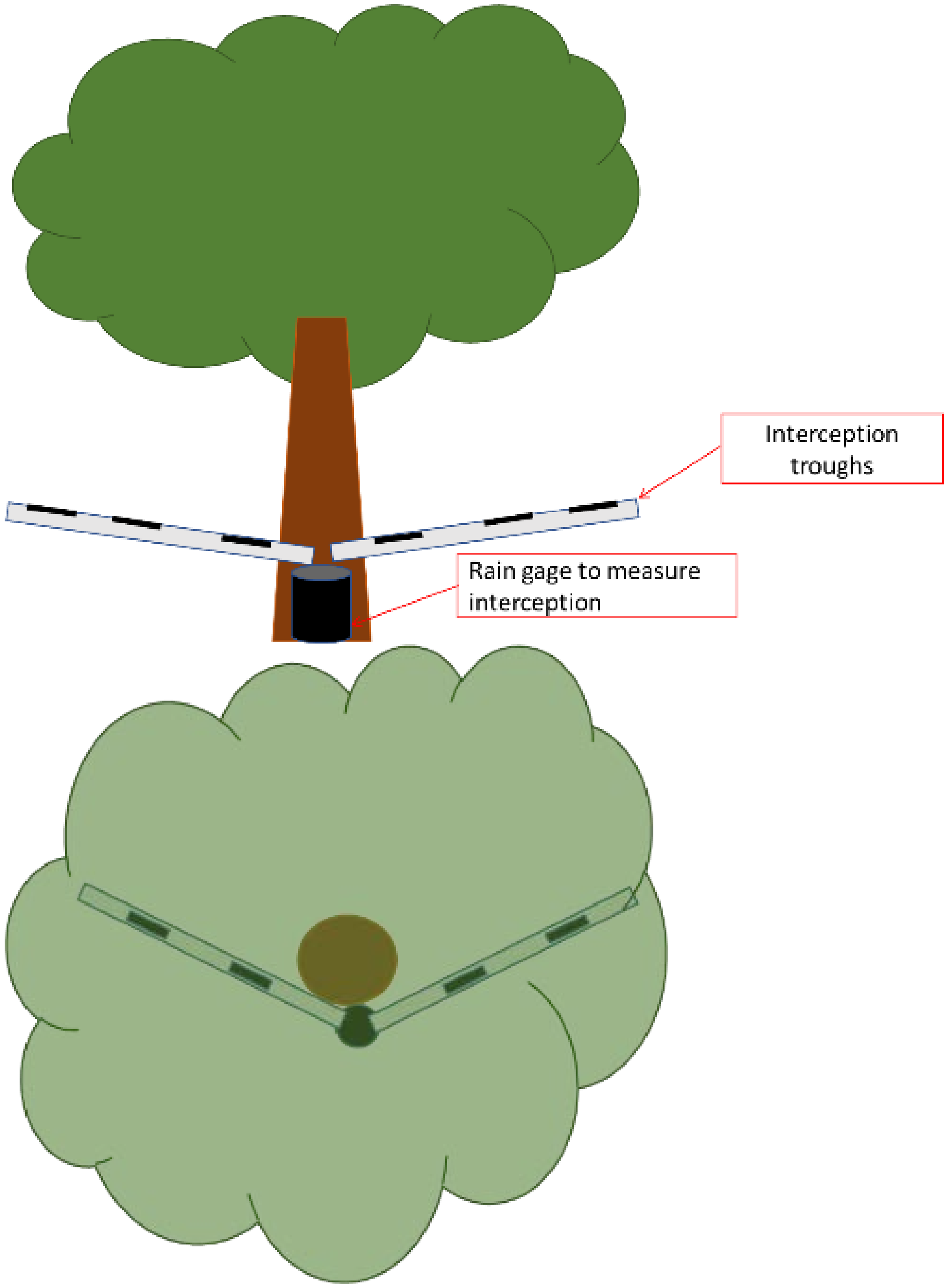


Figure 6: Profile (top) and plan (bottom) views of troughs and rain gage used to measure canopy throughfall

3. Totalized stemflow at 24 trees will be measured by diverting stemflow into a container at the base of each study tree. Collected water will be measured using a graduated beaker and recorded. Once measurement is completed, the collection container will be emptied in preparation for the next storm event(s). The arrangement of stem flow collar and container is depicted below. While stem flow and throughfall will be measured at each tree, the schematics above and below depict only one of the two types of instrumentation. Stem flow

collected in the stem flow container will be measured after every major storm event using a graduated beaker.

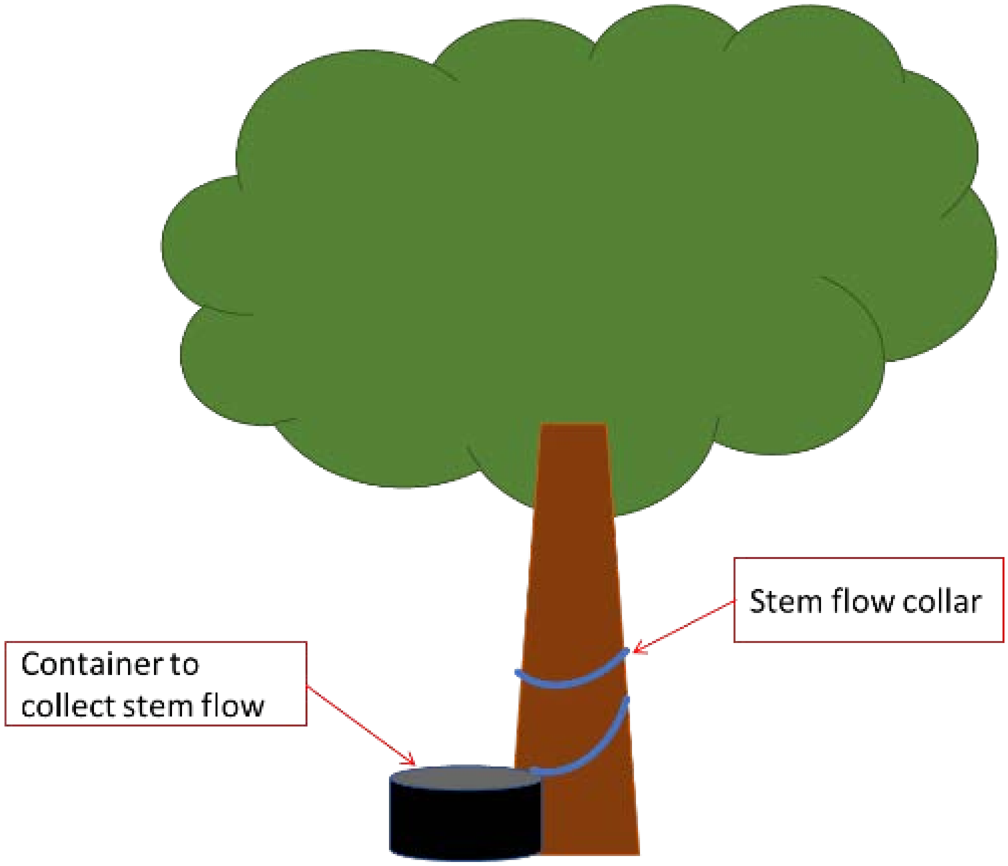


Figure 7: Profile of view shwoing arrangement of stem flow collar and stem flow container

4. Soil moisture data will be measured at each of the 8 study plots. At each tree plot, an array of 5 HOBOnet soil moisture sensors will be deployed at a depth of 30cm to measure soil moisture variability in the root zone. Each soil moisture sensor will be installed per instructions provided by the manufacturer. Data will be transmitted to a central datalogger, which in turn will transmit data to WSU-Puyallup on an hourly basis.
5. Continuously measured sap flux data will be recorded at 64 trees using 8 TDP-Dynamax systems that comprise Granier probes installed at three differing depths into the trees sapwood. Installation of the system is highly specialized and is not meant to be replicated by anyone other than a trained professional. In our study, installation of these probes will be carried out by Drs. Duberstein and Fischer. In brief, probes will be installed at various depths depending on the diameter of the tree

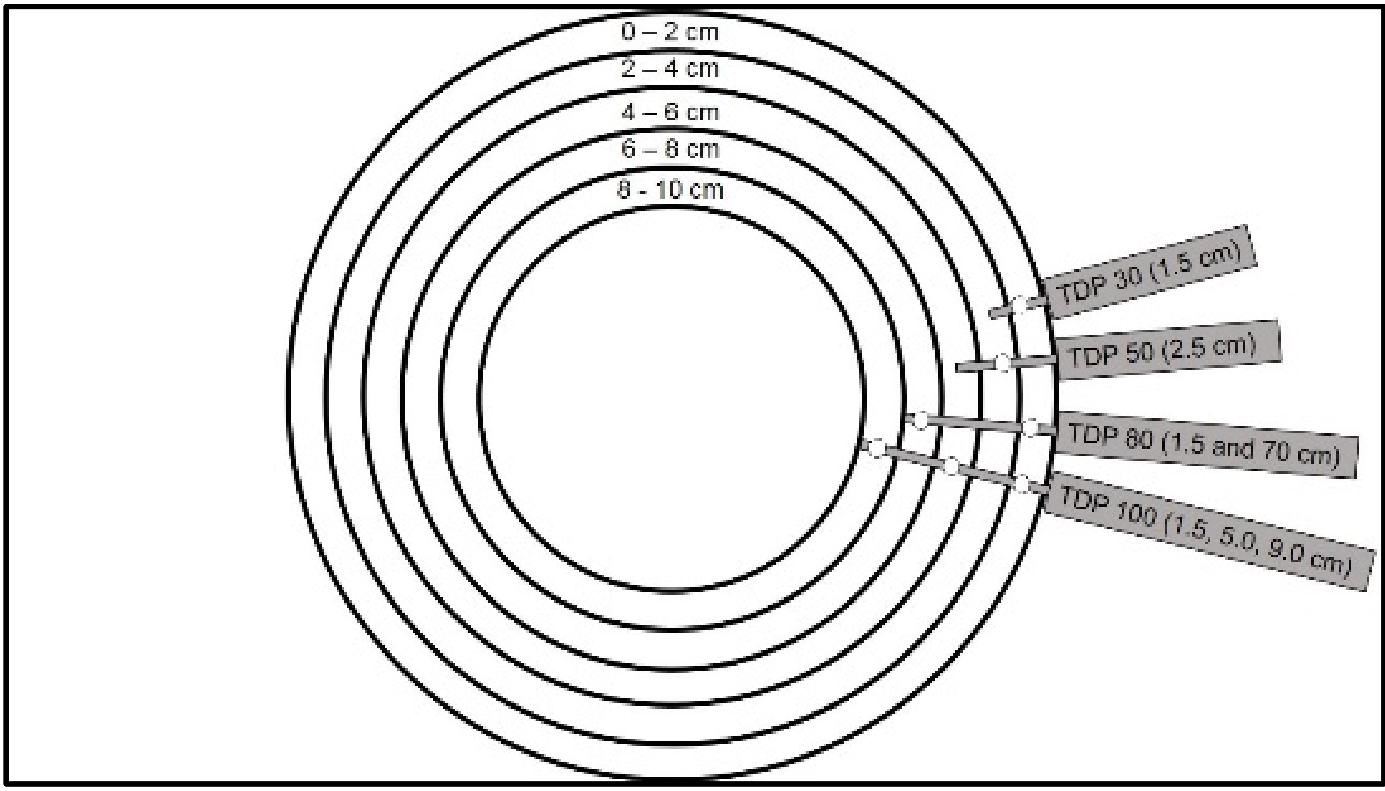


Figure 8: Figure TDP. Radial depth bands of sap flow rates are computed from data collected from TDP sensors. Open circles indicate locations of thermocouples. Very little flow (or none) occurs at depths exceeding 9.0 cm for most tree species.

6. Tree metrics such as canopy area, leaf area index, tree diameter at breast height, will be measured for all 64 instrumented trees once at the beginning of the study. At the end of the study, each tree will be cored to assess approximate tree age.

8.6 Field Log Requirements

A field log will be maintained for all two-weekly maintenance and data download trips. Information recorded will include but not be limited to:

- Date and time
- Field staff names
- Monitoring location, # of plot, # of tree
- Relevant climate conditions (i.e. general conditions like raining, dry, overcast, sunny)
- Sampling equipment condition
- Instrument calibration procedures
- Space for adding comments about activities or issues that may influence the quality of the data
- Stem flow volume collected

A more detailed template is provided in the Appendix A.

9.0 Measurement Procedures

9.1 Procedures for Collecting Field Measurements

All data recorded for this study will be collected through sensor technology. All field data will therefore either be transmitted to a central hub at WSU Puyallup or will require download from dataloggers. The only field measurements taken will be that of stem flow, where water from a stem flow collar is diverted into a collection container. The volume of water in every stem flow container will be measured by carefully emptying the contents of the container into a 1-liter graduated beaker. Once the graduated beaker is at maximum capacity, it will be emptied out and refilled until the stem flow collection container is empty. The number of times the graduated beaker was filled and the volume of the last partially filled beaker allows for an estimation of stemflow at that tree since the last storm event. The total volume of stem flow, the date and time the measurement was taken, and the tree identification number will be recorded.

10.0 Quality Control

10.1 Field QC Required

Field notes will be maintained, and all equipment will be routinely maintained over the study. Specifically, the following activities will be carried out:

1. Develop and consistently follow instrument and equipment calibration checks per manufacturer recommendations
2. Create an equipment maintenance and instrumentation calibration schedule that identifies equipment, procedures, and frequency
3. Develop and consistently follow record keeping procedures (see section 11.0, Data Management)
4. Provide proper training to the field staff on all procedures

For the sap flux data collection, the following steps will be carried out:

1. Confirm that there is not a problem with any computer software involved in downloading/analyzing data. Retrieve data again from a different computer using Campbell software. Attempt to plot data using different software (e.g. Excel or R-Studio).
2. Visit site and check cable connectivity and wiring diagram.
3. Repair any shorts or connectivity issues (one at a time). This may include kinked cabling or linkages clogged with dirt/debris. Clean connections using isopropyl alcohol and ensure a tight connection complete with rubber o-rings.
4. If no issues appear, replace probes and watch signal for 24-48 hours to make sure sap flux pattern is stable. A stable pattern should include raw values between 3 and 8 and should appear diurnal (Figure 9 - Good). An unstable signal is sporadic and may include values well outside of the acceptable range (Figure 10 – Bad).
5. Check replaced probes for shorts etc., and categorize them as in need of repair, trash, or undamaged.
6. If replaced probes are undamaged, and signal from new probes is still bad, go back to step 2.

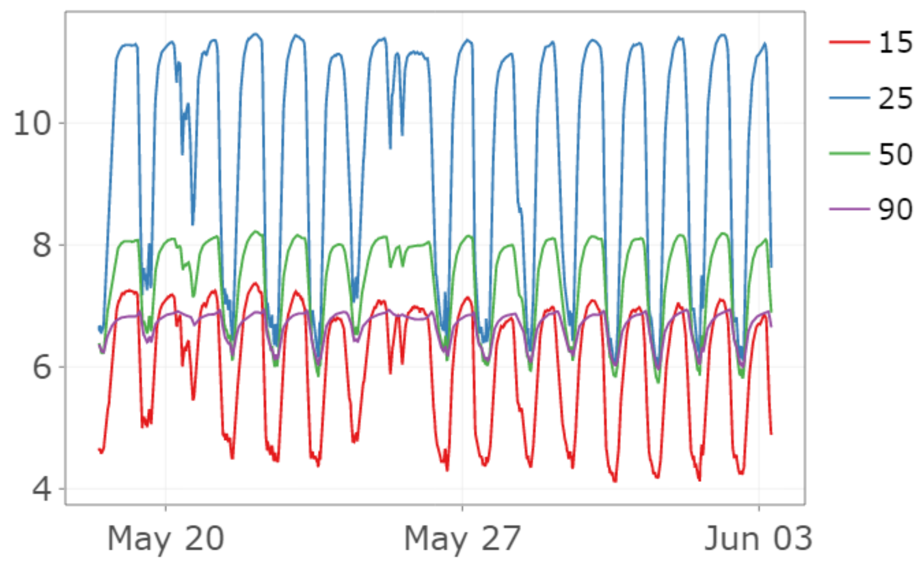


Figure 9: Example of good sap flux data

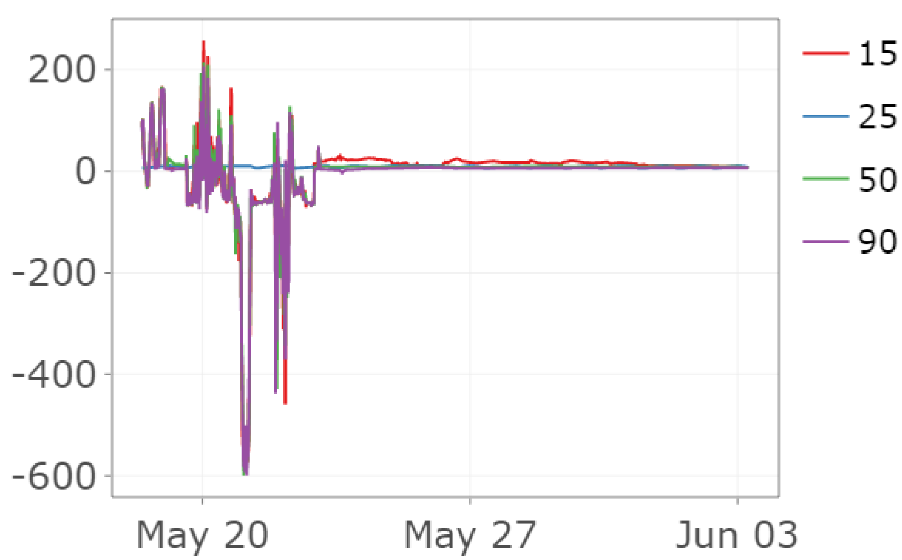


Figure 10: Example of poor sap flux data

10.3 Corrective Action

Corrective actions will be required to respond to either (1) physical failure of instrumentation or interception troughs (e.g. due to damage, vandalism, obstructions, etc.), or (2) apparently erroneous data has been collected (e.g. data gaps in data collection, bias due to drift, etc.). Corrective actions to correct physical failures of the monitoring equipment will be implemented through inspection of monitoring equipment prior to anticipated storm events (as possible within the budget allotment). If physical failures of equipment are identified prior to or during storm events, simple actions to correct the issue will be taken immediately (e.g. removing debris or reinstallation). Reinstallation of monitoring equipment will otherwise be conducted when best feasible either during or between storm events. Identification of erroneous data will not occur until data is downloaded from each site (semimonthly). Correction of erroneous data will be conducted through the data review and correction process (see Section 11.1).

11.0 Data Management Plan Procedures

11.1 Data Recording & Reporting Requirements

All project related data will be stored at WSU-Puyallup and backed up daily. A backup will also exist at TESC. All sap flux, throughfall, climatic, stem flow, and soil moisture data will be reviewed within a week of the site maintenance visits to identify potential problems and address and minimize data gaps or errors. All data will be verified using the following steps.

1. Data will be reviewed for missing data values and determine if the gaps can be filled with estimated or alternate data. For example, if the facility rain gauge is offline a nearby rain gauge might be used to fill in the gap. The process for filling in each gap will be documented
2. Anomalies or outliers will be identified. Examples of anomalies are sudden changes data despite the lack of a storm event to trigger a change in environmental conditions. Additionally, if the data appears to flat line despite a storm event or a change in environmental conditions that would normally yield a change in conditions. The process for addressing each anomaly will be documented.
3. All data will be cross checked against field forms and calibration records. Sensors may need to be adjusted for drift or offset.
4. Data may also be compared across rainfall events. Are expected yields/patterns across events consistent? Do throughfall or stem flow rates yield similar amounts for similar rainfall events.

11.2 Electronic Transfer Requirements

Data from all weather stations, rain gages (throughfall), and soil moisture sensors will be transmitted from each sensor to a central receiving station, one station at TESC and one at Webster Nursery Farm using a 900 MHz wireless mesh technology. From two receiving stations, data will then be transmitted to a central database at WSU via cellular modem network.

11.3 Laboratory Data Package Requirements

Not applicable

11.4 Procedures for Missing Data

1. Missing data will be filled in when appropriate through interpolation techniques such linear or spline fitting to fill in the gaps. However, data missing over a 24-hour period is unlikely to be suitable for this type of gap filling. When appropriate, missing climatic data can be filled in using data from other proximal weather stations.
2. All missing data will be coded appropriately to show that the data are “filled” through interpolation or matching from local sensors.
3. Missing data will be reported with results.

11.5 Acceptance Criteria for Existing Data

Not applicable

11.6 Data Upload Procedures

Data will be stored in a secure site on WSU servers, and made available to non-WSU partners via two cloud storage services - DropBox[1] and GitHub[2]. The choice will be based on what suits the partners the best. Data will also be stored on the SAM project page. Data will be stored as comma-limited text files with appropriate data qualifying codes, on all the above-mentioned locations. Data will be processed using the R statistical computing environment, and other non-proprietary software. Data will also be made available to the public through the Shiny[3] interactive web app.

---

1 https://www.dropbox.com/
2 https://github.com/
3 https://shiny.rstudio.com/

12.0 Audits

Project technical leads will conduct monthly audits throughout the period of the study to ensure that field and data processing are meeting previously detailed QC steps. The outcomes of these monthly audits will be documented and included in quarterly reports to SAM. The Ecology Program manager and DNR Project Manager may conduct audits as needed.

12.1 Technical System Audits

Audits of the technical system include:

1. Verifying that field staff are following the SOPs for sensor maintenance, sensor calibration, and field measurements (stem flow)
2. Verify the data management procedures are followed including field data recording

13.0 Data Verification and Usability Assessment

13.1 Field Data Verification

All data generated will also be reviewed by other project partners associated with each aspect of data collection (i.e. sap flux, throughfall, tree physiology, and climatic data). Data measured by all sensors will also be corroborated against additional equipment installed at both sites that are not a part of this study.

13.3 Data Usability Assessment

Upon completion of the data verification the project technical lead will make a final determination of the data usability. If data meet the Data Quality Objectives (DQO) listed in 6.0, then the data will be deemed useable for meeting the study objectives. The project data analyst will look at qualified data and evaluate its impact to the overall DQO. If data are rejected, a determination must be made of whether the quantity and quality of the valid data are enough to meet the study objectives. Thorough documentation will be made of any decision to reject data as it may require additional effort to replace the intended data. Usable data is acceptable for all study related analysis.

14.0 Data Analysis Methods

14.1 Data Analysis Methods

Data will be analyzed using standard statistical methodology for analyzing time series data as well as using multivariate regression techniques. Parametric and non-parametric statistical techniques will be used dependent upon data distribution. Significance will be assessed at $\alpha = 0.05$. Normality of data sets will be assessed using Shapiro-Wilk's method. All data analyses and figure-generation will be carried out using the free open source software R. However, MS Excel will be used as well to ensure that those project partners unfamiliar with R can view and manipulate data.

Null hypothesis that will be tested are:

1. Climatic conditions at both sites are similar.
2. All trees manage rainfall in a similar way – i.e. interception and transpirative processes are similar amongst four native tree species.
3. Climatic and soil moisture conditions do not influence interceptive and transpirative processes for an individual tree

Dependent variables for analysis include throughfall data by which interception by tree species can be calculated over the period of study, sap flux data by tree that will be scaled up by tree size to estimate tree water use, and lastly totalized stem flow measured after each storm event. Lastly changes in soil moisture, day of year, and climatic data especially rainfall (R) will be used as independent variables, or predictors of how well each species of trees can manage rainfall. Ultimately, the amount of rainfall that a tree can "manage" through interception and transpiration over the period of this study, is the volume of water that would ultimately not be available as stormwater runoff.

14.2 Data Presentation

Field data results and statistical modeling will be delivered in narrative, tabular and graphical formats in the form of a final project report. Electronic copies of QC reviewed data files will also be provided to the SAM project manager.

15.0 Reporting

Study findings will be disseminated by both DNR and WSU as project presentations made by technical leads and students, project fact sheets, research papers, and a final project report. All final reporting documents will be located on the Ecology SAM - Effectiveness Studies website (https://ecology.wa.gov/Regulations-Permits/Reporting-requirements/Stormwater-monitoring/Stormwater-Action-Monitoring/SAM-effectiveness-studies).

16.0 References

Asadian, Y., 2010. Rainfall interception in an urban environment (Doctoral dissertation, University of British Columbia).

Asadian, Y. and Weiler, M., 2009. A new approach in measuring rainfall interception by urban trees in coastal British Columbia. Water Quality Research Journal, 44(1), pp.16-25.

Calder, I.R., 1982. Forest evaporation. In Proc. Can. Hydrol. Symp (Vol. 82, pp. 173-193).

Ecology, 2011. Technical Guidance Manual for Evaluating Emerging Stormwater Treatment Technologies: Technology Assessment Protocol – Ecology (TAPE). 2011: Washington State Department of Ecology, Olympia, WA. Publication No. 11-1003-030. https://fortress.wa.gov/ecy/publications/summarypages/1110061.html

Environmental Protection Agency (EPA). 2013. Stormwater to Street Trees: Engineering Urban Forests for stormwater Management, U.S. Environmental Protection Agency Office of Wetlands, Oceans and Watersheds Nonpoint Source Control Branch (4503T) 1200 Pennsylvania Ave., NW Washington, DC 20460 September 2013 EPA 841-B-13-001.

EPA, 2002. Guidance for Quality Assurance Project Plans. EPA QA/G-5. December 2002. Office of Environmental Information, Washington, D.C. p. 111.

EPA, 2006. Guidance on Systematic Planning Using the Data Quality Objectives Process. EPA QA/G-4. February 2006. Office of Environmental Information, Washington, D.C. p. 120.

Erickson, A.J., P. Weiss, and J. Gulliver. 2013. Optimizing Stormwater Treatment Practices: A Handbook of Assessment and Maintenance. March 2013. Springer. 337pgs.

Granier A. (1987) Evaluation of transpiration in a douglas-fir stand by means of sap flow measurements. Tree Physiology 3: 309-320.

Heal, K.V., Stidson, R.T., Dickey, C.A., Cape, J.N. and Heal, M.R., 2004. New data for water losses from mature Sitka spruce plantations in temperate upland catchments. Hydrological sciences journal, 49(3).

Law, F., 1957. Measurement of rainfall, interception, and evaporation losses in a plantation of Sitka spruce trees, Compt. Rend. Assoc. Intern. Hydrologie Sci., Asemblee Generale de Toronto 1957, 2, 397–411.

Lombard, S., and C. Kirchmer, 2004. Guidelines for Preparing Quality Assurance Project Plans for Environmental Studies. Revised 2016. Washington State Department of Ecology, Olympia, WA. Publication No. 04-03-030. https://fortress.wa.gov/ecy/publications/summarypages/0403030.html

Peters E.B., J.P. McFadden, and R.A. Montgomery. 2010. Biological and environmental controls on tree transpiration in a suburban landscape. Journal of Geophysical Research: Biogeosciences 115.G4.

Unsworth, M.H., Phillips, N., Link, T., Bond, B.J., Falk, M., Harmon, M.E., Hinckley, T.M. and Marks, D., 2004. Components and controls of water flux in an old-growth Douglas-fir–western hemlock ecosystem. Ecosystems, 7(5), pp.468-481.

17.0 Appendices

Appendix A – Maintenance and Field Data Sheet

ROUTINE MAINTENANCE & FIELD DATA SHEET

Field Tech Names: ________________________ Date: _____________________

Site name: ___________________ Plot no.: __________________

Throughfall and Soil Moisture Instrumentation Checks

1. Check every rain gage and interception trough for clogging

Record Tree IDs associated with clogged rain gages

2. Check all rain gages are connected to the RX3000. Check connection to mote and power.

Record Tree IDs associated with faulty rain gages and a "yes" or "no" if fault was remedied

3. Check all soil moisture sensors are connected to the RX3000. Check connection to mote and power.

Record soil moisture sensor number associated with faulty sensors and a "yes" or "no" if fault was remedied

Weather Station and RX3000 Checks

Check physical integrity of system and that data are being transmitted to the main data portal. Check power and sensor connectivity.

System working? Yes / No Follow up maintenance required? Yes / No

Notes:

Sap Flux System Checks

1. Inspect system for physical integrity.
2. Connect to the TDP system with laptop and check for connectivity.
3. Download data – check for channels that have NAN's
4. Inspect cables, and power source.
5. measure deep cycle marine battery voltage: __________V

Notes:

System working? Yes / No Follow up maintenance required? Yes / No

Stem flow volume measurements

1. Check for physical integrity of system
2. Empty stem flow container into graduated beaker and measure total volume by repeatedly filling beaker and emptying until stem flow container is empty.

Beaker volume: ______________ml

Number of times beaker was filled [*record tally marks]:* _________________________

Last aliquot in beaker: ________________ml

Total volume in container: _______________ml

Appendix B – FLGS -TDP Sap Velocity System

FLGS-TDP XM1000
Sap Velocity System

Dynamax

FLGS - TDP Sap Velocity System

FLGS-TDP XM1000 is the newest completely integrated measurement system for TDP sap velocity sensors. The new XM1000 version of our TDP sap flow system includes the latest expanded memory data logger platform and extended features such as real-time sap flow calculations and auto zero. Each FLGS-TDP system can read up to 32 TDP10/30/50 sensors. This basic system can be expanded with an additional subsystem to read an additional 32 sensors. Each TDP thermocouple is connected to a differential channel on the logger. All the necessary electronics, software and sensors are assembled into a full and complete solution.

In addition to the standard FLGS system, customers may add other sensors such as soil moisture, dendrometers, temperature, or solar radiation. Available channels include: six differential (or 12 S.E.) channels, two pulse channels, and one SDI-12 port. Adding sensors requires modification to the logger program. Please contact Dynamax for additional program and customer configuration quotes.

Communication Options

FLGS-TDP Sap Velocity logger offers a variety of communication choices between the logger and user's PC. PC400 software provides direct communication by RS-232 (included) or point to point MODEMs by RF or by cellular phone. GSM cell phone modem packages, provide remote dial-up data retrieval. Radio modules are available to provide RF communication over 20 miles line of sight.

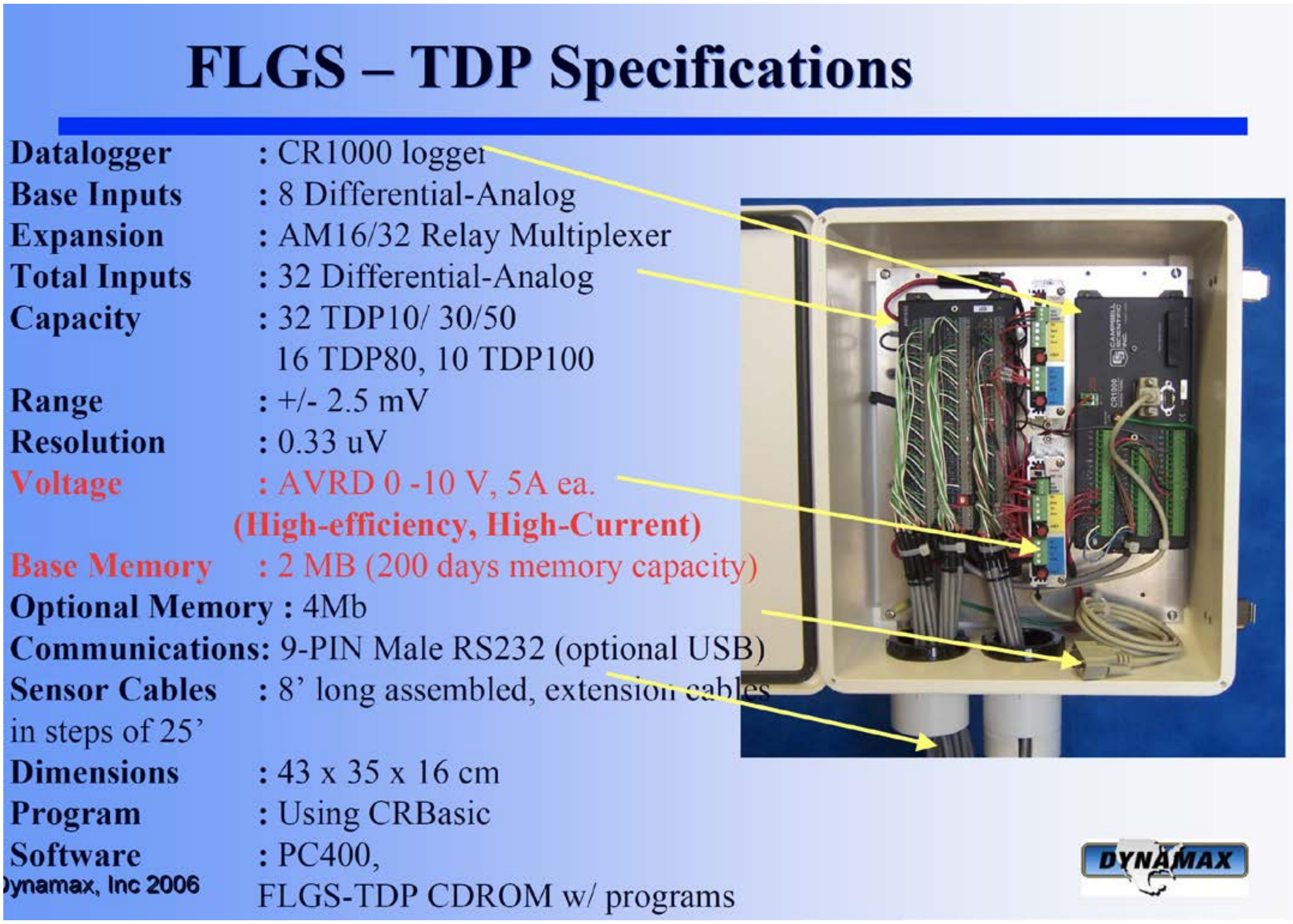
Ordering Information

FLGS-TDP XM1000
TDP Sap Velocity System, fully assembled with CR1000
TDP-10, TDP-30, TDP-50, TDP-80, TDP-100
Sap Velocity Thermal Dissipation Probe
TDPJ1 Installation Kit
Drilling jig, drill bits (4 pieces), and removal prybar
TDPJ2 Installation Kit
Drilling jig, drill bits (4 pieces), battery powered drill, and removal prybar
EXTP-25, EXTP-50, EXTP-75
Extension cables with quick connectors
EXTP-25D, EXTP-50D, EXTP-75D
TDP-80 Extension cables with quick connectors

Features

- **Advanced CR100 data logger**
- **2 MB data memory, for up to 500,000 data values, or 200 days of hourly records for a full 32 sensor system**
- **Built-in Program computes sap flow for specific trees**
- **Automatic night time Zero set. Saves processing time**
- **Input settings for sap wood area and tree indexing by leaf or stem area.**
- **Power down, power saving for nighttime, power reduction**
- **Two AVRD voltage regulators, supply 4 different voltages**
- **Six open channels for weather or soil sensors**

Dynamax, Inc | 10808 Fallstone Rd #350 | Houston TX 77099 | USA | admin@dynamax.com | www.dynamax.com | 800-896-7108


FLGS – TDP Specifications
Datalogger : CR1000 logger
Base Inputs : 8 Differential-Analog
Expansion : AM16/32 Relay Multiplexer
Total Inputs : 32 Differential-Analog
Capacity : 32 TDP10/ 30/50
16 TDP80, 10 TDP100
Range : +/- 2.5 mV
Resolution : 0.33 uV
Voltage : AVRD 0 -10 V, 5A ea.
(High-efficiency, High-Current)
Base Memory : 2 MB (200 days memory capacity)
Optional Memory : 4Mb
Communications: 9-PIN Male RS232 (optional USB)
Sensor Cables : 8' long assembled, extension cables in steps of 25'
Dimensions : 43 x 35 x 16 cm
Program : Using CRBasic
Software : PC400,
FLGS-TDP CDROM w/ programs
Dynamax, Inc 2006
DYNAMAX

Appendix C Hobo Net System

Onset Repeater

ONSET

RXW-RPTR-xxx

HOBOnet Repeater

The HOBOnet Wireless Repeater is designed to work with the HOBOnet Wireless Sensor Network. The repeater is ideal when there is an obstruction between wireless sensors and the RX3000 station or for extending the transmission range of wireless sensors in the network.

Key Advantages:

- 900 MHz wireless mesh self-healing technology
- 450 to 600 meter (1,500 to 2,000 feet) wireless range and up to five hops
- Up to 50 wireless sensors per RX3000
- Simple button-push to join the HOBOnet wireless network
- Onboard memory to ensure no data loss
- Powered by rechargeable AA batteries and built-in solar panel

RXW-RPTR-xxx Specifications

Operating Temperature Range	-25° to 60°C (-13° to 140°F) with rechargeable batteries -40 to 70°C (-40 to 158°F) with lithium batteries
Radio Power	12.6 mW (+11 dBm) non-adjustable
Transmission Range	Reliable connection to 457.2 m (1,500 ft) line of sight at 1.8 m (6 ft) high Reliable connection to 609.6 m (2,000 ft) line of sight at 3 m (10 ft) high
Wireless Data Standard	IEEE 802.15.4
Radio Operating Frequencies	RXMOD-RXW-900: 904–924 MHz RXMOD-RXW-868: 866.5 MHz RXMOD-RXW-922: 916–924 MHz
Modulation Employed	OQPSK (Offset Quadrature Phase Shift Keying)
Data Rate	Up to 250 kbps, non-adjustable
Duty Cycle	<1%
Maximum Number of Motes	50 motes per one RX Wireless Sensor Network
Power Source	Powered by the RX3000 station
Dimensions	Mote: 16.2 x 8.59 x 4.14 cm (6.38 x 3.38 x 1.63 inches) Cable length: 2 m (6.56 ft)
Weight	Mote: 159 g (5.62 oz)
Materials	Mote: PCPBT, silicone rubber seal
Environmental Rating	Mote: IP67, NEMA 6
Compliance Marks	FC RXMOD-RXW-900 CE RXMOD-RXW-868 RXMOD-RXW-922

RX3000 Data Logger

ONSET

HOBO® RX3000 Data Logger

RX3000 Remote Monitoring Station Data Logger

The HOBO RX3000 is Onset's next-generation remote data logging station that provides instant access to site-specific environmental data anywhere, anytime via the internet. The new station combines the flexibility and sensor quality of more expensive systems, an onboard LCD display, and the convenience of plug-and-play operation. The RX3000 has four configurable systems, that can be configured below, that consist of the following part numbers: RX3001-00-01, RX3002-00-01, RX3003-00-01 and RX3004-00-01.

Supported Measurements:

4-20mA, AC Current, AC Voltage, Air Velocity, Amp Hour (Ah), Amps (A), Barometric Pressure, Carbon Dioxide, Compressed Air Flow, DC Current, DC Voltage, Differential Pressure, Event, Gauge Pressure, Kilowatt Hours (kWh), Kilowatts (kW), Leaf Wetness, Light Intensity, Power Factor (PF), Pulse Input, Rainfall, Relative Humidity, Soil Moisture, Temperature, Volatile Organic Comp., Volt-Amp Reactive, Volt-Amp Reactive hour, Volt-Amps (VA), Volts (V), Water Flow, Water Level, Watt Hours (Wh), Watts (W) and Wind

Key Advantages:

- Flexible support for a broad range of sensors
- LCD display for easy field deployment
- Cloud-based data access through HOBOlink
  - Get 24/7 web access to your data via web browser
  - Verify RX3000 system status remotely
  - Set up and manage alarm notifications over the web
  - Schedule automated delivery of data
- Plug-and-play operation
- Alarm notifications via text, email
- Rugged double-weatherproof enclosure
- Cellular, Wifi and Ethernet Option are available
- Configure & check on your RX3000 monitoring station from your mobile devices
- Optional Analog Input and Relay Modules
- Optional third-party sensor can be purchased for Remote Water Level Monitoring
- Access to NEWA plant disease risk and insect pest models

HOBO RX3000 Data Logger Specifications

Operating Range	-40° to 60°C (-40° to 140°F); no remote communications for battery voltage less than 3.9 V DC
Smart Sensor Connectors	10
Smart Sensor Network Cable Length	100 m (328 ft) maximum
Smart Sensor Data Channels	Maximum of 15 (some smart sensors use more than one data channel; see sensor manual for details)
Module Slots	2
Logging Rate	1 second (RX3001 and RX3002) or 1 minute (RX3003 and RX3004) to 18 hours
Time Accuracy	±8 seconds per month in 0° to 40°C (32°F to 104°F) range; ±30 seconds per month in -40° to 60°C (-40° to 140°F) range
Battery Type/Power Source	4 Volt, 10 AHr, rechargeable sealed lead-acid; external power required using one of these options: AC power adapter (AC-U30), solar panel (SOLAR-xW), or external power source 5 V DC to 17 V DC with external DC power cable (CABLE-RX-PWR)
Rechargeable Battery Service Life	Typical 3–5 years when operated in the temperature range -20° to 40°C (-4°F to 104°F); operation outside this range will reduce the battery service life
Memory	32 MB, 2 million measurements, continuous logging
Alarm Notification Latency	Logging interval plus 2–4 minutes, typical
Enclosure Access	Hinged door secured by two latches with eyelets for use with user-supplied padlocks
LCD	LCD is visible from 0° to 50°C (32° to 122°F); the LCD may react slowly or go blank in temperatures outside this range
Materials	Outer enclosure: Polycarbonate/PBT blend with stainless steel hinge pins and brass inserts; Inner enclosure: Polycarbonate; Gaskets: Silicone rubber; Cable channel: EPDM rubber; Cable opening cover: Aluminum with ABS plastic thumb screws; U-Bolts: Steel with zinc dichromate finish
Size	18.6 x 18.1 x 11.8 cm (7.3 x 7.1 x 4.7 in.); see diagrams on next page
Weight	2.2 kg (4.85 lb)
Mounting	3.8 cm (1.5 inch) mast or wall mount
Environmental Rating	Weatherproof enclosure, NEMA 4X (requires proper installation of cable channel system)
CE	The CE Marking identifies this product as complying with all relevant directives in the European Union (EU)
FC	**RX3002:** FCC ID R68XPICOW, IC ID 3867A-XPICOW **RX3003:** FCC ID QIPEHS6, IC ID 7830A-EHS6; approved for use in Taiwan and Japan **RX3004:** FCC ID QIPPLS62-W, IC ID:7830A-PLS62W
Wireless Radio	**RX3003:** GSM/GPRS/EDGE: Quad band 850/900/1800/1900 MHz, UMTS/HSPA+: Five band 800/850/900/1900/2100 MHz **RX3004:** GSM/GPRS/EDGE: Quad band 850/900/1800/1900 MHz UMTS/HSPA+: Seven band 800/850/900/1800/1900/2100 MHz LTE: Twelve Band 700/800/850/900/1800/1900/2100/2600 MHz
Antenna	**RX3003:** Penta band **RX3004:** 4G LTE

Ethernet (RX3001)	
Connector	One RJ45/100BaseT
Wi-Fi (RX3002)	
Network Standards	IEEE 802.11b/g/n

Frequency Range	2.412–2.484 GHz
Antenna Connector	1, no diversity supported
Data Rates	1, 2, 5.5, 11 Mbps (802.11b); 6, 9, 12, 18, 24, 36, 48, 54 Mbps (802.11g); 802.11n, HT20 MCS0 (6.5 Mbps) to HT20 MC87 (65 Mbps)
Number of Selectable Radio Subchannels	Up to 14 channels; profiles available will include USA, France, Japan, Spain, Canada, and "Other" (multiple countries)
Radio Modulations	OFDM, DSSS, DBPSK, DQPSK, CCK, 16QAM, 64QAM
Security	WEP 64/128, WPA-PSK, AES end-to-end encryption
Maximum Receive Level	-10 dBm (with PER <8%)
Receiver Sensitivity	-72 dBM for 54 Mbps, -87 dBm for 11 Mbps, -89 dBm for 5.5 Mbps, -90 dBm for 2.0 Mbps, -92 dBm for 1.0 Mbps
Cellular (RX3003 and RX3004)	
Wireless Radio	**RX3003:** GSM/GPRS/EDGE: Quad band 850/900/1800/1900 MHz, UMTS/HSPA+: Five band 800/850/900/1900/2100 MHz **RX3004:** GSM/GPRS/EDGE: Quad band 850/900/1800/1900 MHz UMTS/HSPA+: Seven band 800/850/900/1800/1900/2100 MHz LTE: Twelve Band 700/800/850/900/1800/1900/2100/2600 MHz
Antenna	**RX3003:** Penta band **RX3004:** 4G LTE

HoboNet Rainfall Sensor

ONSET

RXW-RGE-xxx Sensor

HOBOnet Rainfall (inches) Sensor

The HOBOnet Wireless AeroCone® Rain Gauge records rainfall in 0.01-inch increments. HOBOnet Wireless Sensors communicate data directly to the RX3000 weather station or pass data through other wireless sensors back to the central station. They are preconfigured and ready to deploy, and data is accessed through HOBOlink, Onset's innovative cloud-based software platform.

Supported Measurements:

Rainfall

Key Advantages:

Sensor Features

- Resolution of 0.01 inch
- Bird spikes
- Debris screen that locks in place
- Designed to meet World Meteorological Organization (WMO) guidelines

Wireless Features

- 900 MHz wireless mesh self-healing technology
- 450 to 600 meter (1,500 to 2,000 feet) wireless range and up to five hops
- Up to 50 wireless sensors per RX3000
- Simple button-push to join the HOBOnet wireless network
- Onboard memory to ensure no data loss
- Powered by rechargeable AA batteries and built-in solar panel

RXW-RGE-xxx Sensor Specifications

Sensor

Measurement Range	0 to 10.2 cm (0 to 4 in.) per hour, maximum 4,000 tips per logging interval
Accuracy	±4.0%, ±1 rainfall count between 0.2 and 50.0 mm (0.01 and 2.0 in.) per hour; ±5.0%, ±1 rainfall count between 50.0 and 100.0 mm (2.0 and 4.0 in.) per hour
Resolution	0.01 in.
Calibration	Requires annual calibration; can be field calibrated

Wireless Mote

Operating Temperature Range	-25° to 60°C (-13° to 140°F) with rechargeable batteries -40 to 70°C (-40 to 158°F) with lithium batteries
Radio Power	12.6 mW (+11 dBm) non-adjustable
Transmission Range	Reliable connection to 457.2 m (1,500 ft) line of sight at 1.8 m (6 ft) high Reliable connection to 609.6 m (2,000 ft) line of sight at 3 m (10 ft) high
Wireless Data Standard	IEEE 802.15.4
Radio Operating Frequencies	RXW-RGE-900: 904–924 MHz RXW-RGE-868: 866.5 MHz RXW-RGE-922: 916–924 MHz
Modulation Employed	OQPSK (Offset Quadrature Phase Shift Keying)
Data Rate	Up to 250 kbps, non-adjustable
Duty Cycle	<1%
Maximum Number of Motes	50 motes per one RX Wireless Sensor Network
Battery Type/ Power Source	Two AA 1.2V rechargeable NiMH batteries, powered by built-in solar panel or two AA 1.5 V lithium batteries for operating conditions of -40 to 70°C (-40 to 158°F)
Battery Life	With NiMH batteries: Typical 3–5 years when operated in the temperature range -20° to 40°C (-4°F to 104°F) and positioned toward the sun (see Deployment and Mounting), operation outside this range will reduce the battery service life With lithium batteries: 1 year, typical use
Memory	16 MB
Dimensions	Sensor: 16.5 cm opening diameter (6.5 in.) x 24 cm (9.5 in.) high; 214 cm2 (33.2 in.2) collection area Cable length: 2 m (6.6 ft) Mote: 16.2 x 8.59 x 4.14 cm (6.38 x 3.38 x 1.63 inches)
Weight	Sensor and cable: 1.2 kg (2.7 lbs) Mote: 223 g (7.87 oz)
Materials	Sensor: UV-stabilized ABS plastic housing; tipping bucket mechanism with magnetic reed switch pivots on metal shaft Mote: PCPBT, silicone rubber seal
Environmental Rating	Sensor: Weatherproof Mote: IP67, NEMA 6
Compliance Marks	FC RXW-RGE-900 CE RXW-RGE-868 RXW-RGE-922

HoboNet Soil Moisture Sensor

ONSET®

HOBO® RXW-SMD-xxx Sensor

HOBOnet Soil Moisture 10HS Sensor

The HOBOnet Wireless Soil Moisture Sensor integrates the field-proven ECH2O™ 10HS Sensor and provides readings directly in volumetric water content. The 10cm probes measure soil moisture over a larger volume of soil, helping to average out any soil variability. The sensor's high-frequency design minimizes sensitivity to salinity and textural effects, and gives it a wide measurement range. HOBOnet Wireless Sensors communicate data directly to the RX3000 weather station or pass data through other wireless sensors back to the central station. They are preconfigured and ready to deploy, and data is accessed through HOBOlink, Onset's innovative cloud-based software platform.

Supported Measurements:

Soil Moisture

Key Advantages:

Sensor Features

- ±3% accuracy in typical soil conditions, and ±2% accuracy with soil-specific calibration
- Measures a large 1-liter volume of soil, providing a more accurate picture of average soil moisture
- High-frequency (70 MHz) circuit provides good accuracy even in high-salinity and sandy soils.

Wireless Features

- 900 MHz wireless mesh self-healing technology
- 450 to 600 meter (1,500 to 2,000 feet) wireless range and up to five hops
- Up to 50 wireless sensors per RX3000
- Simple button-push to join the HOBOnet wireless network
- Onboard memory to ensure no data loss
- Powered by rechargeable AA batteries and built-in solar panel

HOBO RXW-SMD-xxx Sensor Specifications

Sensor

Measurement Range	In soil: 0 to 0.570 m /m (volumetric water content)
Extended Range	-0.659 to 0.6026 m /m ; see Note 1
Accuracy	±0.033 m /m (±3.3%) typical 0 to 50°C (32° to 122°F) for mineral soils up to 10 dS/m and ±0.020 m /m (±2%) with soil specific calibration; see Notes 4 and 5
Resolution	0.0008 m /m (0.08%)
Volume of Influence	1 liter (33.81 oz)
Sensor Frequency	70 MHz
Sensor Operating Temperature Range	0° to 50°C (32° to 122°F). Although the sensor probe and cable can safely operate at below-freezing temperatures (to -40°C/F), the soil moisture data collected at these extreme temperatures is outside of the sensor's accurate measurement range. Extended temperatures above 50°C (122°F) will decrease mote battery life.

Wireless Mote

Operating Temperature Range	-25° to 60°C (-13° to 140°F) with rechargeable batteries -40 to 70°C (-40 to 158°F) with lithium batteries
Radio Power	12.6 mW (+11 dBm) non-adjustable
Transmission Range	Reliable connection to 457.2 m (1,500 ft) line of sight at 1.8 m (6 ft) high Reliable connection to 609.6 m (2,000 ft) line of sight at 3 m (10 ft) high
Wireless Data Standard	IEEE 802.15.4
Radio Operating Frequencies	RXW-SMD-900: 904–924 MHz RXW-SMD-868: 866.5 MHz RXW-SMD-922: 916–924 MHz
Modulation Employed	OQPSK (Offset Quadrature Phase Shift Keying)
Data Rate	Up to 250 kbps, non-adjustable
Duty Cycle	<1%
Maximum Number of Motes	50 motes per one RX Wireless Sensor Network
Battery Type/ Power Source	Two AA 1.2V rechargeable NiMH batteries, powered by built-in solar panel or two AA 1.5 V lithium batteries for operating conditions of -40 to 70°C (-40 to 158°F)
Battery Life	With NiMH batteries: Typical 3–5 years when operated in the temperature range -20° to 40°C (-4°F to 104°F) and positioned toward the sun (see Deployment and Mounting), operation outside this range will reduce the battery service life With lithium batteries: 1 year, typical use
Memory	16 MB
Dimensions	RXW-SMD-xxx soil probe: 89 x 15 x 1.5 mm (3.5 x 0.62 x 0.06 in.) Cable length: 5 m (16.4 ft) Mote: 16.2 x 8.59 x 4.14 cm (6.38 x 3.38 x 1.63 inches)
Weight	RXW-SMD-xxx sensor and cable: 180 grams (6.3 oz) Mote: 223 g (7.87 oz)
Materials	Sensor: Weatherproof Mote: PCPBT, silicone rubber seal
Environmental Rating	Mote: IP67, NEMA 6
Compliance Marks	FC RXW-SMD-900 CE RXW-SMD-868 RXW-SMD-922

****