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 – Phase 2

Prepared For:

Stormwater Action Monitoring
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Table of Contents

List of Figures

1.0 Introduction and Background

1.1 Introduction

Trees in forested watersheds manage large volumes of runoff through interception and transpiration. Trees not only intercept rainfall with their canopies (Interception), but also remove water from soils with their extensive root systems (Transpiration). In the face of urban development, surfaces that typically absorb rainfall, like trees and natural soils, are replaced with impervious surfaces like roads, pavements, and roofs. This alteration of the landscape for urbanization has had serious hydrological consequences, where large amounts of stormwater runoff are generated, causing flooding and the transport of pollutants to sensitive receiving waters. In Washington State, stormwater regulations for new and redevelopment sites require urban runoff to mimic the runoff characteristics of forest conditions in the western half of the state. For existing and future development, reintroducing trees and retaining older trees can limit the volume of runoff where stormwater flows are unmitigated in urban landscapes (Berland et al. 2017; Kuehler et al. 2017; Carlyle-Moses et al. 2020).

Trees reduce the amount of stormwater generated through interceptive and transpirative processes. To maximize the stormwater benefits trees provide, it is essential to understand the environmental and physiological factors affecting tree water-use. This is completed using tree-water budgets for common tree species in their native environments.

1.2 Problem Description

The purpose of this work is to create a hydrologic dataset of measured transpiration in existing common evergreen and deciduous trees in western Washington. We recently completed Phase 1 of this study focused on mature native trees that grow in small, forested stands. Phase 2 (described in this document) will measure transpiration rates in individual younger trees that tend to typify the type of trees growing in urban landscapes. A proper valuation of individual trees and the direct measurement of transpirative processes is a central tenet of this work.

The study is based on instrumenting and comparing individual trees at the Evergreen State College campus and several isolated urban trees in and around Olympia, WA. The trees will be instrumented with sensors that measure transpiration. When combined, data from these sensors will provide a complete view of how much rainfall is managed by individual trees, or in simple terms, the rainfall that did NOT end up as stormwater runoff.

Urban trees located in parks, natural areas, street-side and on private lands can provide excellent opportunities to mitigate the effects of stormwater runoff in the Puget Sound. While the runoff mitigation potential of forest or large tree stands is well known, there is still the need to quantify stormwater mitigation values associated with individual trees. We propose to address this need by measuring transpiration directly through sap flux in individually growing younger trees in urban areas.

1.3 Results of Prior Studies

The current credit system outlined in "[Tree Retention and Tree Planting]" BMP in Ecology's SWMMWW (Washington State Department of Ecology, 2014, BMP T5.16) is based on studies that predate Phase 1 of this project. The current "tree 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 derived from three lysimeter studies conducted in the 1950s (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. They estimated that transpiration ranged between 66% and 68% of the total water vapor flux above the forest canopy.

Phase 1 of this study calculated transpiration and interception rates, Table 3.3.1, as 66% and 53% of annual rainfall for evergreen and deciduous trees, respectively. These values are based on measuring mature trees in small, forested stands.

In Phase 2, we will continue to measure transpiration and interception rates of a subset of trees studied in Phase1 for comparison with individual “street” trees that are likely younger, surrounded by urbanized landscapes, and whose canopy is isolated from other proximal trees.

Table 1.3.1: Summed transpiration and interception values from Phase 1 of this study.

Season	**Leaf-Off (Nov-April)**		**Leaf-On (May-Oct)**		**Annual Totals**	
Storm totals (cm)	124.8		42.9		167.6	
	Median transpiration + interception values by species					
Tree Species	%	cm	%	cm	%	cm
Bigleaf Maple	27.6%	34.4	126.5%	54.3	52.9%	88.7
Red Alder	30.6%	38.2	76.2%	32.7	42.3%	70.9
Douglas-fir	57.2%	71.4	73.1%	31.3	61.3%	102.7
Western redcedar	63.3%	79.0	72.6%	31.1	65.7%	110.1

2.0 Project Overview

The purpose of this study is to continue and expand upon the first phase of the Stormwater Action Monitoring (SAM) study that evaluated stormwater mitigation potential of local individual trees.

The Phase 1 tree study, described above, successfully developed a hydrologic dataset that shows how an individual tree captures rainfall and mitigates stormwater. While Phase 1 focused on mature trees in a forest setting, the aim of the second Phase 1s to expand these methods to include younger and smaller trees near or over impervious surface where stormwater impacts are big, and trees less vigorous.

2.1 Study Goal

The overall goals of this Phase 2 project are to 1) validate that findings from Phase 1 apply across a range of tree sizes, and 2) quantify stormwater mitigation values of young and isolated evergreen and deciduous trees based on the physio-climatic conditions of the western Washington.

Accordingly, our sample design will consist of two sets of sample trees. Trees from Phase 1 that will continue to be measured that will be designated as “Phase 1 – Confirmatory” (P1C), and those new and smaller trees measured in this Phase that will be designated as “Phase 2 – Experimental” (P2E). First, we will select “Phase 1 – Confirmatory” trees across a range of diameters at the location of the Phase 1 sap flux installation. The range will allow us to quantify any potential changes (or lack of change) among trees that vary in size, thereby enhancing our confidence in extrapolating our findings to a variety of small and large trees present in developed areas. Older and larger (<12 inches DBH) trees are also less sensitive to damage, and thus present better opportunities for repeatedly installing the newer Phase 2 sensors without damaging the permanently instrumented tree (e.g., repeated drilling in small trees can result in long term damage and affect our estimates of transpiration). The instrumented trees at the Phase 1 location on the Evergreen State College campus will allow a direct comparison of measurements taken using the standard sap flux set up and the newer Phase 2 probes. The Phase 1 Confirmatory tree design has three purposes: 1) establish the nature of the relationship between tree size and sap flux rates,

2) provide consistent measurements in trees that are more resistant to damage from repeated probe installation, and 3) provide the opportunity to directly compare transpiration estimates from statics and mobile sap flux set-ups – providing a quality check on the newer mobile unit approach.

2.2 Study Description and Objectives:

Two sap flux systems from the original Phase 1 study will be deployed at the previous study locations on The Evergreen State College (TESC) campus. These two sap flux setups will ensure that Phase 1 and Phase 2 of the studies relate to continuously logging sensors that will help maintain continuity of the data record, and associated variability of sap flux data. Ten Douglas fir trees and ten big leaf maple trees will be monitored as part of this work. This phase of the study will measure transpiration rates and canopy interception across a range of tree sizes. Stem flow will be inferred from Phase 1 of the study.

Douglas Fir and Big Leaf Maple trees will be selected for the P1C trees because of the importance and 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. Tree species selected for the P2E trees will depend on their availability in developed areas and selected parking lots.

Phase 2 is designed to target more visible and younger trees which will require better security for equipment and a power supply. This creates a challenge for the sap flux technology which currently requires proximity to a power source and installation of large semi-permanent instrumentation. To account for this challenge, Washington State University (WSU) and TESC have developed a mobile data logger that is smaller and therefore discrete, cheaper, and has its own power supply. These mobile data loggers will be connected to the same thermal dissipation probes (TDP) used in Phase 1 and will be deployed for 24-48 hours periods on 10-20 trees per measurement event, for at least 12 measurement events per year. This will ensure that the devices are not left out in the open for extended periods, minimizing the likelihood of vandalism and theft. Measurement events can also take place across multiple different locations (new locations/trees for each event), maximizing the inference for street tree water use across the region.

The objectives of Phase 2 are to expand on findings and methods developed in Phase 1 to measure and compare Douglas fir and Bigleaf maple trees in different size classes and growing conditions.

Specific project objectives are:

1. Establish baseline relationships between tree size and sap flux for two of the most common trees in our region: evergreen tree (Douglas-fir), and deciduous tree (Bigleaf Maple). These baseline relationships will provide better information for the application of Phase 1 results to trees of variable size in the region.
2. Continue measuring a subset of trees from year 1 to develop a multi-year dataset on annual transpiration rates to ensure quality control for a newer mobile sap-flux measurement approach.
3. Extend sap flux sampling to urban trees in developed areas using a mobile sap flux technology approach. Provide robust estimate for urban tree transpiration based on empirical estimates.
4. Estimate annual canopy interception rates for urban trees based on Phase 1 results and opportunistic sampling at trees in urban growing conditions (trees planted in medians, sidewalks, or islands near paved locations).

2.3 Study Location

The two study locations in the south Puget Sound region near Olympia, WA will be selected to represent developed or developing landscapes in western Washington.

1. Study Location 1: The Evergreen State College (TESC) located at approximately 47° 4'14"N by 122°59'7"W. This location will leverage established site developed in Phase 1 northeast of the organic farm.
2. Study Location 2: Individual trees on the surrounding urban areas will be selected within 1 mile of Study Location 1 on TESC, but will be selected to include trees growing in urban conditions

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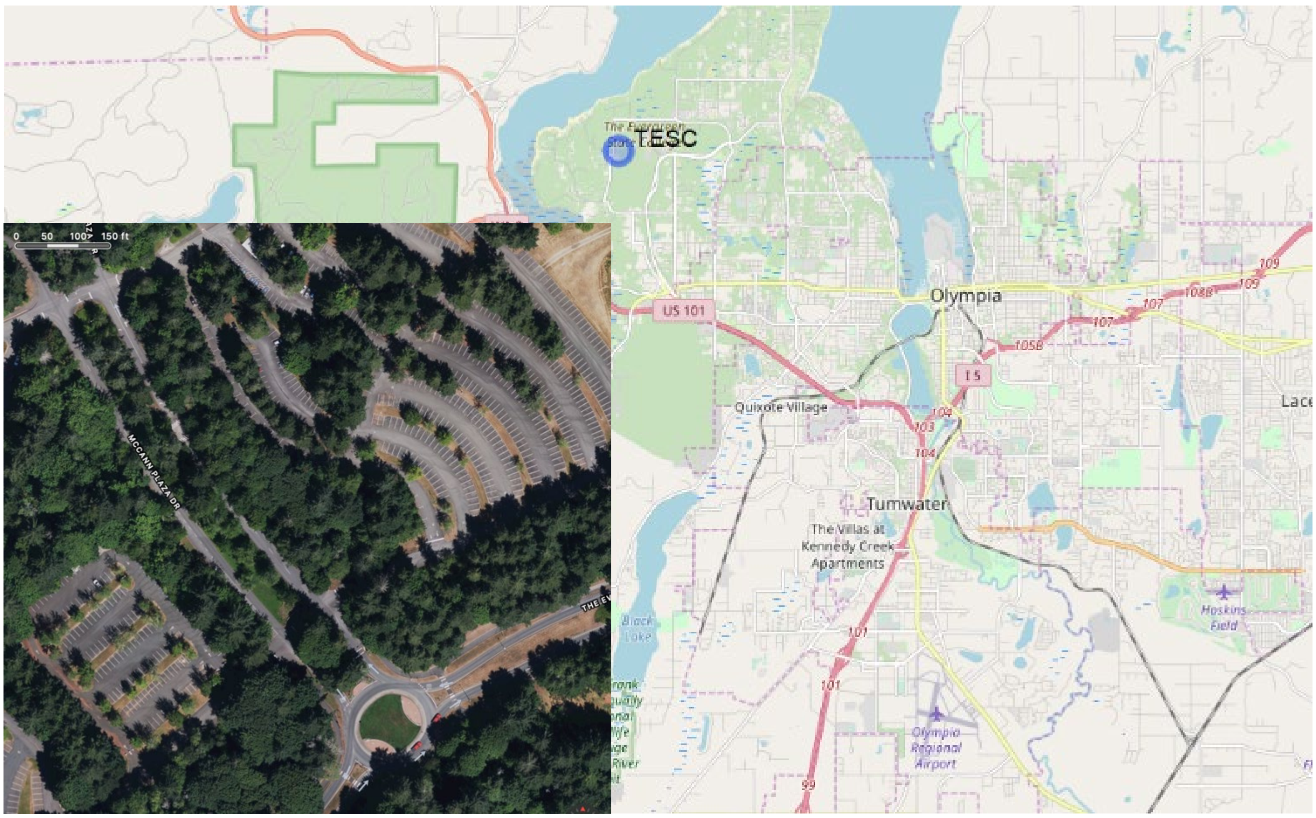

Figure 1: Map of study locations showing The Evergreen State College (TESC) in the Olympia-area of western Washington and the surrounding areas where mobile sensors will be opportunistically and synoptically installed. Inset (lower left color photo) shows parking lot locations at The Evergreen State College where trees have been selected for study.

2.4 Data Needed to Meet Objectives

Data needed to meet the study objectives are:

1. Sap flux:
   - P1C Trees: Sap flux measurements will be made on 10 evergreen trees and 10 deciduous trees intentionally chosen to represent a gradient in tree sizes at TESC.
   - P2E Trees: We will deploy mobile sapflux units episodically throughout the growing season at individual trees located around the TESC campus and its neighborhoods (as availability allows).

2. Climatic data at TESC using a research-grade weather station 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
3. Throughfall rates: Throughfall will be measured by installing rain gages at locations under tree canopies measured for sap flux.
4. Canopy Interception: Canopy interception will be estimated by subtracting measured rainfall under a tree canopy from rainfall measured under no canopy or open canopy.

2.5 Tasks Required to Conduct Study

- Task 1 – Phase 1 Factsheet development (completed)
- Task 2 – Project Administration

  DNR will facilitate project administration by ensuring that project deadlines are met, completing purchasing needs, and ensuring timely communications with SAM.
- Task 3 – Quality Assurance and Project Protocol (QAPP) amendment

  Prepare a Quality Assurance Protocol Plan (QAPP) for approval by Dept. of Ecology.
- Task 4 – Instrument installation and monitoring

  Sensors will be installed at all site locations with effort provided by all parties involved, including personnel from WSU, WA DNR, 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, Process and Submittal

  Data will be analyzed using open source statistical and graphing software.
- Task 7 – Final Report
- Task 8 – Outreach/communication

2.6 Potential Constraints

Vandalism of instrumentation at TESC is a potential constraint, as is the potential for sensor failure at the site. 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 conditions that may impact the project schedule, budget, or scope. If potential constraints 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.3.0 Organization and Schedule

3.1 Key Project Team Members: Roles and Responsibilities

Key Team Members	Role	Responsibility
Abby Barnes, WDNR Abby.Barnes@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
Dylan Fischer, TESC fischerd@evergreen.edu	Project Technical co-lead	Oversight of research at TESC
Chelsea Morris Ecology SAM project manager chelsea.morris@ecy.wa.gov	Ecology Project Manager	Reviews all deliverables, including QAPP.
Brandi Lubliner SAM Coordinator, Ecology brandi.lubliner@ecy.wa.gov	QA Review	Provides Ecology QA approval of the QAPP.
Steven Quick, TESC Steven.Quick@evergreen.edu	data analyst	Graduate Student, data collection and analyses

Table 3.2 TAC - Effectiveness of Trees in Mitigating Stormwater Runoff Members

Name	Title	Roles
Joseph Hulbert	WSU Ravenholt Urban Forest Health, Lab Director	TAC Member
Mike Carey	City of Tacoma, Urban Forester	TAC Member
Chelsea Morris	Ecology SAM project manager	SAM Coordinator

3.2 Project Schedule

Task 2. Project Administration	D 2.1. Bi-Annual Report 1	3/31/2023
	D 2.2. Bi-Annual Report 2	6/30/2023
	D 2.3. Bi-Annual Report 3	12/31/2023
Task 3. QAPP Amendment	D 3.1. Draft QAPP	2/1/2023
	D 3.2. Final approved QAPP	2/15/2023
Task 4. Instrument Installation and Monitoring	D 4.1. Email and installation photos confirming successful installation of instruments with photos	2/31/2023
Task 5. Instrument Maintenance and Data Downloads	D 5.1 Email confirming successful installation of instruments with photos	2/31/2023
Task 6. Data analysis, process, & submittal	D 6.1 Copy of data in excel format	3/31/2024
Task 7. Final report	D 7.1 Draft report to Ecology for comment	4/30/2024
	D 7.2. Final report	5/31/2024
Task 8. Outreach/communication	D 8.1 Copy of presentation with stormwater managers and SWG	6/30/2024
	D 8.2. Electronic copy of Fact sheet draft	6/30/2024

4.0 Quality Objectives

The primary data quality objectives for this project are to ensure that the measured data adequately represent sap flux, throughfall, soil moisture, and climatic conditions in and around the 20 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 in this section and only those data that meet and exceed our data quality requirements will be used for additional analyses.

4.1 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
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%.

4.2 Precision

Precision is the measure of agreement among repeated measurements of the same property taken under identical or 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
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.

4.3 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). Some environmental sensors used in this study will be deployed to measure data on a continuous basis, while others will be intermittently deployed 1-2 times per month during the growing season. 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 throughout each year in the region.

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

Sensor	**Approaches for Addressing Representativeness**
Weather station	Data will be recorded at 15-minute intervals over the entire 24-month period of the study. A weather station is installed in an open canopy area which measures climatic conditions at that location. 12 storm events, and 12 inter-storm (dry) events will be considered representative.
Sap flux sensors (P1C)	Data will be measured at 15-minute intervals over the entire 24-month period of the study. Phase 1 Confirmatory (P1C) sap flux sensors will be installed at each study tree with the objective of measuring sap flux enabling the estimation of transpiration within the entire sap wood cross section for that particular tree. A total of 10 evergreen and 10 deciduous trees will be instrumented.
Sap flux sensors (P2E)	Phase 2 Experimental (P2E) sap flux sensors will be installed at ~10 ornamental deciduous trees at the Evergreen Parking Lot site, and in the P1C trees identified above. Probes will be installed in the sapwood of each tree, and measurements will be taken 1-2 days per month during the growing season.
Through fall gage	Two rain gage transects under a single canopy will ensure some level of representativeness assuming homogeneity in canopy density between the two transects. 12 storm events, and 12 inter-storm (dry) events will be considered representative.

4.4 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
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. A weather station is installed in an open canopy area to measure climatic conditions at the 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 for the P1C trees. Sap flux sensors will be installed at each study tree with the objective of measuring sap flux in the sapwood, enabling estimation of transpiration within the entire sap wood cross section for that tree. For P2E trees, sensors will be activated for 24–48-hour periods, at least once a month during the growing season in the period of the study.
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. 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.

4.5 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
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.

4.6 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
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%)

5.0 Experimental Design

5.1 Study Design Overview

Interception and transpiration rates will be measured for 30 trees selected to represent a range of size classes and growing conditions. Twenty trees will be instrumented at TESC to determine transpiration rates in one evergreen and one deciduous tree species. Additionally, mobile sap flux sensors will be deployed at 10 isolated trees on the TESC campus in built/developed locations (parking lots, parking islands, sidewalk green-strips). At TESC, a weather station is installed to measure microclimatic variability. For the mobile locations, publicly available climatic data will be recorded using nearby weather stations (e.g., https://weather.evergreen.edu).

5.2 Sampling-Site(s) Selection Process

The Evergreen State College (TESC) was selected as a sampling-site for this study. The location of this site is presented in Figure 1. The site was chosen based on successes from Phase 1.

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. Two plots on campus were chosen and 20 trees were tagged as candidates. These areas are northeast of the organic farm (Figure 2). Within each area, two sap flow stations were marked with 10 trees within a 50 ft. perimeter assigned to each station.

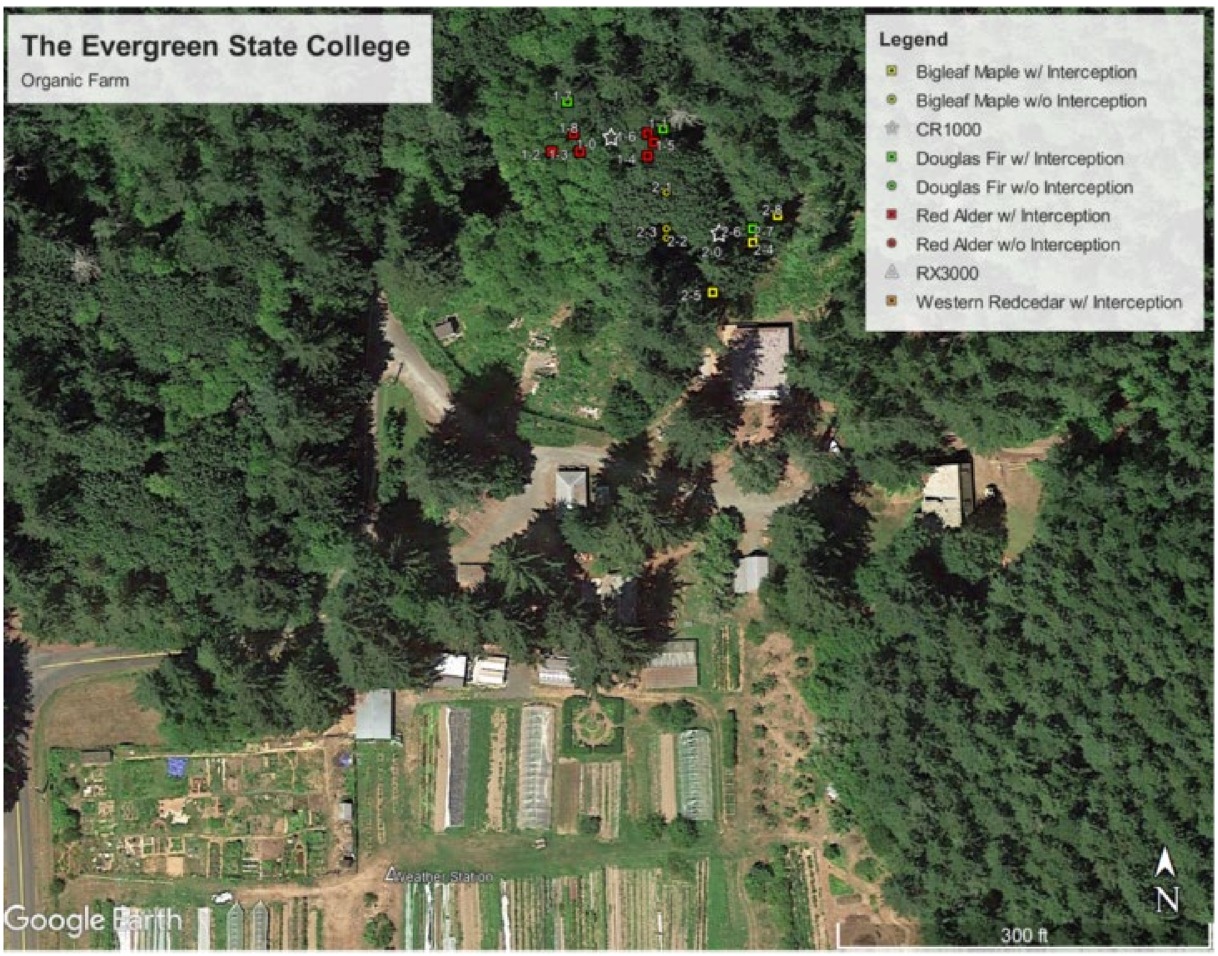

Figure 2: Two plots in the organic farm area of TESC. CR1000 deP1Cts one sap flux datalogger. RX3000 denotes one interception-soil moisture datalogger.

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5.3 Tree selection process

Some trees from Phase 1 of this study will continue to be monitored in order to ensure data continuity. We will select 20 new trees that are smaller than 12” DBH from within plots at the organic farm and the parking lot on TESC campus.

Table 7.3.1: Summary trees by size class that will be instrumented for sap flux.

	Tree ID	Species	DBH (cm)	Size class	Fixed or Mobile	Throughfall	Experimental Design
1	1	BM	8	<12-inch DBH	Fixed	No	Phase 2 - Experimental
2	2	BM	24	<12-inch DBH	Fixed	No	Phase 2 - Experimental
3	3	BM	53	>12-inch DBH	Fixed	No	Phase 1 - Confirmatory
4	4	BM	63	>12-inch DBH	Fixed	No	Phase 1 - Confirmatory
5	5	BM	96	>12-inch DBH	Fixed	Yes	Phase 1 - Confirmatory
6	1	DF	24	<12-inch DBH	Fixed	No	Phase 2 - Experimental
7	2	DF	45	>12-inch DBH	Fixed	No	Phase 1 - Confirmatory
8	3	DF	61	>12-inch DBH	Fixed	Yes	Phase 1 - Confirmatory
9	4	DF	68	>12-inch DBH	Fixed	No	Phase 1 - Confirmatory
10	5	DF	91	>12-inch DBH	Fixed	Yes	Phase 1 - Confirmatory
11	1	BM	9	<12-inch DBH	Fixed	Yes	Phase 2 - Experimental
12	2	BM	13	<12-inch DBH	Fixed	No	Phase 2 - Experimental
13	3	BM	40	>12-inch DBH	Fixed	Yes	Phase 1 - Confirmatory
14	4	BM	55	>12-inch DBH	Fixed	No	Phase 1 - Confirmatory
15	5	BM	84	>12-inch DBH	Fixed	No	Phase 1 - Confirmatory
16	1	DF	24	<12-inch DBH	Fixed	Yes	Phase 2 - Experimental
17	2	DF	27	<12-inch DBH	Fixed	No	Phase 2 - Experimental
18	3	DF	41	>12-inch DBH	Fixed	No	Phase 1 - Confirmatory
19	4	DF	65	>12-inch DBH	Fixed	No	Phase 1 - Confirmatory
20	5	DF	74	>12-inch DBH	Fixed	No	Phase 1 - Confirmatory
21	TBD	BM	< 35	<12-inch DBH	Mobile	Yes	Phase 2 - Experimental
22	TBD	BM	< 35	<12-inch DBH	Mobile	Yes	Phase 2 - Experimental
23	TBD	BM	< 35	<12-inch DBH	Mobile	Yes	Phase 2 - Experimental
24	TBD	BM	< 35	<12-inch DBH	Mobile	Yes	Phase 2 - Experimental
25	TBD	BM	< 35	<12-inch DBH	Mobile	Yes	Phase 2 - Experimental
26	TBD	DF	< 35	<12-inch DBH	Mobile	Yes	Phase 2 - Experimental
27	TBD	DF	< 35	<12-inch DBH	Mobile	Yes	Phase 2 - Experimental
28	TBD	DF	< 35	<12-inch DBH	Mobile	Yes	Phase 2 - Experimental
29	TBD	DF	< 35	<12-inch DBH	Mobile	Yes	Phase 2 - Experimental
30	TBD	DF	< 35	<12-inch DBH	Mobile	Yes	Phase 2 - Experimental
31	TBD	Assorted	< 35	<12-inch DBH	Mobile	No	Phase 2 - Experimental
32	TBD	Assorted	< 35	<12-inch DBH	Mobile	No	Phase 2 - Experimental

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	Tree ID	Species	DBH (cm)	Size class	Fixed or Mobile	Throughfall	Experimental Design
33	TBD	Assorted	< 35	<12-inch DBH	Mobile	No	Phase 2 - Experimental
34	TBD	Assorted	< 35	<12-inch DBH	Mobile	No	Phase 2 - Experimental
35	TBD	Assorted	< 35	<12-inch DBH	Mobile	No	Phase 2 - Experimental
36	TBD	Assorted	< 35	<12-inch DBH	Mobile	No	Phase 2 - Experimental
37	TBD	Assorted	< 35	<12-inch DBH	Mobile	No	Phase 2 - Experimental
38	TBD	Assorted	< 35	<12-inch DBH	Mobile	No	Phase 2 - Experimental
39	TBD	Assorted	< 35	<12-inch DBH	Mobile	No	Phase 2 - Experimental
40	TBD	Assorted	< 35	<12-inch DBH	Mobile	No	Phase 2 - Experimental

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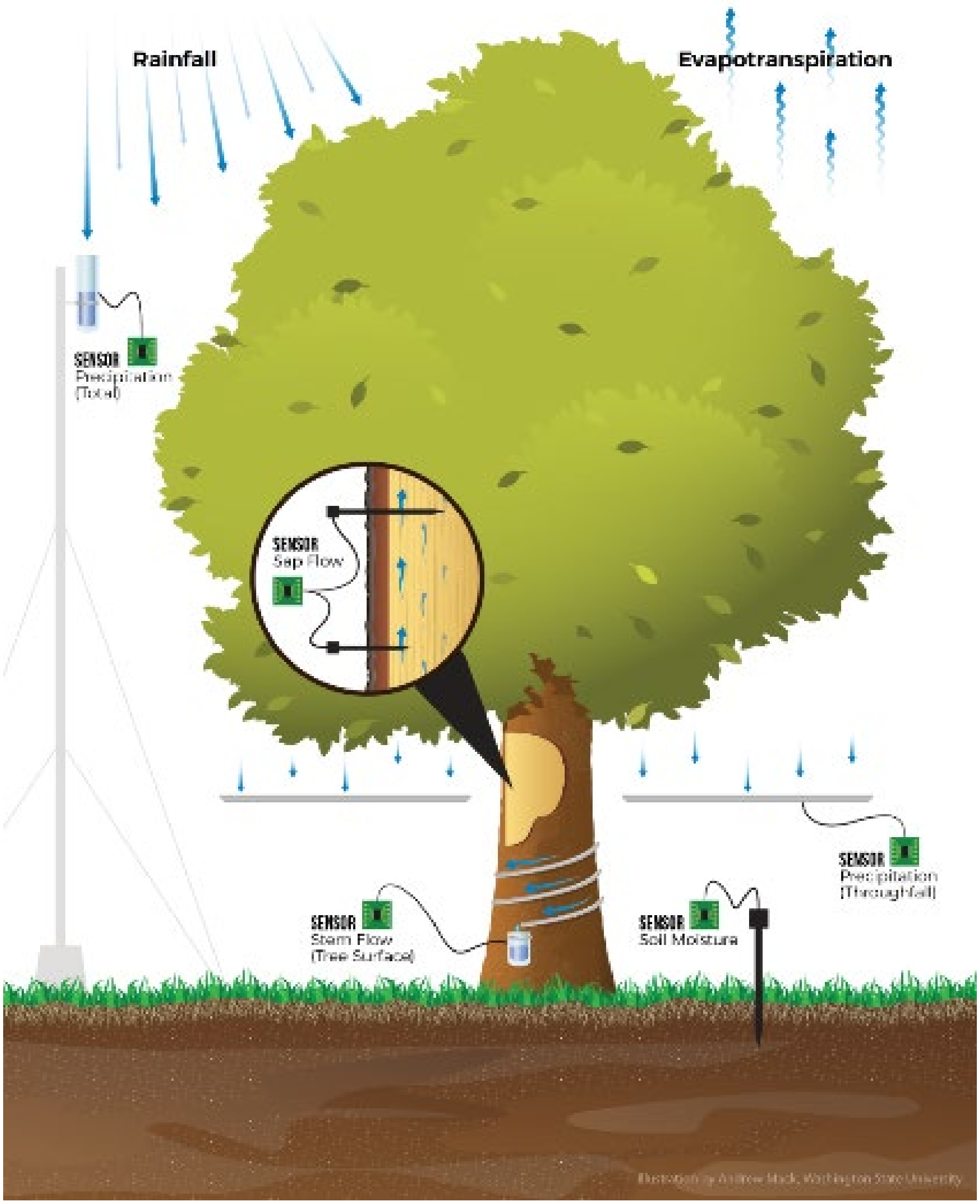

Figure 3: Sensor deployment strategy designed to quantify interception and transpiration

5.4 Testing and validating mobile sensors

The mobile sensors are developed. The following steps will be undertaken to test and validate the mobile sensors

1. Confirm adequate battery life to run the desired number of probes for at least 24 hours

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- Use Digital Multimeter (DMM) to measure the current from a mobile probe setup in lab conditions, confirm the battery selected has large enough capacity to power device for 24 hours
- Test mobile probe setup in field conditions to confirm realized battery capacity will run the probes for the minimum 24-hour period. This will take place on test trees at the WSU-PREC campus.

2. Confirm adjustable voltage regulator on the mobile probe setups are supplying probe heaters consistently with the correct voltage.
   - Measure the output voltage on the adjustable voltage regulator using a DMM and compare the DMM values to the displayed values on the digital display of the voltage regulator. If values displayed differ from the DMM by ± 5%, a DMM should be used to set voltage before deployment
   - Test the adjustable voltage regulator for consistency and drift by deploying a mobile tree probe setup for 8 hours and taking DMM voltage measurements every hour. Confirm that output stays within ± 5%.

3. Confirm sap-flux readings are accurate and reliable
   - Gravimetrically calibrate probes to sap-flow rates using methods described in Zeng et al. 2022.
   - Probe test trees at TESC with both mobile probe setups and Dynamax TDP system. Compare values of both systems to confirm mobile probe readings match those of the Dynamax system.

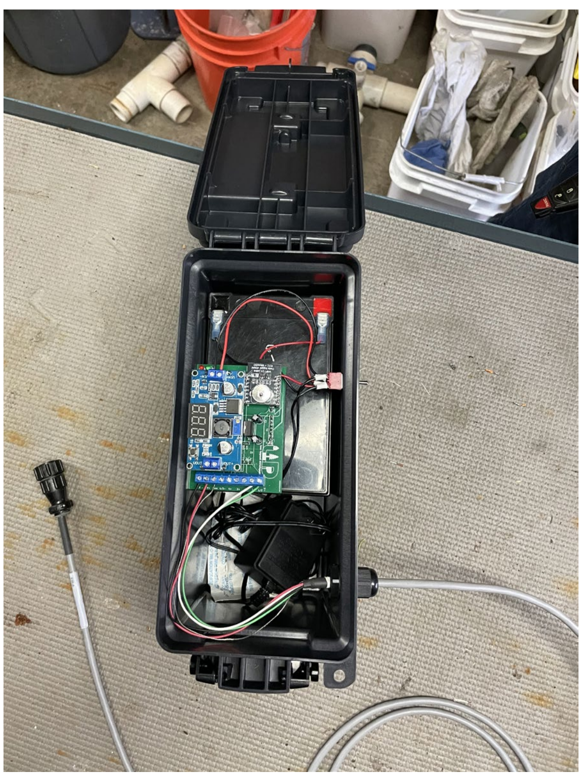

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Figure 6: Completed mobile sensor with datalogger, power supply, and housing.

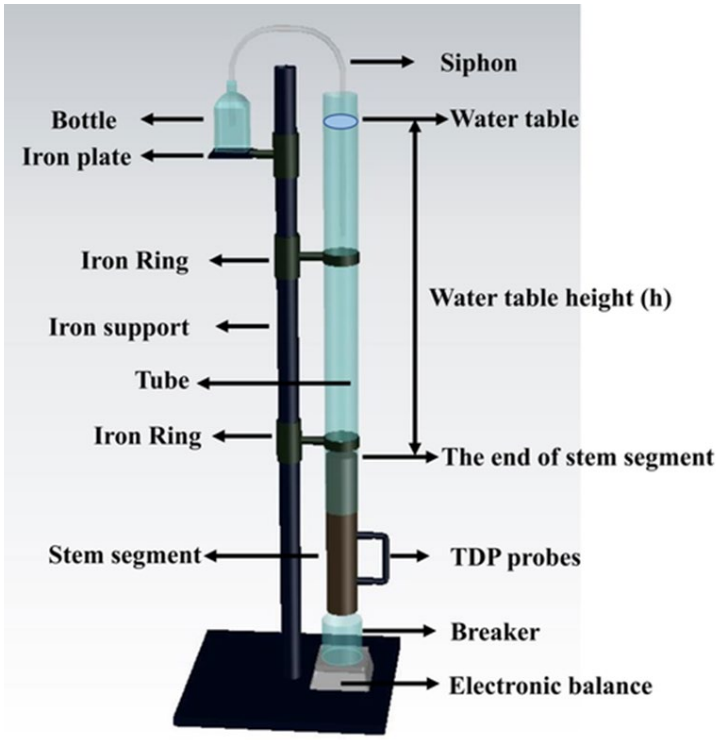

Figure 7: Gravimetric TDP calibration setup for testing TDP probes connected to the mobile datalogger unit.

5.5 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 TESC. 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 20 trees. The 20 trees will be distributed amongst locations, tree plots, and tree species as best as possible. Based on initial investigations at TESC, 10 Big Leaf Maple, and 10 Douglas Fir have been identified for instrumentation of canopy throughfall.
3. Continuously measured sap flux data recorded at 15-minute intervals at 20 trees that are distributed across the study plots. Based on initial investigations at both sites, 10 Big Leaf Maple, and 10 Douglas Fir have been identified for continuous sap flux instrumentation.
4. We will measure sap flux from other street trees using a mobile sap flux sensor unit over discrete 24–48-hour periods.

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5. Discretely measured tree metrics such as canopy area, leaf area index, tree diameter at breast height, will be measured for every one of the 20 instrumented trees.

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

6.0 Sampling & Monitoring Procedures

6.1 Standard Operating Procedures

1. Climatic data will be measured using a weather station (HOBO-Onset) installed at the Organic Farm at TESC. Weather station was 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 bi-monthly basis. A rain gage calibration kit will be used to ensure the rain gage is appropriately calibrated. Maintenance will ensure that batteries are charged and that sensors are not obscured by debris.
2. Canopy throughfall instrumentation will comprise arranging 4 rain gages in two lines, as shown in the figure below. Two rain gages will be placed along each line, so that they represent a third of the distance between the tree trunk and canopy drip line. The 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.

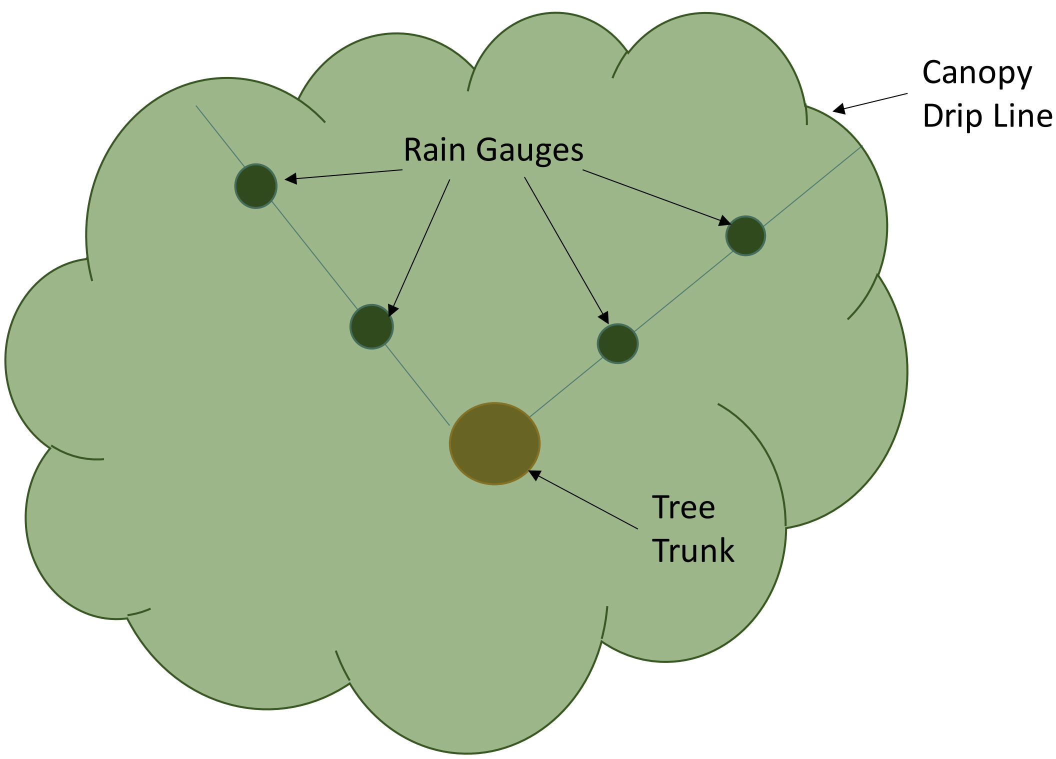

Figure 8: Profile (top) view of rain gages used to measure canopy throughfall.

3. Soil moisture data will be measured at each of the 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.

4. Continuously measured sap flux data will be recorded at 20 trees using 4 Dynamax DL2e systems connected to Granier probes installed 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 Dr and Fischer. In brief, probes will be installed at various depths depending on the diameter of the tree
5. Tree metrics such as canopy area, leaf area index, tree diameter at breast height, will be measured for all 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 and sapwood area.

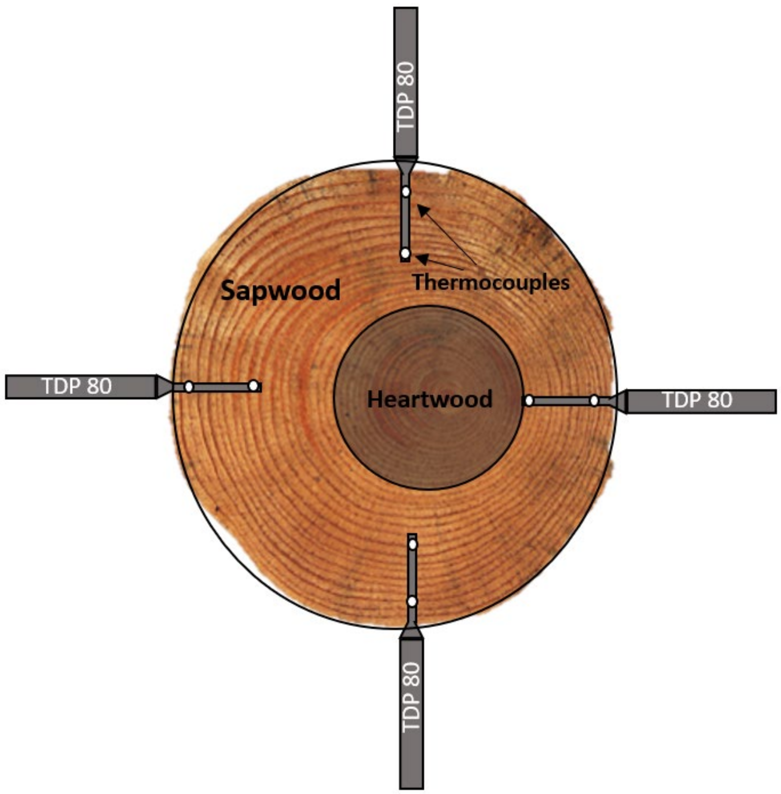

Figure 9: Profile view of TDP sensors installed in the sapwood of a tree. Probes are placed evenly around the circumference of the tree to compensate for non-uniform growth patterns and sap flow variations around the circumference of the tree.

6.2 Field Log Requirements

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

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- 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.

7.0 Measurement Procedures

7.1 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.

9.0 Quality Control

9.1 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

9.2 Corrective Action

Corrective actions will be required to respond to either (1) physical failure of instrumentation (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).

For erroneous sap flux data, or TDP sensors that are not connecting properly, 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.

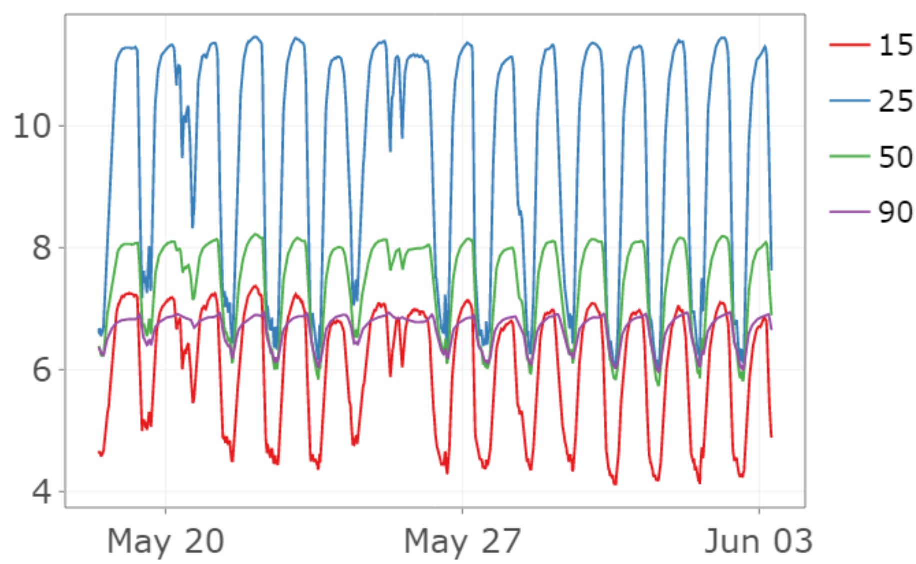

Figure 10: Example of good sap flux data

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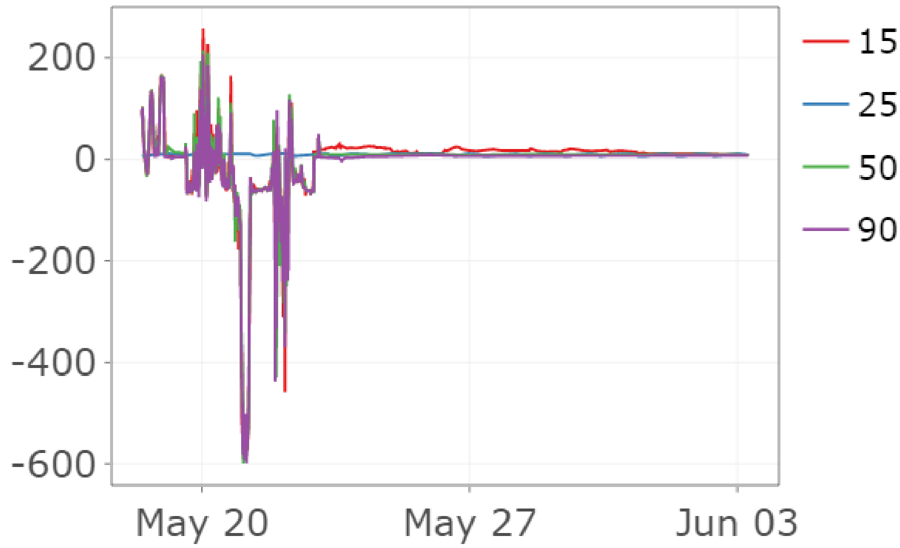

Figure 4: Example of poor sap flux data

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10.0 Data Management Plan Procedures

10.1 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, and climatic 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 in 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.

10.2 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 at TESC using a 900 MHz wireless mesh technology. From the receiving station, data will then be transmitted to a central database at WSU via cellular modem network.

10.3 Laboratory Data Package Requirements

Not applicable

10.4 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.

10.5 Acceptance Criteria for Existing Data

Not applicable

****

10.6 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 and MS Teams. 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.

11.0 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.

11.1 Technical System Audits

Audits of the technical system include:

1. Verifying that field staff are following the SOPs for sensor maintenance and sensor calibration
2. Verify the data management procedures are followed including field data recording

12.0 Data Verification and Usability Assessment

12.1 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 sites that are not a part of this study.

12.2 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.

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13.0 Data Analysis Methods

13.1 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.

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. 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. 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 not be available as stormwater runoff.

13.2 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.

14.0 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).

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16.0 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

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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

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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

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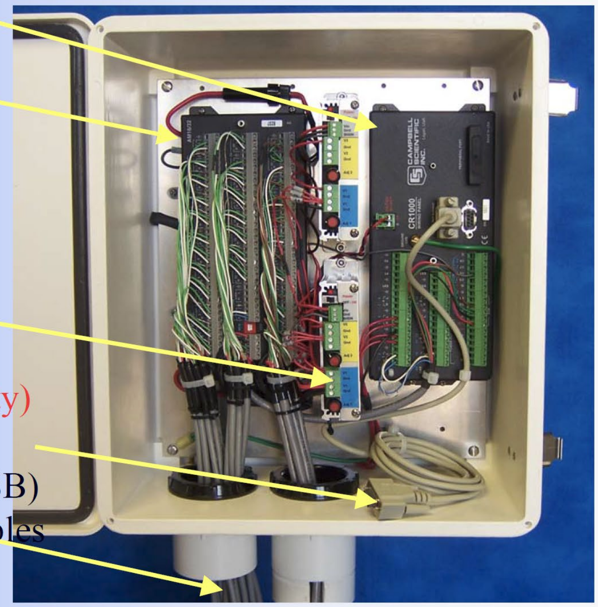
FLGS – TDP Specifications

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



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Appendix C Hobo Net System

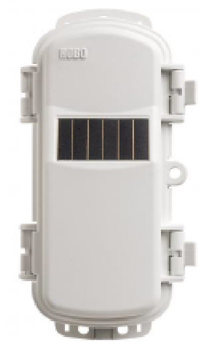
Onset Repeater

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

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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

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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

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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

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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

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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

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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

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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

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