Stormwater Action Monitoring - Effectiveness Studies

Quality Assurance Project Plan (QAPP) -

Evaluation of Hydraulic Control Approaches for Bioretention Systems

Prepared For:

Contact Name:	Brandi Lubliner PE
Lead Entity Jurisdiction	Washington State, Department of Ecology
Department	Stormwater Action Monitoring
Address	P.O. Box 47600
City, Washington, Zip Code	Olympia, Washington, 98504-7600
Phone Number	(360) 407-6158

Prepared By:

Washington State University	Geosyntec Consultants
Puyallup Research and Extension Center	920 SW Sixth Ave
2606 W Pioneer Ave	Suite 600
Puyallup, WA 98371	Portland, OR 97205
253-445-4523	971-271-5912

Date: November 2020

August 20, 2020

QAPP Author and Contact Information

Myles Gray
Geosyntec Consultants
920 SW Sixth Ave., Suite 600
Portland, OR 97204
mgray@geosyntec.com
971-271-5912

Distribution List

Name, Title	Affiliation
Myles Gray	Geosyntec Consultants
Aaron Poresky	Geosyntec Consultants
Ani Jayakaran	Washington State University
John Stark	Washington State University
Carly Thompson	Washington State University
Brandi Lubliner	Washington Department of Ecology
Keunyea Song	Washington Department of Ecology
Mark Weidner	Analytical Resources, Inc.
Dylan Ahearn	Herrera Environmental Consultants
Anita Fichthorn	Port of Tacoma
Doug Hutchinson	Seattle Public Utilities
Tarelle Osborn	Osborn Consulting
Eric Strecker	Terraphase Engineers

Table of Contents

1 Introduction and Background

Bioretention is one of the most used stormwater control measures in Washington State. As part of Phase 1 and Phase 2 Municipal Separate Storm Sewer (MS4) permits, bioretention, or other Low Impact Development (LID) practices must be implemented whenever feasible to manage stormwater runoff from new and redeveloped areas in Western Washington. Under the Stormwater Management Manual for Western Washington (SWMMWW), bioretention can be used to meet Minimum Requirements #5 On-Site Stormwater Management, #6 Runoff Treatment, #7 Flow Control, and #8 Wetlands Protection.

Bioretention areas are typically shallow landscaped depressions designed to infiltrate runoff from small to moderately sized rain events from nearby impervious surfaces. Stormwater directed to them is filtered thru the soil layers to remove pollutants and infiltrate stormwater runoff. They are constructed with specific soil mixes and vegetation designed to remove pollutants and maintain high infiltration rates. In areas with low native soil infiltration rates (e.g., factored rates less than 0.6 inches per hour) or other issues, such as high groundwater tables, subsurface contamination, or geotechnical concerns, bioretention facilities are typically designed with a perforated underdrain so that runoff that does not infiltrate into underlying soils can discharge into stormdrains or other stormwater conveyance features. Because parts of Western Washington are underlain by glacial till soils with low infiltration rates, many bioretention facilities are designed with underdrains that discharge treated runoff to nearby stormdrains. A schematic from the SWMMWW of bioretention with an underdrain is presented in Figure 1.

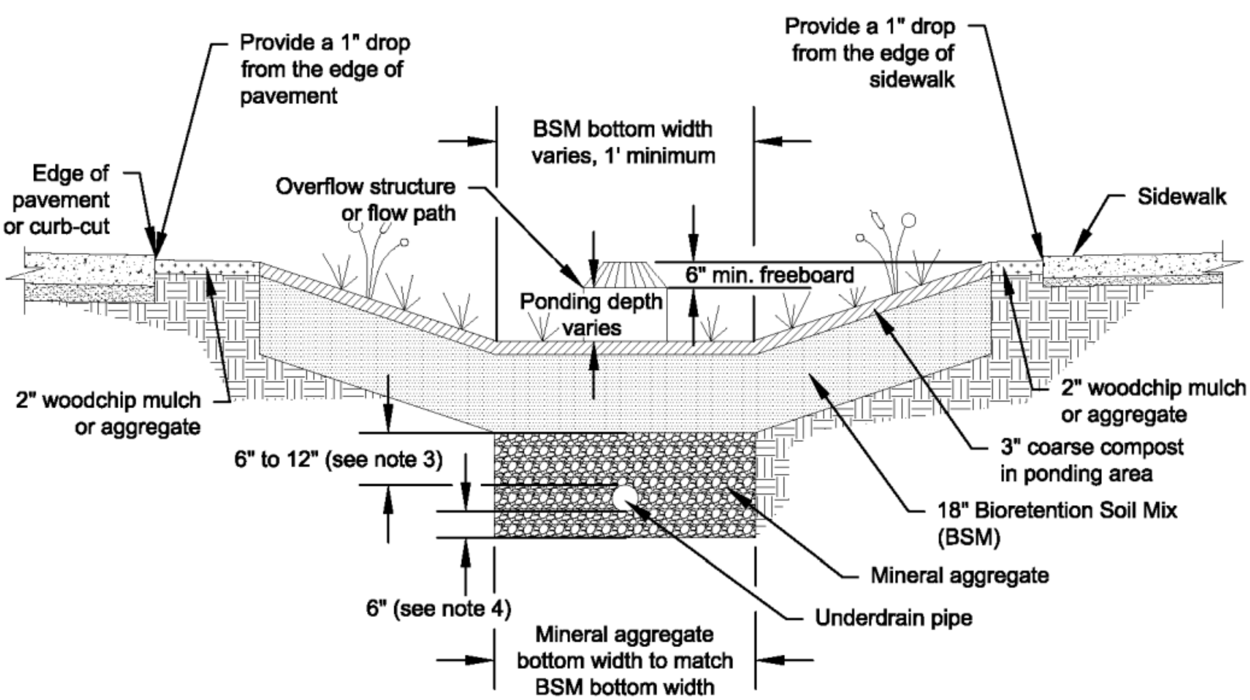

Figure 1: Typical design schematic for bioretention swale from 2019 SWMMWW).

In areas with high native soil infiltration rates, bioretention is typically designed without underdrains, and the flow rate of runoff through bioretention soil media (BSM) is typically controlled by the infiltration of underlying soils. However, in areas with lower soil infiltration rates or other concerns that do not support infiltration, when bioretention is designed with underdrains, the flow rate of runoff through BSM can be controlled either by: relying on the permeability of BSM to restrict flow rates (i.e., “media control”) or by using valves or orifices on underdrain outlets to throttle treatment flow rates below the inherent permeability of the BSM (i.e., “outlet control”). The 2019 SWMMWW permits either hydraulic control approach to be used, however, the majority of bioretention with underdrain systems are designed to operate under media control. Since the permeability of BSM can be 80 inches per hour or higher, runoff can pass through bioretention with underdrains much faster than the design flow rate which is typically 12 inches per hour or less.

This study is intended to compare the side-by-side pollutant removal and hydraulic performance of media controlled bioretention mesocosms to outlet-controlled bioretention mesocosms. The study will be completed by retrofitting the existing mesocosms at the Washington State University (WSU) LID Research facility in Puyallup, Washington. This project will be completed as a collaboration between WSU and Geosyntec Consultants.

1.1 Research Need

The hydraulic conditions within bioretention systems (e.g., saturated vs. unsaturated flow, pore velocity, macropore flow) can influence system performance. Research to date on BSM has focused primarily on the chemical and physical characteristics of BSM and the ability of BSM to sorb and filter pollutants. The hydraulic control approach used for bioretention potentially influences hydraulic residence time, the potential for short circuiting via preferential flow paths, retention of BSM particles (i.e., avoiding media washout), effectiveness of the system to filter and hold pollutants, sensitivity to BSM properties and construction methods, and sensitivity to clogging and macropore formation that can increase short-circuiting of media).

Media-controlled bioretention hydraulics may result in non-ideal filter operating conditions that could affect performance. Specifically, the following characteristics and variability could negatively influence the performance of media-controlled bioretention systems:

- Permeability of fresh BSM is highly variable and can be sensitive to the degree of fines in the mix, the degree of mixing during blending, compaction during installation, the types and maturity of plants, the amount of clogging from particulates in runoff, and other factors.
- Particulate accumulation near the media surface can result in the surface layer becoming the most restrictive layer, potentially resulting in predominantly unsaturated flow conditions beneath the surface layer and/or preferential macropore flow along plant roots.
- Due to initial differences in BSM, particulate accumulation at the media surface and deeper within media, the creation of macropores due to plant rooting, the temperature of stormwater and BSM, and other factors, the actual permeability of BSM is constantly changing.

Outlet-controlled hydraulic design has the potential to create more ideal filtration conditions which could potentially improve performance and alleviate variability in performance, including:

- Outlet control can help mitigate variability in media hydraulic conductivity between BSM batches and across sites, which may result in more consistent residence time and pore velocity in the media. By designing the outlet control to be the flow rate-limiting feature, outlet control designs can achieve a given design flow rate using BSM with any inherent permeability so long as it is greater than the design flow rate.
- Flow through the BSM will tend to be under saturated conditions more often, which can increase the contact of water with particle surfaces where pollutant sorption occurs.
- Outlet control can improve utilization of system volume (pore spaces and surface storage) for detention and potentially provide some level of improvement in flow duration control, even if not designed specifically for Ecology Flow Control requirements (Minimum Requirement #7).
- Outlet control may increase hydraulic residence times, increasing the duration of infiltration into underlying soils, potentially increasing the total amount of runoff that infiltrates into underlying soils, thereby reducing the total amount of runoff that must be managed to comply with Minimum Requirement #7
- Outlet control is inherently adjustable to adapt system operations, as needed.

Even though an outlet-controlled hydraulic approach is permitted under the SWMMWW, there are concerns that this design is complicated and/or susceptible to maintenance issues. Additionally, it has not been studied whether increasing residence times and restricting flow through BSM could have negative effects related to pollutant export or plant health. Finally, the head loss effects associated with water flowing through media upstream of an orifice restriction have not been widely field verified.

This study, which will compare the side-by-side water quality and hydraulic performance of bioretention mesocosms with media-controlled and outlet-controlled bioretention with underdrains.

1.2 Relevance for Municipal Stormwater Permittees

This study will provide information to MS4 permittees to help understand the tradeoffs of media versus outlet hydraulic control approaches in regard to water quality and hydraulic performance. This study will also consider whether outlet-controlled approaches can help to mitigate the inherent variability in BSM permeability. The results of this research will determine if outlet controls aid in contaminant treatment and could support compliance with MS4 Permit requirements for Runoff Treatment (MR#6) for new and re-development projects. Findings are also expected to be relevant for retrofit applications, particularly those projects that seek to maximize pollutant removal and hydrologic improvements but may not be able to design to fully meet new and redevelopment levels of treatment or flow control standards due to site constraints. Results from this study will be distilled into recommendations that could be incorporated into future versions of the SWMMWW or into local guidance and stormwater planning efforts.

This project would address several questions in the Stormwater Work Group (Ecology, 2013) priority topics for both short-term and long-term performance including (paraphrased):

- How can we avoid failures?
- How do we best ensure that LID BMPs are not only properly designed but also properly constructed/installed?
- How can we optimize bioretention designs for pollutant removal and flow control?
- What type and frequency of maintenance is needed to ensure the longevity and long-term performance of bioretention facilities? How does maintenance affect function?

2 Project Objectives and Description

2.1 Project Goal and Objectives

The primary research goal of this research is to compare the performance, operations, and maintenance needs of underdrained bioretention systems with passive, outlet-controlled configurations to those with media-controlled configurations.

Specific study questions include:

- How does the water quality treatment performance of bioretention differ between outlet-controlled and media-controlled configurations?
- How does outlet control vs. media control affect the residence time and residence time distribution of water in the system?
- Are any differences in plant health and vigor notable at a mesocosm scale between outlet-controlled and media-controlled designs?
- Does the use of small orifices as outlet controls pose notable operations and maintenance challenges compared to standard bioretention without underdrain outlet controls?
- What is the flow, stage and discharge relationship of each mesocosm? Is this consistent with theoretical calculations of soil and orifice hydraulics, or do additional effects need to be considered when modeling these configurations?
- How do hydraulic conditions of the systems (i.e., flow-rate-stage-discharge relationships) vary over time and between replicate mesocosms? Does one configuration result in more consistent operation than another?
- Does outlet control improve the degree of hydrologic control provided by a bioretention system of a given size, even if not specifically designed to meet either MR#5 or MR#7 flow control standards? Flow control benefits could be related to flow attenuation (i.e., by reducing treatment flow rates) and/or by increased infiltration into underlying soils with relatively low permeability by extending the residence time of runoff within a system.

Answering these questions will provide recommendations to those implementing bioretention systems about the feasibility, benefits, drawbacks, design, and maintenance of outlet-controlled systems compared to traditional media-controlled systems. Such recommendations could be integrated into future stormwater manuals and other communications related to designing bioretention systems as well as how to assess their potential performance on regional scales.

2.2 Study Overview:

Research will be conducted using the existing Mesocosm Research Facility at the WSU campus in Puyallup. Fourteen of the twenty existing mesocosms will be used in this study, and seven of these will be retrofitted with outlet controls. Six of the mesocosms (3 media-controlled and 3 outlet-controlled) will be used in the study without changing BSM or disturbing existing vegetation while the remaining 8 mesocosms (4 media-controlled and 4 outlet-controlled) will be modified with new BSM and vegetation. All fourteen mesocosms will be continuously monitored for hydraulics, while six of the mesocosms will also be monitored for water quality and other parameters. An overview of the experimental design is presented in Table 5. Additional details for the experimental design are presented in Section 5.

2.3 Study Location

The study will use the existing mesocosm research facility at the Washington State University Stormwater Center (WSC) in Puyallup (Site). The facility was constructed in 2011 in conjunction with the co-located Rain Garden test facility and the Permeable Pavement test facility. The mesocosm facility consists of a flow distribution cistern, twenty 5-foot diameter bioretention mesocosms, and associated hydraulic and water quality monitoring infrastructure. A QAPP (2011 QAPP; Herrera, 2011) for this test facility was approved by the Washington State Department of Ecology in 2011. Figure 2 presents a plan view schematic of the mesocosm test facility that was included in the 2011 QAPP.

3 Organization and Schedule

3.1 Key Project Team Members: Roles and Responsibilities

Table 1. Key project team members.

Key Team Members	Role	Responsibilities
John Stark Washington State University starkj@wsu.edu (253) 445-4568	Principal Investigator	Provide project management and senior review of technical work and deliverables.
Aaron Poresky Geosyntec Consultants APoresky@Geosyntec.com (971) 271-5891	Principal in Charge	Provide senior review of technical work and deliverables.
Myles Gray Geosyntec Consultants mgray@geosyntec.com (971) 271-5912	Consultant Project Manager & QAPP Author	Plan and manage installation and startup, support monitoring phase activities, draft and finalize all deliverables.
Anand Jayakaran Washington State University anand.jayakaran@wsu.edu	WSU On site monitoring support	Support monitoring phase activities, and support preparation of all deliverables.

Key Team Members	Role	Responsibilities
(253) 445-4523		
Carly Thompson Washington State University carly.thompson@wsu.edu (253) 445-4549	WSU Monitoring Lead	Plan, manage, and execute monitoring phase activities, support preparation of all deliverables.
Brandon Boyd Washington State University brandon.boyd1@wsu.edu (253) 445-4549	WSU Technical Support	Support monitoring phase activities
Keunyea Song Department of Ecology Keunyea.Song@ecy.wa.gov (360) 407-6158	Project Manager	Manages the contract, and review and approve project deliverables.
Brandi Lubliner Department of Ecology Brandi.Lubliner@ecy.wa.gov (360) 407-7140	Ecology QA Coordinator	Reviews the draft QAPP and approves the final QAPP.
Mark Weiner Analytical Resources, Inc. Marl.weidner@arilabs.com	ARI Labs	Lab manager for ARI

3.2 Technical Advisory Committee

Table 2. Technical Advisory Committee members.

TAC Member	Affiliation	Contact
Dylan Ahearn	Herrera Environmental Consultants	dahearn@herrerainc.com
Anita Fichthorn	Port of Tacoma	afichthorn@nwseaportalliance.com
Doug Hutchinson	Seattle Public Utilities	doug.hutchinson@seattle.gov
Tarelle Osborn	Osborn Consulting	tarelle@osbornconsulting.com
Eric Strecker	Terraphase Engineers	eric.strecker@terraphase.com

3.3 Project Schedule

A proposed tentative schedule is presented in Table 3. Due to the ongoing COVID-19 emergency in the United States, actual completion of project milestones may be significantly delayed.

Table 3. Project Schedule

Project Milestone	Anticipated Completion	Deliverables
Final QAPP Approved	September 2020	• Meeting notes from project kickoff meeting with TAC • Draft QAPP • Final QAPP
Installation and Startup	September / October 2020	• Table of equipment purchases, and dates received • Installation photolog • Installation and startup report
Vegetation Establishment, Water Quality Event #1, Special Testing Event #1, and O&M Observations	December 2020	• Progress Report #1
Water Quality Event #2 and O&M Observations	March 2021	• Progress Report #2
Water Quality Event #3, Special Testing Event #2, and O&M Observations	October 2021	• Progress Report #3
Reporting and Communication of Findings	November 2021	• Interim Presentation
Water Quality Event #4 and O&M Observations	December 2021	• Progress Report #4
Water Quality Event #5, Special Testing Event #3, and O&M Observations	February 2022	• Progress Report #5
Water Quality Event #6 and O&M Observations	April 2022	• Progress Report #6
Reporting and Communication of Findings	June 2022	• Final Report

4 Quality Objectives

A goal of this QAPP is to ensure that the data collected for this study are scientifically accurate, useful for the intended analysis, and legally defensible. Therefore, the collected data will be evaluated using the following indicators of quality assurance:

- **Precision:** A measure of the variability in the results of replicate measurements due to random error.
- **Bias:** The systematic or persistent distortion of a measurement process that causes errors in one direction (i.e., the measured mean is different from the true value).

- **Representativeness:** The degree to which the data accurately describe the conditions being evaluated based on the selected sampling locations, sampling frequency and duration, and sampling methods.
- **Completeness:** The amount of data obtained from the measurement system.
- **Comparability:** The ability to compare data from the current study to data from other similar studies, regulatory requirements, and historical data.

Measurement Quality Objectives (MQOs) are performance or acceptance criteria that are established for each of these quality assurance indicators. The specific MQOs to be used for this study are described below in separate subsections for hydrologic and laboratory data, respectively.

4.1 Measurement Quality Objectives for Water Quality Data

MQOs for laboratory data are expressed in terms of bias, precision, representativeness, completeness, and comparability. The specific MQOs that have been identified for this project are described below and summarized in Table 4. Note that the term “reporting limit” in this document refers to the practical quantification limit established by the laboratory, not the method detection limit.

Table 4: Method Quality Objectives for Water Quality Data

Parameter	Laboratory Method	Method Detection Limit	Reporting Limit	Laboratory Method Blank	Equipment Rinsate Blank	Control Standard Recovery	Matrix Spike Recovery	Laboratory Duplicate *RPD*[a]	Field Duplicate *RSDp*[b]
Total Suspended Solids	SM2540D	1.0 mg/L	1.0 mg/L	≤RL	≤2 x RL	80 - 120%	NA	≤20% or ±2 x RL	≤35%
Total Phosphorus	SM4500-P	1.0 µg/L	5.0 µg/L	≤RL	≤2 x RL	90 – 110%	75 – 125%	≤20% or ±2 x RL	≤35%
Ortho-phosphate	SM4500-PE	2.5 µg/L	5.0 µg/L	≤RL	≤2 x RL	90 – 110%	75 – 125%	≤20% or ±2 x RL	≤35%
Total Kjeldahl Nitrogen	SM4500-Norg	10 µg/L	100 µg/L	≤RL	≤2 x RL	90 – 110%	75 – 125%	≤20% or ±2 x RL	≤35%
Nitrate + Nitrite	SM4500-NO_3	5 µg/L	10 µg/L	≤RL	≤2 x RL	90 – 110%	75 – 125%	≤20% or ±2 x RL	≤35%
Total Zinc	EPA 200.8	0.5 µg/L	1 µg/L	≤RL	≤2 x RL	90 – 110%	75 – 125%	≤20% or ±2 x RL	≤35%
Dissolved Zinc	EPA 200.8	0.5 µg/L	2.5 µg/L	≤RL	≤2 x RL	90 – 110%	75 – 125%	≤20% or ±2 x RL	≤35%
Total Copper	EPA 200.8	0.2 µg/L	1 µg/L	≤RL	≤2 x RL	90 – 110%	75 – 125%	≤20% or ±2 x RL	≤35%
Dissolved Copper	EPA 200.8	0.2 µg/L	2.5 µg/L	≤RL	≤2 x RL	90 – 110%	75 – 125%	≤20% or ±2 x RL	≤35%
pH	Handheld sensor	NA	NA	NA	NA	NA	NA	≤20%	≤35%

a. The relative percent difference must be less than or equal to the indicated percentage for values that are greater than 5 times the reporting limit. RPD must be ±2 times the reporting limit for values that are less than or equal to 5 times the reporting limit.

b. The pooled relative standard deviation will only be calculated for values that exceed 5 times the RL.

NA = not applicable.
RL = reporting limit.
RPD = relative percent difference.
RSDp = pooled relative standard deviation.

4.1.1 Precision

In this study, overall project data quality will be based on total precision and analytical precision. Total precision is the measure of the variability in the results of replicate measurements due to random error that is introduced during sample collection and processing in the field and the laboratory analytical procedure. Total precision will be estimated based on the pooled relative standard deviation (*RSDp*) of the field duplicates from all sampling events. The *RSDp* of these samples will be calculated using the following formula:

$$S_p = \sqrt{\frac{\sum(Ci_1 - Cj_2)^2}{2m}} \text{ and } RSD_p = \frac{S_p}{\bar{x}} * 100\%$$

Where: S_p= Pooled standard deviation
RSD_p= Pooled relative standard deviation
Ci_1 and Cj_2 = Concentration values

m = Number of pairs
$\bar{x}$ = Mean of all concentration values

When one or both values are less than or equal to 5 times the reporting limit, they will not be included in the RSDp calculation. The specific MQOs for total precision are defined in Tables 3 and 4 for water quality and soil parameters, respectively.

Analytical precision is the measure of the variability in the results of replicate measurements due to random error that is introduced from just the laboratory analytical procedure. Analytical precision will be assessed based on the relative percent difference (RPD) of laboratory duplicates that are run with each batch of samples. The RPD of these samples will be calculated using the following formula:

$$RPD = \frac{|C_1 - C_2|}{C_1 + C_2} * 200\%$$

Where: RPD = Relative percent difference
C_1 and C_2 = Concentration values

The specific MQO’s for analytical precision are defined in Table 4. For all parameters, the RPD must be ±2 times the reporting limit if the duplicate concentrations are both within 5 times the reporting limit. If either of the duplicate concentrations is at or below the reporting limit, the RPD cannot be calculated.

4.1.2 Bias

Bias will be assessed based on analyses of equipment rinsate blanks. Field duplicates, matrix spikes, and laboratory control samples (LCS). The values for method blanks will not exceed the reporting limit, and values for equipment rinsate blanks will not exceed two times the reporting limit. Bias in matrix spikes will be evaluated based on their percent recovery, as calculated using the following equation:

$$\%R = \frac{(S - U) * 100\%}{C_{sa}}$$

Where: $\%R$ = Percent recovery
S = Measured concentration in spiked sample
U = Measured concentration in un-spiked sample
C_{sa}= Actual concentration of spike added

If the analyte is not detected in the un-spiked sample, then a value of zero will be used in the equation.

Bias in LCS will also be evaluated based on their percent recovery. In this case, percent recovery will be calculated using the following equation:

$$\%R = \frac{M}{T} * 100\%$$

Where: $\%R$ = Percent recovery
M = Measured value
T = True value

The specific MQOs for percent recover in matrix spikes as well as LCS are defined in Table 4.

4.1.3 Representativeness

Water quality samples will be collected during synthetic storm events using Site runoff that will be stored in the Mesocosm Cistern. To increase pollutant concentrations to be more representative of typical urban runoff, runoff contained in cisterns will be dosed with additional pollutants as presented in Section 6.2.2.

4.1.4 Completeness

Completeness will be calculated by dividing the number of samples that were collected and analyzed to the number of samples that were intended to be collected and analyzed. If less than 95% of the of the intended samples are collected and analyzed, additional sampling may be conducted.

4.1.5 Comparability

Standard sampling procedures, analytical methods, units of measurement, and reporting limits will be applied in this study to meet the goal of data comparability.

4.2 Measurement Quality Objectives for Hydrologic Monitoring Data

Hydrologic monitoring will involve measurement of test cell discharge, test cell ponding depths, test cell soil moisture, and precipitation depth. The data quality indicators for these measurements are expressed in terms of precision, bias, representativeness, completeness, and comparability. Assessments of precision and bias will be conducted before equipment is deployed in the field and again at the end of the project when the monitoring equipment is retrieved from the field. The MQOs for field data are defined below.

4.2.1 Bias and Precision

The bias and precision of the tipping bucket flow meters and rain gauges will be measured by pouring a known volume of water onto each flowmeter and comparing actual tips to theoretical tips for the known volume. The known volume of water will be equal to 40 bucket tip volumes. This process will be repeated three times, and the resultant coefficient of variation (C_v) will be calculated. The MQO for flow meter and rain gauge precision will be 10 percent and 5 percent, respectively. C_v will be calculated using the following equation:

$$C_v = \frac{\sigma}{\mu} \times 100\%$$

Where:

C_v	=	Coefficient of variation
σ	=	Standard deviation
μ	=	The theoretical number of tips

Soil moisture bias and precision will be assessed by installing the soil moisture sensors in a well graded well mixed 1’ X 1’ X 1’ sand box covered with foil. The soil moisture readings will be recorded on a 5-minute time step for 4 hours. The MQO for soil moisture precision will be 10 percent.

Ponding depth sensors will be assessed by making simultaneous manual depth measurements in partially full five-gallon buckets before the sensors are installed in the mesocosm stilling wells. Three measurements will be collected at three different ponding water levels for each of the fourteen sensors. Precision will be assessed by holding the water level constant at one of the water levels for several hours and assessing sensor drift over this time. The MQO for ponding depth sensors will be 5 percent.

4.2.2 Representativeness

The representativeness of flow monitoring equipment will be ensured by the proper calibration and installation of all hydrologic monitoring equipment.

4.2.3 Completeness

Completeness will be assessed based on occurrence of gaps in the data record for all monitoring equipment. The associated MQO is less than 10 percent of the total data record missing due to equipment malfunctions or other operational problems. Completeness will be ensured through routine maintenance of all monitoring equipment and the immediate implementation of corrective actions if problems arise.

4.2.4 Comparability

There is no numeric MQO for this data quality indicator. However, standard monitoring procedures, units of measurement, and reporting conventions will be applied in this study to meet the goal of data comparability.

5 Experimental Design

5.1 Study Design Overview

This research is intended to compare the water quality and hydrologic performance of bioretention mesocosms with and without outlet controls. This analysis will primarily focus on mesocosms completed with the standard Washington State BSM blend of 60% sand and 40%

compost by volume ("standard 60/40 BSM"). The study will monitor the performance of six mature mesocosms, six newly retrofitted mesocosms containing the standard 60/40 BSM, and two newly retrofitted mesocosms containing an alternative BSM (sand XX%, XX). An overview of the experimental design is presented in Table 5. Additional details regarding BSM specifications are included in Section 5.2.2

Table 5. Study design overview

Type	BSM Design Description	Media Control	Outlet Control	Research Comparison
Mature Mesocosms	Mature Standard BSM (sand / compost) with mature plants	3 replicates[1], 1 with full instrumentation and WQ sampling[2]	3 replicates[1], 1 with full instrumentation and WQ sampling[2]	Effect of outlet control on performance of aged standard BSM with mature plants.
Newly Retrofitted Mesocosms	Standard BSM (sand / compost) with new plants	3 replicates[1], 1 with full instrumentation and WQ sampling[2]	3 replicates[1], 1 with full instrumentation and WQ sampling[2]	Effect of outlet control on newly retrofitted standard BSM mixes.
Newly Retrofitted Mesocosms	Alternative BSM mix with new plants	1 replicate with full instrumentation and WQ sampling	1 replicate with full instrumentation and WQ sampling	Effect of outlet control on newly retrofitted alternative BSM mixes.

1 – All replicates will be monitored for hydraulics, vegetation, and maintenance.
2 – A subset of replicates will be monitored for water quality, soil moisture, and conductivity monitoring.

The study design will include monitoring of fourteen total mesocosms consisting of six distinct treatment combinations (3 mesocosm types and two hydraulic control approaches). All mesocosms will be monitored for flow rate, ponding depth, vegetation health and maintenance requirements. Six of the mesocosms, consisting of one of each treatment combination, will also be fully monitored for water quality and soil moisture.

5.1.1 Types of Monitoring

Monitoring types are presented in Table 6. Detailed sampling and monitoring procedures are presented in Section 6.

Table 6. Types of monitoring

Monitoring Type	Mesocosms	Description
Continuous Hydraulic Monitoring	All fourteen	Continuous monitoring of precipitation, inlet flow, outlet flow, surface ponding depth, overflow, and water temperature
Water Quality Sampling	Six fully instrumented mesocosms	Periodic composite water quality sampling during six synthetic storm events within the monitoring period
Soil Moisture Monitoring	Six fully instrumented mesocosms	Continuous soil moisture monitoring
Vegetation Monitoring	All fourteen	Periodic monitoring events to characterize vegetation health and vigor
Operations and Maintenance Monitoring	All fourteen	Quarterly O&M inspections with a focus on potential orifice clogging
In-Situ Hydraulic Conductivity Monitoring	Six fully instrumented mesocosms	Periodic hydraulic conductivity testing during three events
Tracer Testing of Residence Time Distribution	Six fully instrumented mesocosms	Periodic salt tracer testing during three events.

5.1.2 Monitoring Phases

The project will be broken into the following monitoring periods and events:

- **Establishment Phase**. This phase will immediately follow installation of new BSM in the mesocosms and will allow at least one month for vegetation growth and soil structure development. During this phase runoff will be directed to each mesocosm under passive flow conditions during storm events. Continuous hydrologic and hydraulic data will be collected, and any required hydraulic modifications will be made based on initial monitoring data. Mature mesocosms will be treated the same as newly retrofitted mesocosms during the Establishment Phase.
- **Normal Operating Phase.** This phase represents the primary research monitoring phase and will be conducted for nearly two water years (anticipated as Fall 2020 through Spring 2022). During this phase, storm flows will be routed to each of the mesocosms during storm events and hydraulic data will be collected continuously. Regular Operations and Maintenance observations such as whether the orifice is obstructed will also be made.
- **Periodic Water Quality Testing.** During dry weather periods within the Normal Operating Phase, six water quality sampling events will be conducted periodically during synthetic storm events using modified site runoff.

- **Periodic Special Testing.** During the Normal Operating Phase, periodic hydraulic conductivity, residence time, and vegetation monitoring will be conducted. Each type of monitoring will be conducted three times during the project.

Detailed sampling and monitoring procedures for each monitoring period are in Section 6.

5.2 Mesocosm Test Facility and Modifications

The WSU Mesocosm Research Facility was constructed in 2011 to assess differences in water quality and hydrologic performance of bioretention mesocosms containing different types of BSM (Herrera, 2011).

This facility consists of three primary components which will be used as follows:

- Cistern and flow distribution system will be used to distribute flows to the mesocosms during regular storm events (i.e., during Establishment Phase and Normal Operating Phase) and during synthetic water quality sampling events.
- Fourteen mesocosms will be monitored. They will be completed with BSM and vegetation, and the outlet structures of seven of the fourteen mesocosms will be modified according to Table 7. Monitoring infrastructure will be added to a subset of the mesocosms according to Table 7.
- Seven water quality sampling stations will be used to collect influent and effluent water quality samples during or following storm events for a subset of the mesocosms according to Table 7.

The following subsections detail the three primary components of the Mesocosm Research Facility, and how these components will be modified as part of the outlet control study.

5.2.1 Cistern and Flow Distribution System

The Mesocosm Cistern and the adjacent Rain Garden Cistern receive runoff from a 72,084 square foot impervious drainage area on the WSU campus as presented in Figure 2. Runoff will flow into the cisterns during typical storm events and be distributed to the mesocosms and to the Rain Garden Test Facility. The two cisterns are hydraulically connected as shown in Figure 3. During the study the cistern valves will be calibrated to convey approximately 25% of the total runoff to the mesocosms during the Establishment Phase and during the Normal Operating Phase. Routing 25% of the runoff from the full drainage area results in an effective drainage area of 18,021 square feet that will be routed to the mesocosms.

Each cistern has a total capacity of approximately 3,000 gallons, but each holds only approximately 2,200 gallons of stormwater in the dead storage below the discharge weir box outlets to the mesocosms. Since the dead storage held in the Rain Garden cistern will be pumped to the Mesocosm Cistern during synthetic storm events, 2,200 gallons is the total amount of water that can be routed to the mesocosms during synthetic storm events. Each cistern is equipped with eductors which can be used to stir the cisterns.

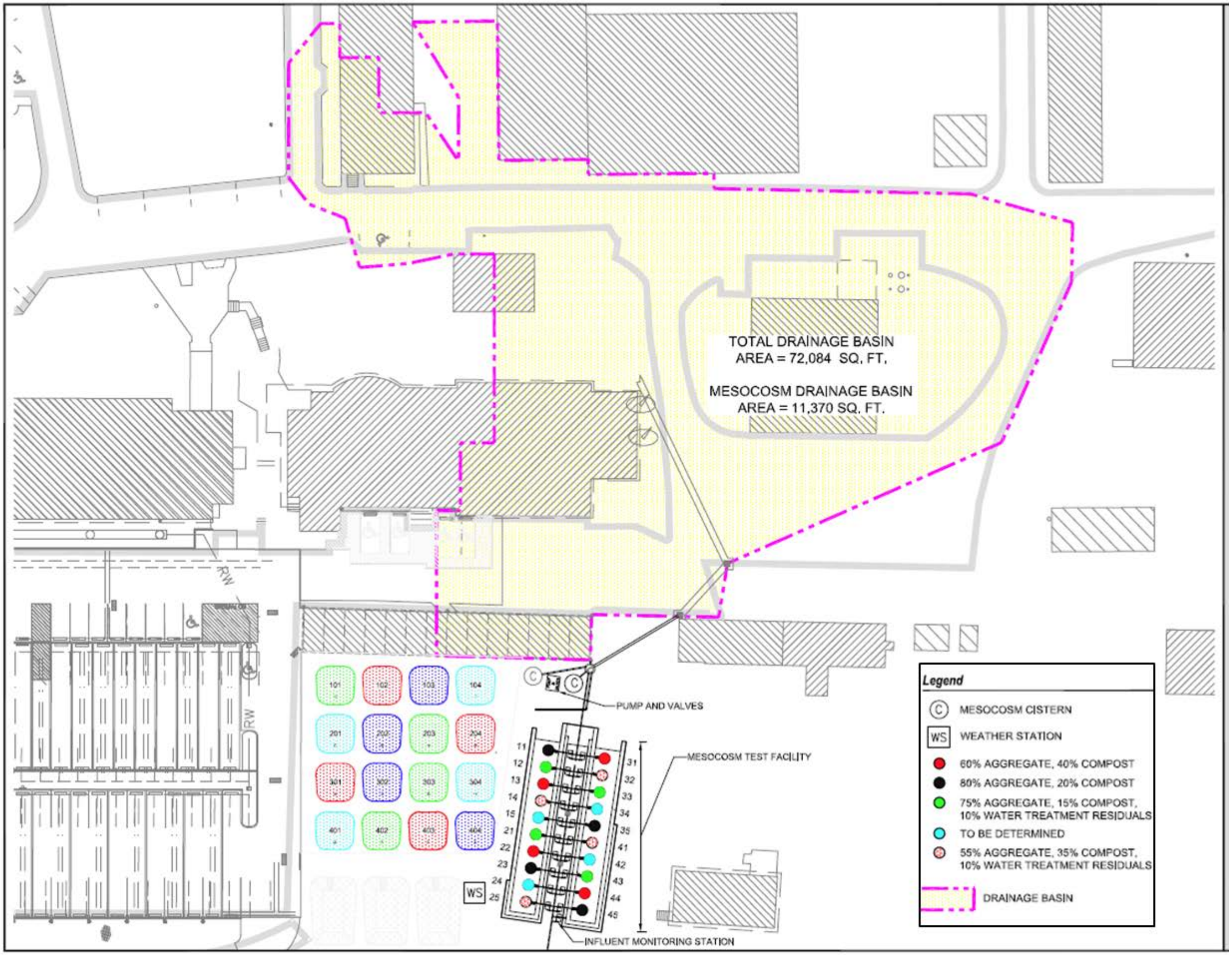

Figure 2. Plan view of mesocosm test facility from the 2011 QAPP.

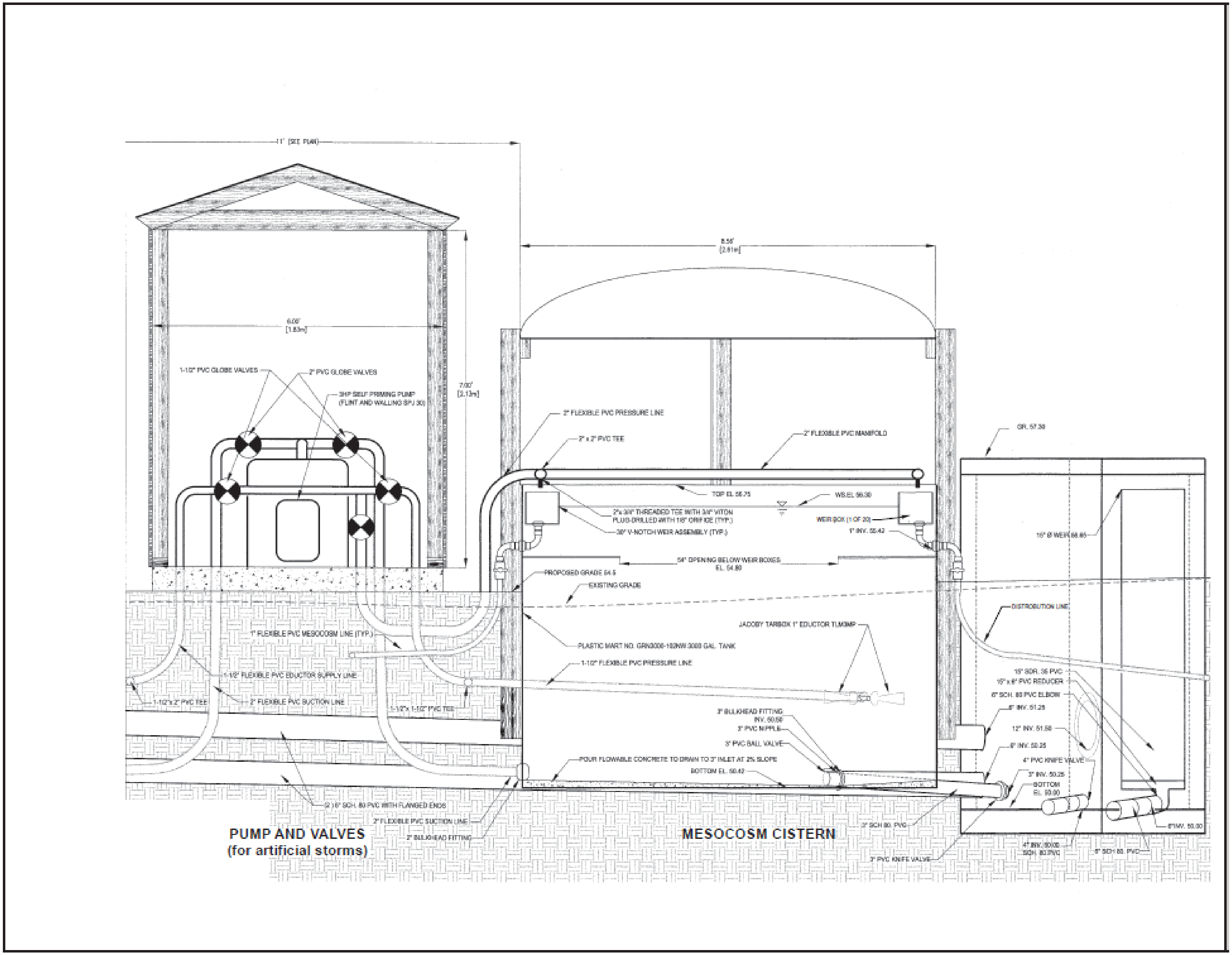

Figure 3. Schematic from the 2011 QAPP of existing pumping system, cistern, and piping.

The Mesocosm Cistern is connected to individual discharge lines which convey runoff to each of the mesocosms and to an influent sampling location. The flow to each of the mesocosms is regulated using calibrated v-notch weir boxes on the inside wall of the cistern. A separate weir box and discharge line is dedicated to influent flow and water quality characterization. All the weir boxes will be calibrated by precisely leveling them prior to the start of monitoring activities to ensure that each mesocosm receives the same amount of flow. To increase the amount of water routed to the 14 mesocosms that will be used in this study, the outlet valves to the remaining 6 unused mesocosms will be shut for the duration of the testing.

An existing TB1-L tipping bucket flow meter measures the flow through the influent sampling line. The flow at this location will be assumed equal to the flow to each of the mesocosms. To confirm the accuracy of this influent tipping bucket flow meter, a Campbell Scientific CS 451 water level sensor will be installed inside the Mesocosm Cistern. Data from this water level sensors will be used to estimate the flow to each of the weir boxes using a V-notch weir equation.

Runoff will be conveyed to the mesocosms and the influent sampling line during the Normal Operating Phase and during periodic water quality and special testing events.

5.2.2 Mesocosms

The twenty mesocosms represent the primary component of the Mesocosm Test Facility. Each mesocosm is constructed from 60-inch diameter plastic cylinders. Each is 52 inches tall and embedded approximately 40 inches into a gravel pad so that approximately 12 inches of the cylinder is exposed above grade. Each mesocosm contains 24 inches of BSM above a gravel drainage layer. The BSM surface in each mesocosm is approximately equal to the surrounding grade, so that the 12 inches of each cylinder extending above ground provides ponding depth. Figure 4 presents a figure from the 2011 QAPP (Herrera, 2010) annotated to show proposed modifications.

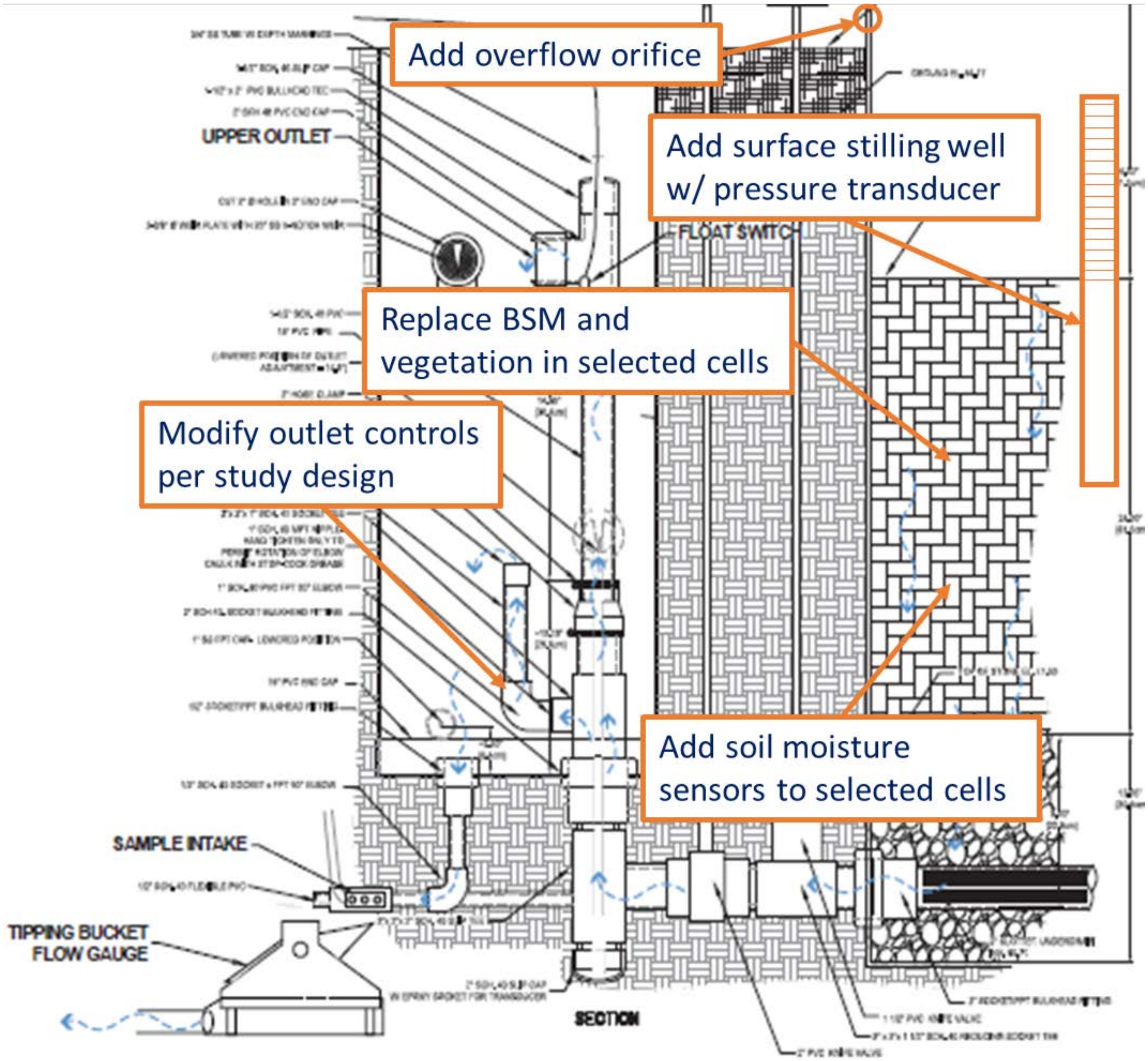

Figure 4. Schematic of mesocosms with proposed modifications.

During prior monitoring efforts, WSU technicians noted that some of the mesocosms were losing water when the mesocosms were brim full, even when both outlet valves were closed. A leak detection Site visit was conducted on March 17-18, 2020 to assess which mesocosms had significant leaks and which had little or no leaking. This event confirmed that 14 of the 20 mesocosms exhibited little or no leaking which is not expected to significantly alter the results of the monitoring proposed in this project. Only the fourteen mesocosms with little or no leaking will be used in this study.

Only those mesocosms with little or no leaking will be used in this study. Table 7 provides a summary of BSM, outlet controls, and monitoring associated with the fourteen mesocosms that will be used in this study. Mesocosm ID #'s refer to values in Figure 5 which were assigned in the 2011 QAPP.

Table 7. Mesocosms included in testing

Bioretention Media	Mature or Newly Retrofitted?	ID#[1] for Media-Controlled Mesocosms	ID#[1] for Outlet-Controlled Mesocosms	ID#[1] for Fully Instrumented Mesocosms
Standard	Mature	13, 23, 25	22, 32, 35	13, 22
Standard	Newly Retrofitted	24, 33, 45	12, 41, 42	12, 33
Alternative	Newly Retrofitted	34	15	15, 34

[1]See Figure 5 for site numbers and locations.

Each of the mesocosms currently contains BSM that was installed in 2011 when the facility was constructed. Figure 5 presents a schematic from the 2011 QAPP presenting the BSM mixtures that are installed in each of the mesocosms. This figure has been annotated to indicate those mesocosms that will be used in this study and what modifications will be made to each.

Eight of the mesocosms currently contain typical BSM containing a mixture of sand and compost, and four more contain a typical BSM to which 10% water treatment residuals (WTRs) was added. The 60/40 mixture represents the current BSM blend in the SWMMWW and contains a mixture of 60% sand and 40% compost. The 80/20 mixtures deviate slightly from the current BSM blend and contain 80% sand and 20% compost. The WTR mix consists of 55% sand, 35% compost, and 10% WTRs. Because some of the mesocosms were noted to have significant leaks, two mesocosms containing each of these fairly standard BSM blends will be used in this study as the mature mesocosms. Since most of the original compost and WTR material has likely broken down since the mesocosms were installed in 2011, the soil in these different mesocosms is likely very similar and representative of 10-year-old BSM formulated according to the SWMMWW. The BSM and vegetation in these mesocosms will remain unchanged. Two mesocosms containing the 60/40 BSM will be fully instrumented according to the study plan and therefore will be the only mature mesocosms containing standard BSM included in water quality sampling.

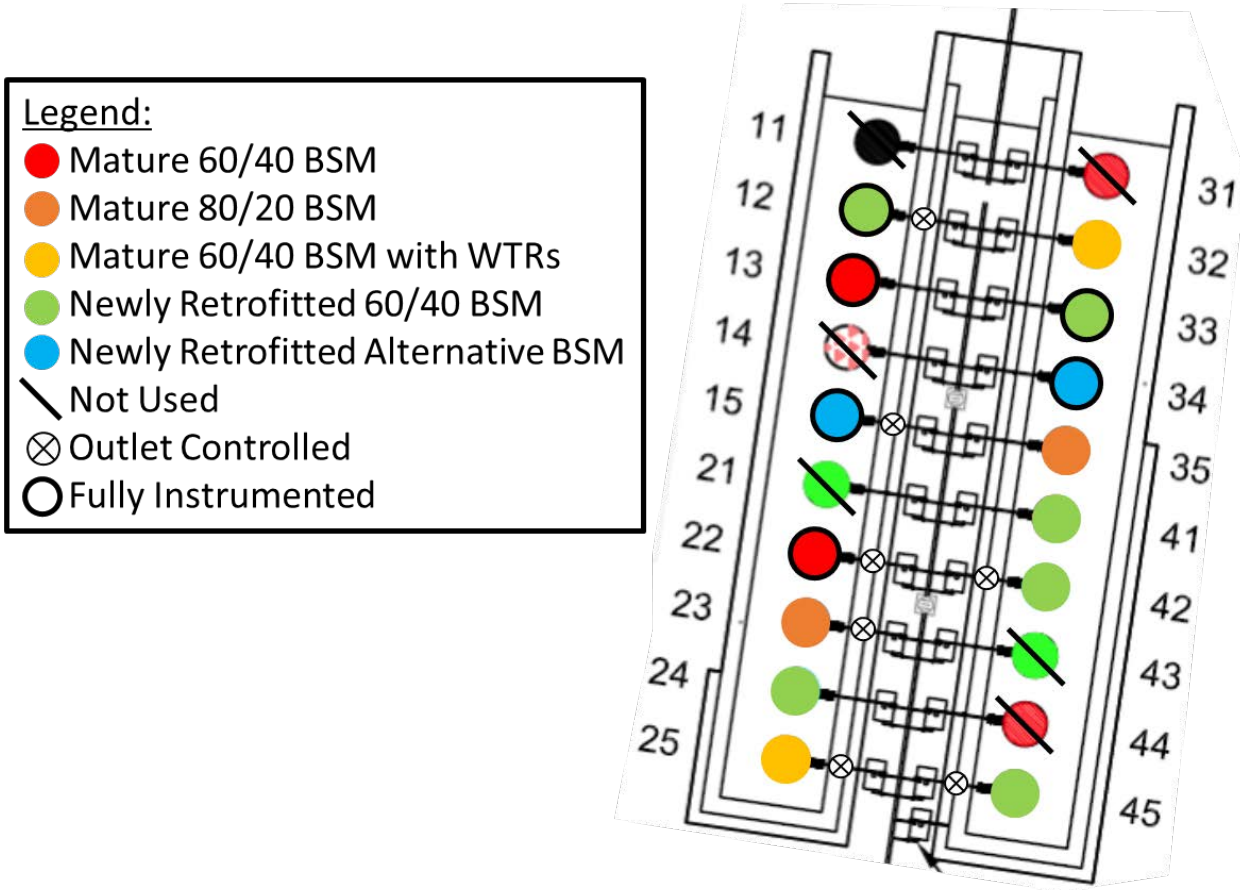

Figure 5.Mesocosms layout and modifications. Those mesocosms that are not used were found to have unacceptable leaking rates during a leak detection Site visit on March 17-18, 2020.

An additional eight mesocosms will be used in the study as the newly retrofitted mesocosms. Vegetation and BSM will be removed from these and disposed. Six of the newly retrofitted mesocosms will be refilled with standard BSM according to the SWMMWW. This material will be sourced from the following suppliers in the vicinity of WSU Puyallup:

- Walrath Soil Products, Tacoma, WA
- Corliss Resources, Sumner, WA
- Cedar Grove Compost

Each standard BSM supplier will be asked to deliver soil that would meet the standard BSM specification in the SWMMWW.

The final two newly retrofitted mesocosms will be refilled with a high-performance alternative media blend that was developed as part of the completed SAM project titled Bioretention Alternative Blends (Herrera, 2020). This blend was developed as a low phosphorus BSM and was shown to meet Basic and Enhanced treatment goals under the Technology Assessment Protocol – Ecology (TAPE) guidance. The alternative blend will consist of 70% sand, 20% coconut coir pith, and 10% biochar and will be sourced from Walrath Soil Products.

All newly installed BSM will be lightly boot compacted in 12-inch lifts during installation. The BSM will have a total depth of 24 inches, which is greater than the 18 inches of media specified for Bioretention in the SWMMWW. Underlying pea gravel will remain undisturbed unless it is found to be clogged or if it is difficult to leave in place during media replacement.

Seven (i.e., half of the fourteen that will be used) of the mesocosms will be modified with outlet control orifices to serve as the outlet-controlled mesocosms. Figure 4 presents a schematic from the Original QAPP that has been annotated to show proposed modifications. The Lower Outlet will be adjusted so that the elevation of the discharge point is equal to the bottom of the BSM. Outlet control orifices will be added to the Lower Outlet by adding 1” PVC caps. Circular orifices will be drilled into each of these caps to restrict flows through each test cell to 6 inches per hour. Based on assumed media hydraulic conductivity of 30 inches per hour, the drilled orifices will be approximately ¼ inch in diameter. The goal will be to maintain outlet-controlled mesocosm flow rates at or slightly above 6 inches per hour, so over the course of the study the orifices may be changed if data indicate test cell flow rates are higher or lower than the 6 inch per hour target rate. The outlet orientation of the remaining seven mesocosms will remain unchanged and these will serve as the media-controlled mesocosms.

A surface ponding stilling well will be added to each mesocosm to support ponding depth and ponding bypass measurements. These will be constructed of 1.5-inch i.d. PVC extending from the top of the mesocosm (i.e., approximately 12 inches above the BSM surface) to approximately 4 inches below the BSM surface. The section above the soil will be slotted PVC to permit ponded water to enter the stilling wells. The section of each stilling well extending below the BSM surface will be solid PVC completed with an end cap so that the stilling well holds water between storms and does not act as a preferential flow pathway. A Meter Environment HYDROS 21 water level sensor will be installed in each stilling well and the datum will be determined relative to the media surface and to the bypass orifice in each mesocosm.

To support ponding bypass monitoring, a 5/8-inch diameter orifice will be drilled four inches below the top of each mesocosm wall. This size orifice would discharge approximately 3.4 gpm under four inches of head (i.e., if the mesocosm were brim full). This flow rate corresponds to a precipitation rate of approximately 0.3 inches per hour across the catchment which is likely greater than the highest expected intensity at the facility. During the fall 2014 – fall 2015 period the highest measured inlet flow rate to the mesocosms was 2.14 gpm, so this orifice sizing should support overflow measurement during extreme rainfall events.

A Meter Environment TEROS 12 soil moisture, conductivity, and temperature sensor will be installed in the six fully instrumented mesocosms. These will be installed by digging a narrow pit into the BSM, and then inserting the sensor into undisturbed soil. They will be installed approximately 12 inches deep.

Each of the mesocosms, and the influent sampling point, are equipped with existing TB1-L tipping bucket flow meters. These will remain undisturbed.

5.2.3 Water Quality Sampling Stations

Water quality samples will be collected from the six fully instrumented mesocosms and from the influent sampling point. During water quality sampling events, ISCO 6712 autosamplers will be deployed to collect samples from existing water quality sampling ports. They will be configured to collect flow-weighted composite samples using flow data form the TB1-L tipping bucket flow meters. Additional water quality monitoring details are presented in Section 6.2.

5.3 The Structural BMP System Sizing

The effective drainage area for the mesocosm cistern will be approximately 18,021 (i.e., 25% of the full drainage area). Runoff in the mesocosm cistern will be routed to the fourteen mesocosms and the inlet sampling point, resulting in a total of fifteen discharge lines from the cistern.

As described in the Original QAPP, each mesocosm is a cylinder with a diameter of approximately 60 inches and a cross-sectional area of approximately 20 square feet. Including the inlet sampling point, the total mesocosm area will be approximately 300 square feet, resulting in the mesocosms being sized at approximately 1.6% of the drainage area (295 sf / 18,021 sf).

The outlet-controlled mesocosms will be configured to restrict flow to approximately 6 inches per hour. This corresponds to an assumed 12 inches per hour hydraulic conductivity for standard BSM with a safety factor of 2. Based on initial analysis using WWHM for a site in Puyallup, bioretention with underdrains sized at approximately 1.6% of the impervious tributary area and a 6 inch per hour treatment flow rate would treat approximately 98% of average annual runoff, indicating that the mesocosms would be oversized compared to typical bioretention with underdrains.

5.4 Types of Data Being Collected

Table 8 presents data that will be collected during the study, the frequency of data collection, the type of data that will be recorded, and the monitoring method. Additional details for sampling and monitoring procedures are presented in Section 6.

Table 8. Types of data that will be collected

Type of Monitoring	**Frequency**	**Data Type**	**Monitoring Method**
Precipitation	Continuous with 5-minute interval	Depth (mm)	TB3 Tipping Bucket Rain Gauge
Mesocosm Inlet Flow Rate	Continuous with 5-minute interval	Flow Rate (Liters/second)	TB1-L Tipping Bucket Flow Gauge at Influent Monitoring Point
Mesocosm Outlet Flow Rate	Continuous with 5-minute interval	Flow Rate (Liters/second)	TB1-L Tipping Bucket Flow Gauges

Type of Monitoring	Frequency	Data Type	Monitoring Method
Ponding Depth	Continuous with 5-minute interval	Depth (mm)	HYDROS-21 Water Level Sensors
Bypass Flow Rate	Continuous with 5-minute interval	Flow Rate (Liters/second)	HYDROS-21 Water Level Sensors with v-notch weir
Soil Moisture	Continuous with 5-minute interval	Volumetric water content (cm^3 water / cm^3 bulk soil)	TEROS 12 Soil Moisture Sensors
Water Quality	Six synthetic storm events	Influent and effluent constituent concentrations	Composite water quality samples and laboratory analysis
Hydraulic Conductivity	Three testing events	Falling head drawdown rate (inches/hour)	Falling head method using HYDROS-21 Water Level Sensors
Hydraulic Residence Time	Three testing events	Influent and effluent conductivity (mS/cm)	Oakton PC 450 meters for electrical conductivity
Vegetation Size and Vigor	Monthly observations	Plant spread width (inches) and qualitative vigor rating	Linear measurements and visual observations
O&M Requirements	Monthly observations	O&M requirements log	Visual observations

6 Sampling Procedures and Monitoring Procedures

6.1 Continuous Monitoring Data Collection

6.1.1 Continuous Monitoring Logging Frequency

All continuous monitoring data will be logged on a 5-minute interval. Additional details regarding data logging and data management are presented in Section 9.

6.1.2 Precipitation Monitoring

Precipitation will be monitored continuously using two existing Hydrological Services TB3 tipping bucket rain gauges installed adjacent to the mesocosms. One gauge is mounted on a five-foot pole and one is at ground level. Data from these gauges is recorded and stored on a Campbell Scientific (CS) CR1000 datalogger and transmitted to local servers via this datalogger. Rainfall data will be logged on a five-minute logging interval. On a monthly basis, field personnel will check that the rain gauges are level.

6.1.3 Inlet and Outlet Flow Monitoring

Inlet flows to each mesocosm will be assumed equal to the flow through an existing Hydrological Services TB1-L tipping bucket flow gauge at the influent sampling point. This flow meter is also connected to the CS CR1000 datalogger and this datalogger will store the 5-minute flow averages. To ensure even distribution of flows to the mesocosms, the height of weir boxes inside the water holding cistern will be checked each month to ensure even flow distribution to each mesocosm and to the inlet sampling point.

Effluent discharge rates from each mesocosm will be measured by separate, existing Hydrological Services TB1-L tipping bucket flow gauges. These flow meters are also connected to the CS CR100 datalogger and data will be logged as five-minute averages.

6.1.4 Surface Ponding and Bypass Flow Monitoring

Surface ponding will be monitored using the HYDROS 21 water level sensors that will be installed in each of the mesocosms. The HYDROS 21 sensors will be configured to store water level data on a 5-minute logging interval on Meter Environment ZL6 cellular data loggers.

Bypass flows from the orifice holes will be calculated using surface ponding data measured using the HYDROS 21 water level sensors combined with the following orifice equation:

$$Q = C_D A\sqrt{2gh}$$

Where Q equals flow rate in cubic inches per second, C_D is an orifice coefficient which will be assumed equal to 0.62, A is the area of the orifice which will be equal to approximately 0.38 square inches for a 5/8-inch diameter circular orifice, g is the gravitational constant, and h is the head acting on the centerline of the orifice which will have a maximum value of 4 inches.

6.1.5 Soil Moisture Monitoring

Soil moisture will be continuously monitored in each of the six fully instrumented mesocosms using a single Meter Environment TEROS 12 soil moisture sensor. The soil moisture sensors will be installed at a depth of approximately 12 inches below the soil surface. They will be configured to log data on a 5-minute recording interval on Meter Environment ZL6 cellular data loggers.

6.2 Synthetic Storm Events and Runoff Dosing

6.2.1 Water Quality Storms

Flow-weighted composite samples will be collected during six synthetic water quality storm events. During each synthetic storm events the full 2,200 gallons stored in the mesocosm cistern will be routed to the six fully instrumented mesocosms and the inlet sampling point, so approximately 4315 gallons will be routed to each water quality sampling point. This equates to approximately 26 inches of water relative to the cross-sectional area of the six utilized mesocosms. Based on the mesocosm sizing factor of approximately 1.6% of the contributing impervious drainage area, this represents a storm depth of approximately 0.4 inches.

Each of the six water quality testing events will be conducted according to one of the following two storm durations presented in Table 9. Water will be routed to the sampling points at a constant flow rate for the duration of each testing event.

Table 9. Water Quality Storm Types

Storm Type	Duration (hours)	Equivalent Catchment Rainfall Intensity (in/hr)	Combined Testing Flow Rate[1]	Water Quality Testing Events
Moderate Intensity	8	0.05	4.6 gpm	#1, #3, #5
High Intensity	4	0.10	9.2 gpm	#2, #4, #6

[1] The combined testing flow rate will be used as the pump flow rate during testing.

All six of the water quality storm events will be scheduled to occur no more than 7 days after the most recent storm event so that water contained in the cisterns is fresh. Sampling events will be conducted according to the following schedule which follows the schedule in Table 3:

- Water Quality Event #1: December 2020
- Water Quality Event #2: March 2021
- Water Quality Event #3: October 2021
- Water Quality Event #4: December 2021
- Water Quality Event #5: February 2022
- Water Quality Event #6: April 2022

6.2.2 Cistern Dosing

Pollutant concentrations in runoff from the mesocosm cistern catchment have historically been lower than pollutant concentrations in typical urban stormwater runoff, except for total zinc. Average pollutant concentrations in cistern samples collected during monitoring events in 2013 are presented in Table 10.

To increase pollutant concentrations to more typical ranges, stormwater runoff contained in the two cisterns will be dosed with select reagents and well-mixed prior to water quality sampling events. Cistern dosing will be conducted to achieve either low or high pollutant concentrations during each of the six water quality sampling events. During the first sampling event, cistern dosing will be based on historical sampling results (i.e., 2013 data in Table 10). For future sampling events, prior to each water quality monitoring event a single cistern sample will be collected and analyzed before the cistern water is dosed. These data will be used to estimate pollutant dosing requirements for water quality sampling event 2 through 6.

Reagents and target pollutant concentrations for the water quality sampling events are presented in Table 10. Because cistern zinc concentrations have been relatively high, it may not be possible to hit the low pollutant dosing target for total zinc.

Table 10. Cistern dosing reagents and target pollutant concentrations.

Pollutant	Reagent	Average Concentration in Cistern[1]	Low Pollutant Storm Dosing Target	High Pollutant Storm Dosing Target
Total Suspended Solids	Sil-co-Sil 106 or street sweeper waste	4.6 mg/L	40 mg/L	120 mg/L
Total copper	Copper sulfate ($CuSO_4$)	2.6 µg/L	10 µg/L	40 µg/L
Total Zinc	Zinc Chloride ($ZnCl_2$)	178 µg/L	50 µg/L	150 µg/L
Total Nitrogen	Potassium Nitrate (KNO_3)	0.77[2]	1 mg/L	3 mg/L
Total Phosphorus	Monopotassium Phosphate (KH_2PO_4)	0.043	0.1 mg/L	0.4 mg/L

[1] Based on data from four monitoring events in 2013
[2] Average nitrogen concentration represents Total Kjeldahl Nitrogen

If a source of street sweeper waste can be identified prior to the first sampling event it may be used to dose for TSS. If such a source is identified, a single load of sweeper waste would be stored under cover for the duration of the project. For dosing calculations, three subsamples would be collected and submitted for analysis of all target water quality parameters and for moisture content. An appropriate amount of sweeper waste would then be added, and the required mass of other reagents would be adjusted accordingly to account for pollutants contained in the sweeper waste.

6.2.3 Synthetic Storm Flow Routing

During water quality sampling events water will be pumped from the rain garden cistern to the bottom of the mesocosm cistern, causing water to flow to the mesocosms via the weir boxes. The pump valves will be adjusted to convey the rates presented in Table 9 for the duration of each storm event. Valves to mesocosms not being used in the water quality sampling will be shut so that water is routed only to the six-water quality sampling mesocosms and the influent sampling point. The eductors in each cistern will be turned on at least two hours prior to the start of pumping and will remain on for the duration of each sampling event to minimize the potential for settling of solids in the cisterns.

6.3 Water Quality Sampling Procedures

6.3.1 Sample Collection

Flow weighted composite samples will be collected from the effluent sample point of each of the six fully instrumented mesocosms and from the influent sampling point. Samples will be collected using Isco Model 6700 series automated samplers. Flow weighting will be conducted by sending data from the TB1-L flow meters to each of the autosamplers.

The autosamplers will be programmed to collect 200-mL aliquots in 20-L composite sampling bottles. Aliquot collection pacing will be programmed to collect approximately 8 L of sample. Final pacing will be based on initial flow monitoring data to estimate the percentage of water routed to each mesocosm that is expected to discharge during each water quality monitoring event.

Prior to sampling events, the composite sampling containers and autosampler tubing will be properly decontaminated (see Section 6.3.5) and ice will be packed in the base of the autosamplers. Within 12 hours of the completion of sampling, the 20-L composite sample containers will be delivered to ARI Labs. After the samples are received, ARI staff will use a churn splitter to split the composite sample into subsamples for laboratory analysis.

6.3.2 Equipment Decontamination

Composite sampling bottles will be properly cleaned and decontaminated by ARI staff prior to the first event and following laboratory analysis for each event. The following decontamination procedure will be followed:

1) Liquinox detergent rinse,
2) Reagent grade water rinse,
3) Two molar nitric acid rinse,
4) Reagent grade water rinse, and
5) Capping bottles with new cap, aluminum foil, or plastic wrap.

Automatic sampler lines will also be cleaned using Liquinox and then rinsed with deionized water following each sampling event.

6.3.3 Sample Identification and Chain-of-Custody

All sample containers for water quality analysis will be labeled with waterproof labels and waterproof ink with the following information:

- Mesocosm and sample ID.
- Date and time of sample collection (month/day/year and time when sampling completed).
- Sampler's initials.

Following sample collection, and before the samples are delivered to ARI, an ARI chain-of-custody form will be properly completed.

6.3.4 Water Quality Sampling Field Logs

Field logs will be filled out during each water quality monitoring event and will include, at a minimum, the following information:

- Sample date, start time, and end time
- Weather

- Name of field crew members
- Sample collection time for each of the 7 water quality samples. This will match the information written on the chain-of-custody
- Estimated sample volume collected in each composite sampling container
- Sampling errors and comments

6.4 Special Testing Events

Hydraulic conductivity and hydraulic residence time testing will be performed on the six fully instrumented mesocosms during Special Testing Events. Special Testing Events will be conducted according to the following schedule which aligns with the Project schedule in Table 3:

- Special Testing Event #1: December 2020
- Special Testing Event #2: October 2021
- Special Testing Event #3: February 2022

Special Testing Events will be scheduled to align with Water Quality Events and will be scheduled to occur after the completion of Water Quality Events, likely within one to two days.

6.4.1 Hydraulic Conductivity Monitoring

Hydraulic conductivity monitoring events would be conducted to characterize saturated hydraulic conductivity in the six fully instrumented mesocosms. This testing will be conducted during three special testing events according to the following general approach:

1. Water will be run through each mesocosm, with the valves open for approximately 10 minutes to prewet BSM.
2. Outlet valves on each of the six fully monitored mesocosms will be shut.
3. Inlet valves to the unused mesocosms and the inlet sampling point will be closed.
4. A hose will be used to add water to the mesocosm cistern and water will be allowed to flow from the cistern to each of the six fully instrument mesocosms via the cistern weir boxes.
5. Once the mesocosms are brim full, the hose will be shut off. The mesocosms will then be left for at least one hour so that water fully saturates the media.
6. The hose will be used as needed to top-off mesocosms back to brim full.
7. Inlet valves will be closed.
8. The 1.5” knife valves will be opened to permit water to discharge from the mesocosms via the unrestricted outlets and the controlled outlets.
9. Flow rates and ponding levels will be monitored normally using the TB1-L and HYDROS-21 sensors, respectively.
10. After all water has discharged from the mesocosms, valves will be reset to their normal positions.
11. Ponding level and outlet flow rate data will be used to calculate hydraulic conductivity according to the falling head method.

Based on initial Site visits in Fall 2019 and winter 2020, some valves are in relatively poor condition and could break if they are opened and closed too many times. If these valves are not considered to be in good enough condition, hydraulic conductivity monitoring procedures may be adapted to reduce valve usage.

6.4.2 Hydraulic Residence Time Monitoring

Hydraulic residence time monitoring will be conducted by applying a short duration salt pulse of known concentration to the each of the six fully instrumented mesocosms, then monitoring electrical conductivity of effluent. The test will be run at a flow rate that results in full saturation of the outlet-controlled mesocosms, but no surface ponding. The pumping system will be used to pump water from the rain garden cistern to the mesocosm cistern at a constant flow rate for approximately 4 hours.

After 30 minutes of pumping runoff contained in the cisterns, a 1 L pulse of 4,000 mg/L $MgCl_2$ will be added to the influent weir box to each mesocosm. This extremely concentrated pulse is expected to provide the ability to detect the pulse as electrical conductivity in the effluent. While extremely concentrated, the pulse is not expected to result in adverse impacts to vegetation or soil because it will be a short pulse that will be quickly diluted after the pulse ends during an extended period.

The following general approach will be used:

1. Calibrate six Oakton PC450 conductivity meter (one for each of the six tested mesocosms) and set to collect data on a 1-minute logging interval.
2. Install the sensors of each Oakton PC450 meter at the effluent of the TB1-L tipping bucket flow meters.
3. Close inlet valves to all unused mesocosms and the inlet sampling point.
4. Turn pump on to convey water from rain garden cistern to mesocosm cistern which will cause water to flow to the six fully instrumented mesocosms. The pump will be adjusted to convey enough water to fully saturate media in outlet-controlled mesocosms but not cause ponding. This is estimated to be a combined rate of 5 gpm for the six mesocosms, however, the actual flow rate will be based on hydraulic monitoring data collected prior to the residence time testing events.
5. After pumps have been running for 30 minutes, add 1L of 4,000 mg/L $MgCl_2$ stock solution to each inlet weir box. Record exact time that pulse is added to each mesocosm.
6. Run pumps for another four hours, or until effluent electrical conductivity values are within 20% of pre-test values.
7. Finish test by removing sensors, turning pump off, and re-opening proper valves.
8. Download data from the six Oakton PC450 meters.
9. Analyze data to estimate hydraulic residence time.

6.5 Vegetation Monitoring

Monthly vegetation size and vigor will be completed for all fourteen mesocosms included in this study. Plant size will be documented by measuring plant height above the soil surface, and two plant spread dimensions. Plant spread measurements will be completed on the same perpendicular axes during each event.

Plant health and vigor will be measured suing the following qualitative ratings:

- 1 = No damage associated with soil conditions, good color, vigorous growth
- 2 = 1-25% damage associated with soil conditions. Color and growth are not as robust as those rated a “1” but are still acceptable and growing well.
- 3 = 26-50% damage associated with soil conditions. Plants show obvious signs of stress associated with the treatment but still show new growth and may recover.
- 4 = 51-75% damage associated with soil conditions. Plants show significant signs of stress associated with the treatment with little new growth.
- 5 = 76-100% damage associated with soil conditions. Plant is dead or is expected to die soon.

6.6 O&M Monitoring

Monthly O&M monitoring events will consist of checking the orifices on outlet-controlled mesocosms to confirm whether they are clogged or partially clogged. Any clogging will be noted and any clogged orifices will be thoroughly cleaned.

7 Measurement Procedures

This section of the QAPP focuses on procedures that will be used for water quality sample analyses. Measurement procedures for other types of monitoring are presented in Section 6.

7.1 Procedures for Collecting Field Measurements

The pH of composite samples will be measured prior to delivering the samples to ARI for laboratory analysis. The composite sample containers will be vigorously swirled to homogenize the collected sample, and approximately 100 mL will be poured into a clean plastic cup. A properly calibrated pH meter will then be used to record the pH of each composite sample.

7.2 Laboratory Procedures

Composite samples will be delivered to ARI lab in 20-L composite sampling bottles under proper chain-of-custody procedures. They will be delivered within 12 hours of collecting the final composite sample aliquots. Composite samples will be split into subsamples using a properly decontaminated churn splitter. Further sample preparation will be completed by ARI in accordance with the analytical methods presented in Table 11.

Table 11. Analytical methods, hold times, and preservation methods.

Analyte	Method	Hold Time Prior to Preservation	Total Hold Time	Preservation
Total Suspended Solids	SM2540D	7 days	7 days	Store at 6 °C
Total Phosphorus	SM4500-P	28 days	28 days	H_2SO_4, Store at 6 °C
Ortho-phosphate	SM4500-PE	48 hours	48 hours	Store at 6 °C
Total Kjeldahl Nitrogen	SM4500-Norg	28 days	28 days	H_2SO_4, Store at 6 °C
Nitrate + Nitrite	SM4500-NO_3	48 hours	28 days	H_2SO_4, Store at 6 °C
Total Copper	EPA 200.8	6 months	6 months	HNO_3, Store at 6 °C
Dissolved Copper	EPA 200.8	12 hours	6 months	Filter, HNO_3, Store at 6 °C
Total Zinc	EPA 200.8	6 months	6 months	HNO_3, Store at 6 °C
Dissolved Zinc	EPA 200.8	12 hours	6 months	Filter, HNO_3, Store at 6 °C

8 Quality Control

8.1 QC for Field Monitoring Instruments

Startup calibrations will include carefully calibrating flow distribution equipment and calibrating all continuous monitoring equipment according to equipment manuals. This will include:

- Carefully leveling the mesocosm cistern weir boxes so that they distribute flow evenly between the mesocosms.
- After weir box calibrations, flows to each of the mesocosms and the inlet monitoring point will be manually measured to confirm even flow distribution. If flows are not evenly distributed, additional modifications will be made to the cistern weir boxes. Cistern weir boxes will be adjusted annually after the initial calibration.
- Careful inspection of all power connections, data logger wiring, and all monitoring equipment.
- Manually confirm accuracy of existing TB1-L tipping bucket flow meters.

- Calibrate HYDROS-21 water level sensors and TEROS 12 soil moisture sensors according to Meter Environment product manuals.

Additional calibrations will be completed during the course of monitoring activities. Specifically, the following quality control activities are anticipated to occur regularly, but at least prior to each of the six water quality sampling events:

- Inspection of all power and data logger connections
- Checking data logger enclosure desiccant and replacing if necessary.
- Inspection of tipping bucket gauges to ensure no debris in the buckets.

8.2 Field Notes

Field notes will be collected during each type of monitoring event and during regular system checks. In addition to data collection tables (which will be tailored for specific event types), all field forms will include, at a minimum, the following information:

- Date and time of observations
- Names of all field staff
- Weather conditions
- Condition of rain gauge
- Whether all weir boxes are properly leveled
- Any modifications to regular sampling and monitoring procedures

8.3 QC for Water Quality Sampling

8.3.1 Equipment Rinsate Blanks

Equipment rinsate blank will be collected during the second, fourth, and sixth water quality sampling events. These samples will be collected form the influent monitoring point to verify that the automated sampler tubing or bottle is not a source of contamination. Equipment rinsate blanks will be collected according to the following approach:

1. The sample line will be rinsed with dilute (1:100) Liquinox detergent solution and then deionized water in accordance with pre-storm event set-up procedures described in the Sampling Procedures section.
2. A pre-cleaned 20 L glass bottle from the laboratory will be placed in the automated sampler.
3. The sample line will be detached at the point of sample collection and placed in a carboy of reagent grade water.
4. The sampler will be programmed to draw 20 L of reagent grade water through the sampler tubing and into the 20 L glass bottle.
5. The 20 L glass bottle will then be removed from the automated sampler, placed on ice, and submitted to laboratory as a separate (blind) sample.

Once in the laboratory, the water from the 20 L glass bottle will be analyzed for parameters listed in

Table *11*.

8.3.2 Field Duplicate Samples

Field duplicates will be not be collected for this study. The only way to collect field duplicates is to split the influent line into two lines from the mesocosm cistern and sample both lines. Currently, the infrastructure to support that does not exist. Another SAM study ("The effects of mulch on stormwater treatment and maintenance effort in bioretention systems") that uses the same infrastructure at WSC also does not include field duplicate sample collection for the same reason.

8.3.3 Laboratory QC

ARI will conduct typical quality control procedures including method blanks, control standards, matrix spikes, laboratory duplicate split samples, and churn splitter rinsate blanks.

Method Blanks
Method blanks consisting of de-ionized and micro-filtered pure water will be analyzed with every laboratory sample batch. A laboratory sample batch will consist of no more than 20 samples and may include samples from other projects. Blank values will be presented in each laboratory report.

Control Standards
Control standards for each parameter will be analyzed by the laboratory with every sample batch. A laboratory sample batch will consist of no more than 20 samples and may include samples from other projects. Raw values and percent recovery (see formula in the Quality Objectives section) for the control standards will be presented in each laboratory report.

Matrix Spikes
For applicable parameters, matrix spikes will be analyzed by the laboratory with every sample batch. A laboratory sample batch will consist of no more than 20 samples and may include samples from other projects. Raw values and percent recovery (see formula in the Quality Objectives section) for the matrix spikes will be presented in each laboratory report.

Laboratory Duplicate Split Samples
Laboratory split-sample duplicates for each parameter will be analyzed for specifically labeled QA samples submitted with every sample batch. This will represent no less than 10 percent of the project submitted samples. Raw values and relative percent difference (see formula in the Quality Objectives section) of the duplicate results will be presented in each laboratory report.

Churn Splitter Rinsate Blanks
Rinsate blanks will be collected from the churn splitter used to process samples for this study in order to verify it is not a source of contamination. At a minimum, two rinsate blanks will be collected for this purpose; the first prior to sampling the first storm event in any given monitoring year, and the second midway through the monitoring year. Each rinsate blank will be collected from churn splitter after it has been cleaned in accordance with standard laboratory procedures.

9 Data Management

All continuous hydrologic data will be stored on 5-minute logging intervals on data loggers. Data collected using the existing tipping bucket rain gauges and flow meters will be stored on existing Campbell Scientific CR1000 data loggers. These data loggers are hardwired to the WSU network and this data will be downloaded on a weekly basis during the rainy season and on a monthly basis during the dry season.

Data collected using Meter Environment HYDROS 21 water level sensors and TEROS 12 soil moisture sensors will be stored on Meter Environment ZL6 cellular data loggers. This data will be uploaded on an hourly basis to the Meter Environment Zentra Cloud. It will be downloaded from the Zentra Cloud on a monthly basis.

Downloaded hydrologic data will be stored in a relational database. All hydrologic data will be stored on 5-minute intervals. Quality control checks and data gap identification will be completed during each data download. Any missing data will be flagged.

Water quality analytical results and field form data will be stored in spreadsheets. Laboratory analytical results will be reported in Electronic Data Deliverables which will be incorporated into a master data spreadsheet for the project. Field form data will be manually entered into a separate field data log.

Monitoring data collected during special testing events will also be stored in spreadsheets. Much of this data will be manually recorded and transcribed into spreadsheets.

Monitoring data will be compiled and submitted to Ecology as part of Progress Reports which will be submitted following Water Quality Events according to the Schedule in Table 3.

The compiled result data including final summary and the original data after completing data verification described in the section 11 will be sent to SAM project manager in an excel format at the end of the project.

10 Audits

Audits will be performed after data is received following each water quality sampling event. These reviews will ensure that all data are consistent and accurate. In the event of a potential issue with data, the Project Team will assess whether any response actions are required. Response actions in this case might include the collection of additional samples, reanalysis of existing samples if not yet past holding time or advising the laboratory that methodologies or QA/QC procedures need to be improved.

11 Data Verification

11.1 Field Data Verification

The following data verification will be completed for field data:

1. Precipitation data from the study will be reviewed to identify any significant gaps from both the two precipitation gauges. If possible, these gaps will be filled using data obtained from a nearby rain gauge.
2. The available discharge data from each tipping bucket flow meter will be verified based on comparisons of the associated hydrographs to the hyetographs for individual storm events. Gross anomalies (e.g., data spikes), gaps, or inconsistencies that are identified through this review will be investigated to determine if there are quality assurance issues associated with the data that limit their usability. Irrigation records will also be considered when assessing discharge data from the mesocosms.
3. Soil moisture data from each soil moisture sensor will be verified based on comparisons of soil moisture variations associated with individual natural and synthetic storm events. Gross anomalies (e.g., data spikes), gaps, or inconsistencies that are identified through this review will be investigated to determine if there are quality assurance issues associated with the data that limit their usability.
4. Surface ponding and bypass data will be verified based on comparisons of variations associated with individual storm events. Gross anomalies (e.g., data spikes), gaps, or inconsistencies that are identified through this review will be investigated to determine if there are quality assurance issues associated with the data that limit their usability.
5. Hydraulic conductivity testing data and residence time data will be reviewed for accuracy and data will be compared to expected ranges and compared to previously collected data.
6. Metrics of plant growth and weeding effort will be reviewed to identify significant changes over short periods to ascertain if those metrics reflect real world conditions or if they are errors in measurement.

11.2 Laboratory Data Verification

In order to ensure the validity of laboratory analysis, a variety of quality laboratory controls will be included in this project, including:

- Completeness
- Methodology
- Laboratory Holding Times
- Method Blanks
- Reporting Limits
- Matrix Spikes
- Control Standards

Completeness
In order for a sample batch to be considered complete, at least 95 percent of the samples submitted must be judged to be valid (not rejected). This will be calculated by dividing the number of non-rejected samples (non *R* values) by the total number of samples. If less than 95 percent of the samples are judged to be valid, then more samples will need to be collected and this sample event may be void.

Methodology
Laboratory methods for analysis will follow those methods presented in

Table 11. Lab procedures will follow those detailed in this QAPP and any deviations will be documented in an addendum to this QAPP. Deviations deemed unacceptable will result in rejected (*R*) values.

Laboratory Holding Times
After samples are submitted to the laboratory, specific holding times are required for each analytical parameter which are presented in Table 11. Violations in these holding times will result in either estimation (*J*) or rejection (*R*) flags.

Method Blanks
Method blank values will be compared to the MQO's defined in Table 4. If an analyte is detected in a method blank to be at or above the reporting limit the associated data will be labeled with a *U*. This will essentially increase the reporting limit for the samples and associated batch samples within five times the newly defined reporting limit (the *U* flagged measurement) will be flagged with a *J*. In each of these cases, the de facto reporting limit for that analyte will be recorded along with the raw data, equipment will be decontaminated, and samples will be rerun if possible.

Reporting Limits
Laboratory reporting limits will be included in each report and reviewed in each audit. If proposed limits are not met by the laboratory, the laboratory will be requested to reanalyze the samples or revise the method, if time permits.

Matrix Spikes
Matrix spike results exceeding the MQOs for this project will be noted in the quality assurance worksheets, and associated values will be flagged as estimates (*J*). However, if the percent recovery exceeds the MQOs and a value is less than the reporting limit, the result will not be flagged as an estimate. Non-detected values will be rejected (*R*) if the percent recovery is less than 30 percent.

Control Standards
Control standard results exceeding the MQOs for this project (see Table 4) will be noted in the quality assurance worksheets, and associated values will be flagged as estimates (*J*). If the objectives are severely exceeded (such as more than twice the objective), then associated values will be rejected (*R*).

12 References

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.

Ecology, 2013. Stormwater Work Group, Priority Topics List. Washington State Department of Ecology.

Herrera Environmental Consultants, 2011. Quality Assurance Project Plan: Low Impact Development Research Program: Mesocosm Performance Monitoring. Prepared for Washington

State University Puyallup Research and Extension Center.
https://www.wastormwatercenter.org/files/library/mesocosm-qapp-final-9-16-10.pdf

Herrera Environmental Consultants, 2020. Bioretention Media Blends to Improve Stormwater Treatment: Final Phase of Study to Develop New Specifications Final Report. Prepared for King County.