Evaluation of Hydraulic Control Approaches for Bioretention Systems

Final Report

Prepared for:

Stormwater Action Monitoring and

Washington State Department of Ecology

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Executive Summary

Under the Stormwater Management Manual for Western Washington (SWMMWW), bioretention facilities are commonly used to provide on-site stormwater management, runoff treatment, and flow control. Sites with poorly infiltrating soil often require underdrains to be designed to keep the water moving through the bioretention facilities. For bioretention facilities that are underdrained, there can be two different hydraulic control approaches that the flow rate through the system can be controlled; bioretention facilities can be designed to rely on the permeability of filtration media to restrict flow rates (i.e., "media control") or incorporate flow-restricting devices (valves or orifices) on the underdrain outlets to throttle flow rates through the system (i.e., "outlet control"). The hydraulic control approach used in bioretention facilities has the potential to change the operations and performance of these systems. This research compares outlet-controlled and media-controlled designs to assess differences in water quality treatment performance, hydraulic characteristics, flow control performance, maintenance requirements, and plant health.

The existing Mesocosm Research Facility at WSU Puyallup campus was modified to create seven pairs of mesocosms with different types and ages of bioretention soil media (BSM), where each pair included a media-controlled and an outlet-controlled version. New standard BSM, mature standard BSM, and alternative high-performance BSM were tested. Stormwater runoff was routed through the mesocosms over 18 months, and the mesocosms were monitored continuously for hydraulic performance (inflow, outflow, ponding depth, and soil moisture content). Additional hydraulic and water quality performance data were collected within the monitoring period as part of periodic special testing events. Operations and maintenance inspections were performed monthly. Vegetation was monitored quarterly.

Data were analyzed to evaluate the effect of outlet control compared to media control. Additionally, a modeling study was conducted to augment the results of the mesocosm monitoring study.

Key findings from this research include:

BIORETENTION MESOCOSMS

OUTLET HYDRAULIC CONTROL

WATER QUALITY MONITORING

- Outlet control positively and negatively affected water quality treatment compared to media control. This varied from pollutant to pollutant. Some pollutants prone to leaching from standard BSM showed greater leaching when outlet control was used; however, other pollutants were more effectively retained using outlet control. These effects were relatively minor compared to the effect of BSM types and age.
- Outlet control increased residence time and resulted in more consistent and predictable stage-discharge relationships. The hydraulic conductivity of BSM varied substantially between BSM types and vendors, with associated variability in hydraulic response for media-controlled mesocosms. Outlet control mitigated this variability to produce a more stable hydraulic residence time and predictable outflow relationship.
- Outlet control results in a more steady and predictable flow rate leaving the bioretention facilities. The flow restriction via outlet control resulted in improvement in flow attenuation during all but the smallest storm events. The degree of improvement in flow control depended on sizing and outlet design. With increasing size, the flow control benefit associated with outlet control became more pronounced compared to media control.
- The Western Washington Hydrology Model (WWHM) can reliably represent outlet-controlled configurations, allowing the benefits of different design scenarios to be evaluated.
- Outlet control had no apparent impact on plant health during the 18-month study period, with the potential for minor positive effects.
- The small orifice controls (0.25-inch diameter) used in the outlet-controlled mesocosms did not require maintenance during the 18-month study period.

Overall, the results of this study suggest that outlet control has a limited positive effect on water quality treatment for traditional pollutants assessed in this study. Where traditional water quality treatment is the primary goal of bioretention design, outlet control benefits do not appear to justify the added complexity in design and minor increased risk of pollutant leaching.

Outlet control has the potential to provide substantial value where project design goals call for (1) an increase in residence time to improve the removal or transformation of specific pollutants, (2) an increase in the uniformity of flow through the bioretention media bed, reducing potential short-circuiting, and/or (3) more predictable flow control characteristics to meet flow control design goals. In these cases, outlet control should be paired with BSM selection strategies to reduce pollutant export.

1. Introduction

1.1. Introduction and Background

A critical basis for this work is funding from the MS4 permittees through the SAM process. We gratefully acknowledge their support of this work, and their interest in improving water quality and quantity in western Washington through optimally designed bioretention facilities. 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 is the only single best management practice that is approved to meet Minimum Requirements (MR) #5 On-Site Stormwater Management, #6 Runoff Treatment, #7 Flow Control, and #8 Wetlands Protection. Therefore, even minor improvements to the design of bioretention facilities can have deeply impactful outcomes on stormwater management in western Washington.

Bioretention facilities 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 through 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 adequate native soil infiltration rates (> 0.3 inches per hour corrected infiltration rate), bioretention is typically designed without underdrains; water infiltrates underlying soils. In areas with lower native soil infiltration rates (e.g., factored rates less than 0.3 inches per hour) or other issues that limit infiltration, such as high groundwater tables, subsurface contamination, or geotechnical concerns, bioretention facilities are typically designed with a perforated underdrain when the underlying soils limit infiltration, or when those soils are contaminated. Perforated underdrains ensure treated stormwater can discharge into storm drains 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 storm drains. A schematic from the SWMMWW of bioretention with an underdrain is presented in *Figure 1-1*.

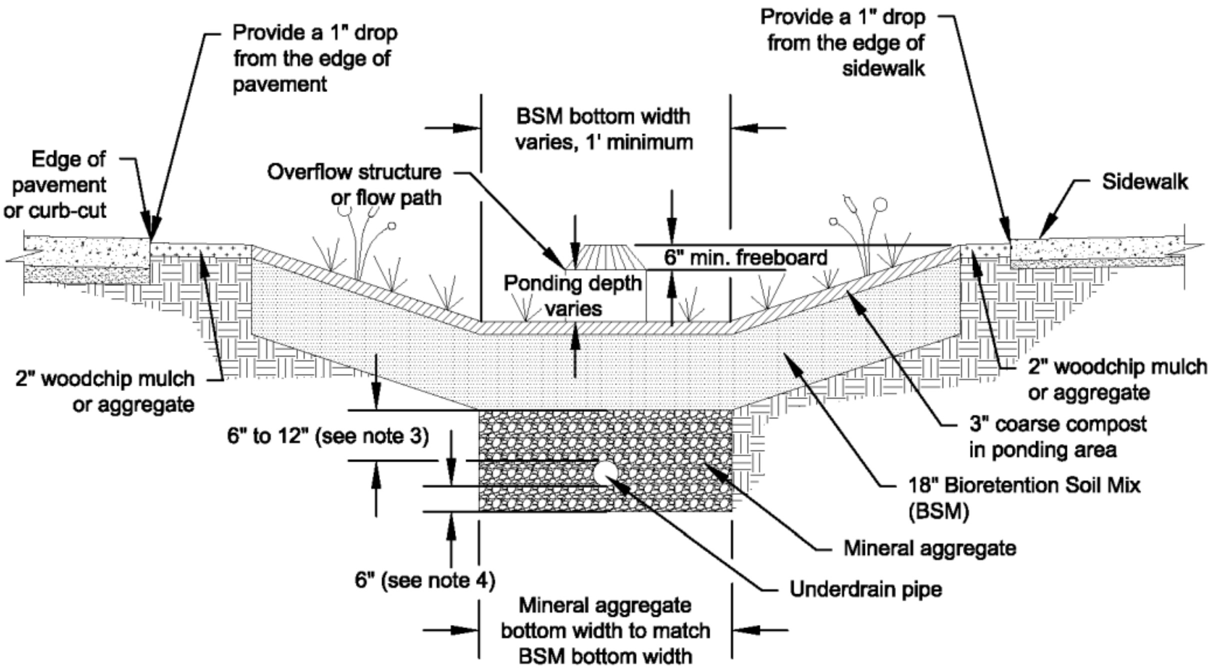


Figure 1-1: Typical design schematic for bioretention swale from 2019 SWMMWW.

When bioretention is designed with underdrains, the flow rate of runoff treated through BSM can be controlled though two paradigms. A media-controlled configuration relies on the permeability of BSM to restrict flow rates. An outlet-controlled configuration uses valves or orifices on the underdrain outlets to throttle treatment flow rates to a rate that is lower than the inherent permeability of the BSM. An example cross section and plan view of a bioretention facility with underdrain and outlet control structure recently designed and built in Western Washington is presented in Appendix A.

The 2019 SWMMWW allows either of these hydraulic control approaches to be used. However, most bioretention with underdrain systems are designed using a media-controlled approach. Since the permeability of BSM can be as high as 80 inches per hour, runoff can pass through bioretention with underdrains much faster than the default design flow rate, typically 6 inches per hour or less. Therefore, adding outlet controls could substantially change flow through rate and contact times with the bioretention soil media.

This study compared the side-by-side pollutant removal and hydraulic performance of media-controlled bioretention mesocosms to outlet-controlled bioretention mesocosms. The study was completed by retrofitting the existing mesocosms at the Washington State University (WSU) LID Research facility in Puyallup, Washington.

1.2. Research Need

The hydraulic conditions within bioretention facilities (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), the 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).

The faster treatment rate offered via media-controlled configuration allows more water to be treated within a bioretention facility of a given size and reduces ponding durations, which may be desirable in many applications. In some applications, slowing the rate of water filtration using outlet controls could be desirable to increase treatment contact time, reduce the potential for short-circuiting, increase flow control performance, and cause water to be distributed more evenly through a bioretention facility.

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, there is a need to determine whether increasing residence times and restricting flow through BSM could negatively affect pollutant export or plant health. Finally, more field-scale information is needed to confirm the ability to reliably model an outlet-controlled configuration.

1.3. Study Goals

The primary research goal is to compare the performance, operations, and maintenance (O&M) needs of underdrained bioretention facilities with passive, outlet-controlled configurations to those with media-controlled configurations.

Specific study questions include:

- Question 1: How does the water quality treatment performance of bioretention differ between outlet-controlled and media-controlled configurations?
- Question 2: How does outlet control vs. media control affect the residence time and residence time distribution of water treated by the mesocosms?
- Question 3: Are plant health and vigor differences notable at a mesocosm scale between outlet-controlled and media-controlled designs?

- Question 4: Does using small orifices as outlet controls pose notable operations and maintenance challenges compared to standard bioretention without underdrain outlet controls?
- Question 5: 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?
- Question 6: How do hydraulic conditions of the systems (i.e., stage-discharge relationships) vary over time and between replicate mesocosms? Does one configuration result in more consistent operation than another?
- Question 7: Does outlet control improve the degree of hydrologic control provided by a bioretention facility of a given size, even if not explicitly designed to meet either MR#5 or MR#7 flow control standards? For example, flow control benefits could be related to flow attenuation (i.e., by reducing treatment flow rates) and increased infiltration into underlying soils with relatively low permeability by extending the residence time of runoff within a system.

Section 2 of this report summarizes the study methods used to answer these questions. Section 3 of this report presents the study's results, organized by study element. Section 4 of this report synthesizes study results to provide answers to the seven research questions above.

2. Research Methods

The Quality Assurance Project Plan (QAPP) (Geosyntec & WSU, 2020) details the methods used in the experiment design and monitoring phases. The purpose of this section is to summarize the experimental design, including any adjustments to the original plan.

2.1. Overall Experiment Design

This research was conducted in three phases: 1) Experiment Design Phase, 2) Monitoring Phase, and 3) Analysis Phase.

The existing Mesocosm Research Facility at the WSU campus in Puyallup was redesigned and retrofitted to meet the needs of this study. This resulted in seven pairs of mesocosms with different media types and ages, where each pair included a media-controlled and outlet-controlled version of the same media and age, for a total of 14 mesocosms.

In the monitoring phase, continuous monitoring of the hydraulic performance of the mesocosms was conducted, including flow, water level, and soil moisture. In addition, period special monitoring events were completed to measure plant health, residence time distribution, media permeability, and water quality performance of the mesocosms.

The analysis phase consisted of data analyses and interpretation to answer the study questions in Section 1.3. An accompanying modeling study was completed to augment the analysis of the mesocosm data and documented in the Final Modeling Study Report (WSU & Geosyntec, 2023).

2.2. Mesocosm Facility Modifications

The experiment was conducted at Washington State University's Puyallup Research and Extension Center in the South Puget Sound Region. The existing Mesocosm Research Facility (the facility) was constructed in 2011, consisting of a flow distribution cistern that receives and distributes runoff from a contribution area within the WSU campus and distributes flow to twenty bioretention mesocosms. Continuous flow monitoring systems were built into the original mesocosm design. Aspects of the mesocosm facility were modified to support this study.

2.2.1. Initial Modification of Flow Distribution System

The existing flow distribution consists of two cisterns. The cisterns receive runoff from a 72,100-square-foot drainage area on the WSU campus with an approximate impervious cover of 70% (50,500-square-foof of impervious drainage area). These cisterns have valves that can split flow between the mesocosm facility and a larger-scale rain garden facility that share the same water source. In the original design specified in the QAPP, 25% of the runoff from the full drainage area was routed to the mesocosms, resulting in an effective drainage area of 18,000 square feet. The remaining 75% was routed to the rain garden plots, which were used as part of a separate study.

Within the mesocosm facility, a flow distribution chamber initially distributed to the twenty existing mesocosms using v-notch weir boxes. This study used 14 mesocosms, as discussed further in Section 2.2.3. To retrofit the facility for this study, outlet valves to the six unused mesocosms were shut off. The remaining v-notch weirs were precisely releveled to help provide even flow distribution to each mesocosm.

The 14 active mesocosms are 5 ft in diameter and have a total footprint area of approximately 275 sq-ft. This equates to an effective sizing factor of approximately 2.2% ratio between the total area of bioretention footprint and impervious contribution area).

2.2.2. Additional Modification of Flow Distribution During Study Period

In January 2022, one year after the monitoring period started, the research team reviewed the continuous monitoring data collected in the 12-month period. During the review process, the research team identified that the original contribution area to the mesocosms from the QAPP was insufficient to induce ponding during most of the precipitation events in 2021. Additionally, a separate study utilizing the rain garden facility was completed. As a result, the research team changed the flow distribution system to divert 100% of the runoff from the contribution area to the fourteen mesocosms. This change was made on February 15, 2022, quadrupling the effective drainage area to 72,100 square feet (50, 500-square-feet of impervious drainage area) and the sizing factor to 0.5%. This change resulted in observed ponding in most mesocosms for multiple storm events between February 2022 and the end of the monitoring period (June 2022).

2.2.3. Mesocosm Retrofit

The Mesocosm Facility consists of twenty bioretention mesocosms in total. Each mesocosm was constructed from a 60-inch diameter plastic cylinder with a total height of 52 inches. A previous study initiated in 2011 filled these existing mesocosms with approximately 24 inches of BSMs and planted the mesocosm with typical bioretention plants. The rest of the vertical profile of the mesocosm consists of a pea gravel layer below the media layer and a ponding freeboard depth above the media surface. The mesocosms had 1-inch diameter perforated underdrains that discharged to a tipping bucket flow measurement system. The vertical profile of the mesocosms remained the same during this study.

Fourteen of the twenty mesocosms were used in this study. Figure 2-1 illustrates the fourteen mesocosms used in this study.

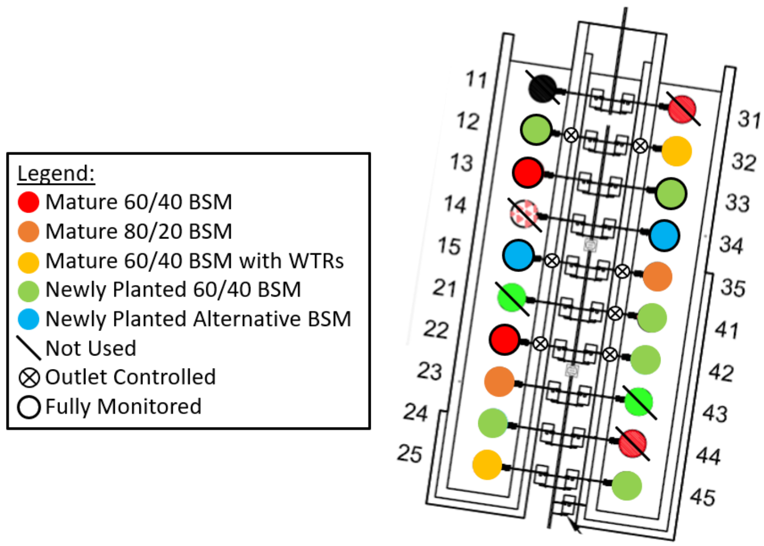


Figure 2-1 Mesocosms Layout and Modifications

The fourteen mesocosms were retrofitted based on four factors that were identified as variables for the evaluation of hydraulic and water quality performance: age of BSM (mature vs. new), BSM type (variation of standard mix vs. alternative BSM), material supplier (three different suppliers were used for new standard BSM) and outlet type (free vs. outlet-controlled). Table 1 summarizes the variables for each of the fourteen mesocosms used in this study. Definitions of BSM types, outlet types, and monitoring types are provided in Section 2.2.4.

Table 1 Bioretention Mesocosm Description

Mesocosm ID	Age	BSM Type	Vendor	Outlet Type	Monitoring
25	Mature	60/40 WTR	NA	Media Control	Standard
32	Mature	60/40 WTR	NA	Outlet Control	Standard
23	Mature	80/20	NA	Media Control	Standard
35	Mature	80/20	NA	Outlet Control	Standard
13	Mature	Standard 60/40	NA	Media Control	Full
22	Mature	Standard 60/40	NA	Outlet Control	Full
34	New	Alternative	Walrath	Media Control	Full
15	New	Alternative	Walrath	Outlet Control	Full
33	New	Standard 60/40	Cedar Grove	Media Control	Full
12	New	Standard 60/40	Cedar Grove	Outlet Control	Full
24	New	Standard 60/40	Corliss	Media Control	Standard
42	New	Standard 60/40	Corliss	Outlet Control	Standard
45	New	Standard 60/40	Walrath	Media Control	Standard
41	New	Standard 60/40	Walrath	Outlet Control	Standard

2.2.4. Explanation of Key Study Variables

Age: Mature refers to the mesocosms that were left in place from the 2011 study. These were approximately 10 years old at the start of the current study. New refers to media procured, placed, and planted as part of the current study.

BSM Type: The following media were tested. All percentages are by volume.

- Standard 60/40 refers to the standard 60%-sand-40%-compost BSM specified in the 2019 SWMMWW. Mixes meeting this specification were procured from three vendors.
- Alternative refers to a blend meeting the high-performance alternative media blend in the 2019 SWMMWW. This included 70% sand, 20% coconut coir pith, and 10% biochar.
- 60/40 WTR refers to a 60/40 blend augmented with water treatment residuals, obtained as part of the 2011 study.
- 80/20 refers to a 80%-sand-20%-compost BSM, obtained as part of the 2011 study.

New plants were also planted for the eight mesocosms that had new media installed. One 6-inch pot of *Pennisetum alopecuroides* ('Little Bunny'), one 6-inch pot of *Deschampsia cespitosa* ('Northern Lights'), and two 6-inch pots of *Cornus sericea* ('Dwarf Dogwood') were planted on each of the eight mesocosms.

Vendor: This refers to the vendors from which new materials were obtained.

Outlet Configuration: One mesocosm in each pair was left to freely drain via the existing 1-inch diameter underdrain and outlet system (i.e., media control). For the size of the mesocosms, the 1-inch underdrain capacity is adequate to provide essentially no flow restriction. The other mesocosm in each pair was retrofitted with outlet control orifices sized to restrict the outflow to approximately 6 inches per hour. This equated to a 0.25-inch diameter orifice drilled into a removable end cap. The effective area of the orifices is approximately 1/16th of the area of the 1-inch underdrains, therefore, this greatly increases flow restriction.

Monitoring: Refers to the instrumentation used in each mesocosm. All fourteen mesocosms were equipped to continuously measure the flowrate leaving the system and pressure transducers in a standpipe to measure the ponding depths. This is referred to as "standard." For the six mesocosms specified for "full monitoring" in Table 1, additional instrumentation was used including soil moisture sensors and flow-weighted composite water quality sampling. Additional information about monitoring design is included in Section 2.3.

Details of the mesocosm retrofit and instrument installation can be found in the Installation and Start-Up Report (WSU & Geosyntec, 2021).

2.3. Monitoring Methods

Media was placed, and plants were planted on December 7, 2020. Runoff was allowed to flow through the mesocosms for the following month. This was used as a conditioning and establishment period before monitoring commenced. Instrumentation was installed and calibrated during this phase, as documented in the Installation and Start-Up Report.

The monitoring phase of this study started on January 8, 2021, and lasted till June 30, 2022. This period of record is referred to as the "monitoring period" in this report. During this monitoring period, continuous monitoring of the hydraulic performance of the mesocosms was conducted. Additional hydraulic and water quality performance data were collected during periodic special testing events. Plant health, operations, and maintenance activities were recorded monthly throughout the monitoring period. These monitoring activities and instrumentation designs were documented in the QAPP. The installation and calibration of system instrumentation is documented in the Installation and Start-Up Report. The following sections summarize each type of monitoring.

2.3.1. Long-term Hydraulics Monitoring

Continuous monitoring of the inflow flowrate, outflow flowrate, and ponding depth was carried out for all fourteen mesocosms in this study throughout the monitoring period, as detailed in Section 6.1 of the QAPP. Data were recorded at 5-minute intervals. It should be noted that per the design of the mesocosm facility, a common inflow flowrate was measured, and this was assumed to represent the inflow to each of the 14 mesocosm. The representative inflow flowrate was obtained from a v-notch weir box of identical design to the weir boxes that distributed water to each mesocosm. The weir boxes were all leveled as part of startup to ensure as similar as possible flow to each weir box. This "inflow" line was routed to the same tipping bucket flow measuring device used for the outflow from each mesocosm.

In addition, soil moisture content was monitored within the six fully-instrumented mesocosms at a 5-minute resolution, and precipitation was monitored via a weather station at the mesocosm facility at a 5-minute resolution.

2.3.2. Special Event Hydraulics Monitoring

Three special hydraulics testing events (Feb 2021, Oct 2021, and Apr 2022) were conducted during the monitoring period, as detailed in Section 6.4 of the QAPP (WSU & Geosyntec, 2020). Each event included hydraulic conductivity testing and residence time testing for the six fully-instrumented mesocosms.

2.3.2.1. Hydraulic Conductivity Testing

The purpose of hydraulic conductivity testing was to measure the hydraulic conductivity of the media bed at points in time during the study. Orifice controls were removed from the mesocosms before running these tests.

To start the test, a cap was placed on the outlet from each of the mesocosms. The mesocosms were filled and allowed to stand for approximately 30 minutes until trapped air escaped from the media. No further inflow was routed to the mesocosms after they were filled. The outlet caps were then removed and the mesocosms were allowed to drain completely. Water level and outflow data were measured during these events.

In addition to the hydraulic conductivity tests documented in the QAPP, two additional drawdown tests were conducted with orifice controls in place for the three fully-instrumented outlet-controlled mesocosms. The methodology for these additional tests was identical to those without the orifices, except that the orifice was left in place during the drawdown period. These tests were intended to isolate the stage-storage-discharge relationships of orifice-controlled mesocosms.

2.3.2.2. Hydraulic Residence Time Testing

Hydraulic residence time testing was performed for the six fully-instrumented mesocosms. During this test, the influent lines to the other mesocosms were closed, such that flow was only routed to the six mesocosms being tested.

Prior to the start of the tests, a pump was used to convey stored water to the mesocosms at a total rate of 28 liters per minute (approximately 4.5 liters per minute per mesocosm). The pump rate was determined such that the six mesocosms were fully wetted but there was limited ponding in the mesocosm prior to the introduction of the tracer. The 4.5 liters per minute corresponds to approximately 6 inches per hour of loading. This rate would engage the orifice of the outlet controlled mesocosms but would not exceed the media hydraulic conductivity. The pre-wetting period was approximately 75 minutes.

After the pre-wetting period, a concentrated dose of 4 liters of 2,500 mg/L potassium bromide was added directly into each of the weir boxes leading to each of the six mesocosms. The pumped flow continued for another 240 minutes, and the electrical conductivity of the effluent was monitored for each mesocosm. These data were used to estimate the hydraulic residence time of the mesocosms.

2.3.3. Water Quality Monitoring

Six water quality monitoring events were conducted throughout the monitoring period, as detailed in Sections 6.2 and 6.3 of the QAPP. During these events, stormwater runoff that had been collected from a previous storm was first augmented with additives to achieve target concentration rates as specified in the QAPP. The augmented stormwater was then fully mixed in the cistern and pumped to the six fully instrumented mesocosms and the influent monitoring point. The inflow pump rates were set to represent moderate-intensity storms for half of the monitoring events and high-intensity storms for the other half. Flow-weighted composite water quality samples were collected using an autosampler from the effluent of each mesocosm and the influent sampling port. These samples were analyzed for nine pollutants of concern at an accredited laboratory, as outlined in the QAPP.

2.3.4. Vegetation Monitoring

Monthly vegetation health and vigor ratings were planned (Section 6.5 of the QAPP) but were found to be infeasible for two reasons: A) our ability to measure plants were not accurate or precise enough to capture monthly variation, and B) the effort to measure monthly was cost-prohibitive (time and effort) given we started this project during COVID-19 restrictions. We chose to collect quarterly measurements and these were completed for all fourteen mesocosms included in this study . These monitoring data were used to assess the plant health differences among bioretention with different hydraulic controls and media types.

2.3.5. Operation and Maintenance Monitoring

Monthly O&M monitoring events included checking the orifices on outlet-controlled mesocosms as detailed in Section 6.6 of the QAPP. These data were used to determine whether the O&M burden is higher for bioretention with orifice outlet control.

2.4. Summary of Resulting Datasets

Table 2 summarizes the resulting monitoring dataset obtained via execution of the study.

The following sections summarize notable aspects of the data inventory and notable adaptations of the study methods described in the QAPP.

Table 2 Summary of Monitoring Datasets

Type of Monitoring	Frequency	Data Type	Scope	Data Availability
Precipitation	Continuous, 5-min interval	Depth (mm)	One station, representing the site	[10/6/20 – 8/15/22] 98% available; 168,515 readings See Section 2.4.1 for discussion.
Mesocosm Inlet Flow Rate	Continuous, bucket tips, converted to 5-minute interval flowrate	Flow Rate (Liters/second)	One location, representative of inflow to each mesocosm	[10/6/20-8/15/22] 98% available; 168,528 readings See Section 2.4.1 for discussion.
Mesocosm Outlet Flow Rate	Continuous, bucket tips, converted to 5-minute interval flowrate	Flow Rate (Liters/second)	14 mesocosms	[10/6/20-8/15/22] 98% available; 168,528 readings Flow rates from Mesocosm 23 were not used due to detected leak; see note in Section 2.4.3.
Ponding Depth	Continuous, 5-minute interval	Depth (mm)	14 mesocosms	[1/7/21-8/25/22] 60% available; 141,422 readings See Section 1.1.1 for discussion. Data loggers lost power resulting in data gaps; see note in Section 2.4.1.
Soil Moisture	Continuous, 5-minute interval	Volumetric water content (cm^3 water / cm^3 bulk soil)	6 fully instrumented mesocosms	[1/7/21-8/25/22] 60% available; 141,422 readings See Section 1.1.1 for discussion. Data loggers lost power resulting in data gaps; see note in Section 2.4.1.

Type of Monitoring	Frequency	Data Type	Scope	Data Availability
Water Quality	Six synthetic storm events	Influent and effluent constituent concentrations	6 fully instrumented mesocosms	Six events completed as planned at one influent station and 6 effluent stations. [2/17/2021, 4/21/2021, 10/25/2021, 12/8/2021, 4/6/2022, 5/17/2022] Sample results below detection limit were replaced with the detection limit.
Hydraulic Conductivity	Three testing events	Influent and effluent conductivity (mS/cm)	6 fully instrumented mesocosms	Three testing events completed as planned for six mesocosms. Event 3 was repeated. [2/18/2021, 10/27/2021, 4/7/2022, 4/13/2022]
Supplemental Drawdown Tests	Two testing events	Outlet flowrate and ponding	3 of the 6 fully instrumented mesocosms, with outlet control	Two testing events completed as planned for three mesocosm. [8/26/2022, 9/1/2022]
Hydraulic Residence Time	Three testing events	Influent and effluent conductivity (mS/cm)	6 fully instrumented mesocosms	Three testing events completed as planned for six mesocosms. Event 3 was repeated. [2/18/2021, 10/27/2021, 4/8/22, 4/21/2022]
Vegetation Health	Quarterly observations	Plant height and spread width (inches) and qualitative vigor rating	14 mesocosms	Despite the QAPP specifying monthly observations, only quarterly observations were made. 7 quarterly observations for each of four species in 14 mesocosms. See Section 2.3.4.dd
O&M Requirements	Monthly observations	O&M requirements log	14 mesocosms	Maintenance observations at 14 mesocosms. Not all were recorded, only when maintenance was performed

2.4.1. Data Gaps due to Datalogger/Sensor Outages

With the newly purchased soil moisture and ponding level sensor, and associated dataloggers, several outages occurred where we found gaps in the soil moisture and ponding data. Notable outages in data (soil moisture and ponding level) are listed below. The outages are specific to four data loggers:

Datalogger	Gaps
DL1 -	no data gaps
DL2 -	4/5/22 data gap
DL3 -	4/5/22 and 11/28/22 data gap
DL4 -	4/5/22 data gap

2.4.2. Inspection of Data Reasonableness

Various factors can affect data quality, including stuck sensors. As part of using data for the analyses described in Section 3, the research team conducted visual inspections to remove data that exhibited irregularities. These irregularities are noted in the final data deliverable. To the extent these irregularities were relevant for the analyses performed, they are discussed in the respective part of Section 3.

2.4.3. Mesocosm 23 Root Damage

An interim review of data reasonableness was performed in January 2022. The data quality check revealed that the total outflow measured at Mesocosm 23 was only 30% of the measured inflow. Upon inspection, the research team found that the issue was caused by the taproot of a dogwood plant damaging the outlet structure, resulting in outflow bypassing the flowmeter. Due to the uncertainty regarding when this incident occurred, the data from this mesocosm was not used as part of the analyses.

2.4.4. Adjustment to Contribution Flow Area

As discussed in Section 2.2.2., the contribution area routed to the bioretention mesocosms was increased approximately four times to increase the effective loading rate inducing ponding more frequently within the mesocosms. This went into effect on February 15, 2022.

2.4.5. Change in Conservative Tracer for Hydraulic Residence Time Testing

The QAPP called for using magnesium chloride as a conservative tracer for hydraulic residence time testing. Upon further investigation, the research team decided to use potassium bromide as an alternative conservative tracer to limit the potential for ion interference.

3. Results & Discussion

3.1. Hydraulic Monitoring

This section presents results for various elements of the hydraulic monitoring study, starting from granular elements of mesocosm behavior (e.g., hydraulic conductivity, residence time, stage-discharge, soil moisture) and progressing to full system performance, expressed in flow attenuation during discrete storms and flow duration control curves.

3.1.1. Media Hydraulic Conductivity

Media hydraulic conductivity was measured at six mesocosms as part of three special hydraulic testing events. These tests were conducted with orifices removed during these drawdown tests to estimate the media hydraulic conductivity without hydraulic restriction from the orifices.

These tests directly measured the change in water level during the falling head period divided by the time for the water level to fall. Using these data, combined with the thickness of the media bed, hydraulic conductivity can be calculated using the same method used in a falling head permeameter:

$$K = \frac{2.303L}{t} Log_{10} \frac{h1}{h2}$$

Where:

K = hydraulic conductivity

L = Length of the sample (24 inches)

t = Elapsed time of test

$h1$ = Elevation of water in the standpipe at t = 0 (measured from base of the column)

$h2$ = Elevation of water in the standpipe at time equal to t

Table 3 provides the media hydraulic conductivity derived from the drawdown testing data.

Table 3. Hydraulic Conductivity Results

Mesocosm	Hydraulic Conductivity (inches/hour)				
	Special Event #1	Special Event #2	Special Event #3	Average	Coefficient of Variation
12: New Standard BSM, outlet controlled	4.2	10.5	10.6	8.4	0.36
33: New Standard BSM, media controlled	4.9	18.2	15.8	12.9	0.45
22: Mature Standard BSM, outlet controlled	32.0	37.3	30.8	33.4	0.08
13: Mature Standard BSM, media controlled	34.7	34.0	37.0	35.2	0.04
15: Alternative BSM, outlet controlled	35.6	46.1	35.6	39.1	0.13
34: Alternative BSM, media controlled	26.9	38.3	34.4	33.2	0.14

No consistent difference in hydraulic conductivity was apparent when comparing the outlet-controlled mesocosms with their media-controlled counterpart.

The most notable finding from the hydraulic conductivity comparison is that the mesocosms with new standard BSM (MC 12 & 33) showed much lower hydraulic conductivity than those with mature standard BSM and those with new alternative BSM. In addition, there was a greater change (increase) in hydraulic conductivity over time in the new standard BSM than in the other media types. This indicates that aging processes such as weathering, and plant root growth may increase hydraulic conductivity over time. In most mesocosms, the hydraulic conductivity was well higher than the default design value for standard BSM specified in the SWMMWW. This is consistent with general knowledge.

3.1.2. Hydraulic Residence Time

Salt-pulse testing with a potassium bromide tracer was conducted during the three special hydraulic monitoring events to assess the hydraulic residence time (HRT) of the six full-instrumented mesocosms. Section 6.4 of the QAPP provides details of the experimental method. Data collected from Events 1 and 2 were analyzed. Event 3 was discarded due to sensor malfunction, as discussed in Section 2.4.

An example of the effluent electrical conductivity results for Event 2 is shown in Figure 3-1. Tracer pulses were added at the zero point on the X-axis. It should be noted that the new standard BSM had significant background electrical conductivity, which is seen in the data before the tracer pulse.

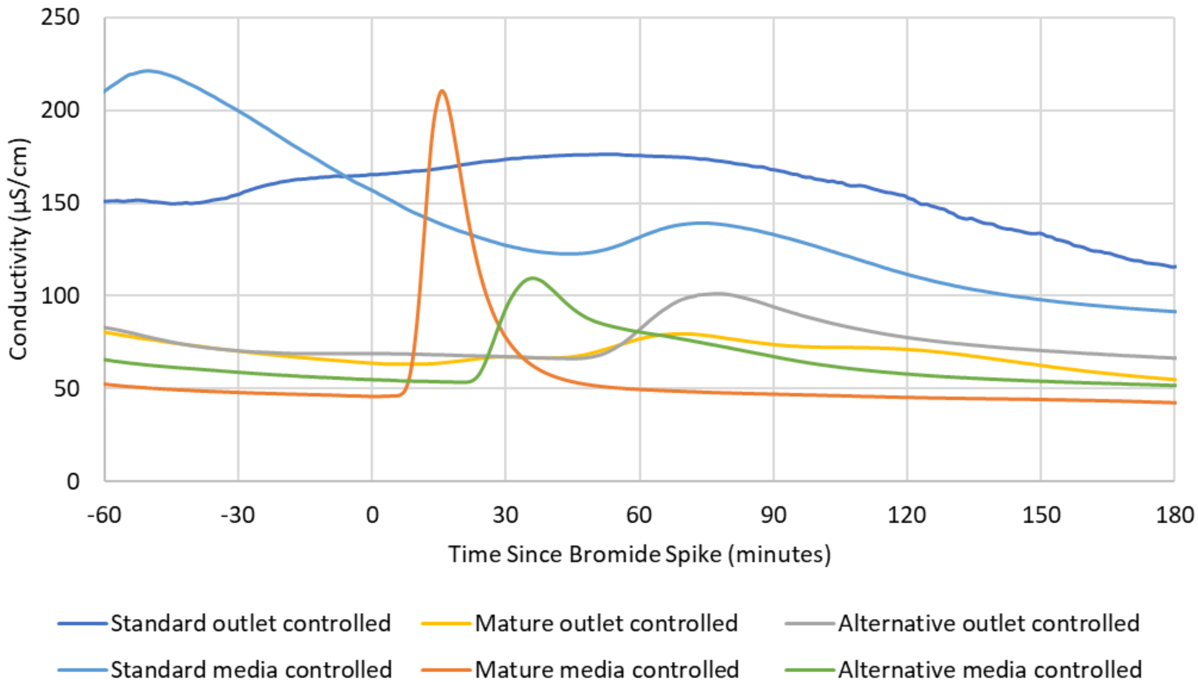


Figure 3-1 Example of Mesocosm Effluent Electrical Conductivity Monitoring Results during Event 2

Residence time distribution (RTD) curves and mean residence times (MRT) were calculated according to Equations 1 and 2 (Levenspiel, 1999).

$$E(t) = \frac{C(t_i)}{\int_0^\infty C(t_i)dt} = \frac{C(t_i)}{\sum_{i=1}^{n} C_i \Delta t} \qquad (1)$$

$$MRT = \int_0^\infty t_i E(t_i)dt = \sum_{i=1}^{n} t_i E_i \Delta t \qquad (2)$$

where t_i = sample collection time, C = salt concentration, and n= number of samples. $E(t)$ is defined as the RTD and has the same shape as the breakthrough curve. RTD is normalized so that the area under the curve equals 1, making comparisons between different mesocosms possible. MRT is the arithmetic average of the RTD curve. RTD curves and MRT were calculated using the data collected from the two valid special events and shown in Table 4.

Table 4 Mean Residence Time Comparison

Mesocosm	Event 1	Event 2	Average
	MRT (min)	MRT (min)	MRT (min)
12: New Standard BSM, outlet controlled	118	83	101
33: New Standard BSM, media controlled	81	88	85
22: Mature Standard BSM, outlet controlled	114.	95	104
13: Mature Standard BSM, media controlled	33	29	31
15: Alternative BSM, outlet controlled	108	94	101
34: Alternative BSM, media controlled	70	63	67

As shown in Table 4, MRTs of outlet-controlled mesocosms are longer than the MRTs of their media-controlled counterparts for all media types during both events, except for the new standard BSM (Mesocosm 12 & 33) during Event 2. This observation showed that the orifice outlet control effectively extends the MRT during the drawdown of the mesocosms. Table 4 also shows that the MRTs of outlet-controlled mesocosms are consistent regardless of media types, ranging between 100 and 104 minutes. In contrast, the MRTs of media-controlled mesocosms vary widely between 30 and 85 minutes. This observation suggests that outlet control effectively regulates the underdrain effluent flowrate to achieve consistent hydraulic conditions, relatively independent of the media properties' variability.

Wilcoxon signed-rank tests were conducted with the paired (media-controlled vs. outlet-controlled) MRT data for each event and media type to evaluate the impact of outlet control (as shown in Figure 3-2). The Wilcoxon signed-rank test is a non-parametric statistical hypothesis test to determine the statistical significance of the median difference between paired data. In this analysis, the absolute value of differences between data pairs are ranked and subsequently attributed a positive or negative sign based on the sign of the observed difference. The Wilcoxon test produces two test statistics: W+ and W-, the sum of all positive and negative ranks. The null hypothesis is that W+ and W- will be equal. This is tested by calculating a critical value based on the number of samples and p-value. The null hypothesis can be rejected if the smaller of W+ or W- is less than the critical value. For this analysis, the critical value ($n=6$, $p=0.1$) was 2, and the test statistic W was 1, which indicates that the null hypothesis could be rejected and the MRTs for orifice-controlled mesocosms are significantly longer than the MRTs media-controlled counterparts.

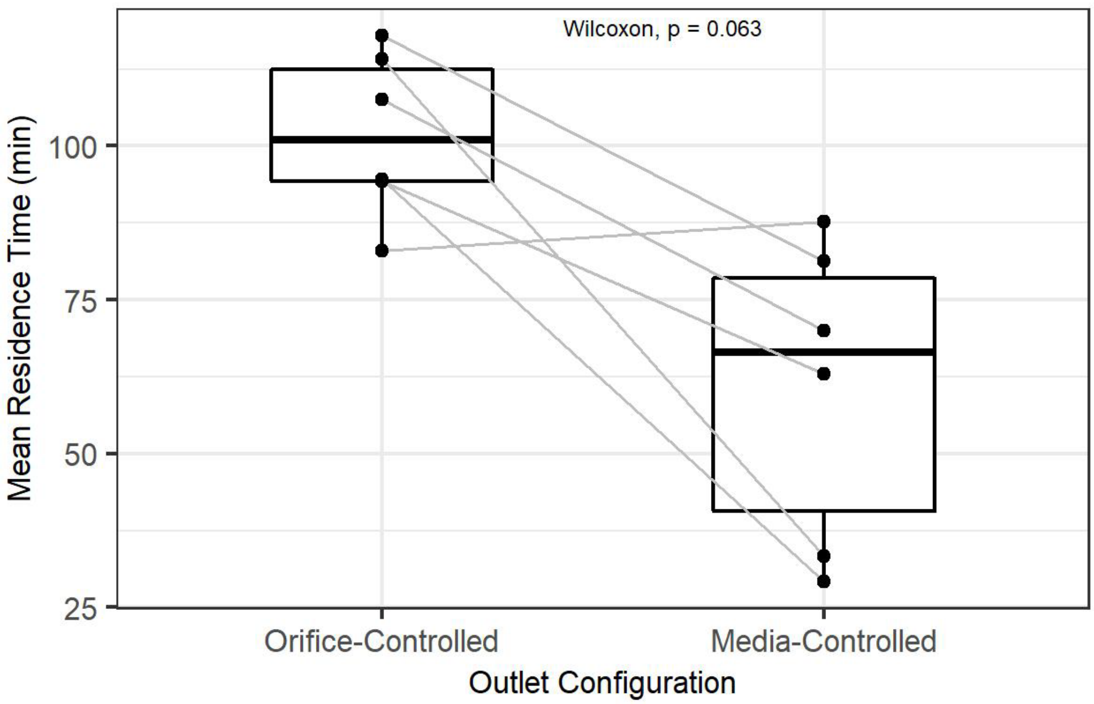


Figure 3-2 Mean Residence Times Grouped by Outlet Configuration

3.1.3. Stage-Discharge Relationships

Stage-discharge curves define the discharge as a function of the water level in the system. Stage-discharge curves were developed for each mesocosm using the monitoring data obtained from special hydraulics monitoring events. The Modeling Report describes the specific methodology to interpret data to develop stage-discharge curves.

Figure 3-3 shows stage-discharge relationships derived for three outlet-controlled mesocosms (MC 12 – new standard BSM, MC 15 – alternative BSM, and MC 22 – mature standard BSM). Stage is measured from the orifice discharge elevation. This plot also includes the theoretical discharge calculated using the orifice equation and the actual orifice size used in the experiment without considering losses within the soil media.

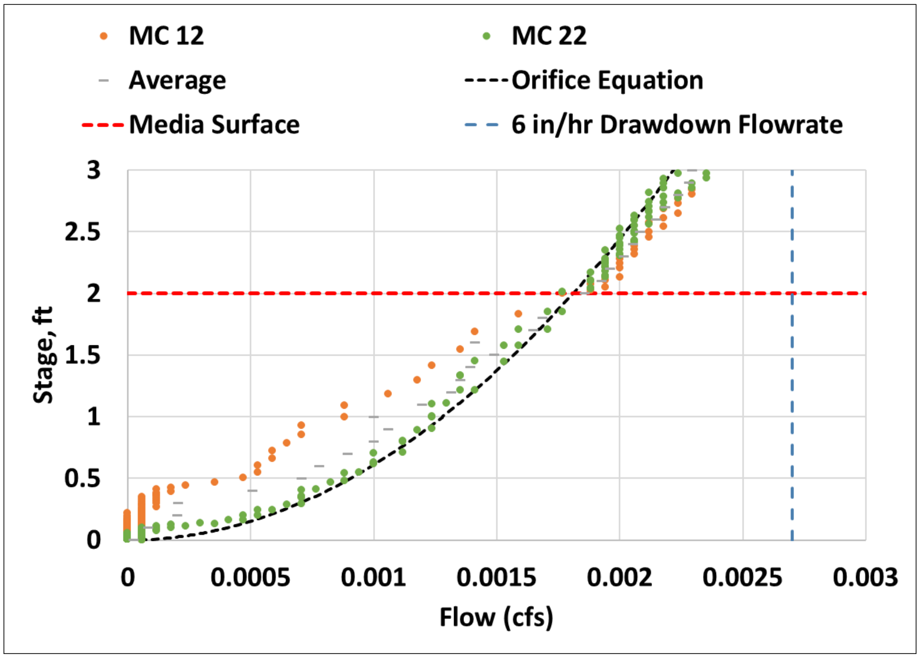
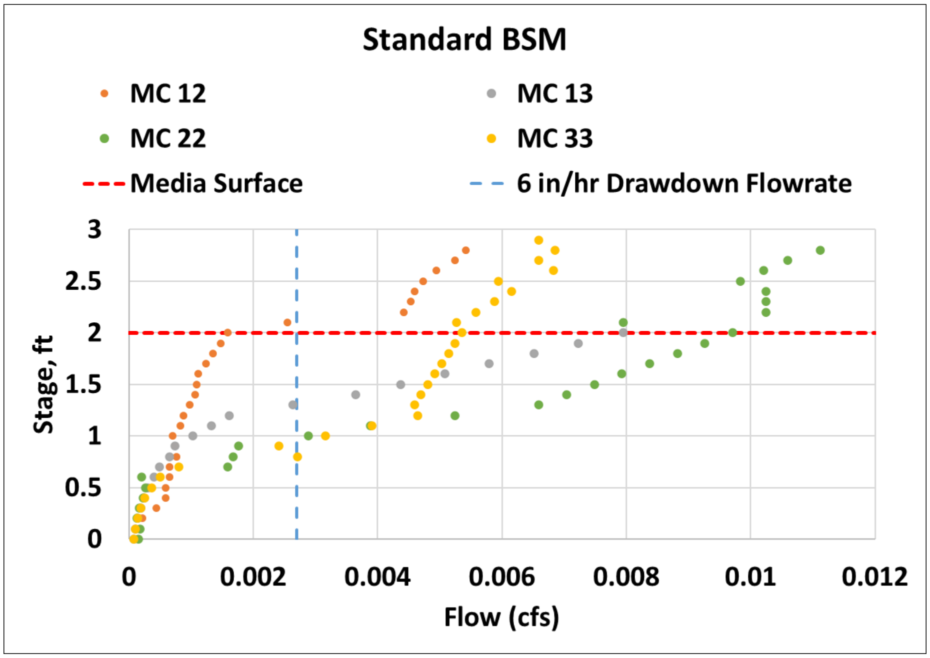


Figure 3-3 Stage-Discharge Relationships of Outlet-Controlled Mesocosms

Figure 3-3 shows relatively consistent stage-discharge relationships between these three mesocosms, regardless of media types and age of media. The consistency in stage-discharge among different mesocosms indicated that the orifice installed at the underdrain regulates the outflow consistently. The three stage-discharge curves also closely match the theoretical discharge calculated using the orifice equation and the actual orifice size used in the experiment, with coefficients of determination (R^2) ranging between 0.93 and 0.99. The consistency between the observed and theoretical stage-discharge relationships indicated that the hydraulic characteristics of bioretention facilities with outlet-controlled are relatively predictable.

Figure 3-4 shows stage-discharge relationships without the orifice regulating the discharge from the underdrain. Some of the mesocosms are the same as reported in Figure 3-3 but with the orifices removed for these special tests.



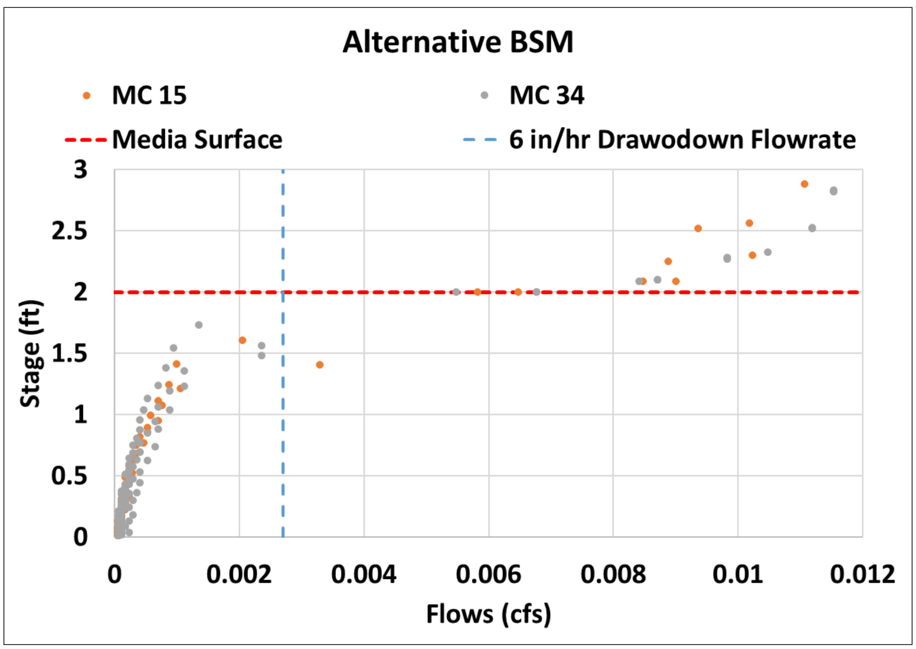


Figure 3-4 Stage-discharge Relationships of Media-Controlled Mesocosms

Figure 3-4 shows that the stage-discharge relationships of media-controlled configurations varied considerably among mesocosms with the same biofiltration media type, particularly for the standard BSM. While the stage-discharge curves are similar at the lower stage (0 to 0.5 feet), the curves diverge widely among all four mesocosms with standard BSM. At stages above the media surface (i.e., ponding stage), the outflow from the mesocosm with the highest flow rate (MC 13 – mature standard BSM) is four times the flow rate from the mesocosm with the lowest discharge (MC12 - new standard BSM). Generally, the two mesocosms with mature standard BSM (MC 13 & 22) discharged faster than the two with new standard BSM (MC 12 & 33), indicating that the increase in media permeability between new and mature BSM (which is noted in Section 3.1.1) is reflected in the stage-discharge relationships in media-controlled configurations.

Stage-discharge relationships are more consistent between the two mesocosms with alternative BSM (MC 34 & 15). Both stage-discharge curves approach the media surface depth asymptotically and show a significant increase in flowrate as the stage rises above the media surface.

To compare the stage-discharge relationship between media control and orifice control mesocosms, a flowrate of 6 inches per hour drawdown rate was plotted on all stage-discharge diagrams (Figure 3-3 and Figure 3-4). The comparison shows that the orifice control restricted the discharge rate at mesocosm brim full stage (3 feet) to just below the 6 inches per hour drawdown rate regardless of the media type. Without the orifice control, the discharge rates above the media surface for all types of BSMs are significantly higher than the 6 inches per hour drawdown rate.

3.1.4. Soil Moisture in BSM

Continuous volumetric water content (m^3/m^3) measurements were collected within the BSM in the six fully instrumented mesocosms. Sensors were located approximately 12 inches below the BSM surface near the center of the mesocosms. These monitoring data were used to assess the frequency of media saturation between media-controlled and orifice-controlled mesocosms.

As described above, the research team quadrupled the contribution area flowing to the mesocosms in February 2022, which increased the hydraulic loading rate. This is referred to as the “flow adjustment” in this section. The time series data were divided between pre- and post-flow-adjustment during the monitoring period.

The soil moisture data were summarized as water-content-duration curves for both the pre-and post-flow-adjustment periods and grouped by media type (alternative, new standard, and mature standard BSM). Figure 3-5 and Figure 3-6 show results for the pre-flow-adjustment and post-flow-adjustment periods, respectively.

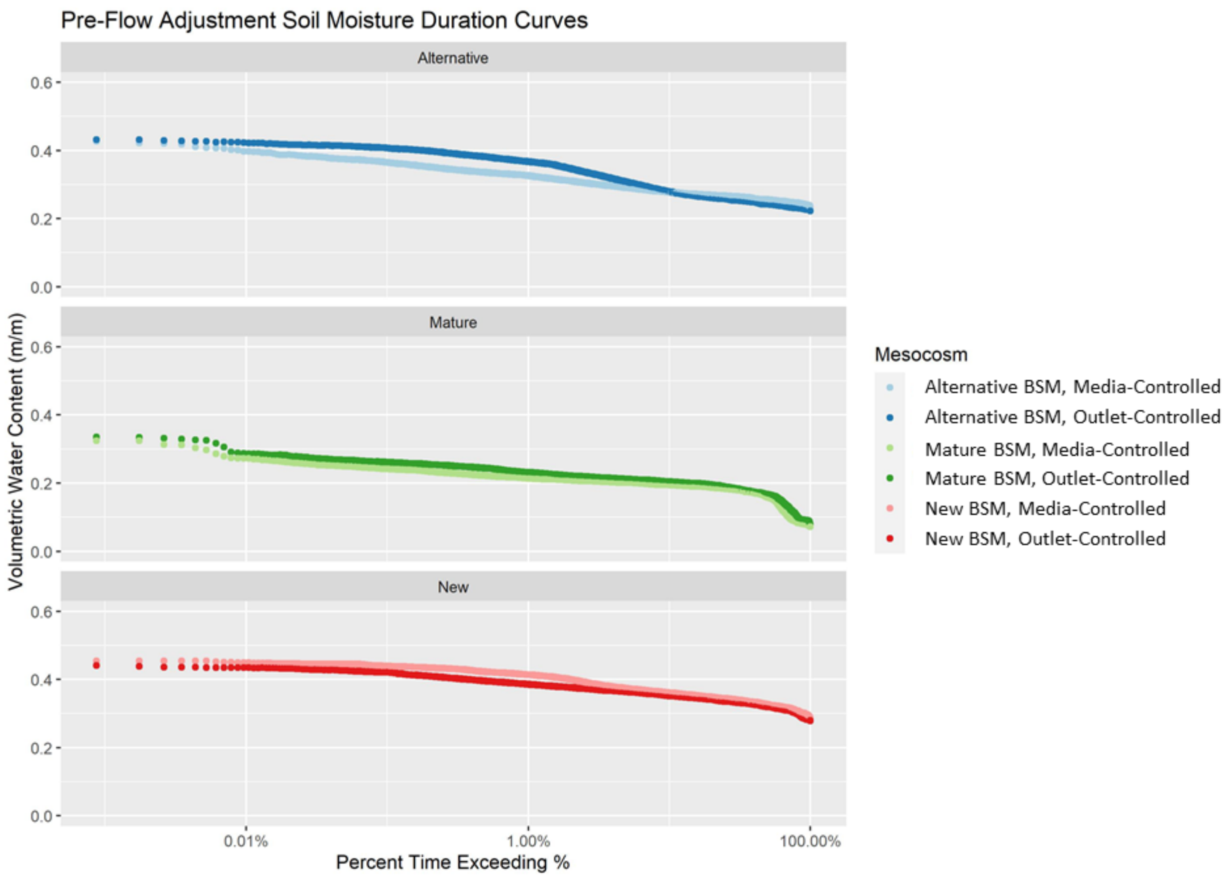


Figure 3-5 Pre-Flow Adjustment Period Soil Moisture Duration Curves for Mesocosms grouped by BSM Type

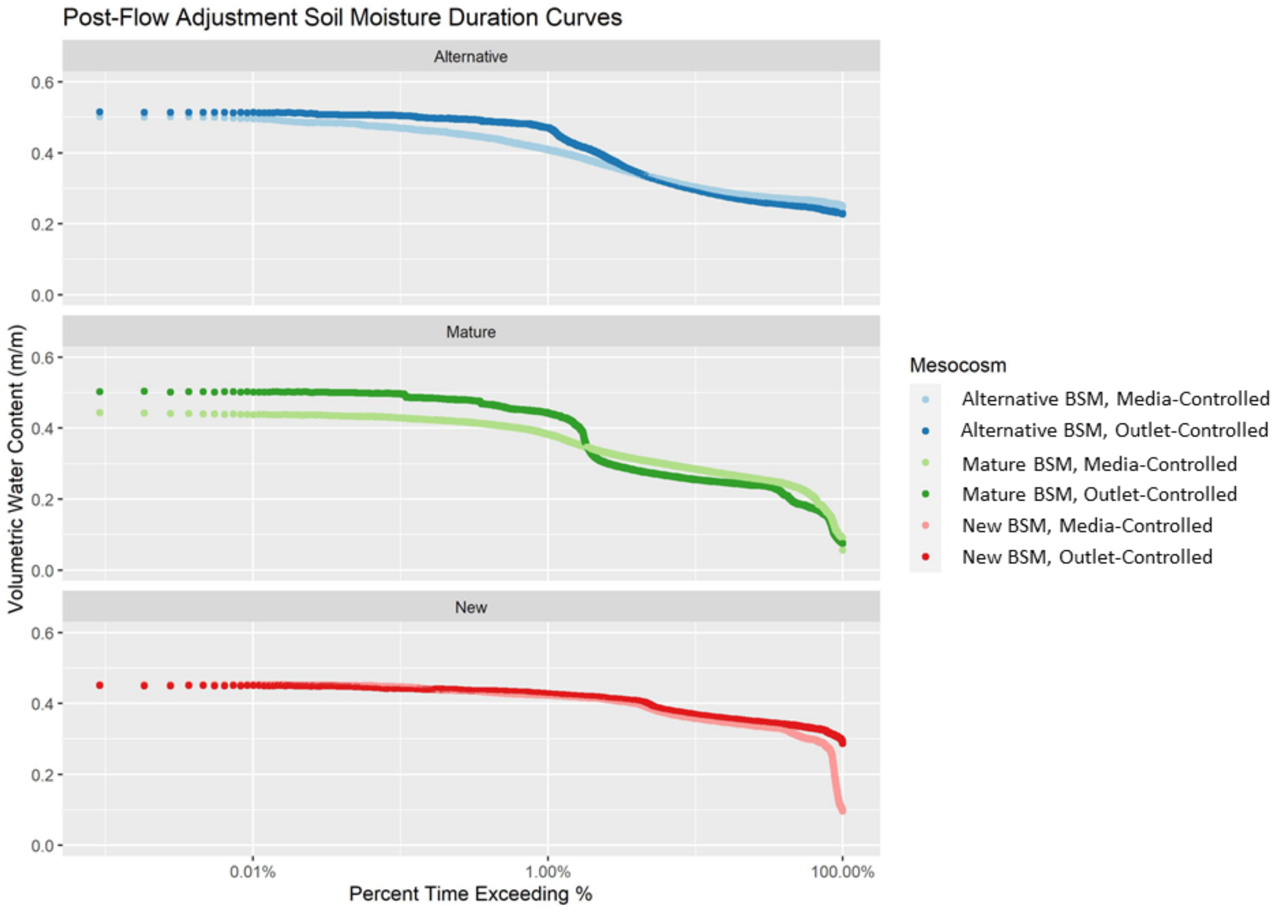


Figure 3-6 Post-Flow Adjustment Period Soil Moisture Duration Curves for Mesocosms grouped by BSM Type

As shown in Figure 3-6, during the post-flow-adjustment period, outlet controls appeared to increase soil moisture in the alternative BSM mesocosms for 5% of the time compared to media-controlled systems and increased soil moisture in the mature standard BSM for approximately 2% of the time compared to media-controlled systems. New standard BSM has a higher saturation level than the other two BSM types. For this BSM, outlet control has little to no effect on the long-term moisture content. Similar trends were observed during the pre-flow-adjustment period (Figure 3-5), although the difference between the moisture duration curves for outlet-control and media-control was smaller.

In addition to analyzing the continuous moisture content, the degree of media saturation was also analyzed discretely for data obtained during five of the six water quality testing events. Soil probes malfunctioned during Event 5, removing these data from further analysis. Results are shown in Figure 3-7.

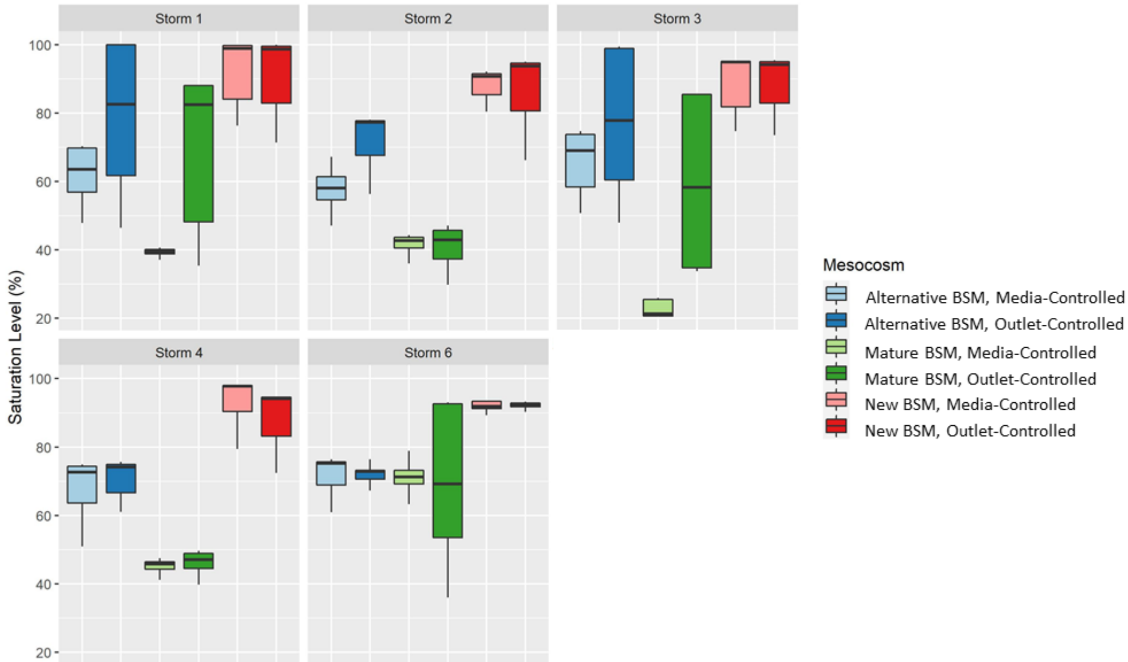


Figure 3-7 Soil Saturation Levels during Water Quality Testing (Synthetic Storm) Events

During the synthetic storm events, outlet controls sometimes increased the saturation level in the alternative and mature standard BSMs but had little effect on the new standard BSMs. The new standard BSMs also appeared to retain water better than alternative and mature standard BSM, which is consistent with the long-term observation and the lower hydraulic conductivity of the new standard BSM discussed in Section 3.1.1.

The combination of findings from long-term and event-specific soil media moisture content analyses suggested that outlet control can result in some increase in soil media saturation, particularly for BSM with higher hydraulic conductivity.

3.1.5. Peak Flow Control for Discrete Storms

Continuous inflow and outflow hydrographs from the mesocosms provide an opportunity to investigate the difference in storm event response between outlet-controlled and media-controlled mesocosms. These data were used to evaluate the peak flow reduction performance in discrete storm events, including comparisons between media types and outlet configurations. Figure 3-8, Figure 3-9, and Figure 3-10 compare the inflow, outflow, and ponding water level responses for three representative storms. Each of these storms occurred after the increase in contribution area that was implemented in February 2022. Note that the media surface has a different vertical datum for the ponding depth time-series in each plot; however, the flat portion of each line is effectively at the media surface.

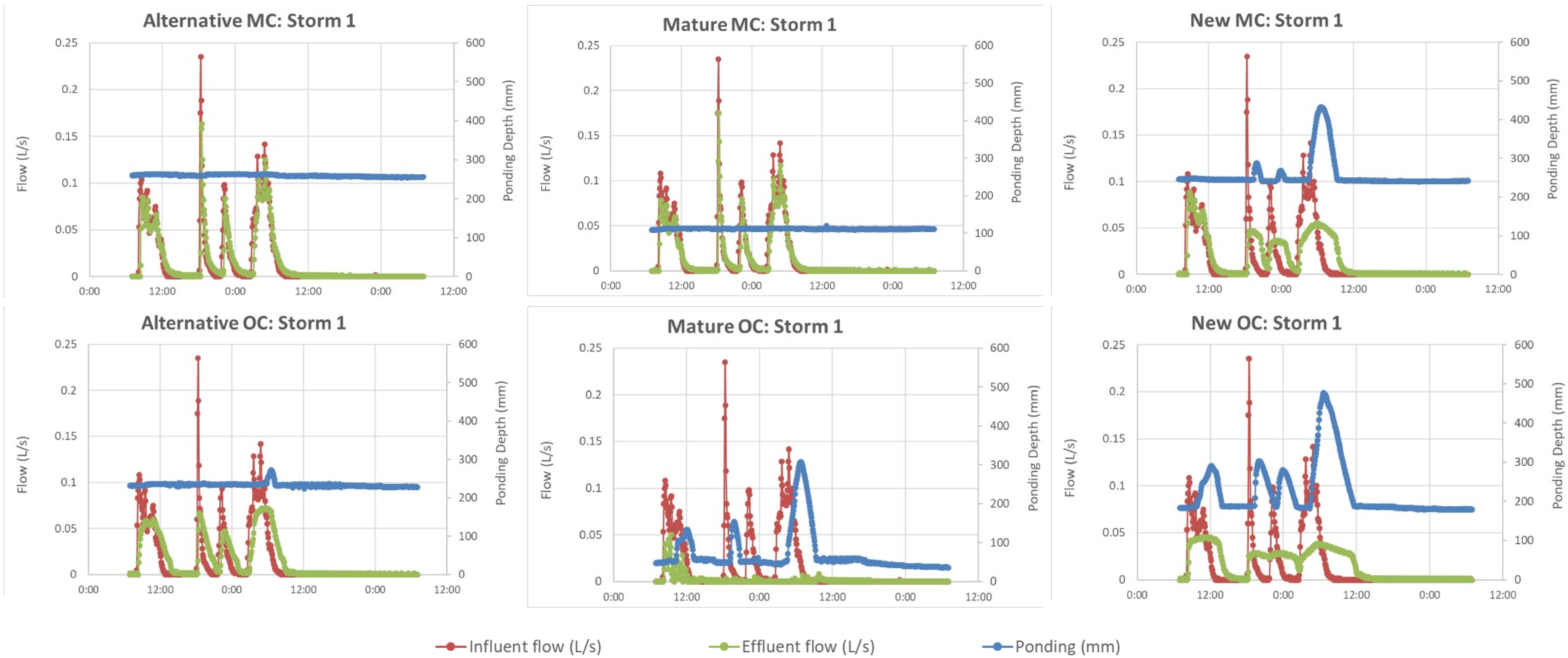


Figure 3-8 Inflow, outflow, and ponding level in six mesocosms during a natural storm (5/6 – 5/8, 2022)

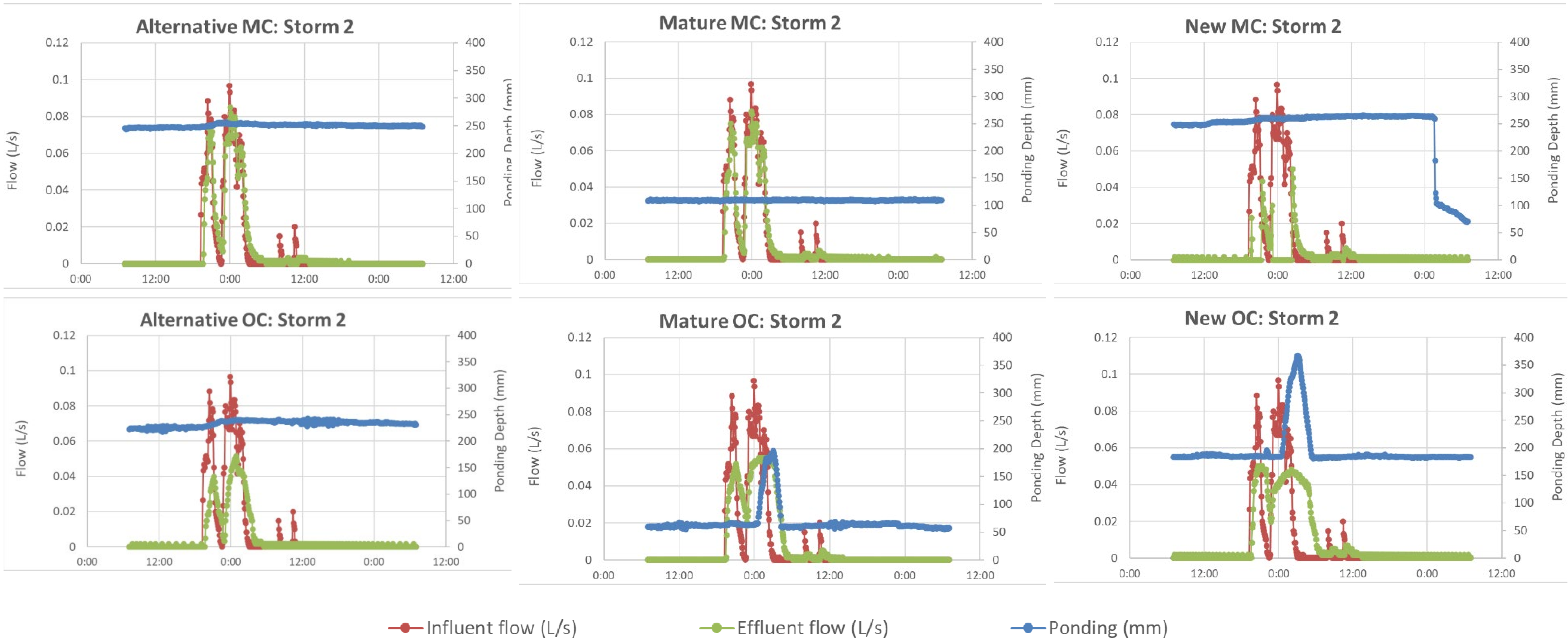


Figure 3-9 Inflow, outflow, and ponding level in six mesocosms during a natural storm (6/4 – 6/6, 2022)

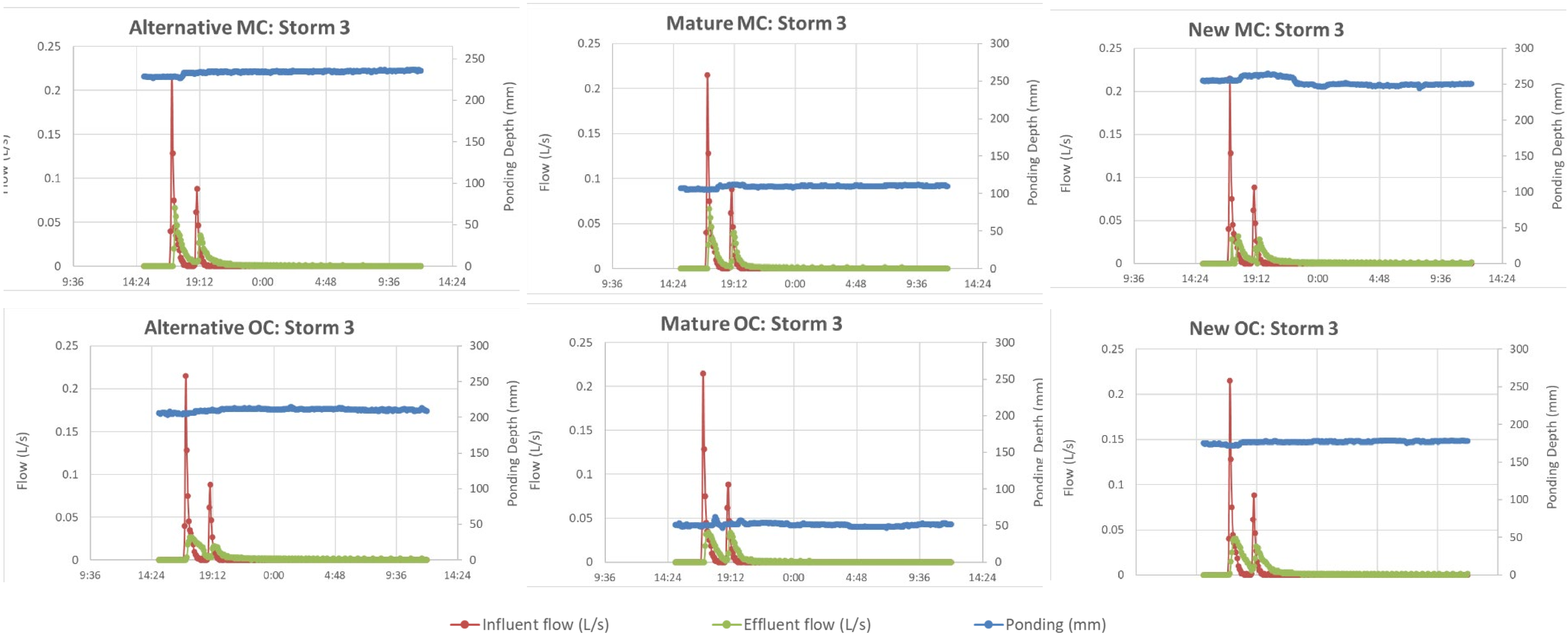


Figure 3-10 Inflow, outflow, and ponding level in six mesocosms during a natural storm (5/27 – 5/29, 2022)

Table 5 provides summary statistics from these storm events. Table 6 provides a comparison of peak outflow flowrates from these events.

Table 5. Summary Statistics for Discrete Storm Events

Storm Event	Date Range	Total Precipitation Depth, inches	Event Duration, hours	Peak 1-hour Intensity, in/hr	Peak Inflow Rate, L/s
1	5/6/2022-5/8/2022	1.11	32.5	0.23	0.23
2	6/4/2022 – 6/6/2022	0.70	18.0	0.11	0.10
3	5/27/2022-5/29/2022	0.65	4.5	0.19	0.22

Table 6. Peak Flow Control Response for Selected Discrete Storm Events

Storm Event	BSM Type	Peak Inflow Rate, L/S	Outlet Configuration			
			Media Controlled		Outlet Controlled	
			Peak Outflow Rate, L/S	% Reduction	Peak Outflow, L/s	% Reduction
1	Alternative	0.23	0.17	26%	0.07	70%
	Mature Standard		0.18	22%	0.05	78%
	New Standard		0.09	61%	0.04	83%
2	Alternative	0.10	0.09	10%	0.05	50%
	Mature Standard		0.08	20%	0.05	50%
	New Standard		0.05	50%	0.05	50%
3	Alternative	0.22	0.07	68%	0.03	86%
	Mature Standard		0.07	68%	0.04	82%
	New Standard		0.03	86%	0.04	82%

The time series plot above shows that outlet control induced ponding more frequently. The difference was more apparent for alternative BSM and mature standard BSM, which has a higher hydraulic conductivity than new standard BSM. Outlet control substantially improved the attenuation of peak flowrates, even for events where relatively limited ponding occurred. The exception was for new standard BSM where the media-controlled and outlet-controlled mesocosms were relatively similar in some events.

While these are only a subset of all events, these observations are believed to represent the difference in response between outlet-controlled and media-controlled mesocosms within discrete storm events.

3.1.6. Flow Duration Control

A flow duration control curve shows the flowrate (y axis) that exceeds a certain percentage of the time during the analysis period (x axis). The long-term inflow and outflow hydrographs from thirteen mesocosms were summarized in flow-duration curves grouped by media types to compare the flow control benefit provided by the mesocosms with different media types, age, and hydraulic control. Flow-duration curves for standard BSMs sourced from different vendors (duplicates) were averaged to produce a single flow-duration curve for all duplicates.

As described above, the research team quadrupled the contribution area flowing to the mesocosms in February 2022, which increased the hydraulic loading rate. This is referred to as the "flow adjustment" in this section. As a result, the long-term effluent monitoring data were divided into pre- and post-flow-adjustment periods for flow control analysis. Figure 3-11, Figure 3-12, and Figure 3-13 show flow duration results.

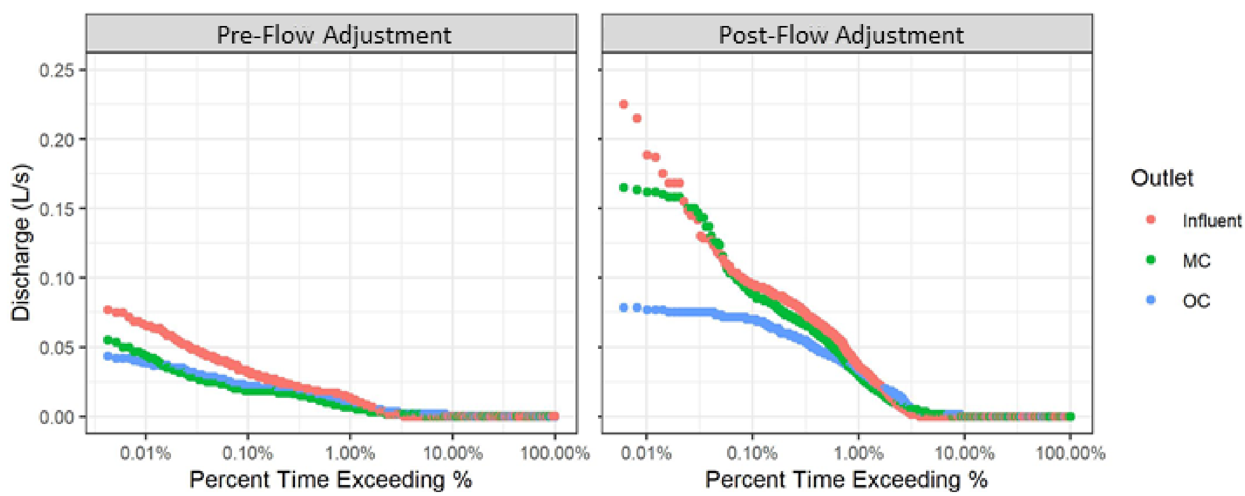


Figure 3-11 Flow Duration Curve for Mesocosms with Alternative BSMs

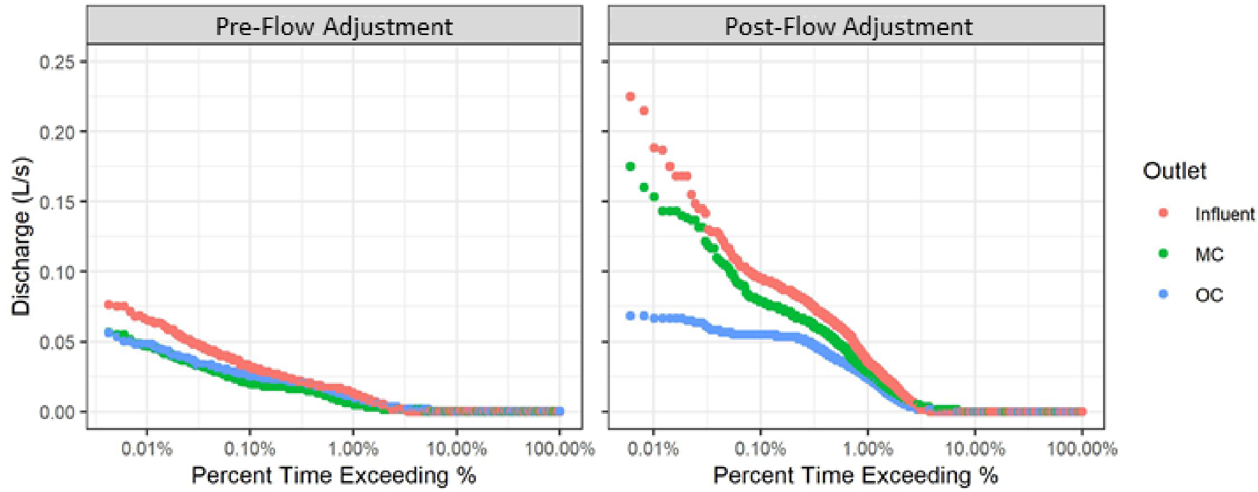


Figure 3-12 Flow Duration Curve for Mesocosms with Mature Standard BSMs

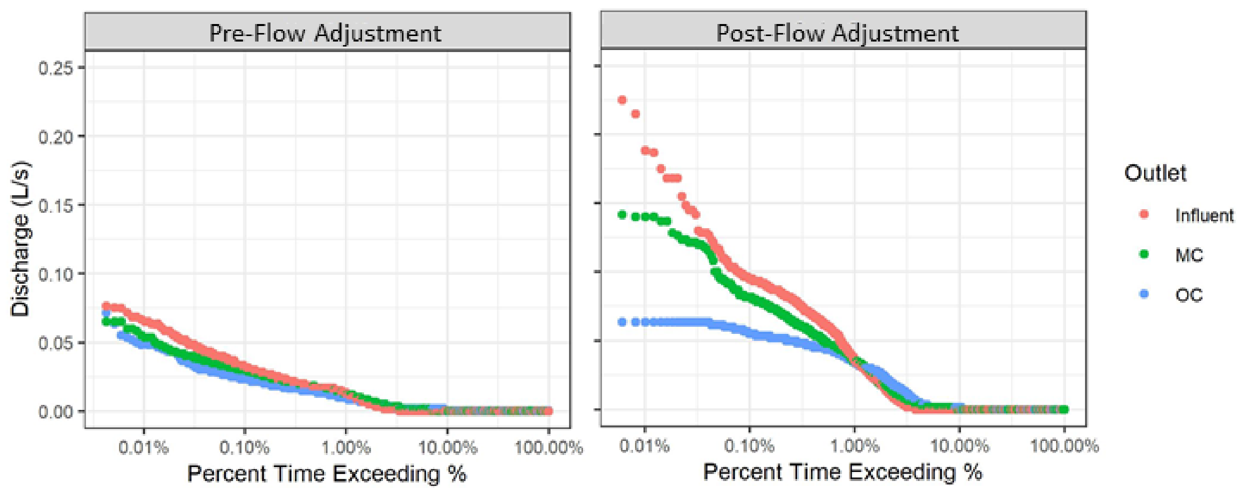


Figure 3-13 Flow Duration Curve for Mesocosms with New Standard BSMs

At the relatively low loading rates observed in the pre-flow-adjustment period, the orifices were not often engaged to slow the discharge of water (i.e., insufficient head was built up for the orifice to be the limiting factor of the discharge rate). The maximum influent loading was approximately 0.08 L/s during this period, corresponding to only about 6 inches per hour loading rate. The corresponding effluent FDC shows a marginal divergence from the influent hydrograph during this period, indicating little outlet engagement and limited difference between the media-controlled and outlet-controlled mesocosms. After the flow adjustment in February 2022, the hydraulic loading rate increased approximately four times. The maximum influent reached 0.25 L/s (about 18 in/hr). During this period, the media-controlled mesocosms showed a moderate departure from the inflow hydrograph, while the outlet-controlled mesocosms showed substantially greater flow duration control than the media-controlled mesocosms.

The findings from this flow duration analysis suggested that if the footprint and orifice of outlet-controlled bioretention facilities were sized such that stormwater from its contribution induced little to no ponding, there would be little to no flow control benefit by using an orifice restrictor. And inversely, if the drainage area and orifice size combination are such that the orifice will restrict flow, this can substantially improve flow duration control compared to a media-controlled configuration.

3.2. Water Quality Monitoring

This section presents a summary of pollutant concentrations obtained from water quality monitoring. This section also presents the results of statistical tests to evaluate whether differences in effluent concentrations between outlet-controlled and media-controlled mesocosms are statistically significant. Summaries are based on 6 sampling events. This is less than the number of events needed per the Washington State Technology Acceptance Protocol-Ecology (TAPE) guidelines. This study is intended to compare the side-by-side performance of outlet-controlled and media-controlled systems in a controlled study. It is not intended to support TAPE certification.

3.2.1. Pollutant Concentration Summary – Geometric Means

Influent and effluent flow-weighted composite samples were collected during the six water quality monitoring events and analyzed for the nine common stormwater analytes. The geometric mean of influent and effluent concentrations was computed for the six monitored mesocosms (Table 7). The geometric mean was selected as a representative statistic for a high-level comparison.

Table 7 Geometric Mean Concentration of Water Quality Analytes

Analyte	Influent	TAPE Influent Range[1]	Alternative BSM		Mature Standard BSM		New Standard BSM	
			Outlet-Control	Media-Control	Outlet-Control	Media-Control	Outlet-Control	Media-Control
Total Copper, ug/L	32	NA	5.7	5.8	8.4	5.0	14	12
Dissolved Copper, ug/L	5.8	5 to 20	3.0	3.2	7.5	4.5	9.4	7.2
Total Zinc, ug/L	158	NA	6.4	6.5	5.0	5.1	8.6	11
Dissolved Zinc, ug/L	72	20 to 300	4.5	4.4	4.6	6.1	4.6	5.0
Nitrate-Nitrite as N, mg/L	2.0	NA	1.2	1.2	1.2	1.6	2.0	2.4
Total Kjeldahl Nitrogen, mg/L	0.93	NA	0.68	0.66	1.2	0.78	3.1	2.1
Ortho-Phosphorous as P, mg/L	0.27	NA	0.12	0.14	0.04	0.05	0.37	0.60

Analyte	Influent	TAPE Influent Range[1]	Alternative BSM		Mature Standard BSM		New Standard BSM	
			Outlet-Control	Media-Control	Outlet-Control	Media-Control	Outlet-Control	Media-Control
Total Phosphorus, mg/L	0.50	0.1 to 0.5	0.17	0.18	0.06	0.07	0.58	0.74
Total Suspended Solids, mg/L	76	20 to 200	6.1	10	2.4	2.3	8.9	27

[1] – Per 2018 TAPE Guidelines (Ecology, 2018)

In general, influent concentrations were reasonably representative of stormwater runoff in Western Washington. Dissolved Copper in the influent was toward the low end of the TAPE range, and total Phosphorus was toward the upper end of the TAPE range.

The following observations are based on visual inspection of data and are not based on statistical tests:

- All combinations in this study effectively remove total suspended solids (TSS), total and dissolved Zinc, and Total Copper (removal of greater than 50%).
- The alternative BSM is also effective in removing dissolved Copper, forms of Phosphorus, and Nitrogen.
- Mature standard BSM showed the removal of all analytes in the media-controlled configuration. Apparent minor increases in the concentration of dissolved Copper and nitrate-nitrite-N were observed in the outlet-controlled configuration.
- The new standard BSM showed apparent increases in dissolved Copper, phosphorus species, and nitrate-nitrite-N in both media-controlled and outlet-controlled configurations.

Overall, the relative magnitudes of differences between outlet-controlled and media-controlled configurations were minor compared to the effect of media type and age.

3.2.2. Statistical Tests of Outlet-Controlled versus Media-Controlled Configurations

The effect of orifices on pollutant reduction was assessed by performing a Wilcoxon Signed-Rank test to compare outlet-control and media-control effluent concentrations, pairing the data by water quality testing events and BSM type. The median effluent concentration and Wilcoxon signed-rank test results were summarized in Table 8, and boxplot comparisons for each analyte are provided in Appendix B.

Table 8 Comparison of Effluent Concentrations between Media-Controlled (MC) and Outlet-Controlled (OC) Mesocosms by Media Type and Age

	Alternative BSM				Mature Standard BSM				New Standard BSM				
	Median Effluent Concentration		Wilcoxon Signed-Rank Test		Median Effluent Concentration		Wilcoxon Signed-Rank Test		Median Effluent Concentration		Wilcoxon Signed-Rank Test		
Analyte	OC	MC	W	p-value	OC	MC	W	p-value	OC	MC	W	p-value	**Unit**
Total Copper	4.5	4.9	9	0.84	8.0	4.7	21	0.03	14	13	15	0.44	µg/L
Dissolved Copper	3.1	3.43	7	0.56	7.2	4.6	21	0.03	9.2	7.1	21	0.03	µg/L
Total Zinc	4.0	2.9	5	0.42	4.5	4.5	5	0.57	7.5	13	3.5	0.34	µg/L
Dissolved Zinc	2.9	2.9	NA[1]	NA[1]	2.9	2.9	NA[1]	NA[1]	5.3	5.6	3.5	0.71	µg/L
Nitrate-Nitrite as N	1.4	1.8	6	0.09	1.9	2.3	0	0.03	1.8	2.4	6	0.44	mg/L
Total Kjeldahl Nitrogen	0.60	0.50	2	0.59	1.1	0.75	15	0.06	3.3	2.6	20	0.06	mg/L
Ortho Phosphorus	0.11	0.15	2	0.03	0.04	0.05	6.5	0.46	0.39	0.51	1	0.06	mg/L
Total Phosphorus	0.14	0.17	10	0.44	0.07	0.08	5	0.31	0.63	0.63	3	0.16	mg/L
Total Suspended Solids	7.0	9.5	0	0.09	2.0	2.0	7.5	1.00	19	24	1	0.06	mg/L

Colors signify the results and directionality of statistical testing. A p-value of 0.1 is used to determine significance. Orange highlighting indicates OC effluent concentration > MC effluent concentration, Green highlight indicates OC effluent concentration < MC effluent concentration. Blue indicates no statistically significant difference.

1 - NA for dissolved Zinc reflects a numerical tie in the effluent concentration data because several samples across both treatments were listed as non-detect - therefore, numerically identical.

Based on the statistical testing results presented in Table 8, the effect of outlet control varies depending on the media type:

Alternative BSM: For alternative BSM, outlet control had no statistical effect on Copper, Zinc, TKN, and Total Phosphorus. Outlet control improved effluent concentration somewhat for nitrate-nitrite as N, ortho-phosphorus, and TSS. As shown in Table 7, the alternative BSM effectively reduced the concentration of all analytes, regardless of hydraulic control configuration.

Mature Standard BSM: For mature standard BSM, outlet control showed improved effluent concentration for nitrate-nitrite as N compared to media control. Outlet control showed a minor increase in effluent concentration for Copper and TKN compared to media control. For both dissolved Copper and TKN, outlet control showed a minor increase in effluent concentration compared to influent concentration, while media control resulted in a minor reduction in effluent concentration compared to influent concentration. This may be attributable to increased residence time.

New Standard BSM: For new standard BSM, dissolved copper, TKN, nitrate-nitrite as N, TP, and ortho-P exhibited concentration increase compared to influent. This is a known issue with this media type. Outlet control improved ortho-P (reduced export rate) and TSS (improved removal rate). Outlet control resulted in higher effluent concentrations (greater export) for dissolved Copper and TKN.

Overall, it appears that outlet control may exacerbate the leaching of TKN and dissolved Copper in compost-based media but may reduce the risk of leaching ortho-P and nitrate-nitrite as N. Outlet control appears to improve TSS retention.

3.2.3. Statistical Tests of Mature versus New Standard BSM

To further assess the effect of standard BSM age on pollutant reduction was also assessed by performing a Wilcoxon Signed-Rank test comparing two BSM types using paired effluent water quality data. The mature standard BSMs used in this study were about 9 years older than the newly installed standard BSMs, and for nearly every analyte, the mature media performed better in reducing the effluent concentration, as shown in Table 9.

In particular, phosphorus species were effectively removed by mature BSMs, whereas they leached from the new BSMs throughout the study. While we do not know when exactly the BSM standard blend matures enough to cease leaching phosphorus, it is presumably somewhere between 1.5 years (age of the newly installed standard BSM and length of this study, and the 9-year-old mature standard blend used in this study. Standard BSM of both ages effectively removed dissolved Zinc, and no significant difference was found between the two. Nitrate-nitrite was also not significantly altered by the age of the standard blend. The improvement between new standard BSM and mature standard BSM could be related to reduced compost leaching and increased biological activity with system maturity, including larger plants and a better-established root network.

Table 9 Comparison of Effluent Concentrations between Mesocosms with Newly-Installed and Mature Standard BSM

	Median Effluent Concentration			Wilcoxon Signed-Rank Test	
Analyte	**Mature Standard BSM**	**New Standard BSM**	**Unit**	**W**	**p-value**
Total Copper	6.2	14	µg/L	3	0.002
Dissolved Copper	5.4	8.1	µg/L	2	0.001
Total Zinc	4.5	7.5	µg/L	3	0.024
Dissolved Zinc	2.9	5.4	µg/L	8	0.091
Nitrate-Nitrite	2.1	2.1	mg/L	29	0.470
Total Kjeldahl Nitrogen	0.85	2.7	mg/L	0	0.003
Ortho Phosphorus	0.05	0.48	mg/L	0	<0.001
Total Phosphorus	0.08	0.63	mg/L	0	<0.001
Total Suspended Solids	2.0	23	mg/L	1.5	0.004

Color indicates results of statistical tests. Green highlight indicates Mature Standard BSM effluent concentration < New Standard BSM effluent concentration; Blue indicates no statistically significant difference at $p = 0.1$.

3.2.4. Statistical Tests of Media Type

The differences between standard BSM and alternative BSM on water quality treatment performance were assessed by performing a Wilcoxon Signed-Rank test with paired effluent concentration data between mesocosms with the standard BSM and the alternative BSM. Because the newly and mature standard BSMs differ significantly in water treatment performance, the comparison with alternative BSM was made for both new and mature standard BSM separately.

Table 10 and Table 11 show the Wilcoxon Signed-Rank test results for the effluent analyte concentration comparisons between alternative BSM and the new and mature standard BSM, respectively.

As shown in Table 10, the alternative BSM performs better than the new standard BSM for almost all analytes included in this study (except for TSS). These differences are statistically significant and substantial in magnitude compared to the difference between media control and outlet control, as shown in Table 10.

Compared to the mature standard BSM (Table 11), the alternative BSM performs better for dissolved Copper, TKN, and nitrate-nitrite. Alternative BSM has somewhat higher effluent concentrations than other analytes. Effluent concentrations are generally low for both alternative and mature standard BSM.

Table 10 Comparison of Effluent Concentrations between Alternative BSM and New Standard BSM Mesocosms.

	Median Effluent Concentration			**Wilcoxon Signed-Rank Test**	
Analyte	**Alternative BSM**	**New Standard BSM**	**Unit**	**W**	**p-value**
Total Copper	4.9	14	µg/L	11	0.027
Dissolved Copper	3.4	8.1	µg/L	0	<0.001
Total Zinc	<2.9	7.5	µg/L	0	0.006
Dissolved Zinc	<2.9	5.4	µg/L	0	0.013
Nitrate-Nitrite	1.6	2.1	mg/L	5	0.005
Total Kjeldahl Nitrogen	0.55	2.7	mg/L	0	<0.001
Ortho Phosphorus	0.12	0.48	mg/L	0	<0.001
Total Phosphorus	0.16	0.63	mg/L	0	0.004
Total Suspended Solids	9.5	23	mg/L	18.5	0.117

Color indicates results of statistical tests. Green highlight indicates Alternative BSM effluent concentration < New Standard BSM effluent concentration; Blue indicates no statistically significant difference at p = 0.1.

Table 11 Comparison of Effluent Concentrations between Alternative BSM and Mature Standard BSM Mesocosms.

Analyte	Median Effluent Concentration			Wilcoxon Signed-Rank Test	
	Alternative BSM	**Mature Standard BSM**	**Unit**	**W**	**p-value**
Total Copper	4.9	6.2	µg/L	34	0.733
Dissolved Copper	3.4	5.4	µg/L	1	<0.001
Total Zinc	<2.9	4.5	µg/L	12	0.798
Dissolved Zinc	<2.9	<2.9	µg/L	0	0.371
Nitrate-Nitrite	1.6	2.1	mg/L	3	0.005
Total Kjeldahl Nitrogen	0.55	0.85	mg/L	7	0.023
Ortho Phosphorus	0.12	0.05	mg/L	78	<0.001
Total Phosphorus	0.16	0.08	mg/L	66	0.004
Total Suspended Solids	9.5	2.0	mg/L	64.5	0.006

Color indicates results of statistical tests. Orange highlight indicates Alternative BSM effluent concentration > New Standard BSM effluent concentration; Green highlight indicates Alternative BSM effluent concentration < New Standard BSM effluent concentration; Blue indicates no statistically significant difference at p = 0.1.

3.3. Summary Findings from Modeling Study

A modeling study was performed to augment the results of the mesocosm monitoring. This section highlights relevant findings from the Modeling Study Report.

3.3.1. Long-Term Capture Efficiency and Volume Reduction

Restricting flow via an outlet control can reduce the treatment flowrate of a bioretention facility and reduce the amount of water captured and treated over a long-term period. The Modeling Study used WWHM to evaluate the long-term effect of outlet control on the amount of water captured and treated. The Modeling Study evaluated paired scenarios sized identically per SWMMWW Minimum Requirement #6 (91% treatment) using default SWMMWW assumptions. One set of each pair included outlet controls to restrict flow to 6 inches per hour. The other set included media control based on representative soil properties in the mesocosm study. Results are presented in Section 5.1 of the Modeling Study Report.

The Modeling Study found that outlet control somewhat reduced long-term capture efficiency, but the systems continued to meet the 91% treatment criterion. Media control resulted in about 4 to 6% greater long-term capture efficiency.

Outlet control resulted in minor increases in long-term volume reduction (2 to 10% increases) via longer periods of water detention and greater opportunity for infiltration into underlying soils. This would only apply if systems were unlined and depended on underlying soil infiltration rates.

3.3.2. Long-Term Pollutant Load Reduction

The concentration reductions reported in Section 3.2 were combined with the long-term capture efficiency and volume reduction estimates reported in the Modeling Study Report to estimate the effect of outlet control versus media control on long-term pollutant load reduction. Table 12 summarizes the long-term pollutant loading reduction estimate.

Pollutant load reduction estimates are based on:

- Long-term capture efficiency – see Modeling Study Report for scenario results.
- Long-term volume reduction – see Modeling Study Report for scenario results.
- Geometric mean concentrations for alternative BSM and mature standard BSM are reported in Section 3.2.1. (Table 7).

Water quality data from only the mature standard BSM is used for this analysis (instead of both new and mature standard BSM) to represent the longer-term performance of bioretention facilities.

Results are presented to compare outlet control to media control regardless of statistical significance. Table 12 highlights loading reduction percentages in bold font if statistically significant effluent quality differences were detected between media and outlet control scenarios (Table 8). All modeled bioretention facilities are identical in size and dimension and include an underlying soil infiltration rate of 0.6 inches/hour.

Table 12. Pollutant Loading Reduction Estimate from Idealized Bioretention Model Scenarios

Model Scenario	Total Copper	Dissolved Copper	Total Zinc	Dissolved Zinc	Nitrate-Nitrite as N	Total Kjeldahl Nitrogen	Ortho-Phosphorous as P	Total Phosphorus	Total Suspended Solids
Alternative BSM, Media Control	80%	45%	94%	92%	**41%**	29%	**46%**	62%	**85%**
Alternative BSM, Outlet Control	79%	51%	90%	88%	**46%**	33%	**57%**	66%	**87%**
Standard BSM, Media Control	**84%**	**22%**	96%	91%	**23%**	**16%**	83%	86%	97%
Standard BSM, Outlet Control	**72%**	**-13%**	91%	88%	**44%**	**-11%**	81%	83%	91%

Pollutant loading reduction percentages are highlighted in bold font if significant difference is found between media-controlled and outlet-controlled effluent water quality data for the BSM type and analyte.

The difference in concentration reduction and long-term capture efficiency can mainly explain the difference in pollutant load reduction between media and outlet control scenarios. Overall differences were relatively minor and varied by analytes. For analytes that showed better concentration reduction in outlet-controlled bioretention (nitrate-nitrite for alternative BSM, nitrate-nitrite, ortho phosphorus, and TSS for standard BSM), load reduction was higher in the outlet-controlled scenarios despite the lower long-term capture efficiency.

Outlet control bioretention with standard BSM showed increases in the effluent concentration of Copper and TKN compared to media control, resulting in lower load reduction with outlet control. Media-controlled scenarios resulted in higher load reduction due to the higher long-term capture efficiency for the other analytes with similar concentration reduction between media and outlet control bioretention.

3.3.3. Long-Term Flow Control Benefits

The Modeling Study evaluated the expected performance of idealized scenarios for peak flow reduction and flow duration control. The idealized scenarios were sized for Minimum Requirement #6, a pollutant treatment standard. Therefore, any incremental flow control benefits provided by outlet control would be a supplemental benefit but not the original design purpose. Results are presented in Section 5.3 of the Modeling Study Report.

The Modeling Study found that for systems sized to MR#6, neither outlet-controlled configurations nor media controlled-configurations provided significant flow control benefits. The total volume of these systems was relatively limited.

The Modeling Study evaluated the combined effect of sizing and hydraulic control configuration. Figure 3-14 shows the flow duration curve comparison between media-controlled and outlet-controlled scenarios for 0.8% footprint size (the minimum to meet MR#6, expressed as the bioretention footprint as a percentage of the contribution area) and 2.4% footprint size. This comparison was based on the standard BSM hydraulic conductivity, 0.1 inch per hour underlying soil infiltration rate, and the same orifice size that was used to control to 6 inches per hour for the MR#6 design.

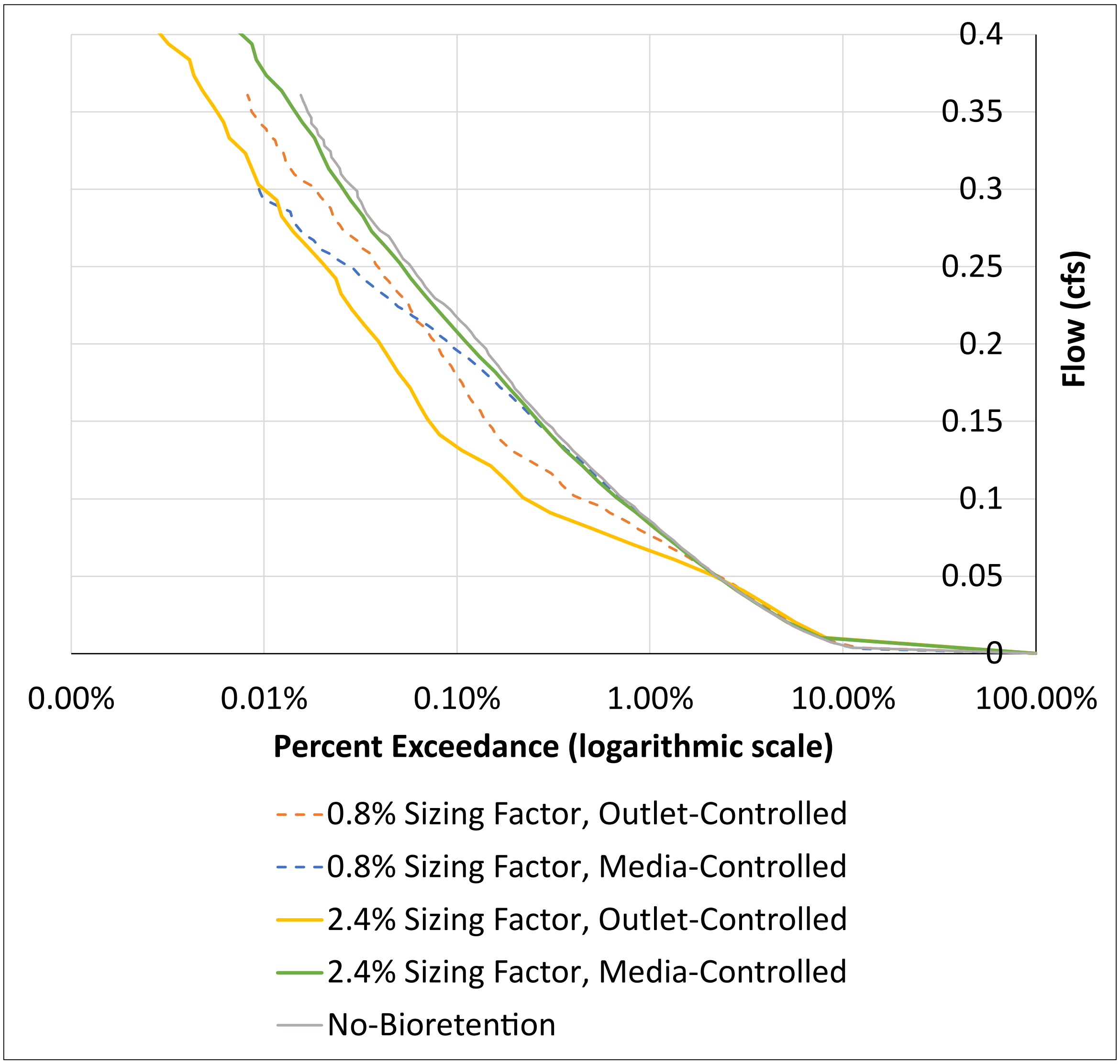


Figure 3-14. Flow Duration Curves Comparison between Media-Controlled and Outlet-Controlled in 0.8% and 2.4% Sizing Scenarios (Standard BSM, 0.1 in/hr Native Soil Infiltration Rate).

As shown in 3-14, the outlet-controlled scenario is relatively similar to the media-controlled scenario when the bioretention footprint is relatively small (0.8% of the contribution area). Both configurations have relatively limited effects.

The performance between media control and outlet control diverges more substantially for bioretention with larger footprints (2.4% of contribution area). The media-controlled configuration becomes very similar to the "no-bioretention" scenario. This is because an increased media bed footprint increases the filtration flowrate, providing less flow restriction that would cause water to be detained. In contrast, the flow-duration performance of the outlet control configuration improved substantially with increased size. This is because more storage volume is available to detain water while the outlet control continues to provide the same level of flow restriction as the smaller footprint scenario.

This is reflected in the results. For instance, at the 0.1% exceedance duration, the outlet-controlled scenario showed approximately 40% flowrate reduction (compared to uncontrolled runoff) in the 2.4% sizing scenario, while the media-controlled scenario showed less than 5% reduction for the exact sizing scenario. This means outlet controls would be more pronounced when applied to larger bioretention facilities, such as those designed for MR#5 or #7.

The divergence between outlet-controlled and media-controlled systems observed in the larger (2.4%) sizing factor is fairly consistent with the mesocosm monitoring results presented in Section 3.1.6.

3.3.4. Modeling Outlet Controlled Configurations in WWHM

One of the purposes of the Modeling Study was to evaluate how well WWHM could represent the hydraulics of an outlet-controlled bioretention configuration. This was assessed by comparing the observed stage-discharge relationship from the mesocosms to the simulated stage-discharge relationship in WWHM.

The Modeling Study found minor differences between the experimental conditions in the mesocosms and the modeling representation in WWHM. These differences are not likely to significantly affect the ability to model bioretention with outlet control in WWHM.

The Modeling Study found that the simulation of media-controlled configurations depends greatly on the specified hydraulic conductivity used in modeling. This value varies between media suppliers and media ages. Therefore, the flow control benefits of media-controlled configurations cannot be reliably simulated in WWHM unless hydraulic conductivity is known.

3.4. Plant Health

Each mesocosm was planted with identical arrangements of *Deschampsia cespitosa* (Northern Lights), *Pennisetum alopecuroides* (Little Bunny), and *Cornus sericea* (Dwarf Dogwood). In the mature mesocosms, plants were already established before the study; these were left in place to assess whether outlet control affects established plants.

Plant health was assessed quarterly during the growing season by measuring plant height and spread and visually observing plant vigor on a scale of 1 = "most vigor" to 5 = "no vigor." We do not present plant height and spread in this report for conciseness. However, those data are available as part of the Data Deliverable requirement for this project. Figure 3-15 summarizes the ratings for plant vigor. Figure 3-16 shows example pictures of plant growth near the end of the plant study (March 2022).

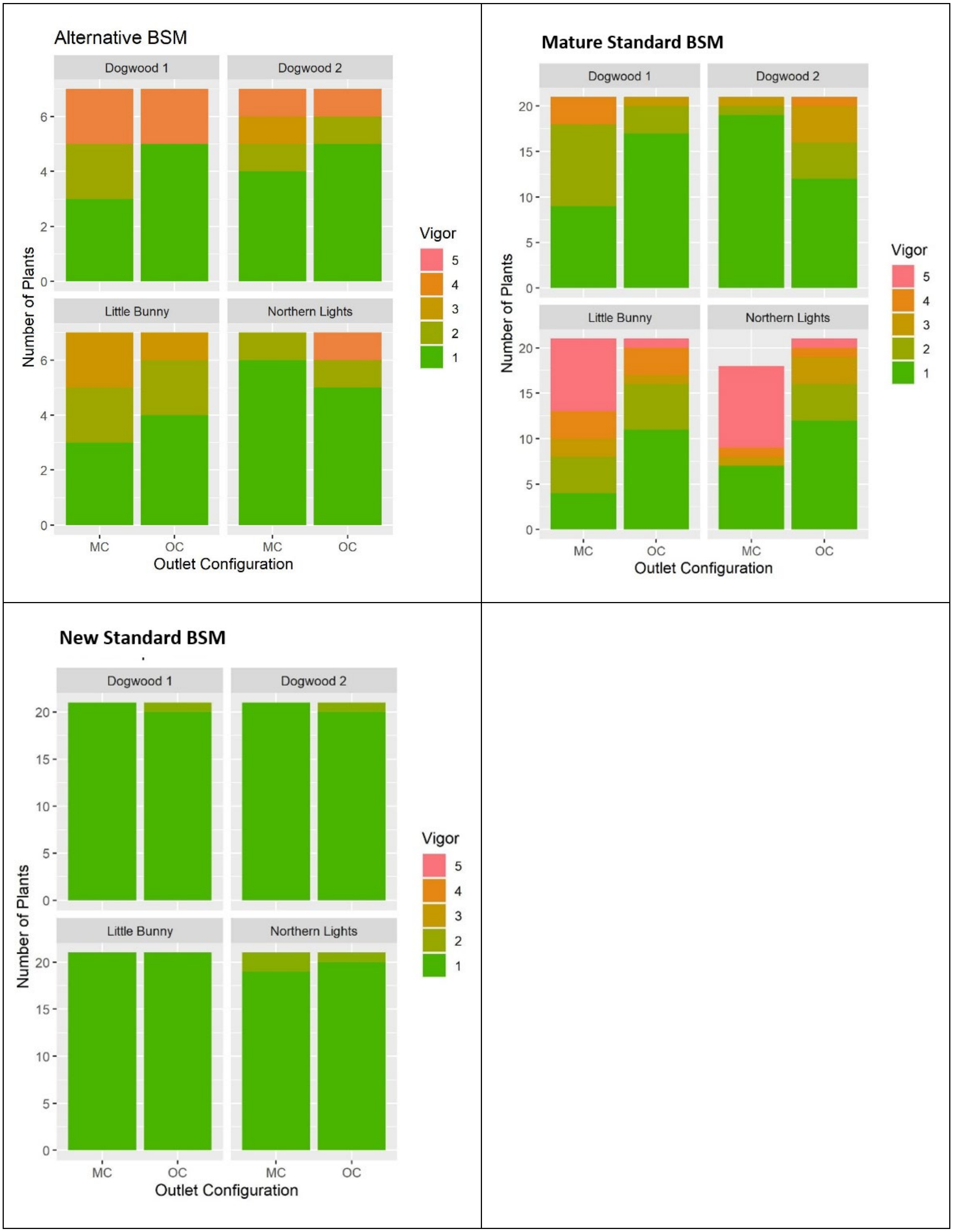
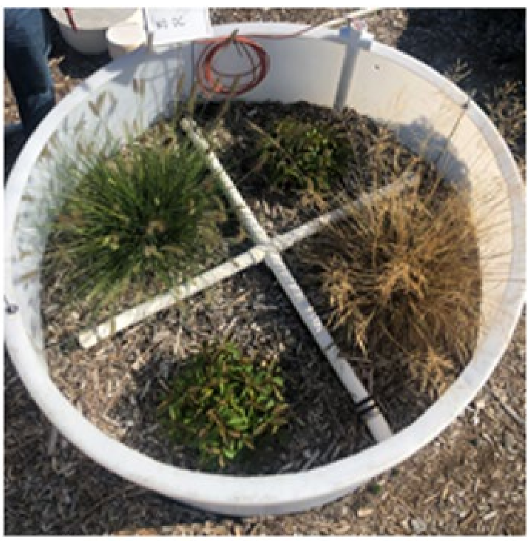


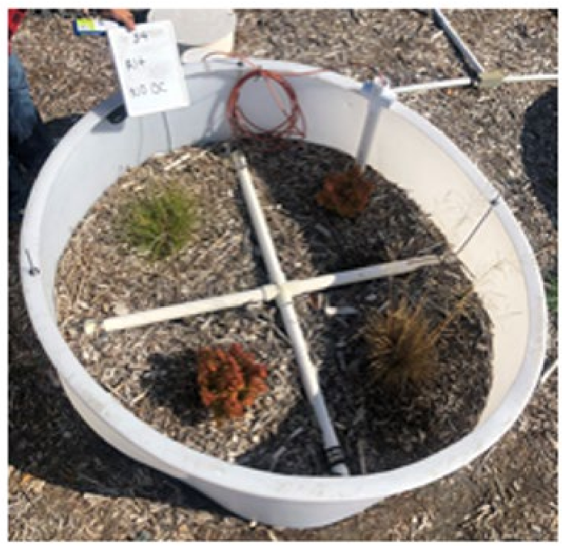
Figure 3-15 Vigor ratings for each plant grouped by BSM

New Standard BSM, Outlet Control

Alternative BSM, Outlet Control



New Standard BSM, Media Control



Alternative BSM, Media Control

Figure 3-16 Plant growth (photo taken near the end of study)

All plants remained alive throughout the study. Among the mesocosms that were freshly planted at the beginning of the study, all plants showed vigor ratings of 3 or higher. In the newly planted alternative BSM, mesocosms without outlet control appear to have higher vigor scores (more 1 scores and fewer 3 scores). In the newly planted standard BSM, plants had a preponderance of top ratings (1) regardless of outlet configuration. Between these sets, the media type greatly affected the plant growth rate, as shown visually in Figure 3-16. Due to limited nutrients in the alternative BSM, plants stayed relatively small.

The Little Bunny and Northern Light plants had the lowest vigor ratings for the mature BSM with established plants. This was due to significant shading from the larger dogwood plants. In these mesocosms, outlet control improves vigor ratings for Little Bunny, Northern Lights, and Dogwood 1, whereas Dogwood 2 showed a reverse relationship but maintained relatively high vigor. The cause of this is not known.

Overall, it is clear that the overall health of the plants in the mesocosms was not significantly impaired through outlet controls. There may have been minor improvements in some conditions. However, it appears that plant vigor was primarily affected by BSM type.

It should be noted that the mesocosms received relatively low hydraulic loading for the first part of the study, from around January 2021 through February 2022. During this period, ponding rarely occurred in either outlet-controlled or media-controlled systems and the loading rates did not commonly engage the outlet control orifice. Therefore, limited difference pertaining to plant health would be expected between the two hydraulic control configurations during this period.

3.5. Operation and Maintenance

O&M monitoring was performed throughout the monitoring period of this study. The orifice sizes were 0.25-inch diameter drilled into a PVC end-cap. Specific attention was given to whether these orifices showed signs of clogging or biofouling. No signs of orifice clogging or biofouling were observed throughout the study.

In broader O&M inspections of the mesocosms, two issues were observed and recorded:

- Biofouling of underdrains was observed at two mesocosms with new standard BSMs, one with media control and one with outlet control. A thick film of biological growth occurred within the underdrains of these mesocosms. Standard BSM obtained from the same supplier was present in both mesocosms that biofouled, suggesting that the specific media product was the source of this issue. There was no difference in the degree of biofouling between the media-controlled and outlet-controlled configurations. This was not one of the mesocosms subject to full instrumentation and water quality monitoring, so it is unknown how the subject media affected water quality performance.
- As discussed earlier, the outlet structure of Mesocosm 23 was damaged by the taproots of the dogwood. This is a media-controlled mesocosm.

In summary, no significant O&M issues were observed related to the small orifices used as outlet controls at any of the mesocosms in the study.

4. Conclusions and Recommendations

This section provides an answer to each research question introduced in Section 1.3. These responses are based on the results presented in this report combined with the results of the Modeling Study Report.

4.1. Q1. Water Quality Treatment Performance

Q1. How does the water quality treatment performance of bioretention differ between outlet-controlled and media-controlled configurations?

The effect of outlet control varies from pollutant to pollutant and differs depending on the type and age of BSM. Where BSM is prone to the leaching of analytes, outlet control appears to increase the leaching potential for some analytes, specifically Copper and TKN. But outlet control improved pollutant retention for a few analytes, specifically ortho-phosphorus, nitrate-nitrite, and TSS. Several combinations of analytes and media type/age showed no statistical difference.

Overall, statistical analyses showed that the differences in pollutant loading associated with media control versus outlet control are smaller than in pollutant loading associated with media type and age. A more detailed discussion of the findings is presented in Section 3.2.

4.2. Q2. Effect on Residence Time

Q2. How does outlet control vs. media control affect the residence time and residence time distribution of water treated by the mesocosms?

Outlet control had, the anticipated effect of increasing residence time compared to media control. The median residence time of media-controlled mesocosms varied from 31 to 85 minutes. The median residence time of outlet-controlled mesocosms varied from 101 to 104 minutes. The variability in media-controlled mesocosm mirrors this study's hydraulic conductivity variability. The variability in media hydraulic conductivity is also present in the outlet-controlled mesocosms, but the outlet-control orifice appears to be effective in mitigating the effects of this variability, producing a consistent median residence time.

Increasing residence time could correspond to an increased ability to remove or transform challenging pollutants in bioretention or media filtration systems. However, as indicated in the water quality monitoring results, an increase in residence time may also contribute to an increase in pollutant leaching of some analytes from compost-based media.

4.3. Q3. Effect on Plant Health

Q3. Are plant health and vigor differences notable at a mesocosm scale between outlet-controlled and media-controlled designs?

Over the 18-month study period, outlet control had little effect on plant health, as measured via vigor and growth. There were some minor apparent improvements in vigor ratings associated with outlet control. Significance was not assessed.

Media type and age had the greatest impact on plant health. Plants had moderate or better vigor ratings in each media but had a limited growth rate in the alternative BSM, which had limited nutrients.

4.4. Q4. Operation and Maintenance

Q4. Does using small orifices as outlet controls pose notable operations and maintenance challenges compared to standard bioretention without underdrain outlet controls?

Over the 18-month study period, neither the media-controlled nor outlet-controlled bioretention mesocosms experienced O&M issues associated with the outlet-control orifice. The orifice was 0.25 inches in diameter, below the lower limit specified in the SWMMWW, but was suitable for this mesocosm-scale study.

One new standard BSM product exhibited biofouling of the underdrains of both media-controlled and outlet-controlled systems. This shows that some BSM blends could result in biofouling. This affected both configurations equally in this case.

4.5. Q5 and Q6. Stage-Discharge Relationships and Hydraulic Consistency

Q5. What is the stage-discharge relationship of each mesocosm? Is this consistent with theoretical calculations?

Q6. How do hydraulic conditions of the systems (i.e., stage-discharge relationships) vary over time and between replicate mesocosms? Does one configuration result in more consistent operation than another?

The Modeling Study Report provides detailed discussions of stage-discharge relationships, the variability between mesocosms, and the ability to estimate these relationships using calculations or models. In summary:

- Implementing orifice outlet control on biorientation facilities with underdrain produces a relatively predictable stage-discharge relationship. This relationship can be predicted reasonably well via an orifice equation. Variability in media properties between BSM types and ages had little effect on stage-discharge relationships when using an orifice control.

- Without outlet control, the stage-discharge relationship is controlled by media hydraulic conductivity. Media variability was observed to vary substantially between mesocosms with standard BSM. This resulted in variable stage-discharge relationships, with different mesocosms exhibiting approximately 4 times difference in discharge for a given stage.

- Variability was less in mesocosms with alternative BSM. This BSM was obtained from a single vendor, so consistency in the stage-discharge relationship is expected.
- When the hydraulic conductivity of the BSM is known, it is possible to reasonably match the stage-discharge of media-controlled mesocosms with the WWHM model. In contrast, it was possible to reasonably match the stage-discharge of outlet-controlled mesocosms without needing to know the hydraulic conductivity of the BSM.

Overall, outlet control provides predictable hydraulic performance. Media control is subject to uncertainty in media properties, which can vary between suppliers. If flow control performance is a design goal, outlet control offers greater predictability. Media hydraulic conductivity cannot be readily estimated at the design phase, and therefore, media control would produce less predictable flow control performance.

Designers can use WWHM to evaluate the sensitivity of media hydraulic conductivity on flow control performance for both media-controlled and outlet-controlled configurations.

4.6. Q7. Effect on Flow Control Performance

Q7. Does outlet control improve the degree of hydrologic control provided by a bioretention facility of a given size, even if not explicitly designed to meet SWMMWW Minimum Requirement (MR) #5 (on-site stormwater management) or MR#7 (flow control) standards?

As discussed in Q5 and Q6, outlet control improves the predictability of flow control. This question deals with whether outlet control improves the magnitude of flow control benefits.

Monitoring data show substantial improvement in peak flow attenuation in discrete storm events when using outlet control. Orifices induced ponding more often and caused the mesocosms to behave similarly to detention basins. Drawdown was still relatively rapid (approximately 2-3 hours); however, peak flows reductions in recurring storm events were significant (typically 50 to 85%). Media-controlled mesocosms often showed substantially less flow control and no ponding. Monitoring data show a substantial improvement in flow duration control via outlet control. The transferability of monitoring results depends on storm size, intensity, and the sizing factor.

The Modeling Study expanded on and confirmed the findings of the mesocosm monitoring. The Modeling Study showed that bioretention size is an important factor in flow control performance: when bioretention facilities are too small, neither outlet nor media-controlled systems have substantial benefits. With increasing size, the outlet-controlled configuration showed substantial improvement in flow duration control performance compared to the media-controlled configuration.

Because flow control benefits are highly dependent on system sizing, outlet design, and site-specific hydrology, the findings of this study are effectively only a proof of concept. As discussed above, WWHM can simulate media-controlled and outlet-controlled configurations to assess whether outlet control is favorable to meeting flow control design goals. Media hydraulic conductivity should be used as a sensitivity variable in these simulations.

4.7. Synthesis of Recommendations

When traditional water quality treatment performance is of primary concern, an outlet control approach provides limited benefit. This approach may increase the risk of leaching pollutants from BSM, particularly for standard mixes that already have the potential to leach.

An outlet control approach could be beneficial for water quality treatment applications where (1) more predictable and longer residence times are desired to target specific analytes, or (2) there is concern about short-circuiting through a portion of the media bed (i.e., a disproportionate amount of flow treated through a portion of the media bed) and exhausting the treatment capacity along the short-circulate pathway, and (3) risks of nutrient and dissolved copper leaching are managed. Outlet control effectively slows the water down, increases residence time, and inundates the full media bed (i.e., increases saturation levels) more often. This study shows no impact on O&M or plant health associated with this approach.

An outlet control approach would benefit the most, where greater flow control predictability and precision are needed to meet project goals. This research has shown that the media hydraulic conductivity is variable within the modeled range.. Flow control via an orifice on the underdrains further mitigates the variability and can be simulated via WWHM. This approach is already allowed in the SWMMWW. This study has shown that this could impact the leaching of nutrients and dissolved Copper when paired with standard BSM but is not expected to impact O&M or plant health.

5. References

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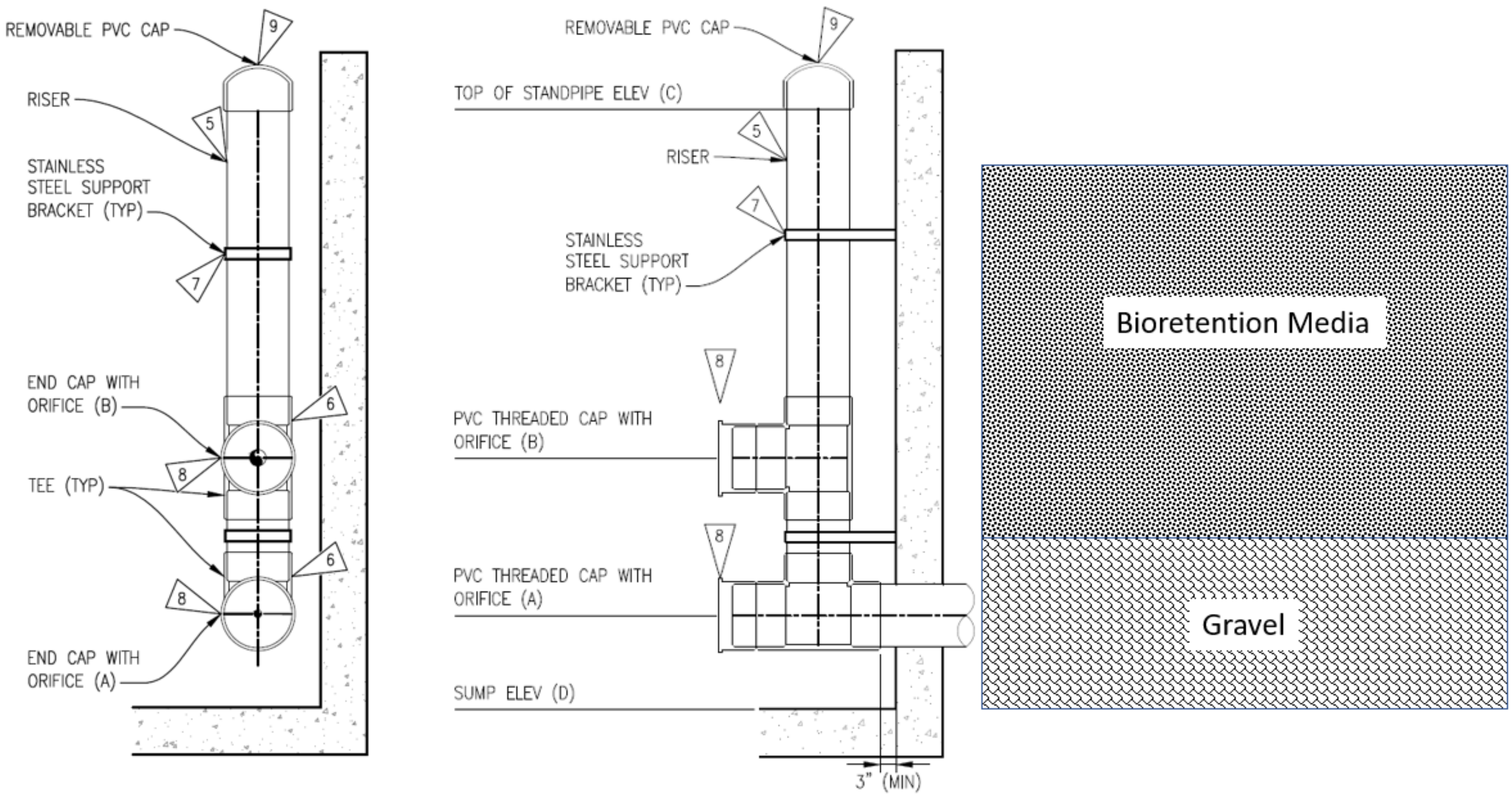
Technology Assessment Protocol – Ecology (TAPE) (2018) Technical Guidance Manual for Evaluating Emerging Stormwater Treatment Technologies. Publication Number: 18-10-038

6. Appendices

Appendix A: **Example Drawing of A Bioretention Facility with Outlet-controlled Underdrain Outlets in Western Washington**



Appendix B: **Comparison Box Plots of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Different Analytes**

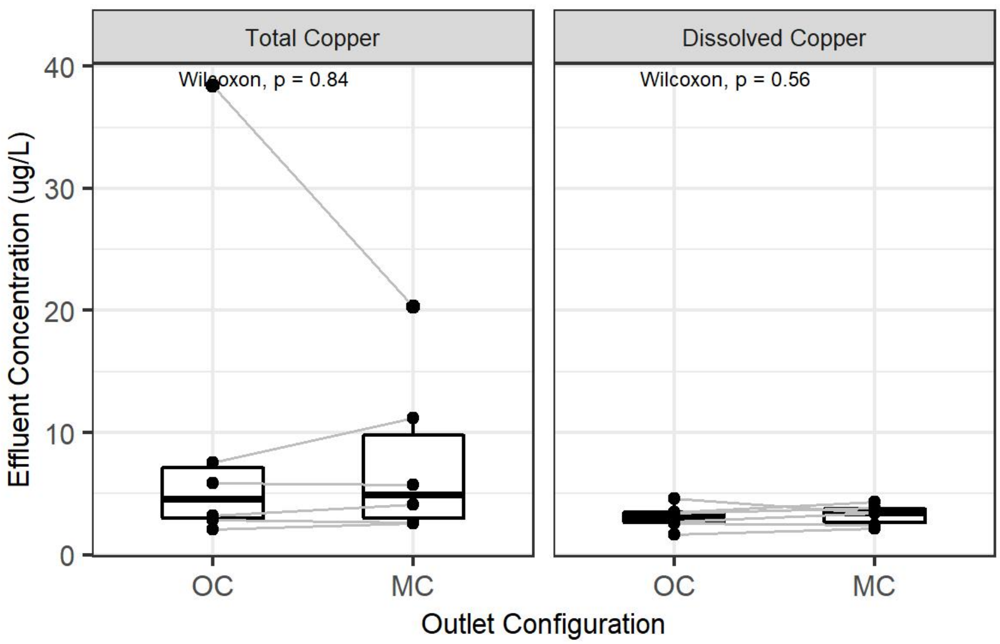


Figure A1: Alternative BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Total and Dissolved Copper

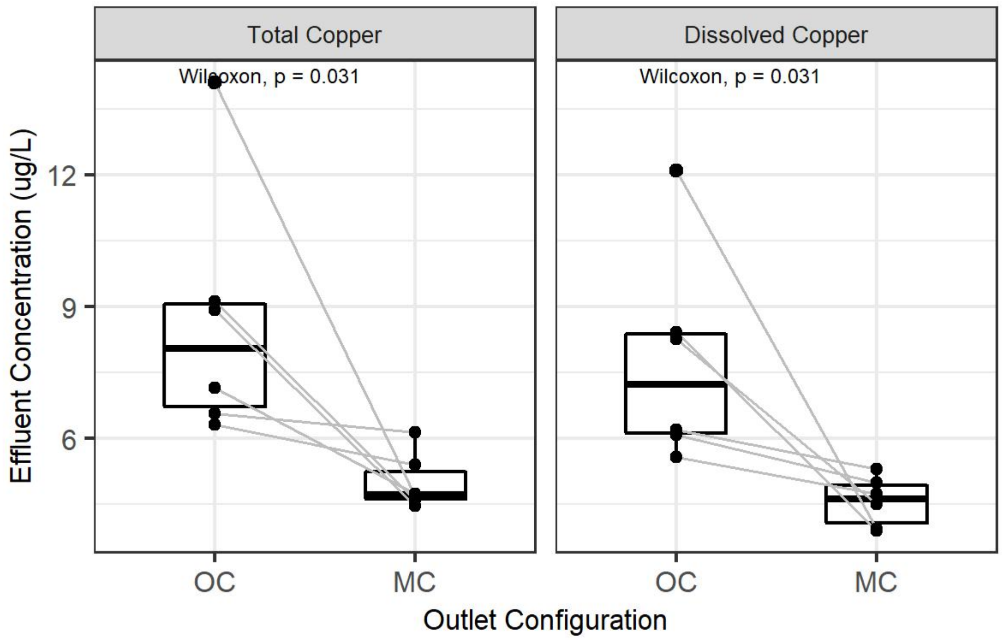


Figure A2: Mature Standard BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Total and Dissolved Copper

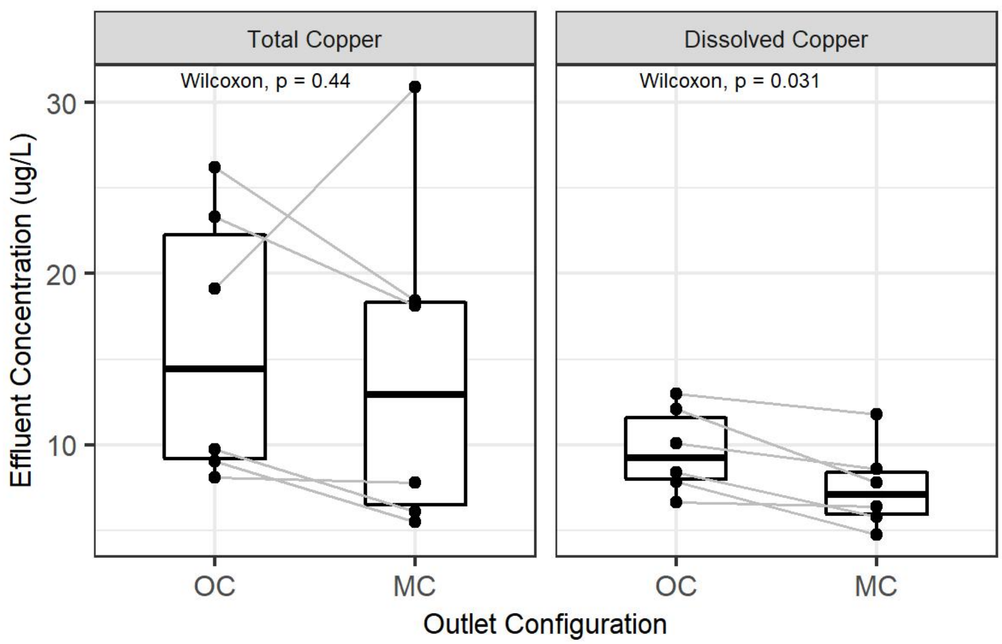


Figure A3: New Standard BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Total and Dissolved Copper

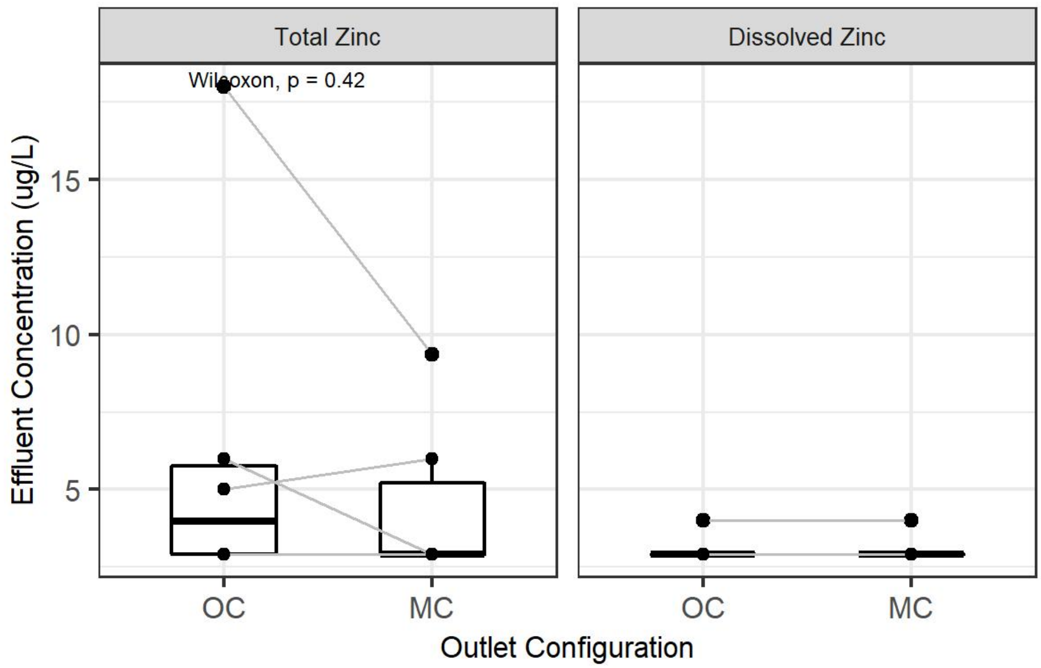


Figure A4: Alternative BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Total and Dissolved Zinc. Dissolved Zinc in several effluent samples across both treatments were listed as non-detect - therefore numerically identical. The Wilcoxon Signed-Rank test could not be evaluated.

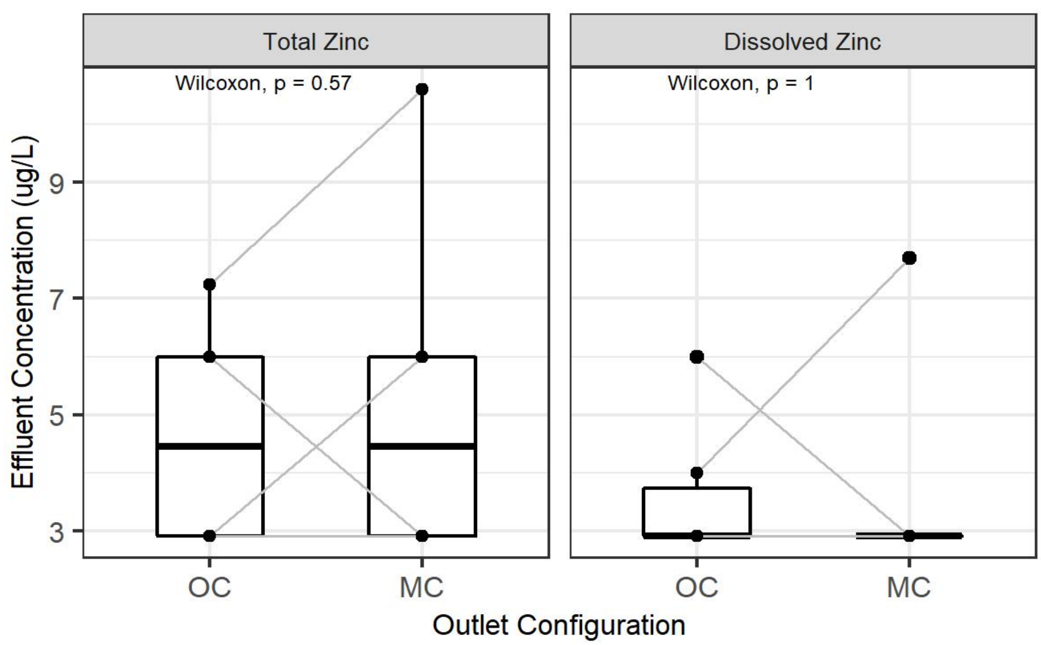


Figure A5: Mature Standard BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Total and Dissolved Zinc

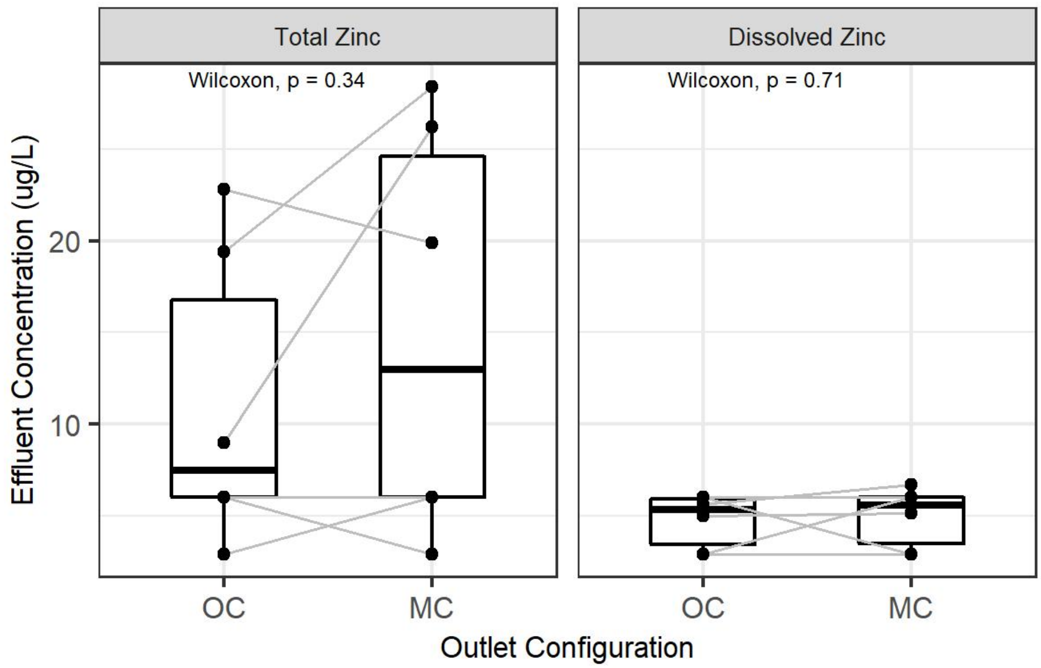


Figure A6: New Standard BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Total and Dissolved Zinc

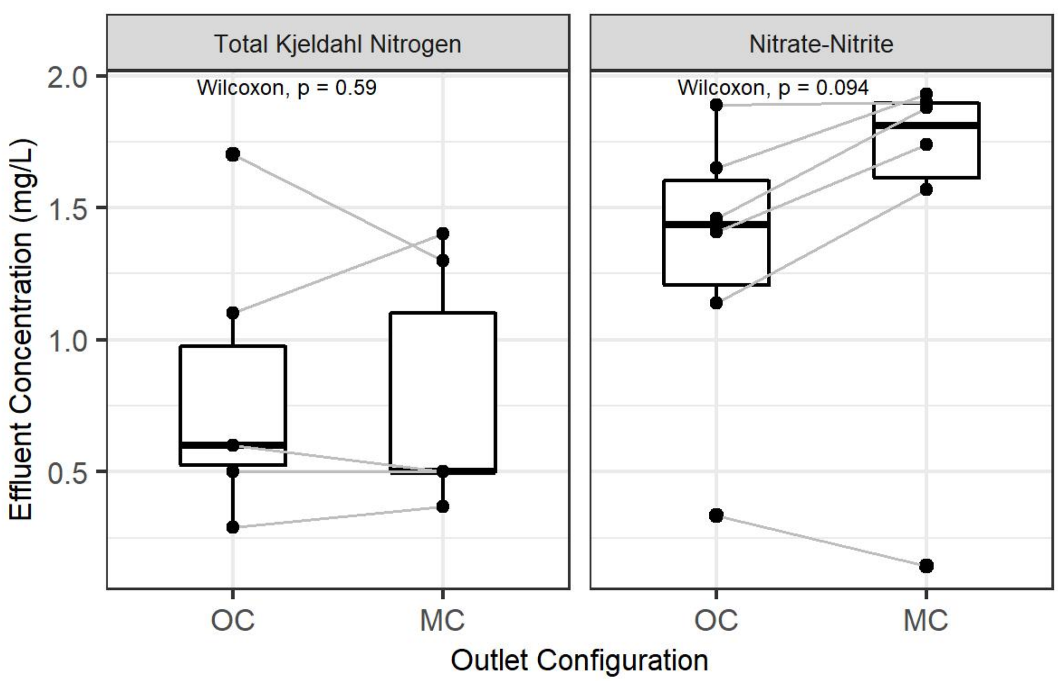


Figure A7: Alternative BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Nitrogen

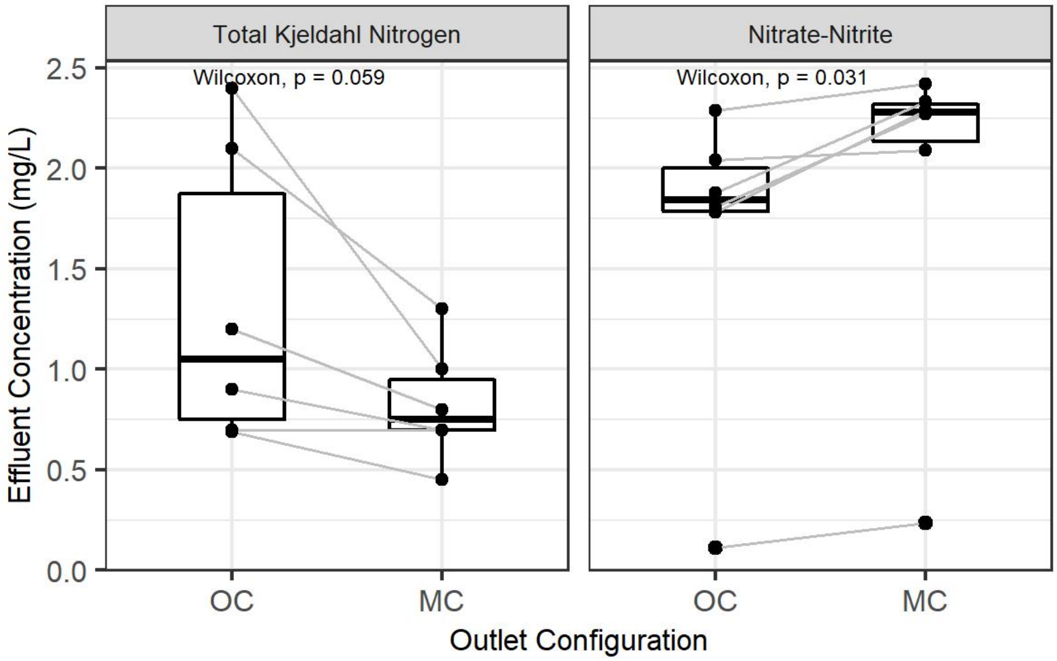


Figure A8: Mature Standard BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Nitrogen

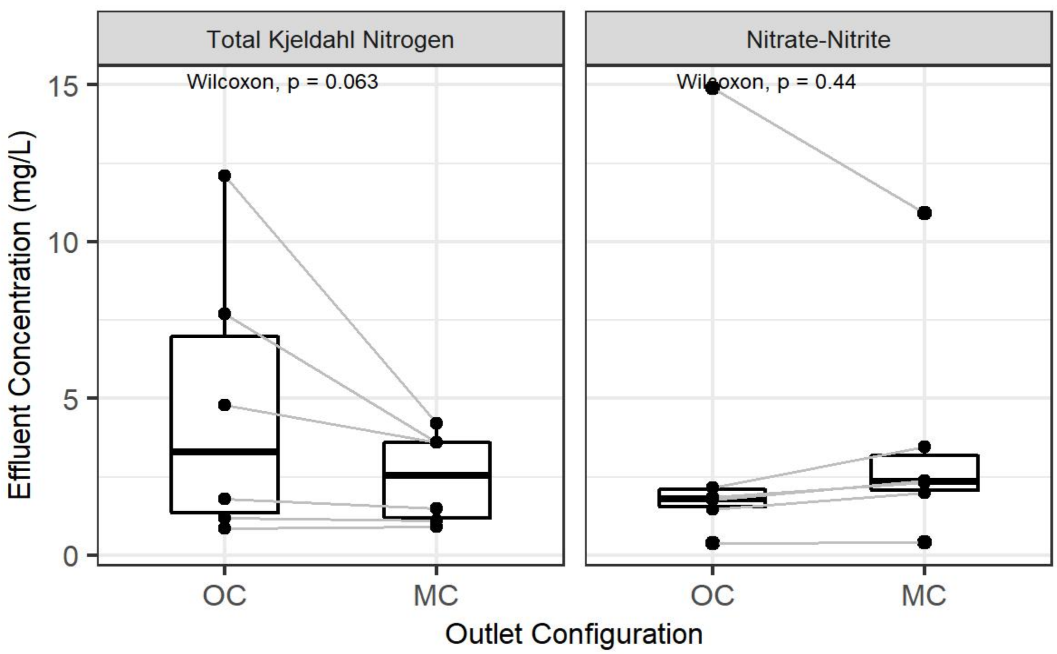


Figure A9: New Standard BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Nitrogen

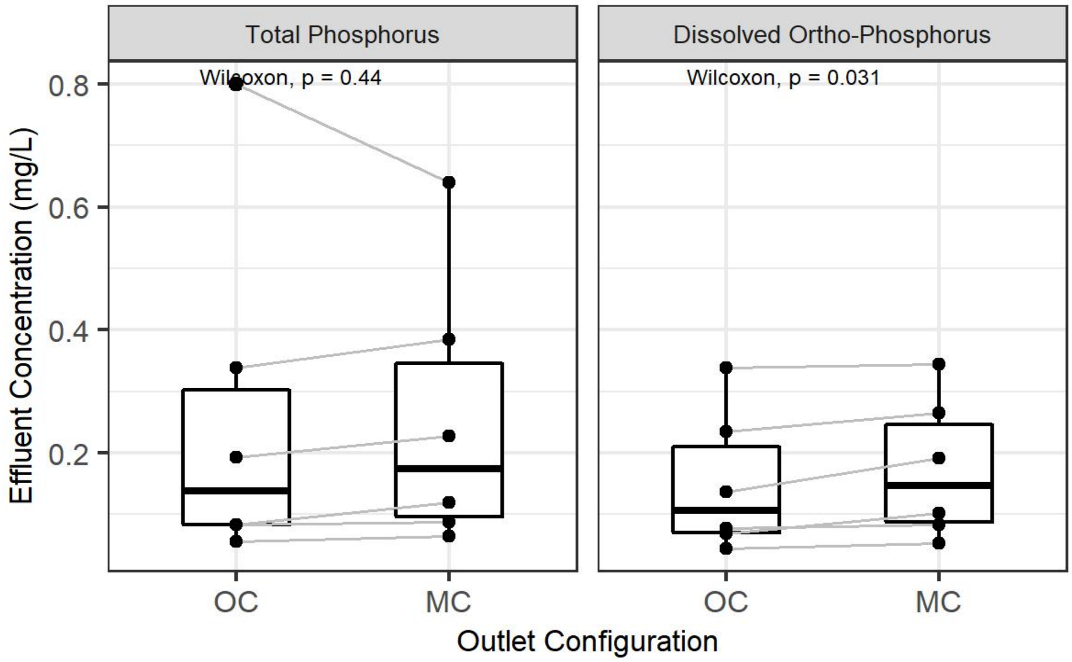


Figure A10: Alternative BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Phosphorus

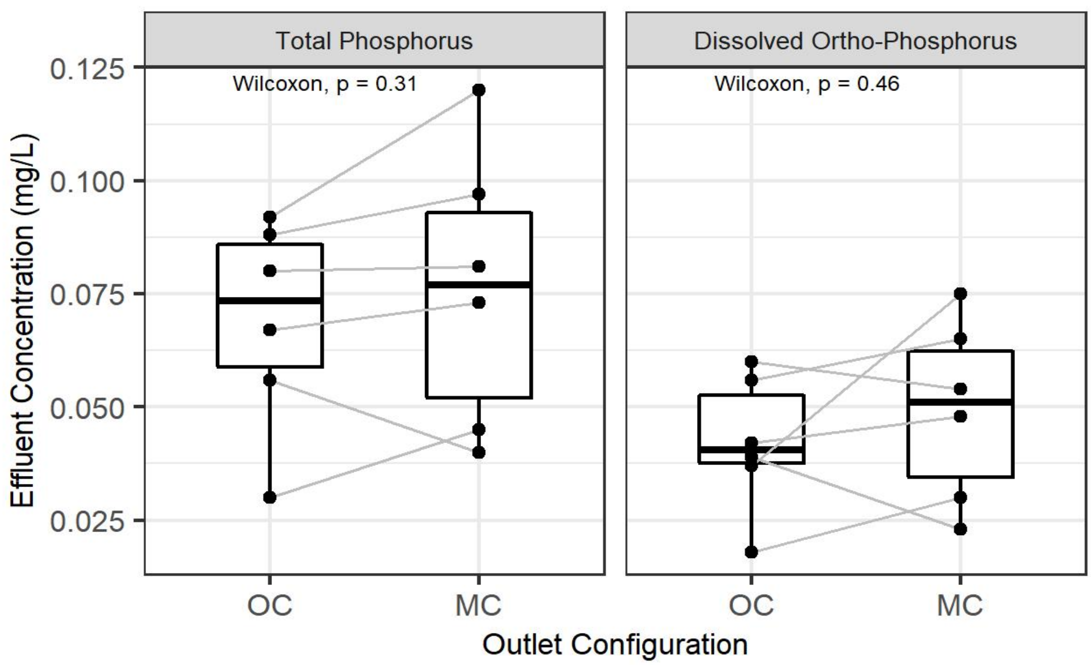


Figure A11: Mature Standard BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Phosphorus

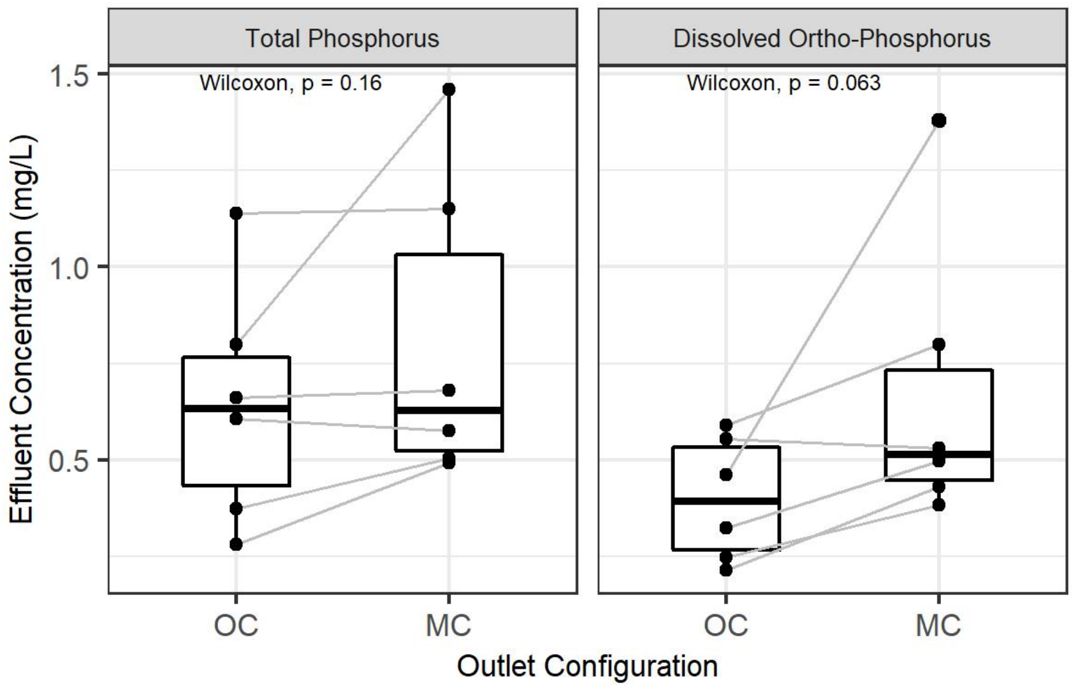


Figure A12: New Standard BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Phosphorus

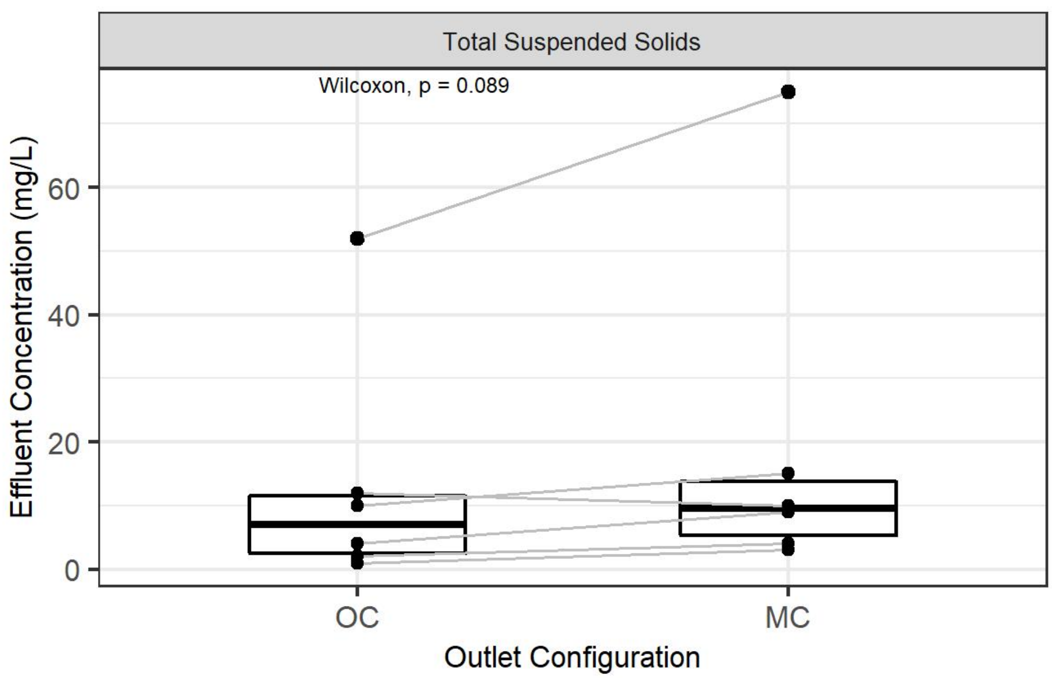


Figure A13: Alternative BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Total Suspended Solids

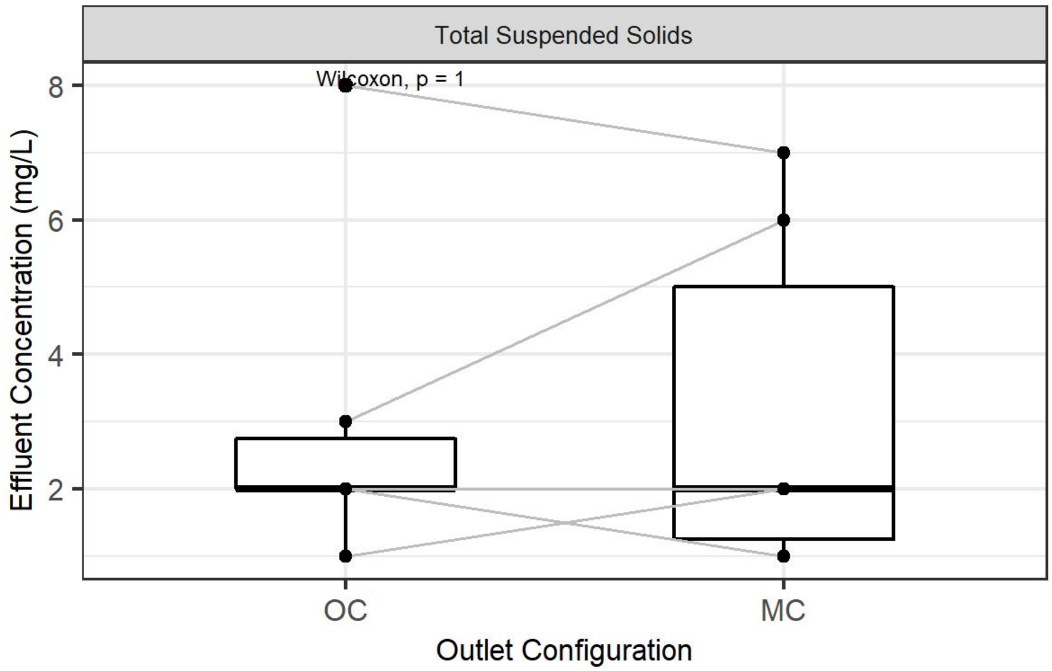


Figure A14: Mature Standard BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Total Suspended Solids

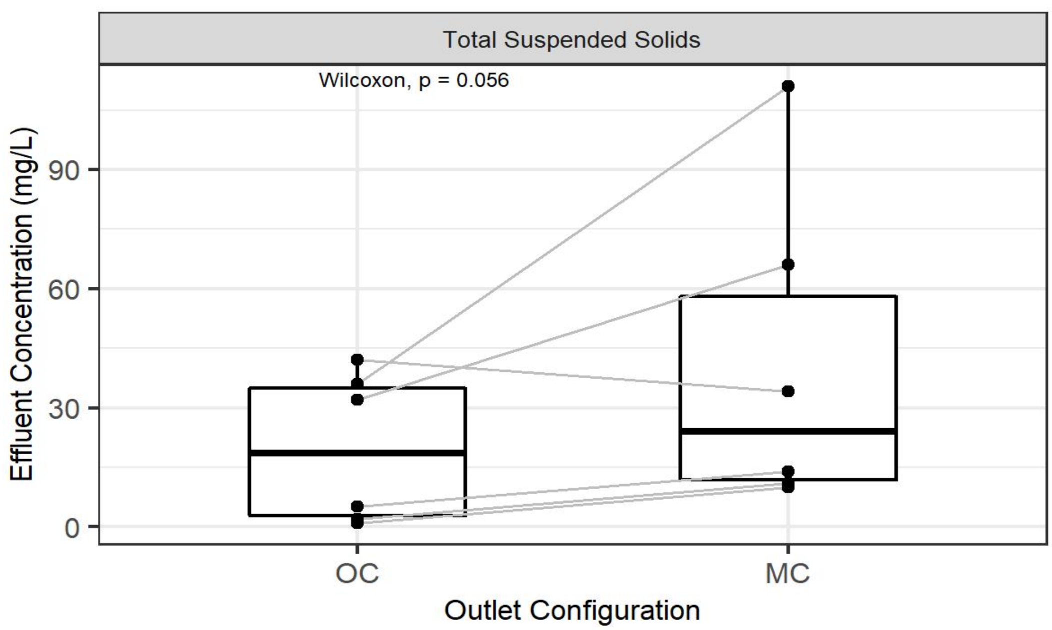


Figure A15: New Standard BSM: Comparison of Effluent Concentration between Outlet-Controlled and Media-Controlled Mesocosms for Total Suspended Solids