Stormwater Action Monitoring - Effectiveness Studies

Modeling Study Report

Evaluation of Hydraulic Control Approaches for Bioretention Systems

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1 Introduction and Background

The Evaluation of Hydraulic Control Approaches for Bioretention Systems Study (the Study) is intended to compare the side-by-side pollutant removal, hydraulic performance, and other aspects of media-controlled bioretention mesocosms to outlet-controlled bioretention mesocosms. Fourteen existing mesocosms at the Washington State University (WSU) LID Research facility in Puyallup, Washington were configured to represent bioretention cells with various filtration media and outlet control configurations.

In accordance with the Quality Assurance Project Plan (QAPP) (Geosyntec & WSU, 2020) the overall study design included a modeling study which is intended to help interpret and extend the mesocosm monitoring results to assess the potential impacts of hydraulic control approaches on idealized case studies in Western Washington. To augment the QAPP, an Outlet Control Study Modeling Plan (Geosyntec & WSU, 2022) outlined the data and methodology used in this modeling study to further understand bioretention performance. The following are the goals of the modeling study as a complement to the mesocosm study.

1. How would the use of outlet control versus media control influence long term capture efficiency (volume of water captured by the bioretention)? The mesocosm study was relatively short and had limited ability to adjust the ratio of drainage area to mesocosm area. Field monitoring data from this project were not intended to describe long term capture efficiency of systems designed per applicable sizing guidance.
2. How would the use of outlet control versus media control influence long term volume reduction (volume of water lost by infiltration or evaporation) in cases where soils below actual systems allow some infiltration? The mesocosms are fully lined, so this aspect was not studied in the field portion of this project.
3. How would the use of outlet control versus media control influence long term flow control? The study was too short to develop an estimate of long-term flow control benefits across a representative range of storm events and bioretention sizing approaches.

The findings from implementation of the modeling study are documented in this report.

2 Availability and Reliability of Monitoring Data for Modeling Study

This section summarizes the monitoring data that are available for use in this modeling study and includes our assessment of the most relevant and reliable monitoring data to support the modeling study. As indicated on the Modeling Plan (Geosyntec, 2023), the modeling study only relied on data relevant to defining stage-storage-discharge relationships of the mesocosms. Separate analyses of additional monitoring data are reported in the Task 5 Final Study Report beyond what are used in this modeling study.

2.1 Summary of Monitoring Data Available for Modeling Study

The installation activities for retrofitting the fourteen mesocosms at WSU’s research facility were completed on January 7th, 2021 (Installation and Start-up Report, March 2021). Following the completion of the retrofit, continuous precipitation and hydraulic monitoring began on January 8th, 2021, and lasted till June 30th, 2022. This period of record will be referred to as monitoring period in this plan. During the monitoring period, the inflow, outflow, surface ponding and bypass occurrences at all fourteen mesocosms were measured and recorded at a 5-mintue interval. A study adjustment, described in the modeling plan, was made in February 2022 to increase the drainage area to the mesocosms, resulting in greater frequency of ponding in the mesocosms. The need for this adjustment to mesocosm operation is further explained in the Task 5 Final Study Report.

Six of the fourteen mesocosms were equipped with soil moisture content meters. Continuous soil moisture content monitoring was also conducted at these six fully instrumented mesocosms throughout the monitoring period at 5-minute interval. In addition, influent and effluent samples were collected at these six mesocosms during six water quality monitoring events; in-situ hydraulic conductivity and residence time testing were also conducted in three special testing events at these six mesocosms. The testing procedures for these discrete monitoring events are documented in the QAPP. The Modeling Study Plan documented additional details of the datasets available for to support the modeling study.

2.2 Data Assessment and Processing for Modeling Study

A subset of the available monitoring data was evaluated for use in this modeling study, including hydraulic monitoring records from special events and continuous hydraulic monitoring records.. In preparation for the modeling study, these datasets were assessed for quality control and pre-processed for the modeling analyses.

2.2.1 Special Event Hydraulic Monitoring

These data include the ponding and flow monitoring data during three hydraulic conductivity testing events and additional drawdown tests for mesocosms with outlet-controlled orifice in place. During these tests, the mesocosms were filled, then allowed to drain completely without further inflow. Data from these special events provides a well-isolated way to estimate the SSD curve of the mesocosms. As a result, data from these tests were the primary basis for the modeling study.

To evaluate the quality of the flow monitoring data, the total sum of outflow from each mesocosm during each testing event was calculated. If the total sum of outflow was substantially less than (more than 50% difference) the estimated volume of water in the mesocosm up to the overflow stage, the flow data from the specific mesocosm during the specific event was removed from the analysis. In each case where data were removed, the measured outflow was less than the expected outflow, indicative of an anomaly in flow measurement. In addition, the outflow data was also visualized as a time series. Events with apparent data gap (no flow measurement for more than 15 minutes) or flow increase during the drawdown period were removed from the analysis. The water level monitoring data from the special events were also visualized in time series plots for quality check purposes but no data gap or abnormal values were observed. Table 1 summarizes the results of the flow monitoring data assessment during special events.

Table 1. Data Quality Assessment Results for Special Events Flow Monitoring

Mesocosm ID	Hydraulic Conductivity Tests			Additional Drawdown Tests	
	Event 1	Event 2	Event 3	Event 1	Event 2
12	**F**	Q	**S**	**S**	Q
13	Q	Q	Q	N/A	N/A
15	Q	**G**	Q	Q	Q
22	Q	Q	**S**	Q	Q
33	**F**	Q	Q	N/A	N/A
34	Q	Q	Q	N/A	N/A

Q: Qualified for analysis
F: Removed from analysis, flow increase during drawdown
G: Removed from analysis, data gap observed
S: Removed from analysis: volume discrepancies

2.2.2 Continuous Hydraulic Monitoring Data

These data include the ponding and flow monitoring data throughout the entire duration of the monitoring period for all fourteen mesocosms. The continuous monitoring data for the period after the study adjustment in February 2022 (increase in tributary area) are most valuable for the modeling study. During this period, ponding occurred more often than prior to the adjustment. Isolating larger storms within this period was one way to estimate SSD relationships.

Quality control checks were also conducted for the continuous hydraulic monitoring data. For each mesocosm, the continuous time series were separated into ponding events by identifying when the inflow starts (starting timestamp of an event) and when the outflow stops (end timestamp of an event). The inflow, outflow and ponding data were plotted as time series for each ponding event and evaluated for the useability to estimate SSD relationships.

Upon inspection, there were some data quality issues and anomalies. Additionally, in real storms, water was flowing into the system at the same time it was draining, requiring a more complicated method of isolating SSD relationships with greater potential error. Addressing anomalies and interpreting dynamic data to isolate SSDs relationships would have required greater effort to address than was allocated for the modeling study. In our technical opinion, the use of these data would not substantially improve our understanding compared to the SSD relationships derived from the special event hydraulic monitoring. Therefore, the research teams decided to not use these data and rely solely on the hydraulic monitoring data during special events to develop the SSD relationships.

3 Stage-Storage-Discharge Relationship Analysis

This section summarizes the steps taken to develop SSD relationships from the flow and ponding monitoring data collected at the mesocosms. For the purpose of the modeling study, the mesocosms were grouped into four categories based on media type (standard and alternative BSM) and hydraulic control type (media- and outlet-controlled). This analysis resulted in a representative SSD relationship for each category and sets of soil parameters in WWHM to attempt to match the modeled bioretention SSD relationship with the observed SSD relationship for each category of bioretention.

3.1 Development of Stage-Storage-Discharge Relationships

For the six fully instrumented mesocosms (12, 13, 15, 22, 33, 34), the flow and ponding data during the special hydraulic events were used to develop stage-discharge curves. During the three hydraulic conductivity testing events, water was pumped into the mesocosms to brim full level with the outlet closed. Subsequently, the outlets were open with the drawdown of ponding and the outflow was recorded until the mesocosms were drained to the invert elevation of the outlet (24 inches below the media surface). The outlet controls were removed from mesocosms 12, 15, and 22 for the duration of these events to allow them to drain freely.

Two additional events were conducted to develop SSD relationships when outlet controls were in place. The same method used in the previous three events was repeated for mesocosms 12, 15, and 22 but flow was restricted with outlet controls.

To estimate the SSD relationships, the vertical profile of each mesocosm was divided into three phases as shown in Figure 1:

- Phase 1: between overflow outlet (12 inches above the media) and the lowest opening of the water level monitoring stand well, which is normally about 2 inches above the media.
- Phase 2: between the lowest opening of the stand well and the media surface; water level is not reliably measured by the transducer within in this phase.
- Phase 3: below the media surface.

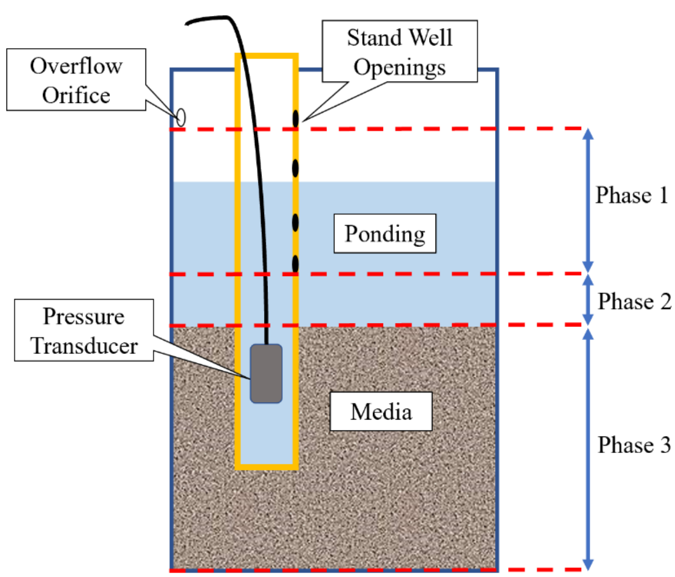


Figure 1. Drawdown Phases in Mesocosm for SSD Analysis

The porosity of the media was calculated first to facilitate the translation between stage and volume in each phase. Phase 1 & Phase 2 of the mesocosms were assumed to have 100% porosity (ponding layer). For Phase 3, the total volume of water discharged in Phase 3 was divided by the gross volume of the mesocosm in Phase 3 to estimate the effective porosity of the media during each drawdown test.

In Phase 1, the stage-discharge relationships were developed by directly correlating the outflow measurement and the ponding stage data and the stage-volume relationship was calculated based on the footprint of the mesocosm. Once the water was below the stand well's lowest opening (Phase 2 & 3), no direct stage measurement was available and the volume of water left in the mesocosm was estimated using a level-pool analysis, which calculates the volume storage at the end of a time step.

The volume at the end of each time step during Phase 2 & 3 of the drawdown test was then translated into stage using the porosity estimates. Lastly, the volume and stage were correlated directly with the measured outflow rate to develop the stage-storage-discharge relationships.

Combination of stage-discharge relationship in all three phases in the mesocosms created an overall stage-discharge relationship. For the purpose of inputting this information into WWHM for this modeling study, the mesocosms were then divided into four groups by type of media (standard or alternative) and the outlet configurations (media-controlled or outlet-controlled). The stage-discharge curves for each group were then derived by averaging the stage-discharge relationship of all mesocosms within the group. The stage-discharge for the individual mesocosms and each group of mesocosms are illustrated in Figure 2.

Key Observations

In the absence of an outlet control, the variability between media suppliers and age affected the stage-discharge curve. There was relatively wide variation in stage-discharge curves for standard media without outlet control (Figure 2, Graph 1), with a range of approximately 5x in discharge rate at a given stage. There was less variation across media-controlled mesocosms with alternative media (Figure 2, Graph 3), which is expected given that this is the same media of the same age from the same supplier.

The outlet-controlled mesocosms (Figure 2, Graph 2 and 4) showed very little variability between media suppliers and mesocosm. The type of media did not appear to have a significant effect on the stage-discharge curves for orifice-controlled mesocosms. Outlet control also effectively reduced the discharge compared to media-controlled mesocosms.

In addition to the SSD development, the research team also observed that all six mesocosms included in the hydraulic conductivity testing completely drained within two hours, indicating that the flow restriction as a result of the outlet control device did not cause the bioretention mesocosm to exceed the 24-hour maximum drawdown time requirement per the Stormwater Management Manual for Western Washington (SMMWW).

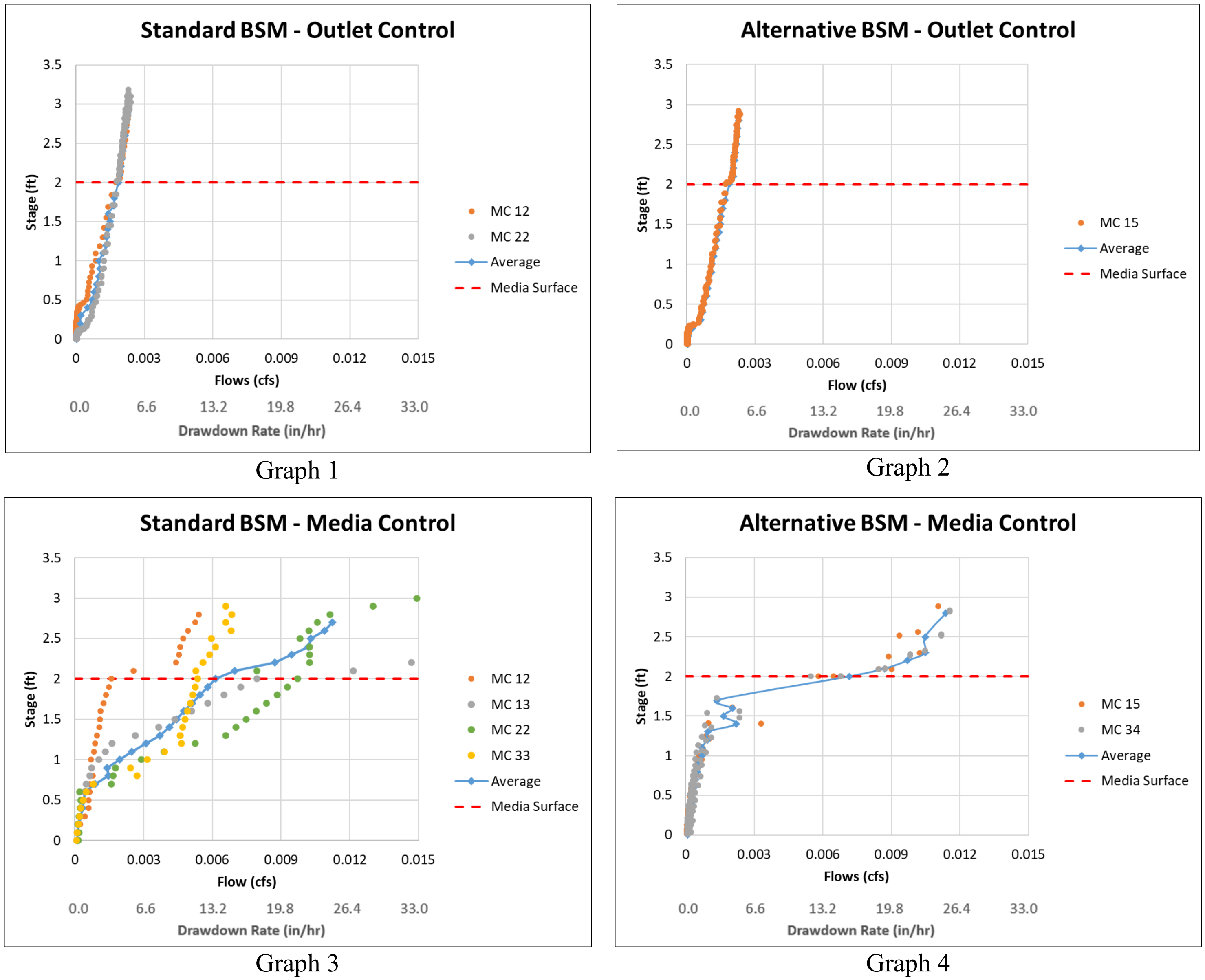


Figure 2. Stage-Discharge Curves for Four Mesocosm Scenarios

3.2 Representing Bioretention with Underdrains in WWHM

To represent the observed SSD relationships derived from the monitoring data in this study, two custom soil types were created in WWHM and parameterized to closely match the observed hydraulic performance for both standard and alternative bioretention soil media (BSM).

The default bioretention media in WWHM (referred to as the "SMMWW" meed) was used as the baseline soil type for the creation of the custom soil types. The default uncorrected K_{sat} of this media is 12 inches per hour. This is a design assumption specified in the SMMWW. The actual infiltration rates of this type of media could be higher. For modeling in WWHM, a correction factor of 2 was applied to the default uncorrected design rate, resulting in a modeled rate of 6 inches per hour in the default media modeling scenarios. The default bioretention media had a porosity of 47%. Based on the observed data collected in this study, the standard BSM and the alternative BSM show effective porosity of 15% and 18% respectively. As a result, the porosity of the two custom soil types were lowered to match the observed data.

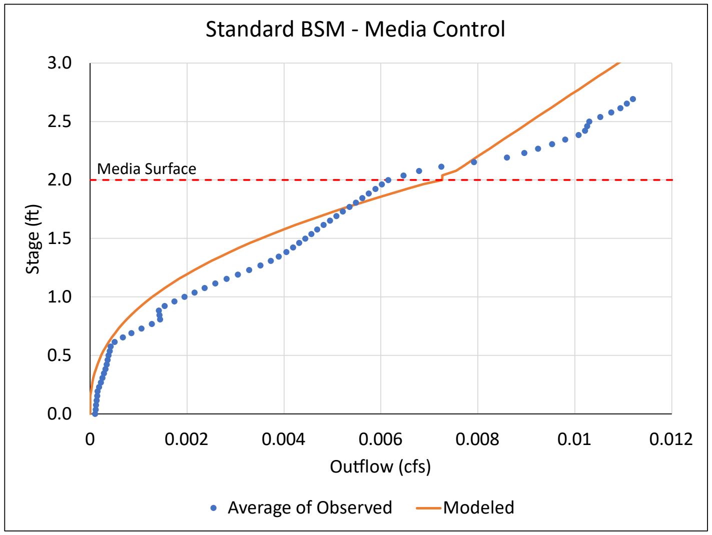
To adjust the K_{sat} of the custom soil types, bioretention elements with an underdrain and the same surface area and media depth as the mesocosm used in the experiment were created in WWHM. Subsequently, the K_{sat} of both custom soil types (standard and alternative BSM) were adjusted at one inch per hour intervals until the modeled and observed stage-discharge curves under the media surface (0 to 2 feet depth) yielded coefficient of determination (R^2) closest to 1.0 for both media-controlled and outlet-controlled bioretention.

The resulting soil parameters for each custom soil type modeled in WWHM are summarized and compared to the standard "SMMWW" bioretention soil in Table 3. Figure 3 shows the best fit comparison between the average of the measured stage-discharge curves and the modeled stage-discharge curves. As shown on Table 3, the comparison between modeled and observed stage-discharge yielded R^2 greater than 0.9 for standard media and R^2 greater than 0.85 for alternative media, indicating good fit between the modeled and observed stage-discharge.

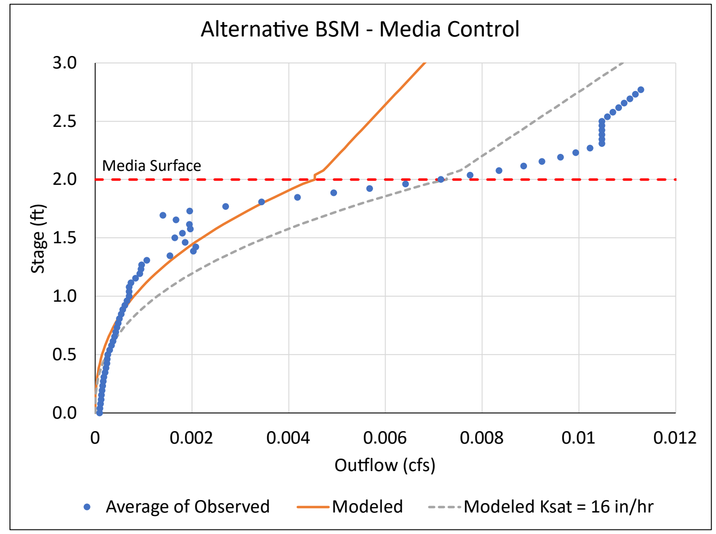
Table 2. Summary of Soil Parameters in WWHM.

	SMMWW	Best Fit for Standard Media	Best Fit for Alternative Media
K_{sat} (in/hr)	6	16	10
Porosity	0.47	0.15	0.18
Media-controlled Stage-Discharge R^2 Value[1]	N/A	0.94	0.85
Outlet-controlled Stage-Discharge R^2 Value[1]	N/A	0.93	0.87

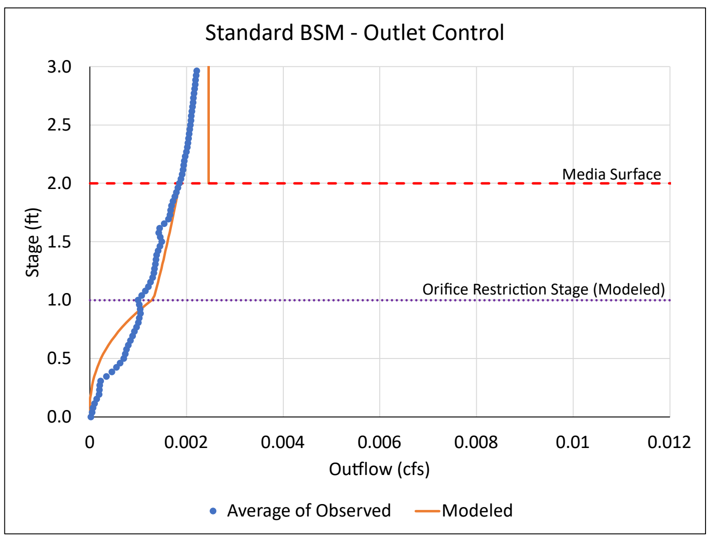
[1] R^2 was calculated for stages below the media surface.



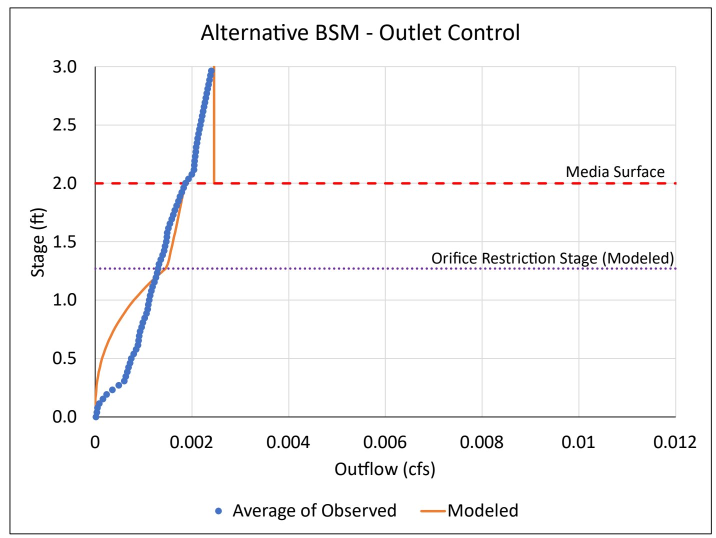
Graph 1



Graph 2



Graph 3



Graph 4

Figure 3. Stage-Discharge Curve Comparison between Observed and Modeled Bioretention

Key Observations

The SSD relationships could only be adjusted by changing the value for K_{sat}. Consequentially, it was not possible to change the SSD relationship below the media without changing the SSD relationship above the media. For media-controlled mesocosms, it was not possible to find a single K_{sat} that had a good fit both below and above the media surface. When the K_{sat} value for alternative BSM was set to 10 in/hr, the SSD relationship underestimated discharges when the water stage was above the media surface. When the K_{sat} value was adjusted to 16 in/hr, the SSD relationship overestimated discharges when the water stage was below the media surface. Discharge values below the media surface were prioritized to place greater emphasis on permeability and hydraulic retention time. The SSD relationship for alternative BSM modeled with a K_{sat} value of 16 in/hr has been included on Figure 3, Graph 2 for comparison to the selected SSD relationship. This effect is relatively minor in the overall scope of this study. As presented in the next section, the results for standard BSM and alternative BSM are very similar despite differences in K_{sat}.

The modeled SSD relationships for orifice-controlled mesocosms (Figure 3, Graphs 3 and 4) can be divided into three stages: 1) Low stage before orifice is engaged for flow restriction; 2) Medium stage above the first phase and below the media surface; 3) Ponding stage. The accuracy of matching the modeled and observed SSD are discussed for each stage.

Within the low stage, the modeled stage-discharge allows the media, instead of the orifice, to control flowrate. This results in modeled outflow rate lower than the observed outflow within the low stage. It appears that WWHM is modeling greater soil-induced flow restriction in this phase compared to what was observed in the mesocosms. Within the medium stage, the stage-discharge relationship is close to a straight line and the modeled and observed stage-discharge match very closely. Above the media surface within the ponding stage, the observed discharge generally follows the same trajectory in the medium stage and increases with stage. However, the modeled discharge rates remain constant and are not dependent on head, which disagrees with the observed data and Darcy’s Law. We believe this is an artifact of the WWHM model, however this disagreement would have limited effect on modeling study results and limited practical impact on system design.

4 WWHM Scenario Development

WWHM models were developed to perform long-term simulations to assess long-term hydraulic and water quality performance of bioretention facilities with different media types, outlet controls, native soil infiltration rate and sizing scenarios. Results from the SSD analysis (Section 3) were used as input to the WWHM model to match the hydraulic characteristics of the bioretention media. Detailed steps to developing the WWHM model were originally documented in Section 4 of the Modeling Study Plan. This section contains a summary of the steps taken to develop the model as well as an explanation for deviations from the original Modeling Study Plan.

4.1 Model Development

In all model scenarios, runoff from a completely impervious one-acre catchment was routed into a bioretention element in WWHM. A 50-year precipitation record (10/1/1970 – 9/30/2020) in Puyallup, WA from a built-in rain gage in WWHM was used to generate runoff from the catchment. The 50-year record was used instead of the 40-year specified in the original Modeling Study Plan to better quantify the upper erosive flow threshold of the 50-year flow (Q50).

The bioretention element was modeled based on a typical vertical profile depicted in Figure 4. The bioretention cell had 18 inches of media, an overflow structure that allowed 9 inches of ponding above media before overflow, and 6 inches of freeboard above overflow. A gravel layer below the underdrain was not included.

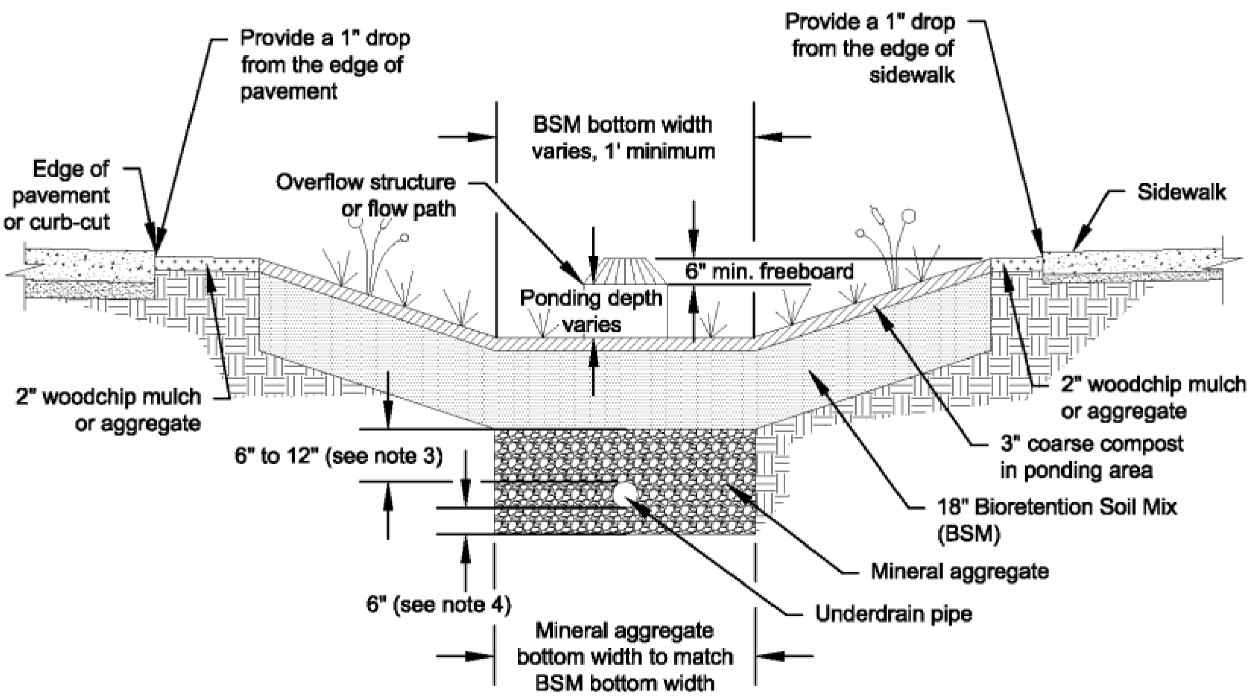


Figure 4. Typical Profile of Bioretention Cell with Underdrain

4.2 Model Scenarios

Sixteen idealized model scenarios were developed for bioretention with underdrains for both Standard BSM and Alternative BSM with and without outlet controls. These scenarios considered two underlying soil infiltration rates and two sizing approaches. The scenarios are detailed in Table 4. Note that these scenarios are for comparison purposes only; they are not intended to describe a design that meets SMMWW minimum requirements.

Table 3. Summary of Modeling Scenarios.

Scenario ID	Media Type	Effluent Control	Native Soil Infiltration Rate, in/hr	Sizing[1]
1	Standard	Media	0.6	Full
2	Standard	Media	0.6	Half
3	Standard	Media	0.1	Full
4	Standard	Media	0.1	Half
5	Standard	Outlet	0.6	Full
6	Standard	Outlet	0.6	Half
7	Standard	Outlet	0.1	Full
8	Standard	Outlet	0.1	Half
9	Alternative	Media	0.6	Full
10	Alternative	Media	0.6	Half
11	Alternative	Media	0.1	Full
12	Alternative	Media	0.1	Half
13	Alternative	Outlet	0.6	Full
14	Alternative	Outlet	0.6	Half
15	Alternative	Outlet	0.1	Full
16	Alternative	Outlet	0.1	Half

[1] Full sizing scenarios were sized to capture and treat 91% of the annual average runoff based on the SWMMWW standard 6 in/hr media treatment rate and 0.3 in/hr underlying infiltration rate; Half sizing scenarios were sized to half of the full-size requirement.

4.2.1 Media Type

The differences between standard and alternative media were represented in WWHM using custom soil type parameterizations. The parameters adjustment was detailed in Section 3.2.

4.2.2 Hydraulic Control

The difference between orifice-controlled and media-controlled bioretention elements modeled in WWHM is the inclusion of an underdrain orifice in orifice-controlled scenarios. The orifice was sized to achieve drawdown rate of 6 inches per hour for both the full-size and half-size bioretention elements. The full size bioretention requires a larger orifice than the half size scenarios.

4.2.3 Native Soil Infiltration Rate

Two native soil infiltration rates were included in the model scenarios: 0.1 and 0.6 inch per hour. The rationale for the selection of these two infiltration rates were documented in the Modeling Study Plan. The difference between the two was modeled in WWHM by adjusting the Measured Infiltration Rate of the native soil.

4.2.4 Sizing

With the aforementioned identical vertical profile for all model scenarios, the sizing of the bioretention elements in WWHM was performed by adjusting the footprint of the bioretention element. As detailed in Section 4.1 of the Modeling Plan (WSU & Geosyntec, 2023), the full-size bioretention was sized to meet Ecology's water quality facility sizing criterion (SMMWW Minimum Criteria #6) to capture 91% of annual average runoff volume from the one-acre impervious tributary area. Based on a 6 inches per hour media filtration rate (12 inches per hour sizing default rate and correction factor of 2) and a 0.3 inch per hour underlying infiltration rate. The resulting 342 square-foot footprint (0.8% of the tributary area) of the bioretention was used for all full-size scenarios. In comparison, a 171 square-foot footprint was modeled in all half-size scenarios. Both represent space-constrained examples.

Note that in our professional experience, the resulting bioretention footprints are relatively small compared to typical designs. This is a function of the 6 inch per hour design filtration rate and sizing for the 91% capture water quality sizing threshold (SMMWW Minimum Requirement #6), as opposed to the full set of potential minimum requirements that could apply to a development site. This resulting footprint is only intended for conducting side-by-side comparison of bioretention modeling scenarios. This footprint does not meet SMMWW Minimum Requirement #5 or #7, which would require substantially larger controls.

5 Modeling Results and Discussion

Results from the WWHM long term simulation models for the sixteen idealized scenarios were extracted and summarized to assess the metrics listed in Section 4.3 and Section 5 of the Modeling Study Plan. In this section, these metrics will be used to compare the long-term hydraulic performance and pollutant loading reduction difference between bioretention with and without outlet control, and between bioretention with standard and alternative media.

The metrics used to assess long-term hydraulic performance included long-term capture efficiency, long-term volume reduction, and flow duration control, and peak flow reduction. The methods for model results extraction and post-processing to calculate these metrics for model scenarios are detailed in Section 4.3 of the Modeling Study Plan.

5.1 Long-term Capture Efficiency and Volume Reduction

Long-term capture efficiency represents the percent of inflow routed to the bioretention that is treated and discharged via the underdrain, infiltrated into the native soil or evaporated. Long-term volume reduction represents the percent of inflow routed to the bioretention that is infiltrated into the native soil or evaporated. The results of the 50-year simulation were extracted from WWHM for all components in the water balance of the bioretention elements, including inflow, treated volume through underdrain, infiltration, evaporation, and overflow. These model results were used to compute the long-term capture efficiency and volume reduction for all sixteen modeled idealized scenarios.

Table 5 summarizes the results from all model scenarios and comparison between model runs grouped by each of the four factors that distinguish the model scenarios (media type, effluent control, native soil infiltration, and sizing) and the impact from each of the four factors on the long-term hydraulic performance is discussed in the section below. Figure 5 illustrates the fractions of inflow leaving the modeled bioretention element via four different pathways (underdrain, overflow, infiltration and evaporation). Infiltration was non-zero because the modeled systems were unlined; however, because the underdrain is at the bottom of the bioretention profile, relatively limited infiltration was expected.

Key Observations

As shown in Table 5, the long-term capture efficiency and volume reduction are very similar between bioretention with standard and alternative BSM. Model scenarios with standard media showed approximately 2% increase in both capture efficiency and volume reduction compared to their alternative media counterpart as a result of the standard BSM has slightly higher permeability (16 in/hr) compared to alternative media (10 in/hr). Because the modeled permeabilities of the two media types are both more permeable than WWHM's default bioretention media SWWMM (6 in/hr), the capture efficiency for all full-size scenarios exceeds Ecology's water quality standard of 91% long-term capture efficiency.

The inclusion of outlet control resulted in a reduction in capture efficiency of about 4 to 6 percent compared to corresponding full-size media-controlled scenarios due to the restricted filtration rate by the orifices. However, all full-sized bioretention elements with outlet-controlled still met Ecology's water quality facility sizing criterion of capturing 91% of annual average runoff volume. This is consistent with the orifices' design to drain the media at a rate of six inches per hour, which was the media filtration rate used to size the full-sized bioretention cells. In addition, the outlet-controlled scenarios result resulted in greater volume reduction in full sized scenarios, up to 10% greater volume reduction, with 0.6 in/hr underlying infiltration rate. This is a function of a minor increase in drawdown time induced by the outlet control.

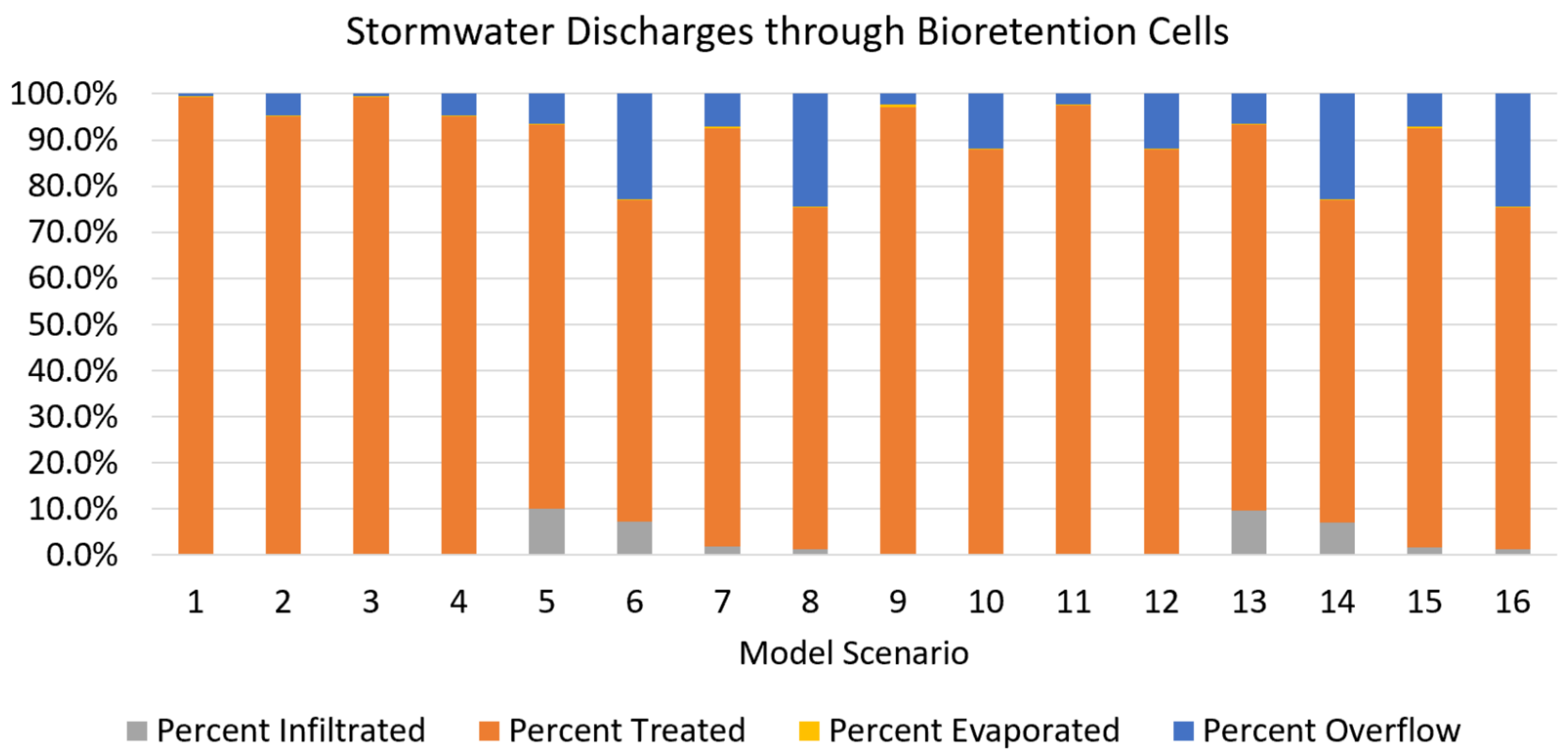
Reducing the bioretention footprint by 50% results in reduction in long-term capture efficiency of approximately 12% on average. This reduction is similar to the reduction from media-controlled to outlet-controlled scenarios because in both cases, the filtration capacity of the media is reduced by approximately 50% through either footprint reduction (full-size vs. half-size) or filtration rate reduction (10-16 in/hr vs. 6 in/hr). The full-size scenarios also showed higher volume reduction compared to the half-size scenarios due to the larger footprint for infiltration and evaporation.

All modeled scenarios included native soil infiltration. Higher native soil infiltration rates improved the volume reduction as expected because infiltration contribute to majority of the volume reduction in all model scenarios. The higher volume reduction also contributed to slightly higher capture efficiency in the scenarios with higher native soil infiltration rate. Designs with a gravel layer below the underdrains would further increase volume reduction in both media-controlled and outlet-controlled systems.

Table 4. WWHM Results for the Sixteen Bioretention Scenarios

Scenario ID	Media Type	Effluent Control	Native Soil Infiltration Rate (in/hr)	Sizing	Total Inflow (ac-ft)	Outflow through Riser (ac-ft)	Treated Outflow (ac-ft)	Infiltration (ac-ft)	Evaporation (ac-ft)	Long-term Capture Efficiency[1]	Long-term Volume Reduction[2]
1	Standard	Media	0.6	Full	130	0.6	129.0	0.168	0.402	99.52%	0.44%
2	Standard	Media	0.6	Half	130	6.1	123.2	0.071	0.218	95.27%	0.19%
3	Standard	Media	0.1	Full	130	0.6	129.1	0.028	0.402	99.52%	0.33%
4	Standard	Media	0.1	Half	130	6.1	123.2	0.011	0.218	95.27%	0.18%
5	Standard	Outlet	0.6	Full	130	8.4	108.3	13.141	0.412	93.58%	10.41%
6	Standard	Outlet	0.6	Half	130	29.7	90.3	9.434	0.224	77.09%	7.45%
7	Standard	Outlet	0.1	Full	130	9.3	118.1	2.381	0.413	92.84%	2.15%
8	Standard	Outlet	0.1	Half	130	31.6	96.1	1.671	0.224	75.60%	1.46%
9	Alternative	Media	0.6	Full	130	2.9	126.4	0.161	0.778	97.78%	0.72%
10	Alternative	Media	0.6	Half	130	15.5	114.0	0.009	0.238	88.07%	0.19%
11	Alternative	Media	0.1	Full	130	2.9	126.9	0.025	0.44	97.78%	0.36%
12	Alternative	Media	0.1	Half	130	15.5	114.0	0.009	0.238	88.07%	0.19%
13	Alternative	Outlet	0.6	Full	130	8.4	108.9	12.555	0.441	93.58%	9.98%
14	Alternative	Outlet	0.6	Half	130	29.7	90.6	9.161	0.238	77.09%	7.25%
15	Alternative	Outlet	0.1	Full	130	9.3	118.2	2.271	0.442	92.84%	2.08%
16	Alternative	Outlet	0.1	Half	130	31.6	96.2	1.619	0.239	75.60%	1.43%
Average Values Across Parameters											
Standard Media					130	11.6	114.7	3.4	0.3	91.10%	2.83%
Alternative Media					130	14.5	111.9	3.2	0.4	88.87%	2.78%
Media-Controlled					130	6.3	123.2	0.1	0.4	95.17%	0.33%
Outlet-Controlled					130	19.8	103.4	6.5	0.3	84.80%	5.28%
Full-Sized					130	4.7	107.2	3.4	0.4	96.38%	2.95%
Half-Sized					130	20.7	105.9	2.7	0.2	84.04%	2.29%
0.6 in/hr Native Soil Infiltration Rate					130	10.9	114.3	4.4	0.4	91.63%	3.70%
0.1 in/hr Native Soil Infiltration Rate					130	13.4	115.2	1.0	0.3	89.70%	1.02%

[1] Long-term Capture Efficiency is the fraction of inflow that is treated, either through flowing through the underdrain or reduction.
[2] Long-term Volume Reduction is the total volume of water removed from the system either through evaporation or infiltration, here expressed as a percentage of total inflow.



1. Standard Media, MC, Full Size, 0.6 in/hr Native Soil
2. Standard Media, MC, Half Size, 0.6 in/hr Native Soil
3. Standard Media, MC, Full Size, 0.1 in/hr Native Soil
4. Standard Media, MC, Half Size, 0.1 in/hr Native Soil
5. Standard Media, OC, Full Size, 0.6 in/hr Native Soil
6. Standard Media, OC, Half Size, 0.6 in/hr Native Soil
7. Standard Media, OC, Full Size, 0.1 in/hr Native Soil
8. Standard Media, OC, Half Size, 0.1 in/hr Native Soil
9. Alternative Media, MC, Full Size, 0.6 in/hr Native Soil
10. Alternative Media, MC, Half Size, 0.6 in/hr Native Soil
11. Alternative Media, MC, Full Size, 0.1 in/hr Native Soil
12. Alternative Media, MC, Half Size, 0.1 in/hr Native Soil
13. Alternative Media, OC, Full Size, 0.6 in/hr Native Soil
14. Alternative Media, OC, Half Size, 0.6 in/hr Native Soil
15. Alternative Media, OC, Full Size, 0.1 in/hr Native Soil
16. Alternative Media, OC, Half Size, 0.1 in/hr Native Soil

Figure 5. Bar Graph Showing Percentages of Stormwater Infiltrated, Treated, Evaporated, and through Overflow.

5.2 Flow-Control Benefits

The flow control benefits from the sixteen idealized scenarios are summarized in flow duration curves and peak flow of key return intervals from Ecology's flow control performance standard, ranging between 8% of the 2-year flow and the full 50-year flow. Both the flow-duration curves and the peak flows of various return intervals were extracted directly from the WWHM model results.

The resulting flow duration curves were illustrated in Figure 6 (for standard BSM) and Figure 7 (for alternative BSM). The flow duration curve of runoff from the 1-acre impervious area is represented in gray for comparison. Red-dashed lines are used to indicate the intersection points between the flow-duration curves of the media and outlet-controlled scenarios. The peak flow from return intervals of interest were summarized in Table 6.

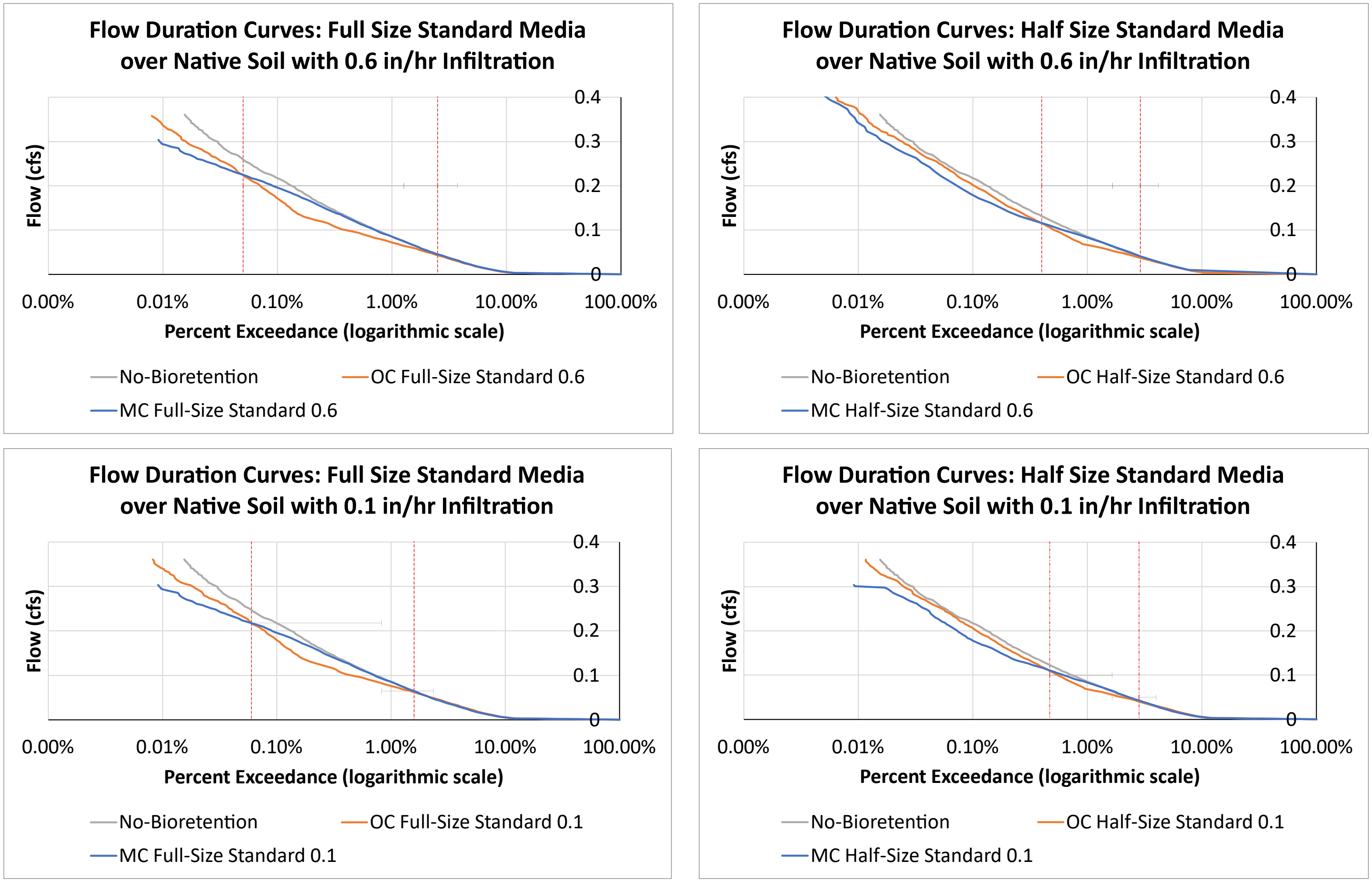


Figure 6. Flow Duration Curve Comparisons for Standard Media between Outlet-Controlled Bioretention, Media-Controlled Bioretention, and Runoff without Bioretention

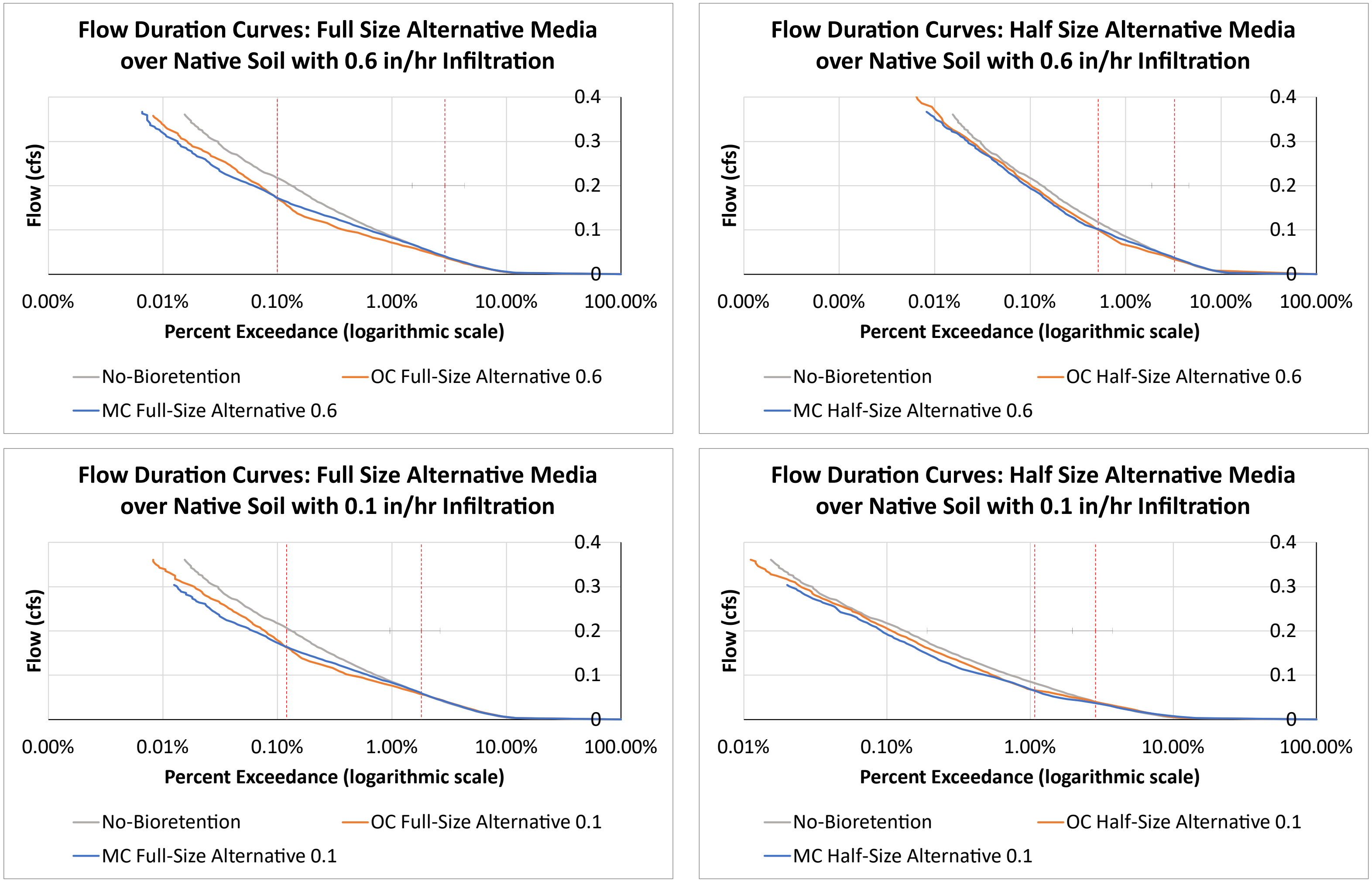


Figure 7. Flow Duration Curve Comparisons for Alternative Media between Outlet-Controlled Bioretention, Media-Controlled Bioretention, and Runoff without Bioretention

Table 5. Peak Flows for the Sixteen Scenarios for Key Return Intervals

Scenarios					Peak Flows (cfs)						
Model ID	**Media Type**	**Effluent Control**	**Native Soil Infiltration Rate (in/hr)**	**Sizing**	**8% of 2-Year**	**50% of 2-Year**	**2-Year**	**5-Year**	**10-Year**	**25-Year**	**50-Year**
1	Standard	Media	0.6	Full	0.024	0.152	0.304	0.419	0.509	0.638	0.746
2	Standard	Media	0.6	Half	0.029	0.183	0.367	0.506	0.611	0.760	0.884
3	Standard	Media	0.1	Full	0.024	0.152	0.304	0.420	0.509	0.638	0.746
4	Standard	Media	0.1	Half	0.029	0.183	0.367	0.506	0.611	0.760	0.884
5	Standard	Outlet	0.6	Full	0.029	0.179	0.357	0.494	0.595	0.736	0.852
6	Standard	Outlet	0.6	Half	0.031	0.192	0.384	0.519	0.621	0.767	0.888
7	Standard	Outlet	0.1	Full	0.029	0.180	0.361	0.495	0.596	0.739	0.856
8	Standard	Outlet	0.1	Half	0.031	0.193	0.387	0.522	0.624	0.770	0.891
9	Alternative	Media	0.6	Full	0.027	0.168	0.335	0.485	0.595	0.747	0.870
10	Alternative	Media	0.6	Half	0.030	0.188	0.376	0.508	0.608	0.750	0.868
11	Alternative	Media	0.1	Full	0.027	0.168	0.335	0.485	0.595	0.747	0.870
12	Alternative	Media	0.1	Half	0.030	0.188	0.376	0.508	0.608	0.750	0.868
13	Alternative	Outlet	0.6	Full	0.029	0.179	0.358	0.494	0.595	0.735	0.850
14	Alternative	Outlet	0.6	Half	0.031	0.192	0.384	0.518	0.621	0.767	0.888
15	Alternative	Outlet	0.1	Full	0.029	0.180	0.361	0.495	0.596	0.738	0.856
16	Alternative	Outlet	0.1	Half	0.031	0.193	0.387	0.522	0.624	0.770	0.891
No Bioretention					0.034	0.211	0.422	0.578	0.695	0.860	0.996

Figure 8 through Figure 11 depict flow duration curves grouped by each of the four deciding factors of the modeled scenarios (outlet control configuration, sizing, media type, and native soil infiltration).

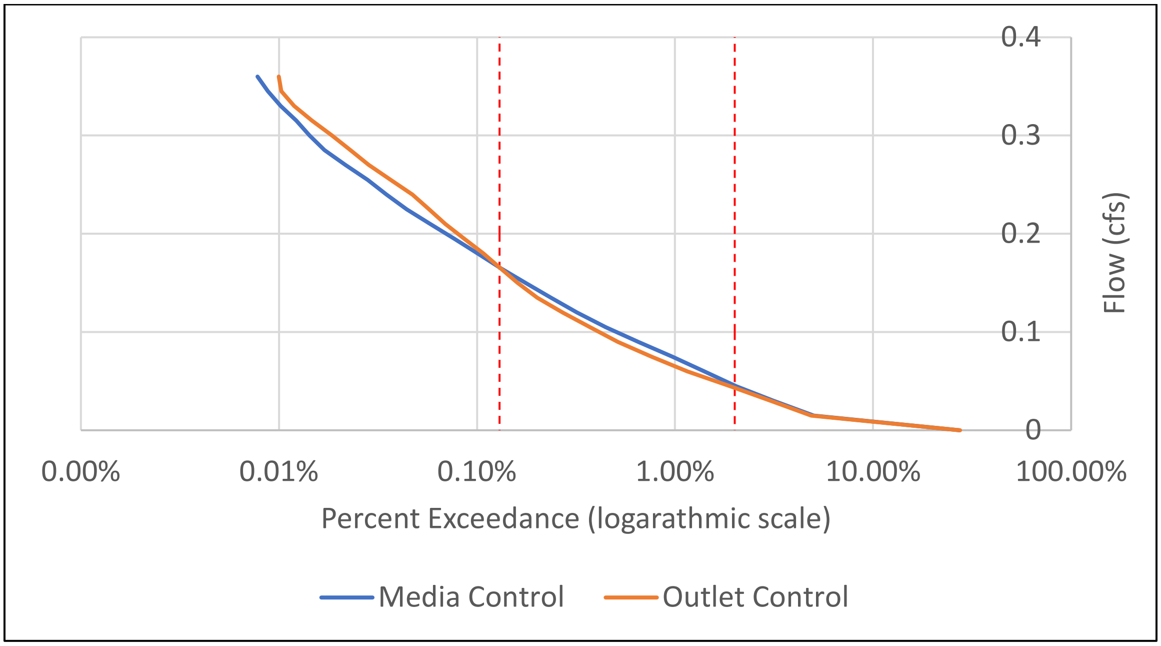


Figure 8. Flow Duration Curves Comparison between Media-Controlled and Outlet-Controlled Scenarios

Outlet Control vs. Media Control

Figure 8 depicts the difference in flow-duration between media and outlet-controlled scenarios from the modeling scenarios. As shown in Figure 8, presence of outlet control made little to no difference in the lower flow range (less than 0.04 cfs) because the without adequate head built up in the bioretention, the filtration rate is still controlled by the media in outlet-controlled scenarios. Within the medium flow range (0.05 to 0.16 cfs), the presence of outlet control reduced the discharge from the bioretention by restricting the underdrain outflow when comparing to the media-controlled counterpart. At higher flow range (greater than 0.17 cfs), the bioretention start to overflow. As a result of the lower underdrain capacity in the outlet-controlled scenarios, the magnitude of overflow is larger and the flow-duration curve of outlet-controlled scenarios exceeded the flow-duration of the media-controlled scenarios.

The differences noted in the paragraph above are minor. The small bioretention footprint of the modeled scenarios (0.8% of the tributary area) results in relatively small storage volume available in all of the model scenarios. As a result, the difference in flow control between media-controlled and outlet-controlled scenarios across the entire flow range is relatively small.

Outlet Control vs. Media Control at Larger Footprint Size

To explore the effect of footprint size on flow control performance, the research team developed media control and outlet controlled scenarios with larger footprint sizes, equivalent to 2.4% of the tributary area. Figure 9 shows the flow duration curve comparison between media-controlled and outlet-controlled scenarios for the 0.8% footprint size and 2.4% footprint size. This comparison was based on the standard BSM, 0.1 in/hr native soil infiltration rate and the same orifice size.

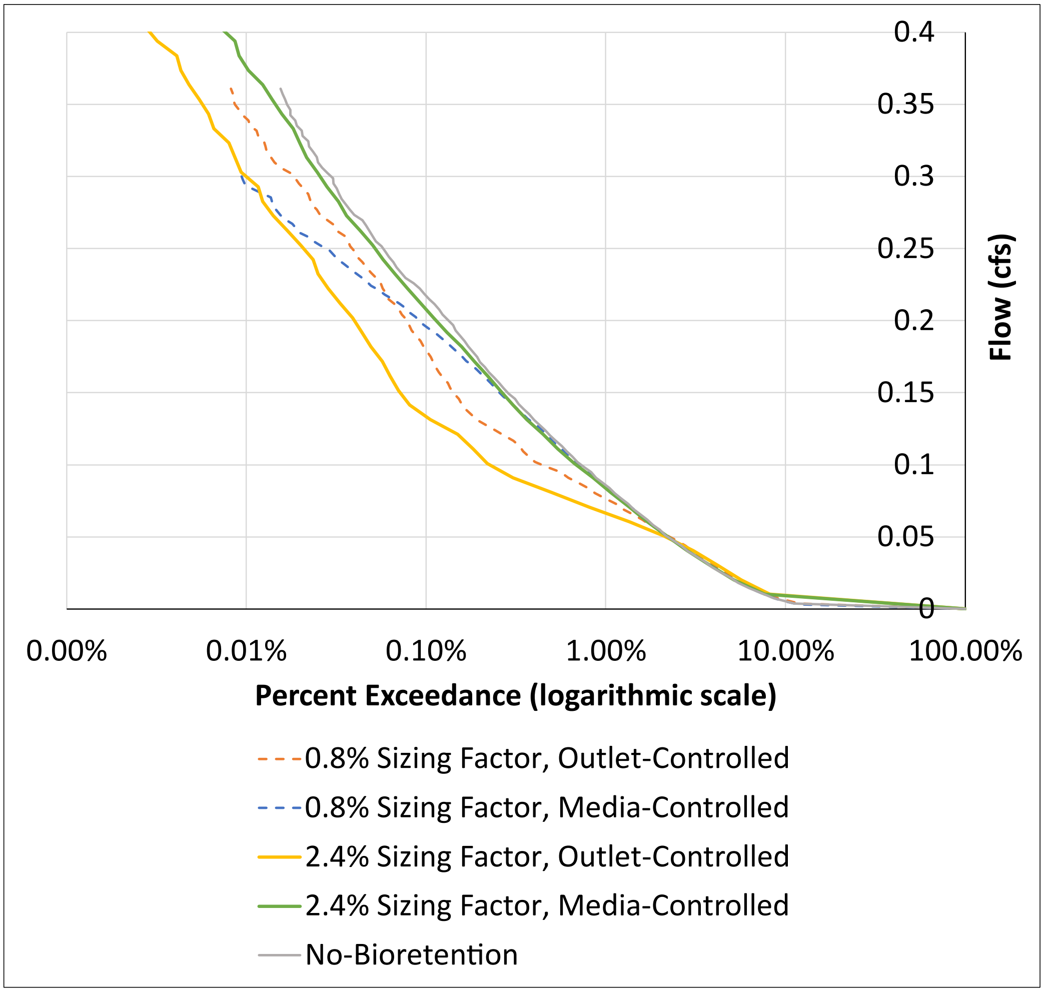


Figure 9. Flow Duration Curves Comparison between Media-Controlled and Outlet-Controlled in 0.8% and 2.4% Sizing Scenarios (Standard BSM, 0.1 in/hr Native Soil Infiltration Rate).

As shown in Figure 9, the outlet-controlled scenario is relatively similar to the media-controlled scenario when the bioretention footprint is relatively small (0.8% of tributary area). Both configurations have relatively limited effect. This is the same as the findings presented earlier in this section.

The performance between media control and outlet control diverges more substantially for bioretention with larger footprints (2.4% of tributary area). The media-controlled configuration shows reduced performance with increased size and is very similar to the “no-bioretention” scenario. This is because 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 there is more storage volume 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 same sizing scenario. This means that the effect of outlet controls would be more pronounced when applied to larger bioretention systems, such as those designed for MR#5 or #7.

Standard BSM vs. Alternative BSM

Figure 10 depicts the difference in flow-duration between standard BSM and alternative BSM without the influence of outlet control (only media-controlled scenarios were illustrated). This shows that the difference between 10 in/hr and 16 in/hr Ksat had limited effect on flow duration results in the range of sizing evaluated.

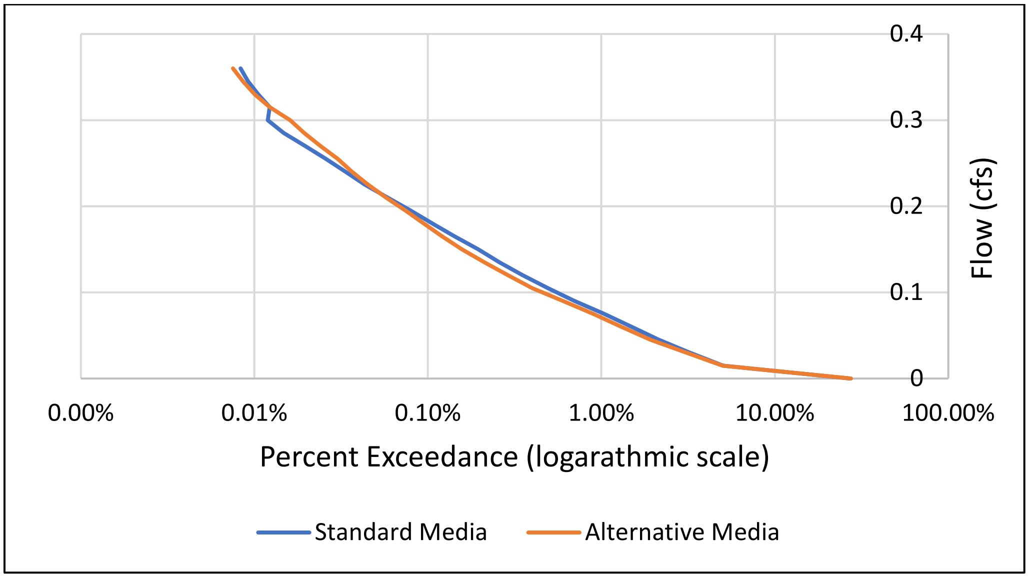


Figure 10. Flow Duration Curves Comparison by Media Types (Media-controlled Scenarios only).

Effect of Native Soil Infiltration Rate

Native soil infiltration had very minimal effect on flow control because the difference in infiltration volume throughout the simulation between scenarios with the two native soil rate is less than 3% of the total inflow to the mesocosms. The average flow duration curves in Figure 11 are nearly identical throughout most of the flow range.

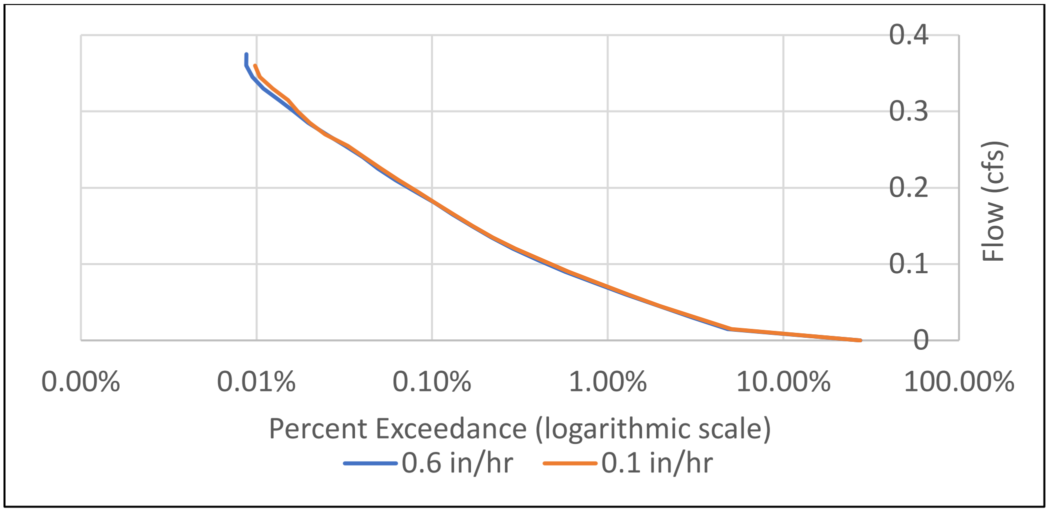


Figure 11. Flow Duration Curves Comparison by Native Soil Infiltration Rates.

6 Summary of Key Findings

In summary, the long-term capture efficiency, volume reduction, and flow control benefit were evaluated in this modeling study using a combination of observed data from the mesocosm experiment and modeling scenarios performed using the WWHM software. Key findings from this modeling study include:

- The SSD relationship of standard BSM in the media-controlled configuration was widely variable between mesocosms. The addition of outlet control to the same media substantially reduced the variability in SSD relationship. The variability noted in the media-controlled configurations would have limited effect on the amount of water treated for water quality benefits. However, the variability in media permeability would limit the ability of designers to reliably predict flow control benefits in media-controlled scenarios. Outlet control improves the predictability of the SSD relationship, enabling greater reliability in predicting the flow control benefits of a proposed design.
- The bioretention media included in this study showed lower effective porosity than the specified sizing defaults for bioretention media SMMWW in WWHM. The average of the observed media permeability (for both standard and alternative BSM) is similar to the uncorrected permeability of SMMWW at 12 inches per hour, but is variable between media mixes and suppliers, as noted above.
- The observed SSD relationship can be reproduced with moderate accuracy in WWHM by adjusting porosity and permeability parameters for a custom soil media type in WWHM.
- WWHM modeling resulted in a relatively small footprint size of 0.8% of the tributary drainage area to achieve the 91% target capture efficiency at a 6 in/hr design media filtration rate. At this relatively small sizing footprint, bioretention had very little effect on flow duration control or peak flow control, regardless of outlet control configuration. This sizing approach is not recommended in actual designs as it does not meet other minimum requirements and may be susceptible to clogging.
- When the bioretention units were increased to a more common range of footprint sizes (2.4% of tributary drainage area), the outlet-controlled configuration showed substantial

improvement in flow duration control performance compared to the media-controlled configuration. The outlet controlled configuration operates analogously to a detention basin with a predictable discharge flowrate and a larger storage volume that is inundated during storm events. In the media-controlled configuration, the treatment flowrate increased with the increased footprint, resulting in less flow restriction to cause water to be detained.
- Compared to media-controlled configuration, outlet control improves bioretention volume reduction slightly but decreases long-term capture efficiency slightly due to slower media filtration rate and more frequent overflow. All full-sized scenarios still captured at least 91% of average annual runoff volume.
- With outlet control, the drawdown time of water was still well less than the 24-hour limit specified in the SMMWW.

Note that the sizing scenarios presented in this modeling study are not intended to follow SMMWW minimum requirements. The sizing scenarios were intended to enable a side-by-side study of theoretical examples only.

7 References

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