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# MEMORANDUM

DATE: 19 June 2020

TO: Eric Christensen, P.E., Water Resources Director, City of Olympia

CC: Bill Taylor, Principal Investigator

FROM: Doug Beyerlein, P.E., Hydrology Lead and Project Manager

SUBJECT: Deliverable 5.2 Hydrologic Model Development and Results FINAL

For Task 5 of the Bioretention Hydrologic Performance Study II we have completed Deliverable 5.2 – Hydrologic Model Development and Results. Deliverable 5.2 summarizes the development of the models for each bioretention based on as-built construction, confirmed drainage area, and site field conditions (depth of soil mix, groundwater, native soil infiltration, etc.). The memo also provides analysis and recommendations for inclusion in Deliverable 5.4.

This deliverable has been internally reviewed by the BHP Study project team and comments received from team members have been incorporated into this final deliverable memo, as appropriate. The City of Olympia and the Washington Department of Ecology staff have also reviewed this deliverable and have provided valuable suggestions and comments. This final deliverable has been updated to include their input to the model development and results discussion.

## Modeling Procedures

The field monitoring provided information that was used as part of the WWHM2012 model input for each of the ten bioretention sites.

The hydrologic monitoring data collection (previously discussed) provided time series data for rainfall, inflow, overflow, groundwater, and ponding at 5-minute intervals for use in the individual site models. Each data time series was copied into (imported into) the individual site model's WWHM2012 data base for later use in either the model's calculations (rainfall data or inflow data) or comparison with the model's results (inflow, overflow, groundwater, and ponding data).

The geotechnical data collection provided information about the bioretention soil mix found at each of the ten bioretention sites and the native soil infiltration rate, as measured on-site. Some of these bioretention sites were constructed without using the standard bioretention soil mix specified by Ecology. Accordingly, we did not expect that all of the soil mixes would meet that specific standard. When it was the case that their general soil characteristics, as they related to water movement, did not match Ecology's standard bioretention soil mix the geotechnical data provided guidance in the selection of appropriate engineered soil mix for the bioretention site in question. The measured native soil infiltration rate was used to determine the appropriate infiltration value to include in each model. As will later be discussed, there were sites where groundwater mounding influenced the native soil infiltration rate during the winter months. These specific sites will be noted in the individual site results section of this memo.

The vegetation data collection was not used directly in the input to the individual site models. However, its potential impact on the hydrologic performance of each site was considered in terms of leaf litter impact on ponding and water infiltrating into the top bioretention soil layer. Also, vegetation influences evapotranspiration from the soil layer. WWHM2012 assumes a standard evapotranspiration rate from the soil that may be dependent based on the type and amount of vegetation.

The other field monitoring data collected for use in the individual bioretention site models were the dimensions of the bioretention facility (length, width, maximum depth of ponding) and the outlet control structure(s), if any. The size of each facility was field measured and compared with design drawings, if available. The elevation of the inlets, outlet riser or weir, and the top of the facility were surveyed. The underdrain elevation and outlet diameter was also measured for the sites that have an active underdrain.

All of the above field data were used in one way or another in either the WWHM2012 model input for each of the ten bioretention sites or evaluating the model output.

As described in Deliverable 2.2, the ten bioretention sites are:

| **Site Name** | **Jurisdiction** | **Project Name** |
|---|---|---|
| BUW | Bellingham | Columbia WQ Improvements |
| BCK | Bellingham | Nevada-Kentucky Bike Boulevard |
| FWI | Tacoma S.D. | Wainwright Intermediate School |
| M1C | Marysville | 1st and 3rd Street SW Retrofit |
| M3Q | Marysville | 1st and 3rd Street SW Retrofit |
| MPP | Monroe S.D. | Park Place Middle School |
| RSH | Renton | Green Connections |
| SSW | Monroe S.D. | Salem Woods Elementary School |
| TBM | Tumwater S.D. | Bush Middle School |
| TWH | Tacoma S.D. | Wilson High School |

The locations of the ten sites in the Puget Sound Basin are shown in the figure below.

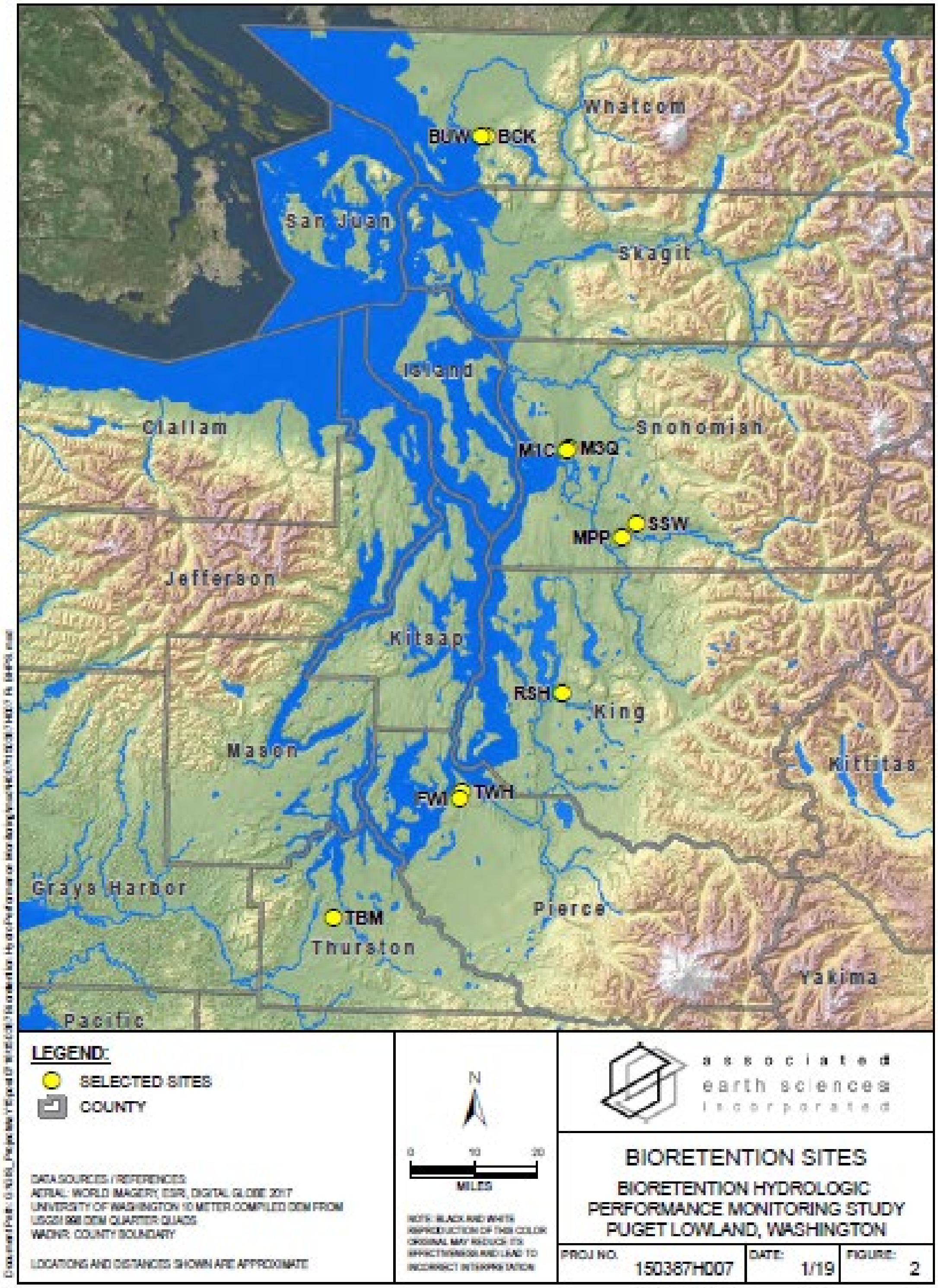
Whatcom
BUW
BCK
San Juan
Skagit
Island
Clallam
Snohomish
M1C
M3Q
MPP
SSW
Jefferson
Kitsap
RSH
King
Mason
Kittitas
FWI
TWH
Grays Harbor
TBM
Pierce
Thurston
Yakima
Pacific
LEGEND:
SELECTED SITES
COUNTY
DATA SOURCES / REFERENCES:
AERIAL: WORLD IMAGERY, ESRI, DIGITAL GLOBE 2017
UNIVERSITY OF WASHINGTON 10 METER COMPILED DEM FROM
USGS DEM QUARTER QUADS
WADNR: COUNTY BOUNDARY
LOCATIONS AND DISTANCES SHOWN ARE APPROXIMATE
N
0
10
20
MILES
NOTE: BLACK AND WHITE REPRODUCTION OF THIS COLOR ORIGINAL MAY REDUCE ITS EFFECTIVENESS AND LEAD TO INCORRECT INTERPRETATION
associated
earth sciences
incorporated
BIORETENTION SITES
BIORETENTION HYDROLOGIC
PERFORMANCE MONITORING STUDY
PUGET LOWLAND, WASHINGTON
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FIGURE:
2

After collection, analysis, and input of the field data into the WWHM2012 models it became apparent that the severe cold weather experienced in the winter of 2018-2019 adversely affected the ability to accurately model this time period. Freezing temperatures and snow were the major problems. Freezing temperatures made all of the monitored rainfall, inflow, overflow, groundwater, and ponding data suspect for this period (see Table 1 for summary of number of days of freezing temperatures by site).

Table 1. Number of days of freezing temperatures per month

| Site | Nov 2018 | Dec 2018 | Jan 2019 | Feb 2019 | Mar 2019 | Apr 2019 | May 2019 | Jun 2019 |
|---|---|---|---|---|---|---|---|---|
| BCK | 1 | 4 | 5 | 19 | 8 | 0 | 0 | 0 |
| BUW | 0 | 5 | 5 | 22 | 8 | 0 | 0 | 0 |
| FWI | 12 | 12 | 17 | 26 | 21 | 1 | 0 | 0 |
| M1C | 0 | 5 | 7 | 22 | 10 | 0 | 0 | 0 |
| M3Q | 4 | 7 | 7 | 21 | 9 | 0 | 0 | 0 |
| MPP | 5 | 13 | 15 | 26 | 25 | 6 | 0 | 0 |
| RSH | 0 | 4 | 4 | 11 | 9 | 0 | 0 | 0 |
| SSW | 8 | 11 | 14 | 26 | 18 | 0 | 0 | 0 |
| TBM | 5 | 7 | 10 | 21 | 12 | 0 | 0 | 0 |
| TWH | 12 | 8 | 15 | 21 | 24 | 1 | 0 | 0 |

In particular, precipitation that fell as snow instead of rain could not be modeled correctly in WWHM2012, inflow and overflow were constricted (if not totally blocked) by ice formation on the ponding surfaces of the bioretention sites, and ponding depths (as measured) were not accurate. To further complicate the monitoring work, we observed some local city and school district maintenance staff using the bioretention facilities for snow storage when plowing the adjacent impervious road and parking lot surfaces. This meant that piles of snow covered the monitoring equipment and affected the monitored readings for days after the surrounding land temperatures had warmed up and the non-piled snow had melted.

There was no way to adjust the monitored field data to compensate for these problems. As a result, a decision was made to limit the model result comparisons to the months of April, May, and June 2019.

## Data Analysis and Results

### Modeling Comparison of Observed versus Design Results

<u>Summary</u>

In general the hydrologic performance of the ten bioretention facilities was well represented by WWHM2012. The range in performance in terms of ponding depths and well point elevations met or exceeded the expected WWHM2012 model graphical results comparison with the monitored data for many of the sites, although there was a frustrating lack of consistency from one site to another. This lack of consistency was observed when two fairly identical sites produced very different monitored data (for example, M1C and M3Q well point data).

In general, the WWHM2012 models of the ten bioretention sites reproduced the monitored bioretention hydrologic performance data with accurate results when viewing the long-term graphical trends. Accurate results are defined as periods where the simulated results match closely with the recorded (monitored) data and other periods where the simulated results are sometimes high and sometimes low. Overall there is no obvious bias high or low.

As noted in our earlier study, it appears that there are two major model inputs that may be influencing the results. The vegetative litter cover can, at some sites, reduce the infiltration rate of the ponded water into the bioretention soil mix. At sites MPP, RSH, SSW, and TWM this vegetative litter cover was modeled using a limiting soil type (ASTM 1, ASTM 2, or ASTM 3). At the other six sites no vegetative litter cover was modeled.

The other major model input that may be influencing the results is the evapotranspiration (ET) from the bioretention soil mix. It is set in WWHM2012 to equal 0.5*PET (Potential ET). There is evidence from the well point data that the 0.5 multiplier factor should be higher. That will help to remove water faster from the bioretention soil mix layer.

<u>Site Characteristics</u>

The field collected data, described in the previous section, was used to provide input data in the construction of the individual WWHM2012 models of each bioretention site. These data are summarized in Table 2 below.

Table 2. Site General Information

| **Site** | Drainage Area (ac) | Top Area (ft2) | Bottom Area (ft2) | Top Area to Drainage Percentage | Overflow Height (ft) | Modeled Depth (ft) | Native Soil Infiltration (in/hr) | Underdrain |
|---|---|---|---|---|---|---|---|---|
| BCK | 0.27 | 71 | 60 | 0.6% | 0.05 | 3.8 | 0.5 | Yes |
| BUW | 0.93* | 38.5 | 38.5 | 0.1% | 0.05 | 2.8 | 0.05 | Yes |
| FWI | 0.33 | 250 | 159 | 1.7% | 1.0 | 2.45 | 0.05 | Yes |
| M1C | 0.03 | 132 | 132 | 10.1% | 0.6 | 1.3 | 17 | No |
| M3Q | 0.02 | 200 | 200 | 23.0% | 0.95 | 6.25 | 15 | No |
| MPP | 0.48 | 1320 | 684 | 6.3% | 3.6 | 2.15 | 3 | No |
| RSH | 0.17 | 68 | 64 | 0.9% | 0.3 | 3.6 | 0.5 | Yes |
| SSW | 0.40 | 1022 | 735 | 5.9% | 1.4 | 2.8 | 16 | No |
| TBM | 0.31 | 366 | 280 | 2.7% | 1.1 | 3.85 | 8 | No |
| TWH | 1.62 | 1269 | 1200 | 1.8% | 0.12 | 4.1 | 0.05 | Yes |

Notes:

* Only a portion of the stormwater runoff from the drainage area actually enters the bioretention site due to inflow inlet restrictions.

The drainage area is the area that contributes runoff to the bioretention site. For each bioretention facility this information was taken from design reports and drawings, if available. The drainage area inflow restriction to BUW is discussed in detail in the BUW site results section of this memo.

The bottom area is the bottom footprint of each of the bioretention cells. The bottom area is calculated from the field survey information. Most of the bioretention sites had a flat bottom area and sloping sides. The side slopes were calculated based on the difference in bottom and top lengths and widths and bioretention cell heights.

The top area is the surface area footprint of each of the bioretention cells at their individual overflow height above the bottom surface. The top area was not measured but was calculated based on the bottom area dimensions, side slopes, and the overflow height.

The top area to drainage percentage is the relative size of the bioretention top area (as defined above) to the contributing drainage area. The larger the percentage the larger the relative size of the bioretention area is to the surrounding area that drains to it. Many of the sites have percentages in the 1-5% rate. According to the 2019 Ecology manual, for design on projects subject to MR#5 (On-Site Stormwater Management) and choosing to use The List Approach for that requirement, the bioretention BMP shall have a horizontally projected surface area below the overflow which is at least 5% of the area draining to it. As shown in Table 2, some of these sites (BCK, BUW, FWI, RSH, TBM, and TWH) do not meet this 5% standard. Sites BCK, BUW, and RSH were field-fit retrofits and were not necessarily designed to meet Ecology's minimum stormwater requirements. As discussed below, FWI, TBM, and TWH either relied on infiltration (TBM) or an underdrain (FWI and TWH) to prevent site flooding, but none of these three sites met MR#5 standards.

The overflow height is the height (depth) from the bioretention soil surface to an overflow. The overflow may be a riser inlet, weir, or lowest spot on the side of the bioretention facility. When the ponding depth reaches this height then water can flow out of the bioretention cell via surface discharge (the other ways that water can flow out are by infiltrating into the native soil or discharging through an underground underdrain).

The modeled depth is the total soil depth modeled in the individual WWHM2012 models. This modeled depth typically includes two modeled soil layers. The top modeled soil layer (Layer 1) is the bioretention soil mix (BSM). The second modeled soil layer (Layer 2) is the soil layer below the BSM soil mix (Layer 1) and above the bottom of the monitored well point. Layer 2 was included in each model to provide a subsurface water depth/height that can be compared with the monitored well point data. The second layer soil is typically gravel or sand and is imported as part of the site design. For the sites with a top leaf litter layer a third modeled soil layer was added. For these sites a top layer (Layer 1) was added above the BSM layer to represent the effect of leaf litter in reducing the water movement into the BSM layer (which in these models is Layer 2). Details of the composition of the modeled depth in each bioretention site are presented in Table 3 below.

Native soil infiltration (inches per hour) for each site was initially based on the infiltration tests conducted as part of the geotechnical field measurements. After discussions with the geotech experts who conducted the infiltration tests, some of the native soil infiltration rates were reduced to compensate for the limiting geology of the underlying native soils.

An underdrain is a set of pipes in the bottom of the bioretention facility that collect water and discharge it through an outlet control structure. Typically underdrains are connected to a storm sewer system. Underdrains are used where it appears that the native soil infiltration rate is insufficient to remove all of the water from the bioretention cell and there is a potential for surface ponding to overtop the facility and flood surrounding properties. Underdrains can prevent this from happening. Five of the ten sites have an underdrain. For each of these sites water can also infiltrate into the native soil. As discussed below, in general underdrain flows were difficult to accurately monitor and usually were connected to the riser surface discharge outflow. They were modeled accordingly.

Table 3 provides information on the modeled soil layers in each bioretention model.

Table 3. Modeled Soil Layer Information

| Site | Layer 1 Soil | Layer 1 Depth (ft) | Layer 2 Soil | Layer 2 Depth (ft) | Layer 3 Soil | Layer 3 Depth (ft) | Native Soil Infiltration (in/hr) |
|---|---|---|---|---|---|---|---|
| BCK | SMMWW 12 | 1.5 | Gravel | 2.3 | none | 0 | 0.5 |
| BUW | ASTM100 | 1.5 | Gravel | 1.3 | none | 0 | 0.05 |
| FWI | ASTM60 | 1.5 | Gravel | 1.4 | none | 0 | 0.05 |
| M1C | SMMWW 12 | 1.3 | none | 0 | none | 0 | 17 |
| M3Q | SMMWW 12 | 1.0 | Sand | 5.25 | none | 0 | 15 |
| MPP | ASTM1 | 0.2 | SMMWW 12 | 1.7 | Sand | 0.25 | 3 |
| RSH | ASTM2 | 1.3 | Gravel | 2.3 | none | 0 | 0.5 |
| SSW | ASTM2 | 0.1 | SMMWW 12 | 1.4 | Sand | 1.3 | 16 |
| TBM | SMMWW 12 | 1.5 | Sand | 2.35 | none | 0 | 8 |
| TWH | ASTM3 | 0.1 | SMMWW 12 | 1.4 | Gravel | 2.6 | 0.05 |

As described above, the modeled depth is the total soil depth modeled in the individual WWHM2012 models. The modeled soil depth is composed two or more individual soil layers.

For BCK, M1C, M3Q, and TBM, Layer 1 represents the bioretention soil mix (BSM) type and depth. The Layer 1 depth is the depth or thickness of the BSM, as measured in the geotechnical field work. For some sites, the actual Layer 1 soil mix was initially unknown, but could be determined by comparing the monitored and modeled surface pond depths and well point depths. WWHM2012 provides the soil input parameter values for the Ecology-standard bioretention soil mix. WWHM2012 also provides soil input parameter values for a range of ASTM (American Society for Testing and Materials) soils. For the purposes of hydrologic modeling the ASTM number specification (for example, ASTM1) refers to the saturated conductivity value (1 inch per hour for ASTM1).

For BUW, FWI, and RSH the soil mix found on site does not meet Ecology's bioretention soil specifications. Water quality treatment is not provided by these soil mixes due to their excessive infiltration rates. It should be noted that for the purpose of the long-term simulation to evaluate compliance with MR#5 and MR#6 that these inappropriate soil mixes were replaced with the Ecology-standard bioretention soil mix. All three sites still failed MR#5, and BUW and RSH failed MR#6.

Layer 2 is not necessarily an engineered bioretention soil mix soil. Layer 2 is the soil layer below the BSM soil mix (Layer 1) and above the bottom of the monitored well point. Layer 2 was included in each model to provide a subsurface water depth/height that can be compared with the monitored well point data. When there was an underdrain, it was located in Layer 2.

For the four sites with infiltration constricted by leaf litter a third modeled soil layer was added. For these sites only a top layer (Layer 1) was added above the BSM layer to represent the effect of leaf litter in reducing the water movement into the BSM layer (which in these models is Layer 2).

<u>WWHM2012 Model Construction</u>

A separate WWHM2012 model was constructed for each of the ten bioretention sites. The bioretention site was located on the appropriate WWHM2012 project site map (see Figure 1 for an example).

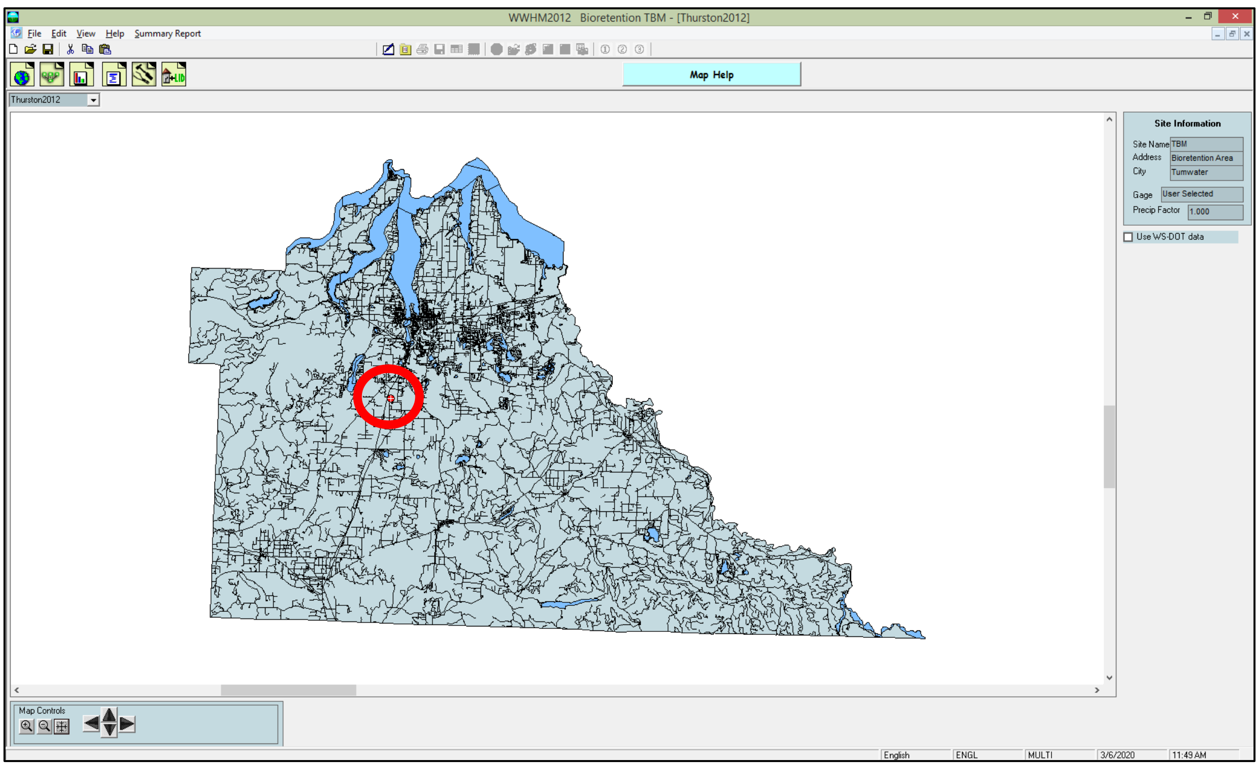



Figure 1. WWHM2012 Project Site (TBM) in Thurston County

The TBM bioretention site is located at the red dot in the center of the red circle in Thurston County.

For each model the corresponding monitored 5-minute data were imported into the specific model's data base file (HSPF WDM file), as shown in Figure 2.


Figure 2. WWHM2012 Time Series Data

Each monitored data set is given a unique data set number (DSN), as shown in Figure 2.

For TBM the monitored 5-minute precipitation time series is data set number 101; the monitored inflow is DSN 131; the pond depth is DSN 111; and the two well point depth time series are DSN 121 and 122. For this site there is no monitored outflow data.

The above monitored time series will be used to compare and evaluate the model results.

The model simulation period time step and start and end dates were changed from the default WWHM2012 simulation values. These changes were made by going to View, Options, Timestep (see Figure 3). The WWHM2012 default time step was changed from 15 minutes to 5 minutes because all of the monitored data were collected in 5-minute intervals. The WWHM2012 simulation start and end dates were changed to run from 12 October 2018 through the end of the data collection period (typically mid-July 2019). Because of above-mentioned freezing condition problems in the winter months the simulation started in October 2018, but the model results were only compared with the monitored data only for the period of April through the end of June 2019. This provided a consistent analysis period for all ten sites.

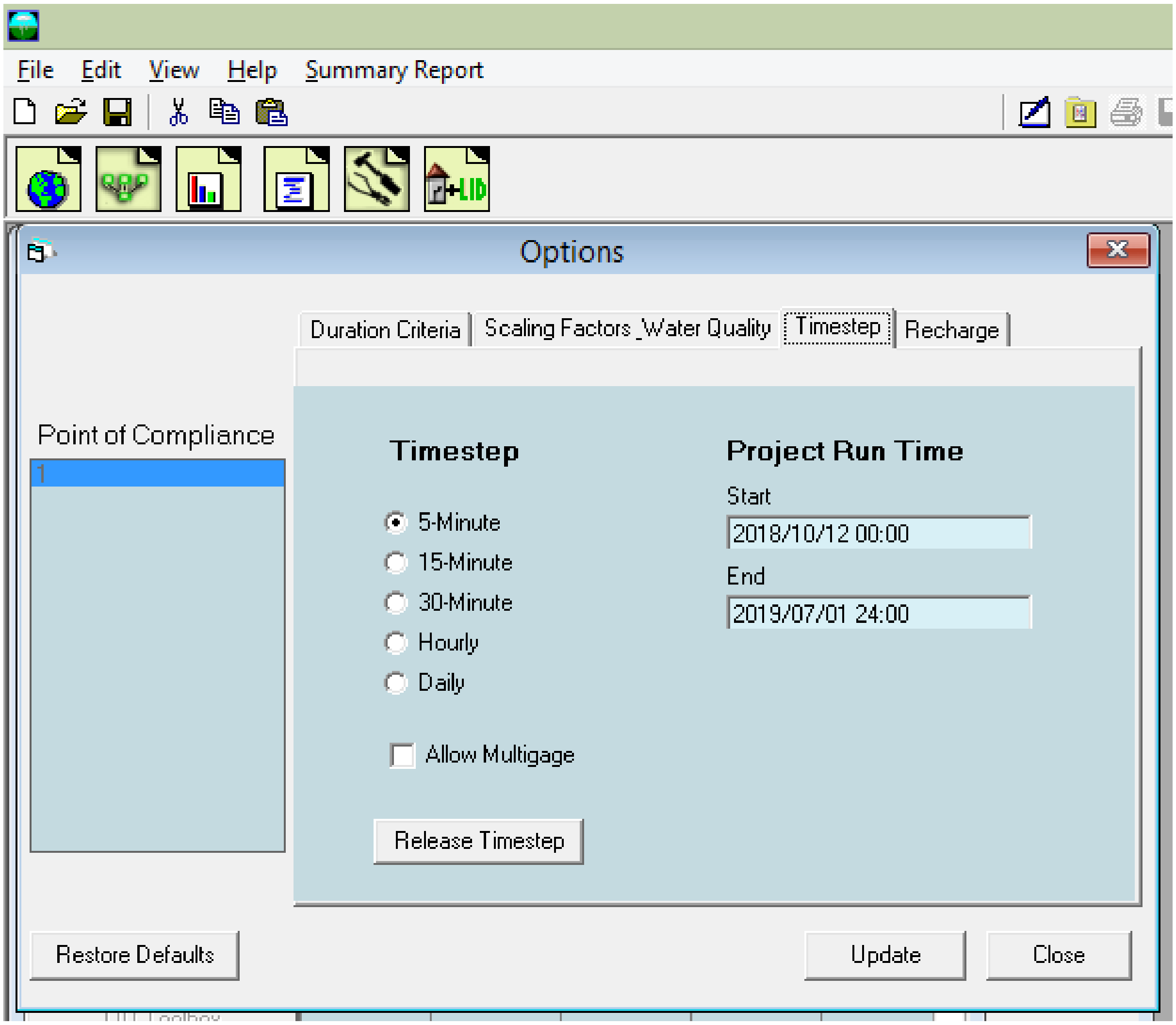



Figure 3. WWHM2012 Simulation Time Step and Start and End Dates (for TBM)

The contributing drainage area for each bioretention facility was determined from design reports and drawings, if available. Where there was a question about the drainage area it was field checked, as described above. The specific acreages were input to each WWHM2012 model using the WWHM2012 Land-use element (see Figure 4).

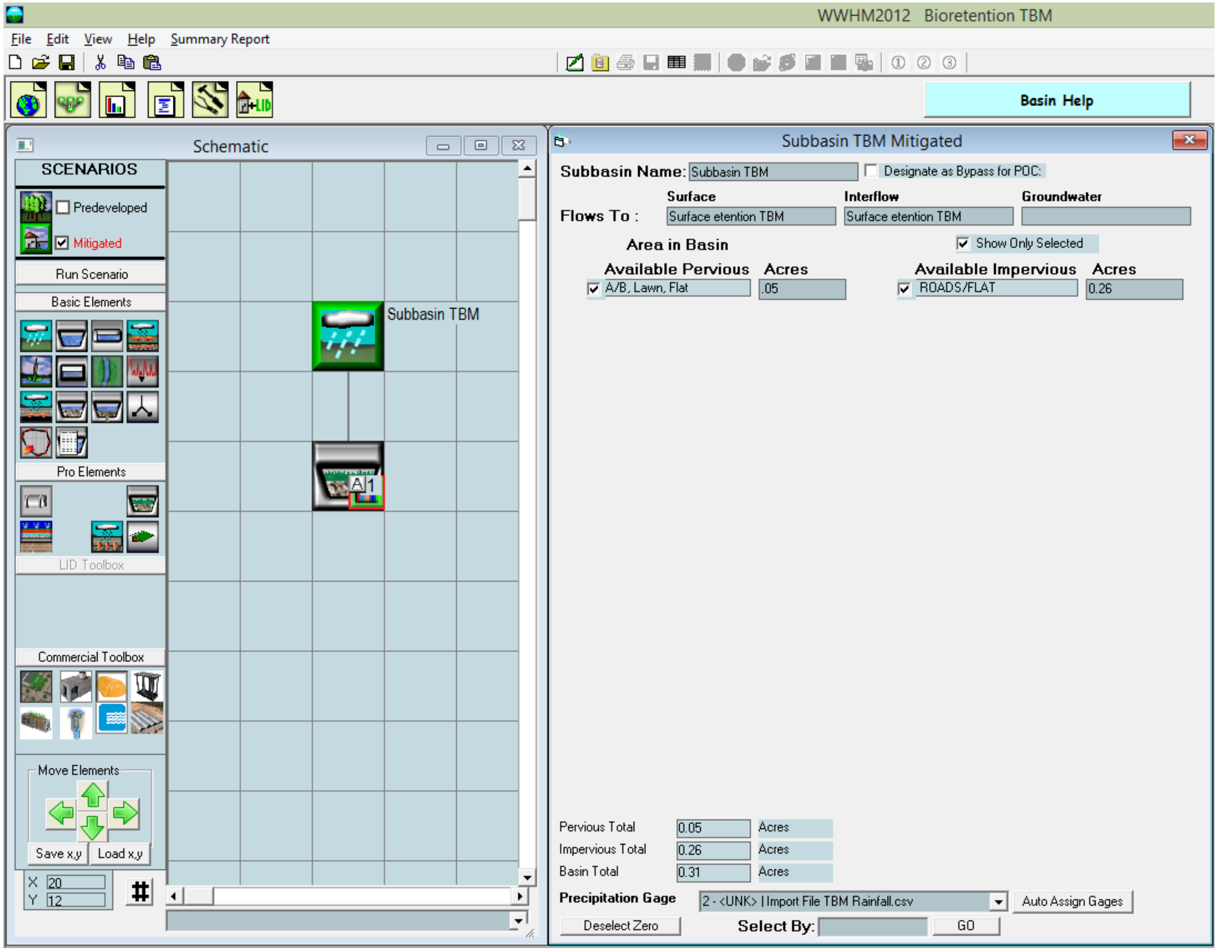



Figure 4. WWHM2012 Land-use Element

The specific bioretention facility is represented in WWHM2012 by the Bioretention element and contains all of the user input for defining the dimensions and characteristics of the bioretention site. The reader is referred to the *WWHM2012 User Manual* for more details about the Bioretention element input and model calculations. The TBM Bioretention element is shown in Figure 5.

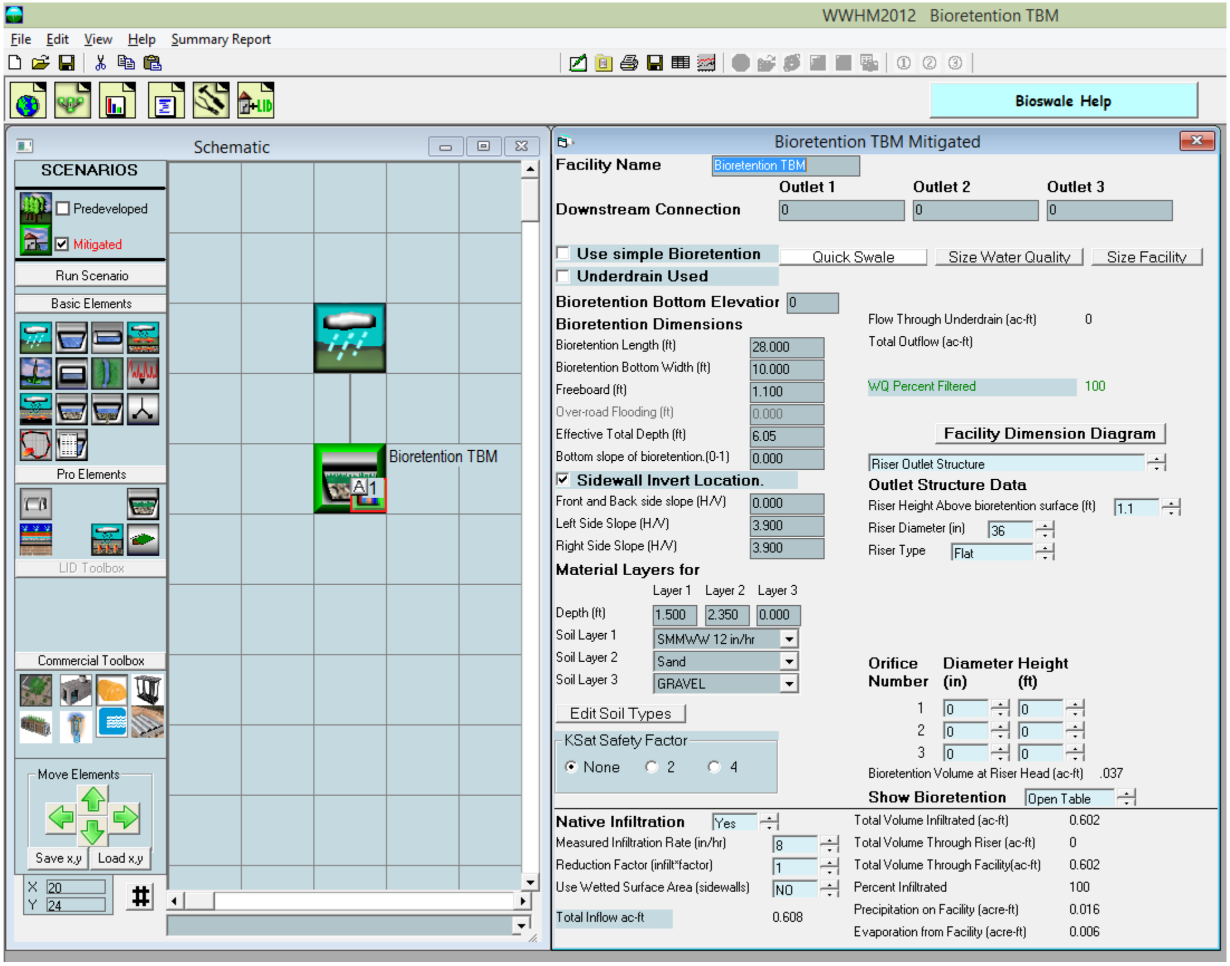



Figure 5. WWHM2012 Bioretention Element (for TBM)

WWHM2012 Model Results

Two sets of WWHM2012 model results were generated and evaluated. For each site WWHM2012 was first set up to compare the model results with the monitored data. For the comparison of the model simulation results with the monitored/recorded data the primary focus was trying to match the simulated and recorded ponding depths and the simulated and recorded well point data. The ponding depths showed how the water ponded on the surface of the bioretention facility. The well point data showed how the water filled up the bioretention soil column. The ponding and well point data are linked. If the well point data shows that the bioretention soil column is completely saturated then water cannot drain from the surface into the bioretention soil and this causes water to pond on the surface. Water can also pond on the surface even if the soil column is not completely saturated if the inflow of water into the bioretention facility is greater than the infiltration into the top layer (Layer 1) of the bioretention soil mix.

Each model was set up with a specific bioretention soil mix for each soil layer and an infiltration rate. These model inputs were then adjusted to produce the best match of the simulated ponding and well point results with the recorded data. Those final model inputs are shown in Table 3. The ponding depth plots and the well point plots are shown for each site in the Individual Bioretention Site Results discussion below.

The model inflow and outflow simulation results were also compared with the monitored inflow and outflow data, where available. A number of issues were found with the monitored inflow data. Specifically, there were numerous periods in December 2018 and January through March 2019 where because of freezing conditions and/or snow the monitored inflow data matched poorly with the monitored rainfall data. For this reason the results comparison was limited to the months of April, May, and June 2019. This decision eliminated the possibility of error in the monitored/recorded inflow data affecting the bioretention results. The simulated inflow volumes were plotted together with the recorded inflow data to identify inconsistencies. The comparison plot for each site is shown in in the Individual Bioretention Site Results discussion below.

For many of the bioretention sites there was no outflow. This was because all of the inflow to the bioretention site infiltrated into the native soil. Also as noted below, outflow, when it did occur, was difficult to measure due to the outlet conditions.

Model results are presented in both statistical and graphical formats. The statistical format compares the model simulated versus recorded/monitored inflow data, pond depths, soil layer water content depths, and underdrain discharge volumes for the ten sites in terms of maximum values, minimum, mean, and standard deviation of the 5-minute data for the data collection period. The statistical comparison periods were limited to the period of April through June 2019 (primarily due to freezing conditions and/or snow in the winter months).

The statistical results are shown in tables 4 through 8 below. Table 4 shows the maximum, minimum, mean, and standard deviation of the 5-minute data for monitored/recorded (R) and model simulated (S) bioretention site inflow results for the period of April, May, and June 2019.

It should be noted that some of the statistical values (particularly the mean values) are very small and are, for all practical purposes, equal to zero due to long periods when the facilities were dry.

Table 4. Bioretention Site Inflow (cfs)

| Site | MAX-R | MAX-S | MIN-R | MIN-S | MEAN-R | MEAN-S | STD DEV-R | STD DEV-S |
|---|---|---|---|---|---|---|---|---|
| BCK | 0.03 | 0.07 | 0.00 | 0.00 | 0.0002 | 0.0006 | 0.002 | 0.003 |
| BUW | 0.12 | 0.10 | 0.00 | 0.00 | 0.0006 | 0.0013 | 0.006 | 0.006 |
| FWI | 0.10 | 0.01 | 0.00 | 0.00 | 0.0005 | 0.0001 | 0.004 | 0.001 |
| M1C | 0.11 | 0.15 | 0.00 | 0.00 | 0.0014 | 0.0006 | 0.006 | 0.005 |
| M3Q | 0.04 | 0.10 | 0.00 | 0.00 | 0.0002 | 0.0004 | 0.001 | 0.003 |
| MPP | 0.07 | 0.07 | 0.00 | 0.00 | 0.0016 | 0.0011 | 0.007 | 0.005 |
| RSH | 0.23 | 0.05 | 0.00 | 0.00 | 0.0006 | 0.0003 | 0.007 | 0.002 |
| SSW | 0.35 | 0.11 | 0.00 | 0.00 | 0.0022 | 0.0016 | 0.014 | 0.009 |
| TBM | 0.06 | 0.08 | 0.00 | 0.00 | 0.0006 | 0.0004 | 0.003 | 0.003 |
| TWH | 0.44 | 0.17 | 0.00 | 0.00 | 0.0024 | 0.0013 | 0.018 | 0.010 |

Table 5. Bioretention Site Pond Depth (feet)

| Site | MAX-R | MAX-S | MIN-R | MIN-S | MEAN-R | MEAN-S | STD DEV-R | STD DEV-S |
|---|---|---|---|---|---|---|---|---|
| BCK | 0.08 | 0.06 | 0.00 | 0.00 | 0.001 | 0.002 | 0.003 | 0.009 |
| BUW | 0.03 | 0.04 | 0.00 | 0.00 | 0.012 | 0.0005 | 0.007 | 0.002 |
| FWI | 0.05 | 0.002 | 0.00 | 0.00 | 0.009 | 0.00003 | 0.008 | 0.0002 |
| M1C | 0.14 | 0.62 | 0.00 | 0.00 | 0.007 | 0.002 | 0.012 | 0.023 |
| M3Q | 0.12 | 0.21 | 0.00 | 0.00 | 0.007 | 0.001 | 0.008 | 0.007 |
| MPP | 0.39 | 0.22 | 0.00 | 0.00 | 0.027 | 0.005 | 0.034 | 0.020 |
| RSH | 0.42 | 0.33 | 0.00 | 0.00 | 0.007 | 0.007 | 0.030 | 0.039 |
| SSW | 0.17 | 0.16 | 0.00 | 0.00 | 0.007 | 0.002 | 0.019 | 0.012 |
| TBM | 0.21 | 0.05 | 0.00 | 0.00 | 0.005 | 0.0003 | 0.013 | 0.002 |
| TWH | 0.20 | 0.10 | 0.00 | 0.00 | 0.005 | 0.001 | 0.010 | 0.006 |

Table 6. Bioretention Site Well Point Depth (feet)

| Site | MAX-R | MAX-S | MIN-R | MIN-S | MEAN-R | MEAN-S | STD DEV-R | STD DEV-S |
|---|---|---|---|---|---|---|---|---|
| BCK | 1.76 | 3.79 | 0.00 | 0.00 | 0.22 | 0.43 | 0.27 | 0.91 |
| BUW | 0.42 | 2.17 | 0.00 | 0.00 | 0.001 | 0.145 | 0.01 | 0.27 |
| FWI | 0.46 | 0.54 | 0.00 | 0.00 | 0.004 | 0.06 | 0.03 | 0.08 |
| M1C | 1.15 | 1.29 | 0.00 | 0.00 | 0.06 | 0.09 | 0.18 | 0.16 |
| M3Q | 0.19 | 2.87 | 0.00 | 0.00 | 0.00 | 0.52 | 0.01 | 0.49 |
| MPP | 1.98 | 0.98 | 0.00 | 0.00 | 0.04 | 0.32 | 0.22 | 0.29 |
| RSH | 1.73 | 2.58 | 0.00 | 0.00 | 0.15 | 0.36 | 0.35 | 0.54 |
| SSW | 0.00 | 1.59 | 0.00 | 0.00 | 0.00 | 0.30 | 0.00 | 0.20 |
| TBM | 1.22 | 2.50 | 0.00 | 0.00 | 0.02 | 0.21 | 0.09 | 0.28 |
| TWH | 0.44 | 1.44 | 0.00 | 0.00 | 0.01 | 0.11 | 0.05 | 0.17 |

Table 7. Bioretention Underdrain Discharge (cfs)

| Site | MAX-R | MAX-S | MIN-R | MIN-S | MEAN-R | MEAN-S | STD DEV-R | STD DEV-S |
|---|---|---|---|---|---|---|---|---|
| BCK* | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| BUW* | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| FWI** | 0.002 | 0.01 | 0.00 | 0.00 | 0.000003 | 0.00011 | 0.00006 | 0.0006 |
| M1C | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| M3Q | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| MPP | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| RSH* | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| SSW | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| TBM | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| TWH* | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

Note:
* could not be measured
** same as outflow

Table 8. Bioretention Site Outflow (cfs)

| Site | MAX-R | MAX-S | MIN-R | MIN-S | MEAN-R | MEAN-S | STD DEV-R | STD DEV-S |
|---|---|---|---|---|---|---|---|---|
| BCK | 0.049 | 0.057 | 0.00 | 0.00 | 0.0001 | 0.0004 | 0.0017 | 0.0029 |
| BUW | 0.045 | 0.100 | 0.00 | 0.00 | 0.00002 | 0.0012 | 0.0010 | 0.0059 |
| FWI** | 0.002 | 0.01 | 0.00 | 0.00 | 0.000003 | 0.00011 | 0.00006 | 0.0006 |
| M1C | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| M3Q | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| MPP | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| RSH* | 0.14 | 0.05 | 0.00 | 0.00 | 0.0005 | 0.0002 | 0.004 | 0.002 |
| SSW | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| TBM | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| TWH | 0.09 | 0.11 | 0.00 | 0.00 | 0.0003 | 0.001 | 0.003 | 0.006 |

Note:
* surface plus underdrain
** underdrain flow (no surface discharge)

The statistical comparisons do not necessarily match well. This can be for a number of reasons, as discussed in the individual site results below. As such, the statistical comparison of results can be misleading. What is more important is the ability to match trends rather than statistics. By looking at graphical trends we can visually see if the model provides the same trends in terms of inflow, ponding, and well point data as the monitored info. The statistics cannot show trends and therefore are less useful in evaluating the modeling results than the graphical comparisons.

A summary of the model graphical comparisons is presented in Table 9. The table presents a comparison of the model simulated versus recorded/monitored inflow data, pond depths, soil layer water content depths, and underdrain discharge volumes for the ten sites.

Table 9. Comparison of Model (S) versus Monitored (R) Results

| Site | S vs R Inflow | S vs R Pond | S vs R Soil Layer | S vs R Outflow | S vs R Underdrain |
|---|---|---|---|---|---|
| BCK | High | Mixed | High | Mixed | Undeterminable |
| BUW | Mixed | High | High | High | Undeterminable |
| FWI | Accurate | Low | Mixed | High | High |
| M1C | Mixed | High | Mixed | N/A | N/A |
| M3Q | High | Mixed | High | N/A | N/A |
| MPP | Mixed | Low | Low | N/A | N/A |
| RSH | Mixed | Accurate | Mixed | Low | Undeterminable |
| SSW | High | Accurate | High | N/A | N/A |
| TBM | Mixed | Low | Mixed | N/A | N/A |
| TWH | Mixed | Low | High | Mixed | Undeterminable |

S vs R Inflow is the comparison of the simulated (S) inflow volume to the bioretention site compared to the monitored or recorded (R) inflow volume. The simulated inflow volume is calculated from the rainfall on the contributing drainage area to the bioretention site. The monitored inflow volume is calculated from the inflow measurements collected at specific input locations entering the bioretention site.

S vs R Pond is the comparison of the simulated (S) bioretention site surface ponding depths compared to the monitored or recorded (R) ponding depths.

S vs R Soil Layer is the comparison of the simulated (S) bioretention site subsurface soil layer water elevations compared to the monitored or recorded (R) well point data.

S vs R Outflow is the comparison of the simulated (S) outflow volume to the bioretention site compared to the monitored or recorded (R) outflow volume.

S vs R Underdrain is the comparison of the simulated (S) bioretention site underdrain outflow compared to the monitored or recorded (R) underdrain outflow.

The comparison categories of “Accurate”, “Mixed”, “High”, and “Low” are somewhat subjective, but are based on a total view of the comparison plot for each type of data. There is no statistical measure or test that can adequately represent the ability of the model results to reproduce the monitored data, due to missing data periods, weather problems, and timing issues. An evaluation of the results by a modeling professional takes these issues into account and allows for an unbiased opinion.

For purposes of this comparison, "Accurate" is defined as a good overall match of the simulated and recorded data. Even if there is not an exact match, both sets of data follow the same trends and magnitudes.

"Mixed" is similar to "Accurate" but shows more variability. With "Mixed" some periods match well while other periods match poorly, but the simulated results are neither consistently high or low.

"High" means that the simulated results are consistently high. There may be a valid reason for this different between the simulated and recorded results, but regardless the difference is noticeable. "Low" is similar, but in the opposite direction (the simulated results are consistently low).

"Undeterminable" means that the monitored data were unable to determine the contribution of the underdrain flow to the total outflow.

Further discussion of these graphical results and the comparison plots from which they were determined is presented below in the individual site modeling section of this report.

The second set of model results were generated based the Ecology-approved design conditions.

The second set of model results was based on the long-term county precipitation data. For each site the long-term (50 years or longer) precipitation record was used to generate long-term simulated ponding and outflow data. For sites that were found not to have the required bioretention soil mix as the top layer the long-term models were adjusted to provide this soil mix as the standard top layer, as per Ecology requirements. In addition, the Ksat Safety Factor was added in accordance with Ecology's requirements related to the contributing drainage area to each site.

These simulated data were not compared against the monitored data, but were used to evaluate the individual bioretention's site ability to meet Ecology minimum requirements #5 and #6.

Minimum Requirement #5 (MR#5) is the LID flow duration performance standard. MR#5 requires that flow durations between 8 percent of the 2-year flow (0.08Q2) and 50 percent of the 2-year flow (0.50Q2) do not increase above the predevelopment land use conditions. For each of these models the predevelopment land use was defined as forested. WWHM2012 provides the appropriate calculations to demonstrate compliance with MR#5.

Minimum Requirement #6 (MR#6) is the water quality performance standard. MR#6 requires that at least 91 percent of the total runoff volume be treated. Treatment in a bioretention facility consists of water movement through the bioretention soil mix. This treated water can then either infiltrated into the native soil or exit via an underdrain or both. Water that discharges through the surface outlet (riser or weir) is not treated. WWHM2012 provides the appropriate calculations to demonstrate compliance with MR#6.

Compliance with MR#5 and MR#6 is shown in Table 10.

Table 10. Minimum Requirement Compliance

| Site | Long-Term Precip Record | Multiplication Factor | MR#5 | MR#6 |
|---|---|---|---|---|
| BCK | Blaine | 0.857 | No | No |
| BUW | Blaine | 0.857 | No | No |
| FWI | 38-in Central* | 1.000 | No | Yes |
| M1C | Everett | 1.000 | Yes | Yes |
| M3Q | Everett | 1.000 | Yes | Yes |
| MPP | Everett | 1.200 | Yes | Yes |
| RSH | Sea Tac | 1.000 | No | No |
| SSW | Everett | 1.200 | Yes** | Yes |
| TBM | Olympia Airport | 1.000 | No | Yes |
| TWH | 38-in Central* | 1.000 | No | No |

* WSDOT precipitation time series used by Pierce County
** after overflow to an infiltration trench

M1C, M3Q, MPP, and SSW pass the MR#5 LID flow duration criterion. The other sites (BCK, BUW, FWI, RSH, RSH, and TWH) do not pass – either because the site is undersized and excessive uncontrolled surface discharge occurs (see Table 2) or because the water moves through the soil column then discharges through the underdrain with no outlet control.

The same sites that fail MR#5 also fail the MR#6 water quality standard, except FWI and TBM, both which pass MR#6. The sites that fail the MR#6 standard fail because they have too much surface discharge (often due to the overflow riser height set too low on the surface) and do not filter at least 91% of the flow through the bioretention soil mix.

Bioretention facilities are not required to meet Minimum Requirement #7 (MR#7) and many do not. MR#7 is the stream protection flow control standard. MR#7 requires that flow durations between 50 percent of the 2-year flow (0.50Q2) and the 50-year flow (Q50) do not increase above the predevelopment land use conditions. While WWHM2012 provides the appropriate calculations to demonstrate compliance with MR#7, we did not evaluate the bioretention facilities for this compliance. This is because they did not have to be designed to meet this standard and to test them for compliance would be potentially misleading as to the effectiveness of their hydrologic performance.

Individual Bioretention Site Results

Individual bioretention model results are discussed below. Each bioretention site has a unique set of characteristics that influenced the model set up and the comparison of model (simulation) results with the monitored (recorded) field data.

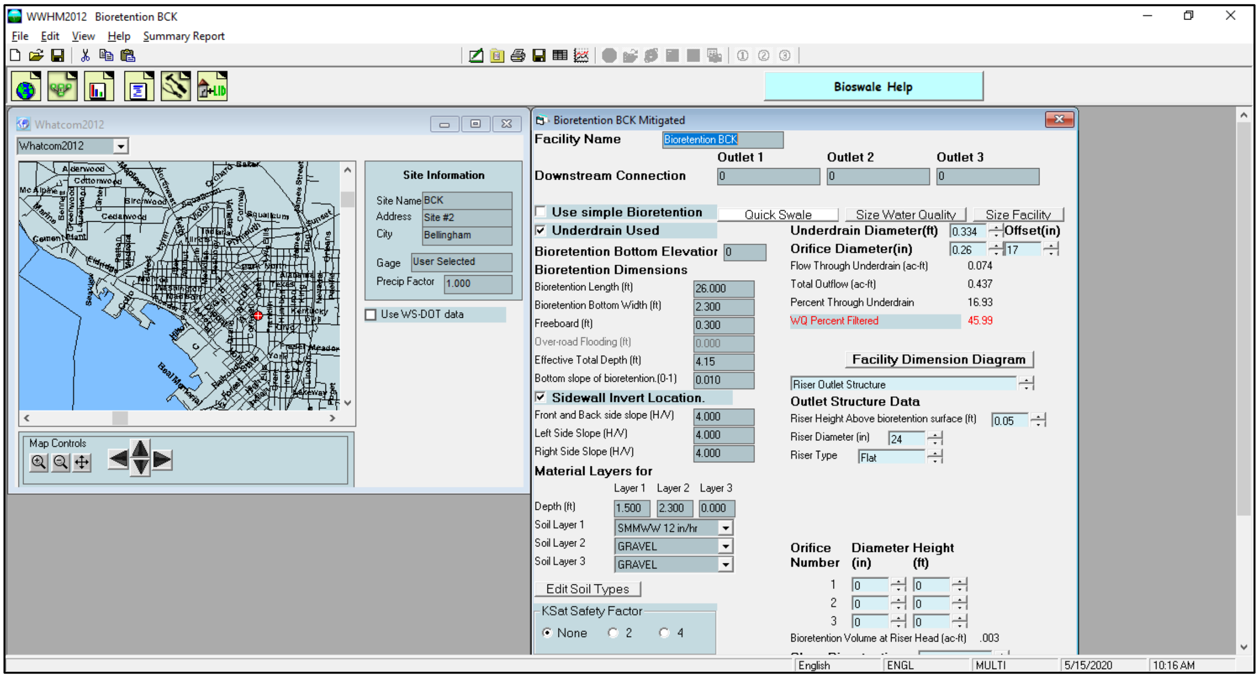
At each site the simulated and recorded daily inflow volumes are plotted and compared. The purpose of this comparison is to identify any potential errors in either the simulated or recorded inflow volumes. The simulated inflow volumes are calculated by WWHM2012 using the monitored rainfall data and the contributing drainage area to the bioretention site. It is possible that either one of those model inputs contains errors. The recorded/monitored inflow volumes are field measured values. These recorded values also may contain errors due to weather conditions (snow and/or freezing temperatures) and/or not recording all of the inflow sources to the bioretention site. By comparing the two sets of daily inflow volumes it is possible to identify problems that can and will affect the ability of WWHM2012 to correctly reproduce the surface ponding and soil layer elevations measured in the field.

At each site the simulated and recorded bioretention surface ponding depths are plotted and compared. The purpose of this comparison is to see how well WWHM2012 can reproduce the recorded/monitored ponding data. Surface ponding is a critical measure of the bioretention site's hydrologic performance. Excessive surface ponding can result in surface discharge via riser or weir that does not provide any water quality treatment or LID flow control.

At each site the simulated and recorded bioretention well point data are also plotted and compared. The well point data shows how the water fills up the bioretention soil column. The ponding and well point data are linked. If the well point data shows that the bioretention soil column is completely saturated then water cannot drain from the surface into the bioretention soil layer and this causes water to pond on the surface. Water can also pond on the surface even if the soil column is not completely saturated if the inflow of water into the bioretention facility is greater than the infiltration into the top layer (Layer 1) of the bioretention soil mix.

It should be noted that the monitored well point data is not a perfect match for the WWHM2012 soil layer moisture calculations. The monitored well point data is a measure of the "free" water in the soil column. This is water that freely drains to the well and fluctuates up and down depending on inflow to the soil from above and infiltration to the native soil below. The WWHM2012 simulated soil layer data is calculated based on the soil's hydraulic conductivity and wilting point (and other factors). Included in these simulated soil moisture calculates is both the "free" water measured in the monitored wells (well point data) and water that cannot freely flow, but remains trapped in the void spaces between soil particles. In WWHM2012 this "trapped" water is removed by evapotranspiration. The "trapped" water is not included in the well point monitored data. This is often the reason for the discrepancy between the simulated and recorded soil layer plotted results.

BCK: Bellingham, Whatcom County




The BCK bioretention site is located in Bellingham, Whatcom County, Washington. The drainage area to BCK consists of 0.27 acres of roads on a flat slope (0-5%).

The BCK surface area footprint is 71 square feet at top of overflow. This equals 0.6% of the tributary drainage area to BCK.

BCK has a surface discharge via riser outlet set at only 0.05 feet above the surface bottom. Most of the inflow to BCK is infiltrated into the native soil beneath the bioretention soil layers. An elevated underdrain is included in the bioretention site, but according to on-site visual inspection and the modeling results, most of the stormwater runoff bypasses the underdrain and either drains laterally, flows into the adjacent underground utility conduit corridor, or infiltrates into the native soil under the bioretention site.

The native soil infiltration rate could not be accurately measured but based on the underlaying geology appears to be low. As such, a native soil infiltration rate of 0.5 inches per hour together with a bioretention top soil layer of Ecology soil mix 12 in/hr and a second soil layer of gravel-like soil best reproduced the monitored soil moisture and surface ponding conditions.

Figure BCK-1 shows the simulated (red) and recorded (blue) daily inflow volumes and, along the top of the figure, the BCK site monitored daily rainfall data. The simulated inflow volumes are considerably larger than recorded daily inflow volumes. It was observed in the field that there may be more inflow to the bioretention site than originally expected and recorded. The comparison of simulated and recorded daily inflow volumes appears to support this observation.

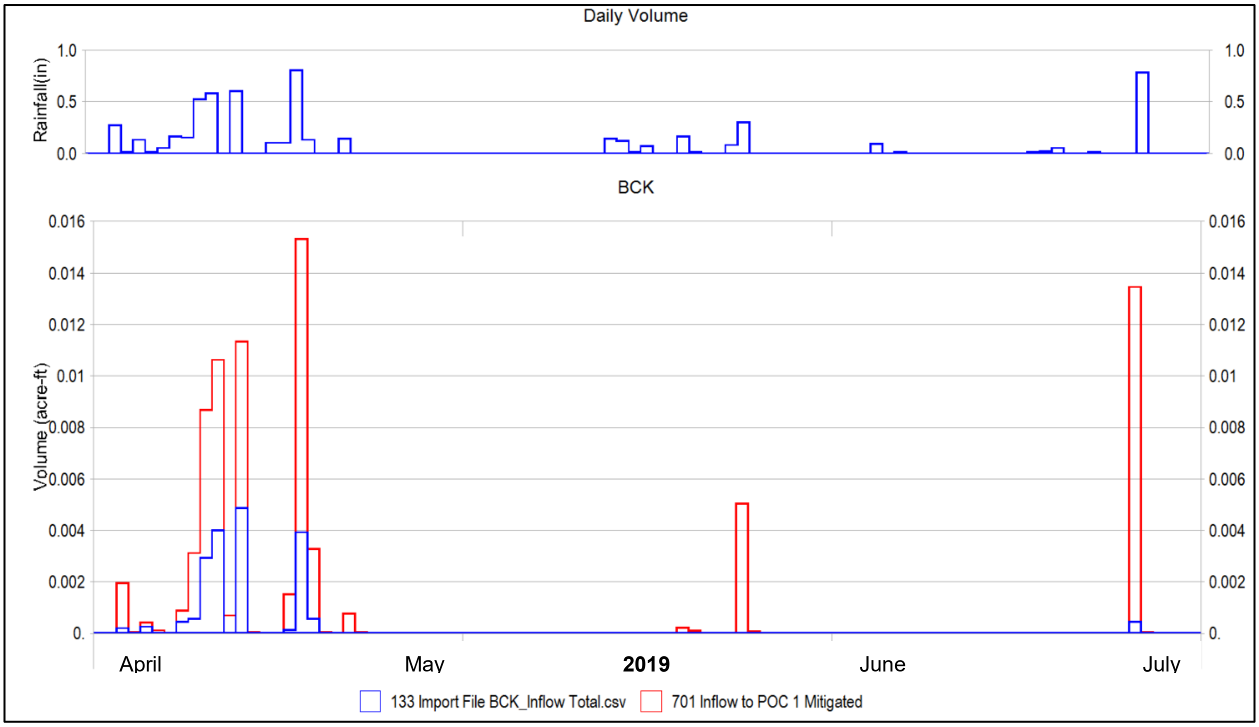



Figure BCK-1. BCK Daily Inflow Volumes

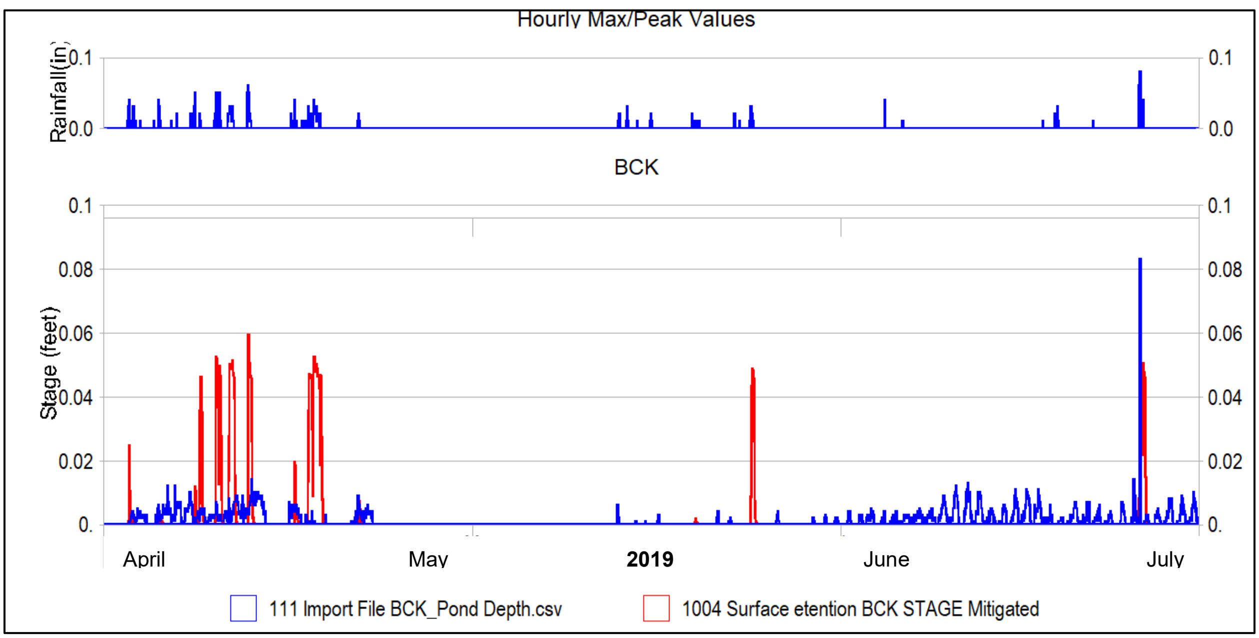



Figure BCK-2. BCK Hourly Surface Ponding Depths

Figure BCK-2 shows the simulated (red) and recorded (blue) hourly maximum 15-minute surface ponding (stage) values and, along the top of the figure, the BCK site monitored hourly maximum 15-minute rainfall data. The simulated and recorded ponding values are mixed. All of the pond depths are very small (less than 0.10 feet). The minor recorded depth fluctuations during the dry periods may either be due to on-site irrigation or monitoring equipment error due to daily air temperature fluctuations. This phenomena was observed at multiple sites.

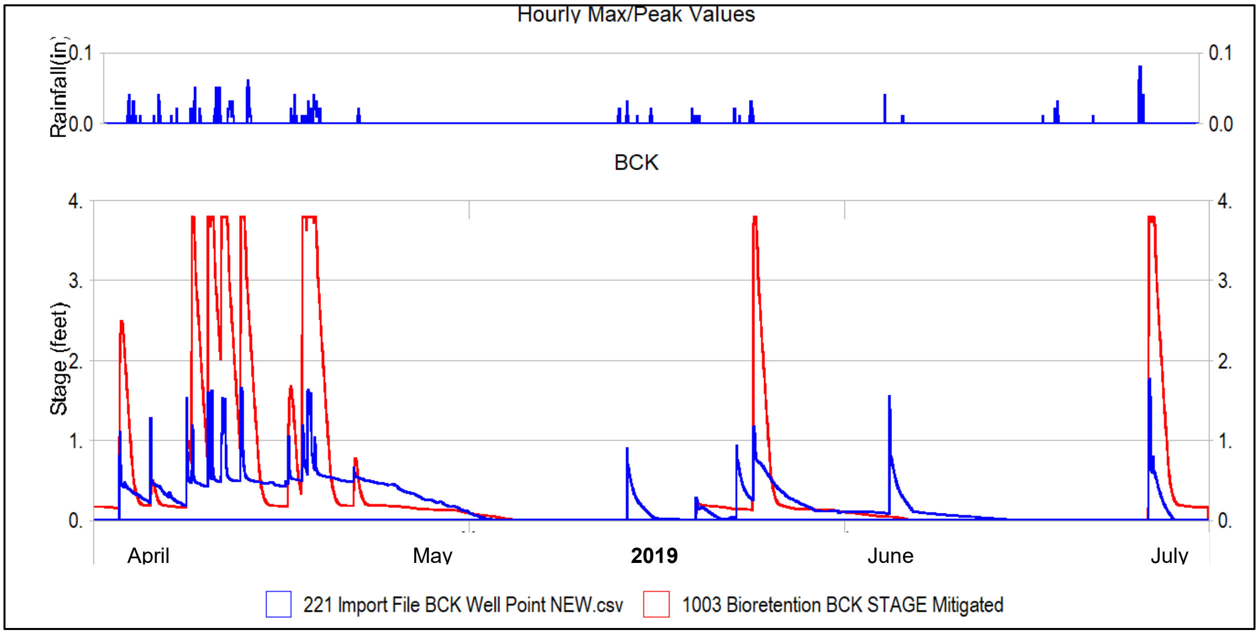



Figure BCK-3. BCK Hourly Soil Layer Well Point Elevations

Figure BCK-3 shows the simulated (red) and recorded (blue) hourly maximum 15-minute soil layer well point elevations (stage) values and, along the top of the figure, the BCK site monitored hourly maximum 15-minute rainfall data. The simulated well point elevations show more fluctuation than the recorded well point data. The recorded well point elevations show less fluctuation. This may be due to stormwater runoff quickly draining laterally into the adjacent underground utility conduit corridor.

BCK has an underdrain, but there was no access to install monitoring equipment to measure the flow exiting the underdrain. As a result of this situation, no underdrain outflow measurements are available. In addition, during the infiltration test conducted by AESI no discharge from the underdrain was observed. The modeling shows that with the designed underdrain outlet configuration that less than 20% of the total discharge exits through the underdrain.

The BCK simulated combined outflow was compared with the measured/recorded outflow to better understand the relative magnitude of the surface discharge and the underdrain outflow.

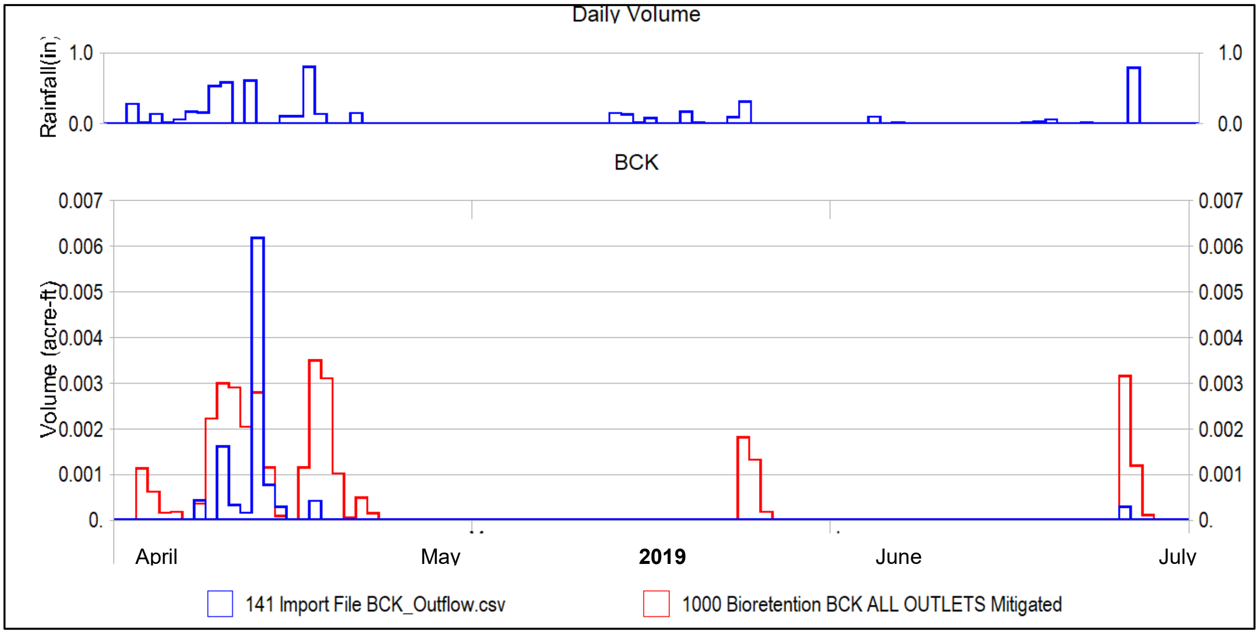


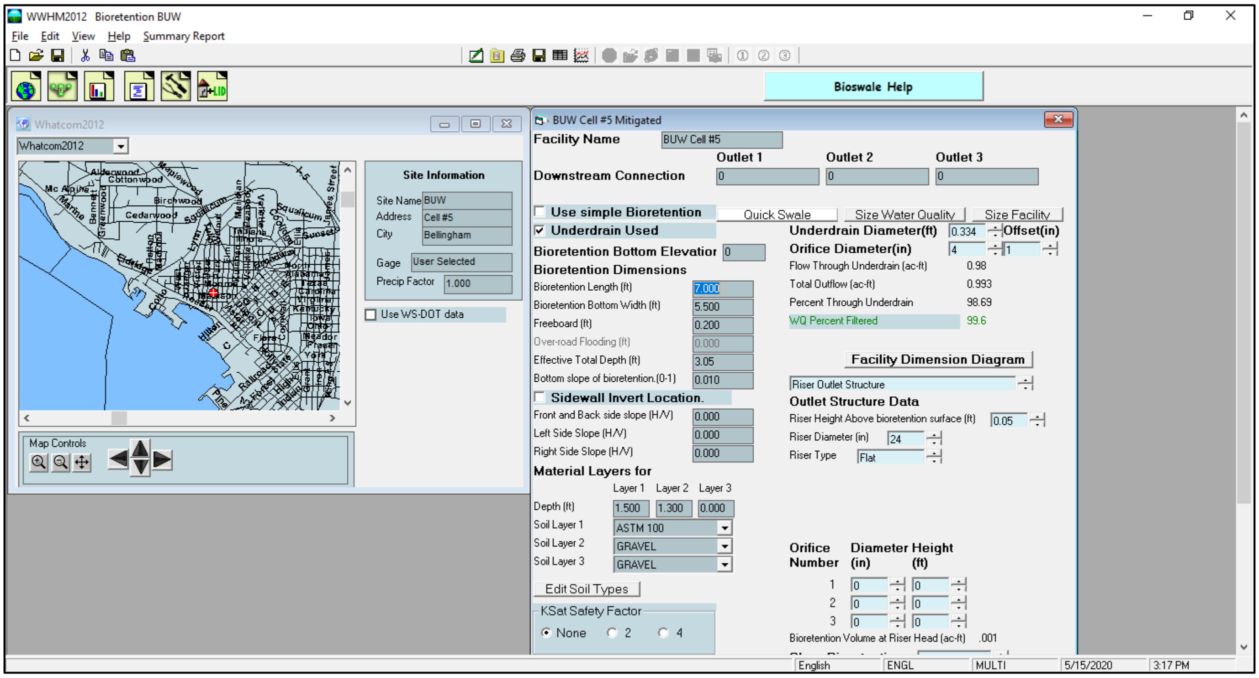

Figure BCK-4. BCK Daily Outflow Volumes

Figure BCK-4 shows the simulated (red) surface discharge and recorded (blue) hourly maximum 15-minute outflow values and, along the top of the figure, the BCK site monitored hourly maximum 15-minute rainfall data.

For most events the combined simulated surface discharge and underdrain outflow volume (red) is greater than the recorded (blue) outflow volume. It is assumed that this is because of the inability to monitor the underdrain flows and subsurface water escaping the site laterally.

The long-term modeling results based on the Whatcom County Blaine rain gage record show that BCK fails both MR #5 and MR #6. BCK's bottom area is only 0.5% of the drainage area to BCK. This site is too small to meet these minimum requirements and is overwhelmed by large runoff events.

BUW: Bellingham, Whatcom County




The BUW bioretention site is located in Bellingham, Whatcom County, Washington. The drainage area to BUW is a neighborhood consisting of 0.49 acres of C soil, lawn vegetation, on a flat slope (0-5%), 0.26 acres of roof, and 0.18 acres of road on a flat slope.

The BUW surface bottom footprint was originally designed to be 210 square feet. Infiltration test monitoring conducted by AESI discovered that due to the bioretention surface slope from north to south that the actual surface area footprint at top of overflow is only approximately 38.5 square feet. This equals 0.1% of the 0.93-acre tributary drainage area to BUW.

Infiltration test monitoring also found that the curb inlets to the BUW bioretention site limit the maximum inflow to 45 gallons per minute. This is equivalent to 0.1 cfs. To represent this inflow limitation situation in the model a flow splitter was added to the model with the flow threshold to the bioretention element set to 0.1 cfs. Flows greater than 0.1 cfs did not enter the bioretention site but continued to flow in the street to a street storm drain inlet downslope.

BUW has a surface discharge via riser set at 0.05 feet (0.5 inch) above the surface bottom. Even with this low riser height, during the spring 2019 monitoring period the majority of the inflow to BUW is infiltrated into the bioretention soil mix and then outflows through an underdrain.

A native soil infiltration rate of 0.05 inches per hour together with a bioretention top soil layer of very high infiltrating soil (estimated at over 100 in/hr) and a second soil layer of gravel best reproduced the monitored soil moisture and surface ponding conditions. The very low native soil permeability creates a perched groundwater lens below the gravel layer.

Figure BUW-1 shows the simulated (red) and recorded (blue) daily inflow volumes and, along the top of the figure, the BUW site monitored daily rainfall data. The simulated inflow volumes are considerably larger than recorded daily inflow volumes, even with the simulated inflow limited to a maximum of 45 gpm (0.1 cfs). It was observed in the field that it was very difficult to measure the inflow at the two inlets to BUW. The comparison of simulated and recorded daily inflow volumes appears to support this observation.

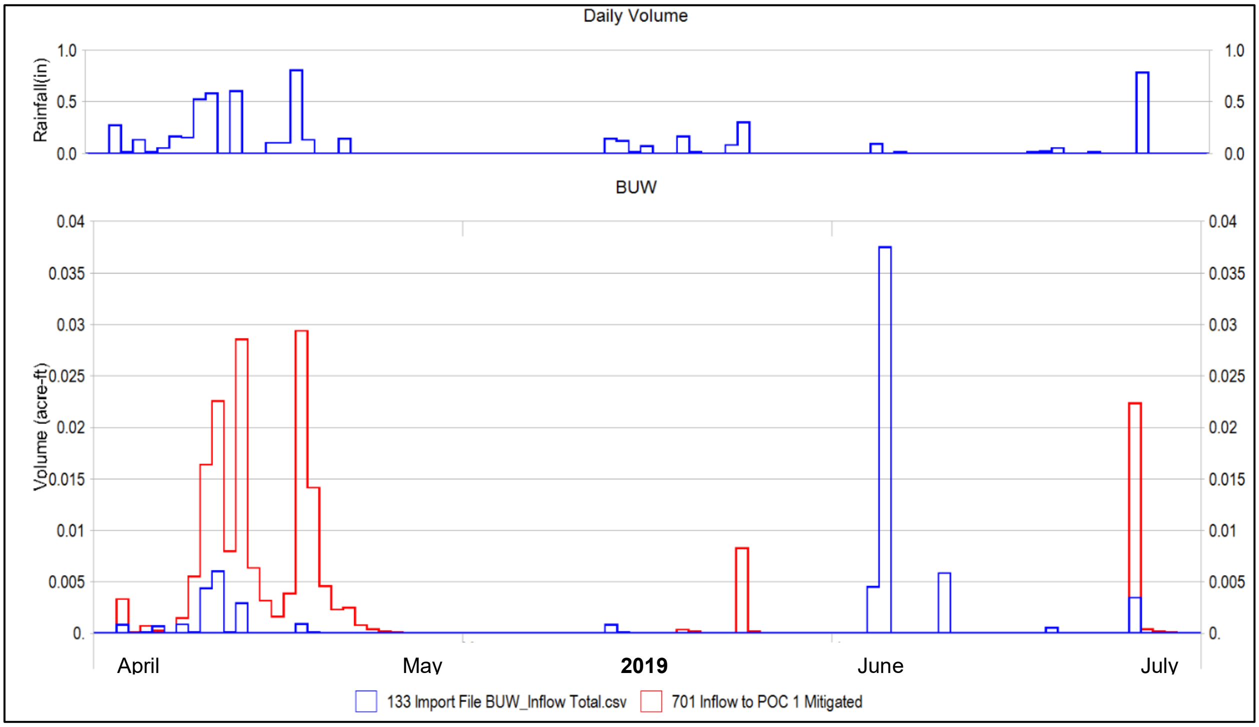



Figure BUW-1. BUW Daily Inflow Volumes

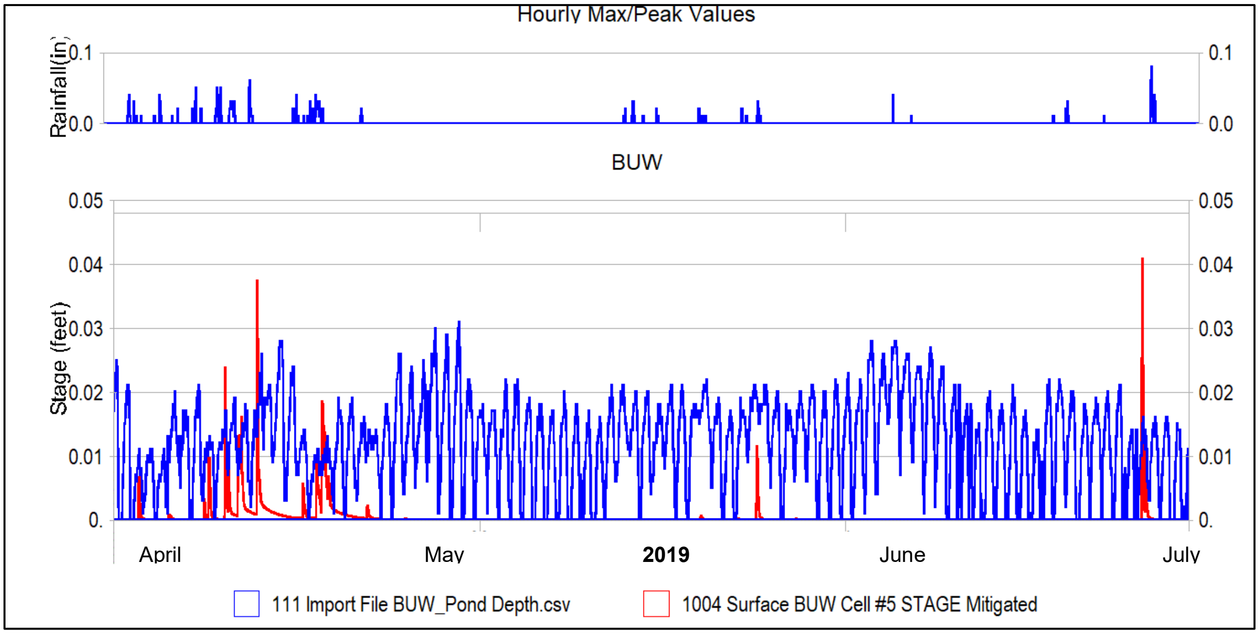



Figure BUW-2. BUW Hourly Surface Ponding Depths

Figure BUW-2 shows the simulated (red) and recorded (blue) hourly maximum 15-minute surface ponding (stage) values and, along the top of the figure, the BUW site monitored hourly maximum 15-minute rainfall data. The simulated and recorded ponding values are mixed. All of the pond depths are very small (less than 0.05 feet). The minor recorded depth fluctuations during the dry periods may be due to monitoring equipment error due to daily air temperature fluctuations. This phenomenon was observed at multiple sites.

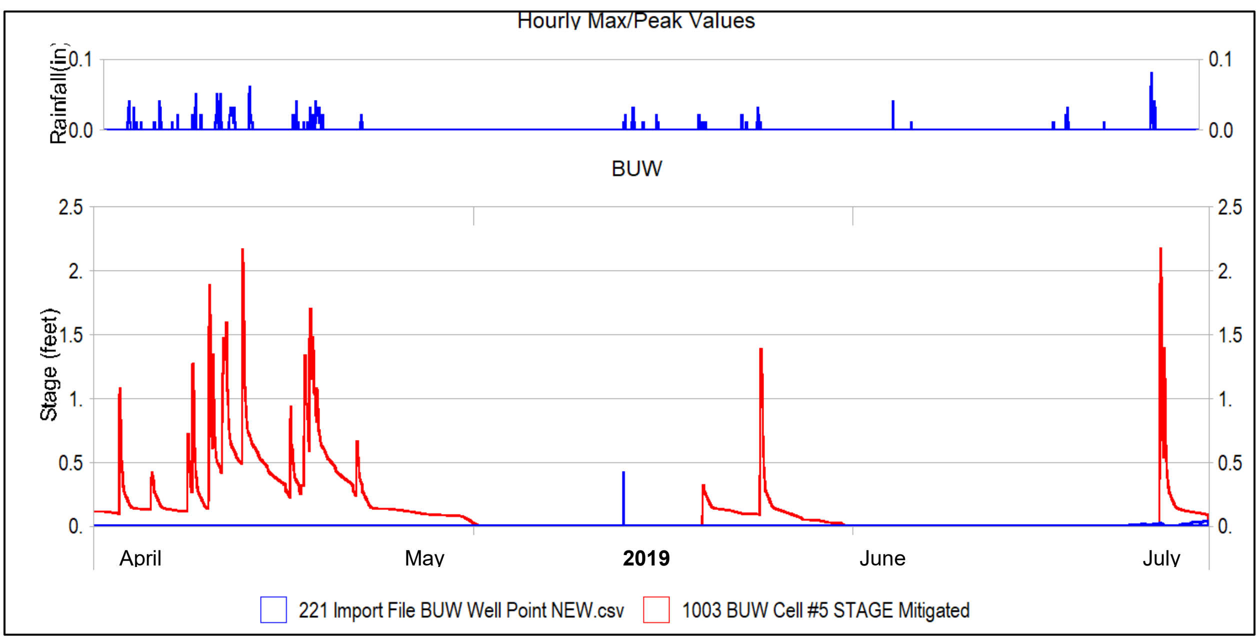



Figure BUW-3. BUW Hourly Soil Layer Well Point Elevations

Figure BUW-3 shows the simulated (red) and recorded (blue) hourly maximum 15-minute soil layer well point elevations (stage) values and, along the top of the figure, the BUW site monitored hourly maximum 15-minute rainfall data. The simulated well point elevations show more fluctuation than the recorded well point data. The recorded well point elevations show almost no fluctuation.

BUW has an underdrain, but there was no access to install monitoring equipment to measure the flow exiting the underdrain. As a result of this situation, no underdrain outflow measurements are available. During the infiltration test conducted by AESI a large amount of discharge from the underdrain was observed. Bryan Berkompas of Aspect, monitoring team leader, noted in an email dated 4/10/20 that:

> "The outflow data show the site almost never discharged which directly contradicts the infiltration testing results. Our data from the infiltration test show that the outlet flow exceeded our weir capacity at times. We have an initial discharge of around 40 gpm and then it spiked to 81 gpm before it exceeded our weir's capacity. I would say 120 gpm is within reason per Jenny's inflow data. But for the rest of the study period, the outfall level almost never rises, despite the underdrain. Either that is the leakiest structure ever or something else is going on. I suspect the relatively shallow and sloping nature of the facility undermined us."

In other words, the monitored outflow data cannot be compared with the simulated results, as seen below.

The BUW simulated combined outflow (riser discharge and underdrain discharge) was compared with the measured/recorded outflow to better understand the problems noted above.

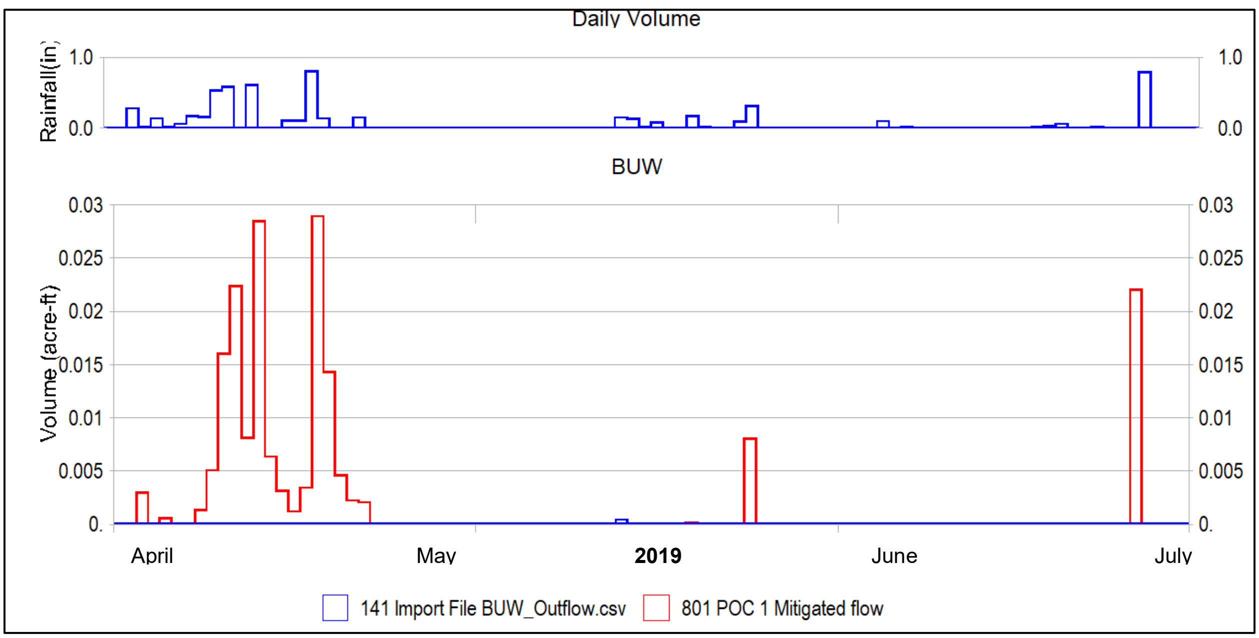


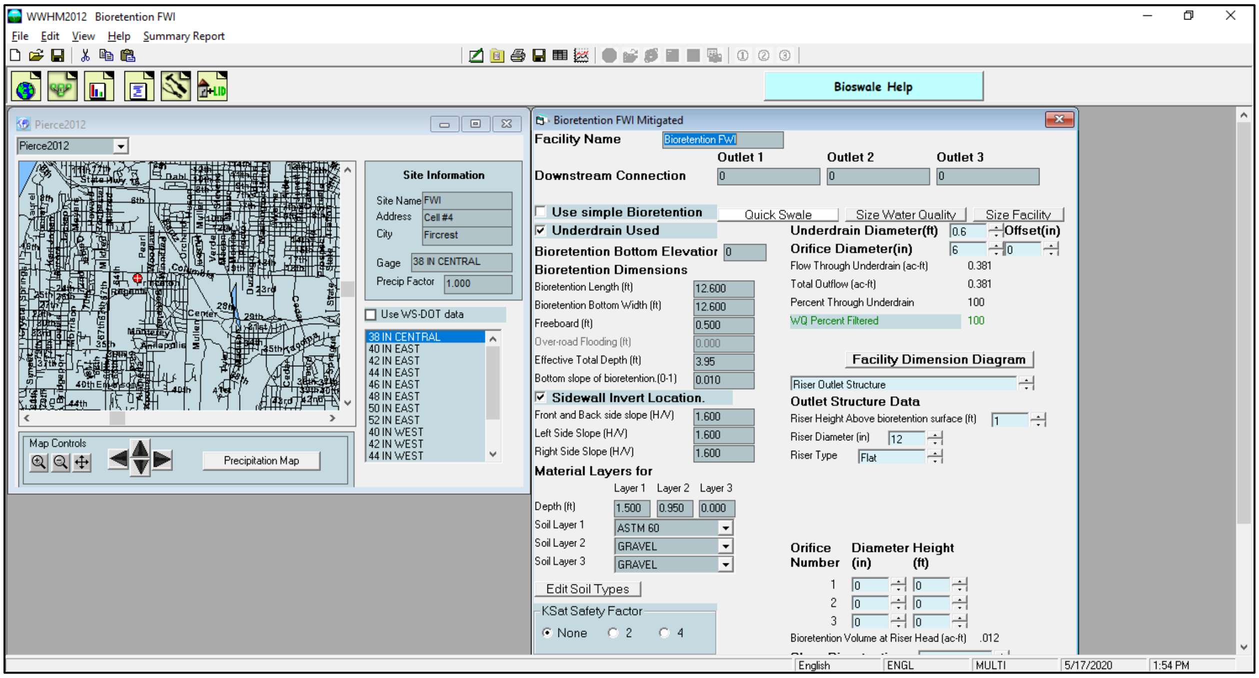

Figure BUW-4. BUW Daily Outflow Volumes

Figure BUW-4 shows the simulated (red) combined surface and underdrain discharge and recorded (blue) hourly maximum 15-minute outflow values and, along the top of the figure, the BUW site monitored hourly maximum 15-minute rainfall data.

There is almost no recorded outflow (blue). The total simulated outflow is much larger than the recorded outflow for the reasons described above, but the simulated outflow results are consistent with the observed rainfall data.

The long-term modeling results based on the Whatcom County Blaine rain gage record show that BUW fails both MR #5 and MR #6. BUW's bottom area is only 0.1% of the drainage area to BUW. This site is too small to meet these minimum requirements and is overwhelmed by large runoff events.

FWI: Fircrest, Pierce County




The FWI bioretention site is located in Fircrest, Pierce County, Washington. The drainage area to FWI consists of 0.23 acres of C soil, lawn vegetation, on a flat slope (0-5%) and 0.10 acres of road on a flat slope (0-5%).

The FWI surface area footprint at top of overflow is 250 square feet. This equals 1.7% of the 0.33-acre tributary drainage area to FWI.

FWI has a surface discharge via riser outlet set at 1.0 feet above the surface bottom. Most of the inflow to FWI is infiltrated into the bioretention soil and then exits via an underdrain.

The original FWI bioretention site modeling assumed no infiltration to groundwater. AESI estimated a lateral infiltration rate of 0.4 in/hr based on historical testing in the weathered zone, but expects that the vertical infiltration rate is near zero. A value of 0.05 in/hr was used in the modeling.

A bioretention top soil layer of very high infiltrating soil (estimated at 60 in/hr) and a second soil layer of gravel best reproduced the monitored soil moisture and surface ponding conditions. The very low native soil permeability soil creates a perched groundwater lens below the gravel layer.

Figure FWI-1 shows the simulated (red) and recorded (blue) daily inflow volumes and, along the top of the figure, the FWI site monitored daily rainfall data. The simulated and recorded daily inflow volumes match well for most storm events.

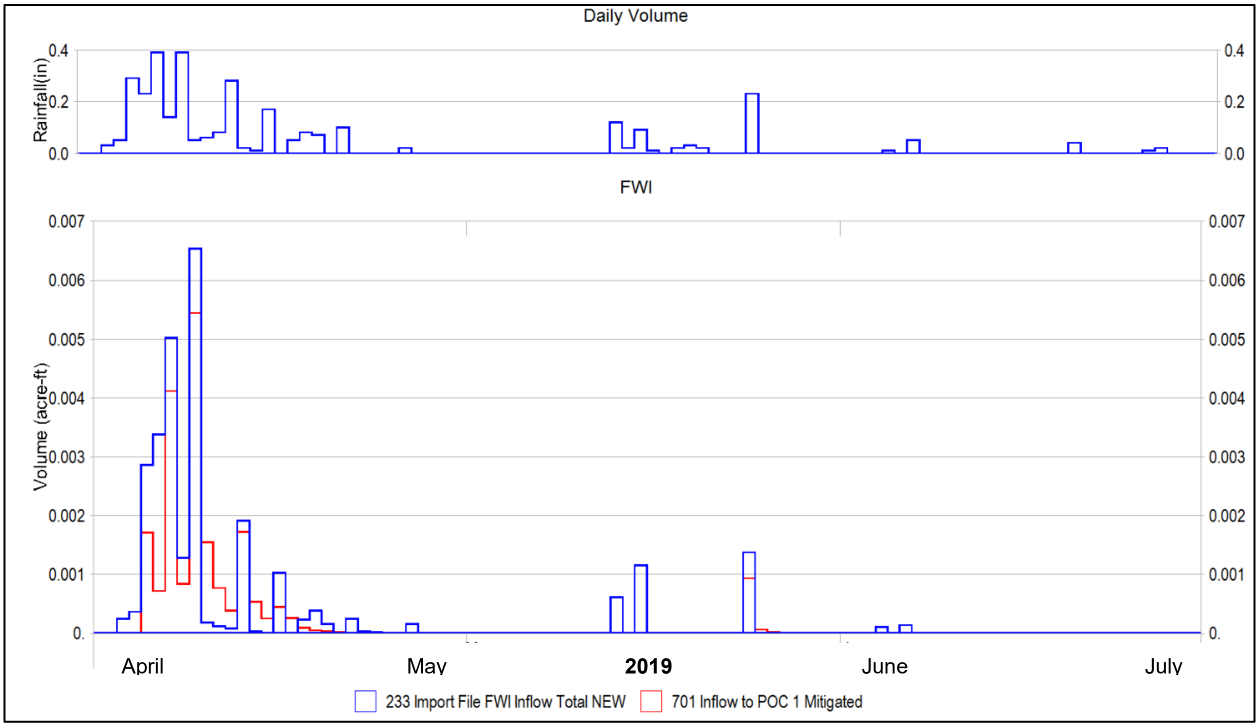



Figure FWI-1. FWI Daily Inflow Volumes

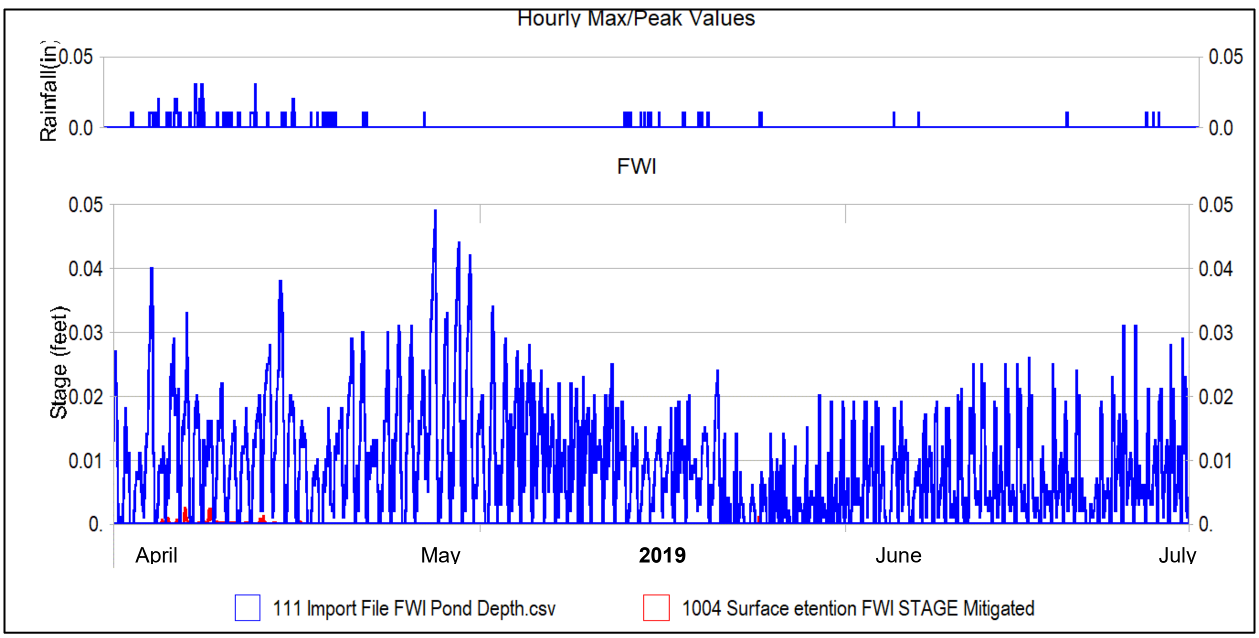



Figure FWI-2. FWI Hourly Surface Ponding Depths

Figure FWI-2 shows the simulated (red) and recorded (blue) hourly maximum 5-minute surface ponding (stage) values and, along the top of the figure, the FWI site monitored hourly maximum 5-minute rainfall data. The simulated pond depths are lower than the recorded ponding values, but all of the pond depths are very small (less than 0.05 feet). The minor recorded depth fluctuations during the dry periods may either be due to on-site irrigation or monitoring equipment error due to daily air temperature fluctuations. This phenomena was observed at multiple sites.

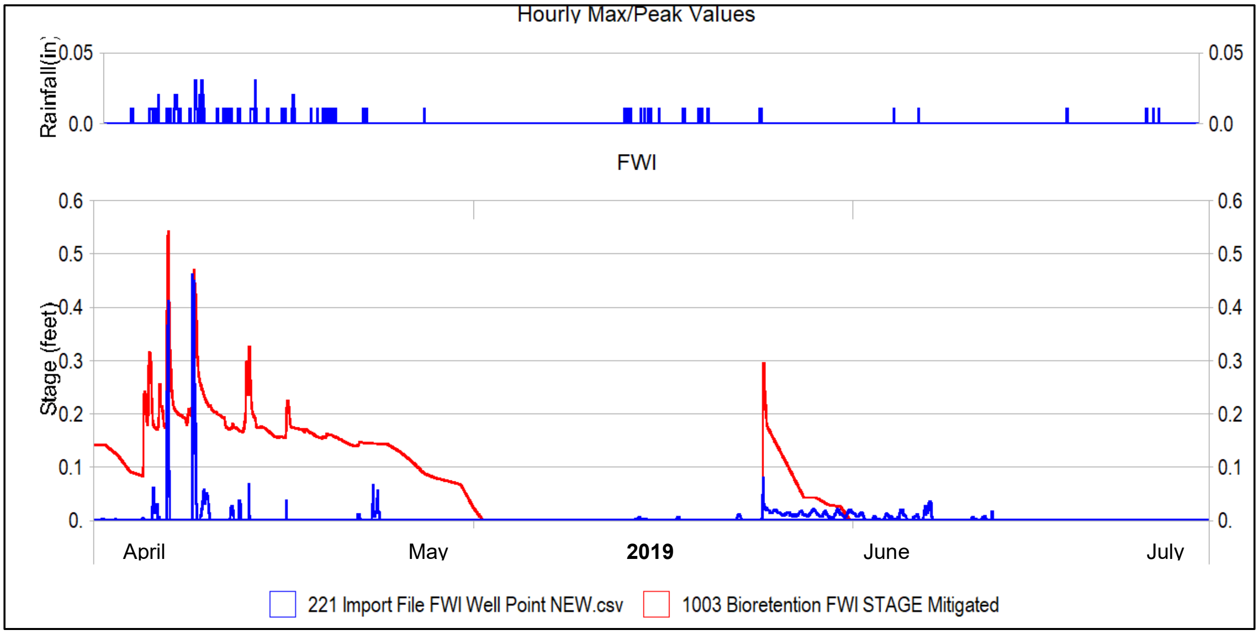



Figure FWI-3. FWI Hourly Soil Layer Well Point Elevations

Figure FWI-3 shows the simulated (red) and recorded (blue) hourly maximum 5-minute soil layer well point elevations (stage) values and, along the top of the figure, the FWI site monitored hourly maximum 5-minute rainfall data.

The simulated well point elevations show more fluctuation than the recorded well point data. The recorded well point elevations show almost no fluctuation. The simulated and recorded well point values match well for the major events.

FWI has an underdrain, but there was no access to install monitoring equipment to measure the flow exiting the underdrain. As a result of this situation, no underdrain outflow measurements are available.

The FWI simulated underdrain outflow (there was no simulated surface discharge) was compared with the measured/recorded outflow.

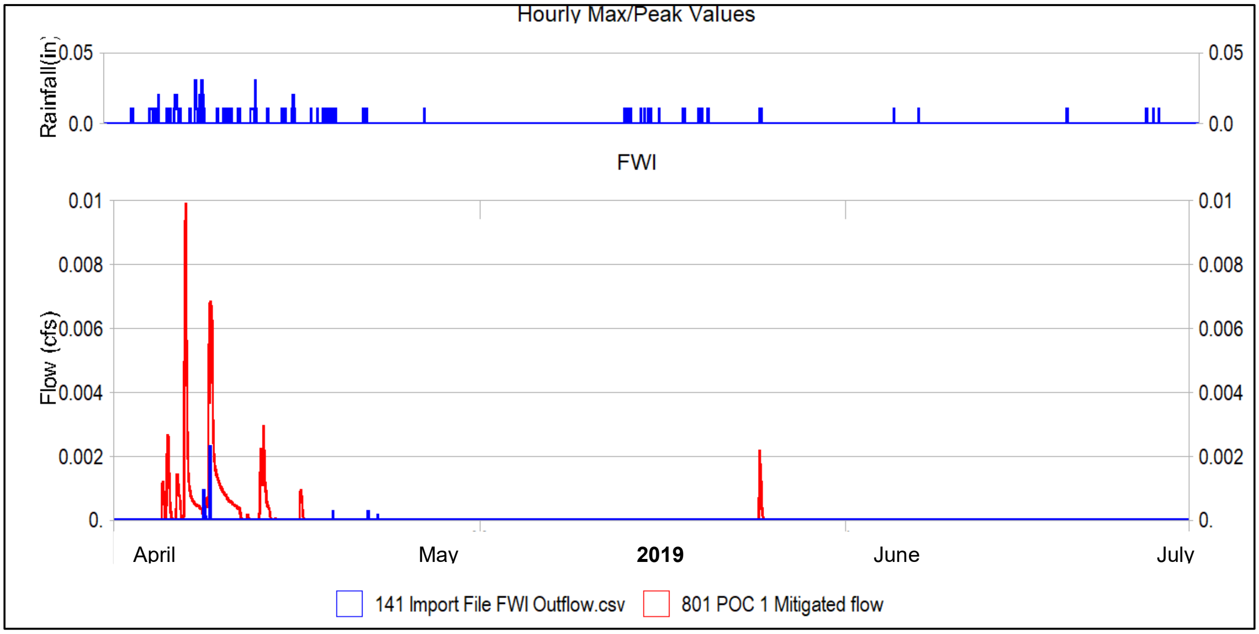


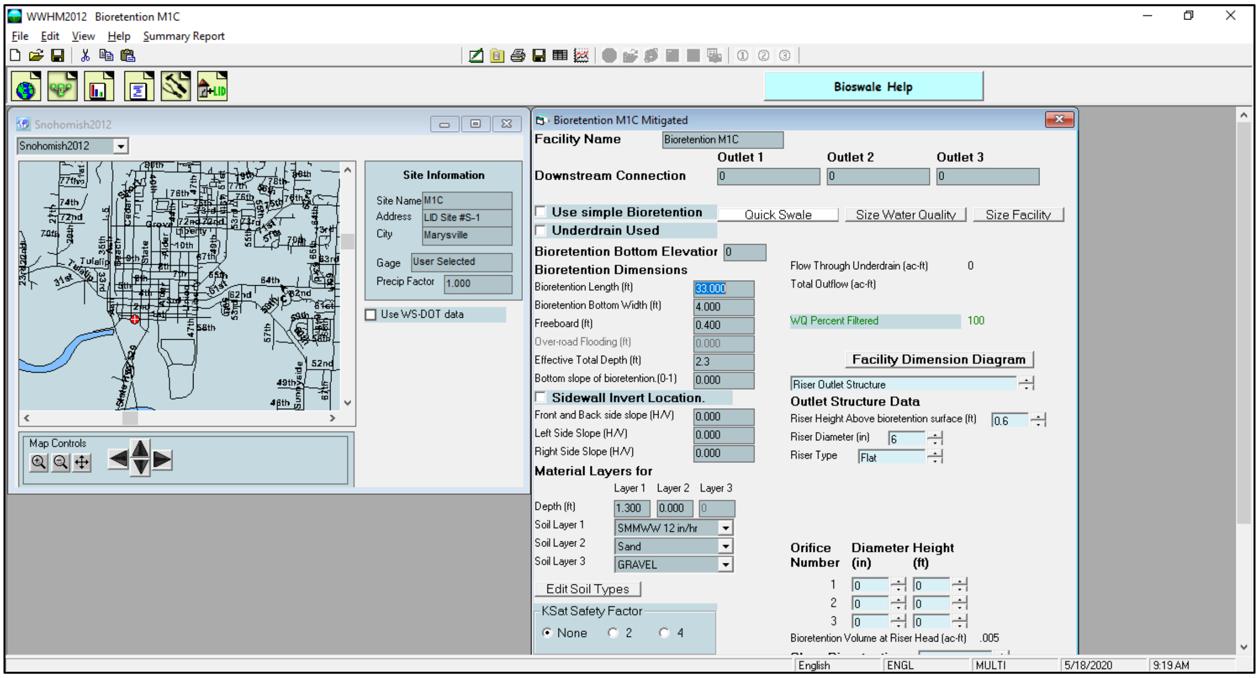

Figure FWI-4. Comparison of FWI Hourly Outflow Simulated and Measured Peak Flows

In Figure FWI-4 the FWI recorded outflow (blue) and the simulated underdrain outflow (red) hourly peak flows are shown. For the measured outflow events the simulated underdrain outflow (red) is greater than the recorded outflow (blue).

For all practical purposes all of the inflow to the FWI bioretention site exits via the underdrain. This was seen in the modeling and this same observation was made by AESI during the infiltration testing. The simulated underdrain outflow is consistent with the simulated inflow. Therefore, it can be assumed that the magnitude of the simulated underdrain outflow peaks is correct and that the recorded peak outflows are actually larger than measured. As noted at some of the other small bioretention sites, this is probably due to the errors inherent with the difficulty of measuring very small outflow rates from this small bioretention facility.

The long-term modeling results based on the Pierce County WSDOT 38-inch Central rainfall record show that FWI passes MR #6 (water quality) but fails MR #5 (LID flow duration). FWI fails MR #5 because the flow out of the underdrain occurs too rapidly and exceeds the flow duration standard for MR #5 (8% of Q2 to 50% of Q2).

M1C: Marysville, Snohomish County




The M1C bioretention site is located in Marysville, Snohomish County, Washington. The drainage area to M1C consists of 0.03 acres of road on a flat slope (0-5%).

The M1C surface area footprint is 132 square feet at top of overflow. This equals 10.1% of the tributary drainage area to M1C.

M1C has a riser for surface discharge set at 0.6 feet above the surface bottom. Most of the inflow to M1C is infiltrated into the native soil beneath the bioretention soil layer.

A native soil infiltration rate of 17 inches per hour is based on the infiltration field test. The bioretention top soil layer of Ecology SMMWW 12 in/hr soil represents the soil found on the site.

Figure M1C-1 shows the simulated (red) and recorded (blue) daily inflow volumes and, along the top of the figure, the M1C-1 site monitored daily rainfall data. The simulated and recorded daily inflow volumes match well, except for periods in late May and late June where inflow was measured but there was no corresponding measured rainfall. It is assumed that this inflow is the product of irrigation of adjacent landscape areas.

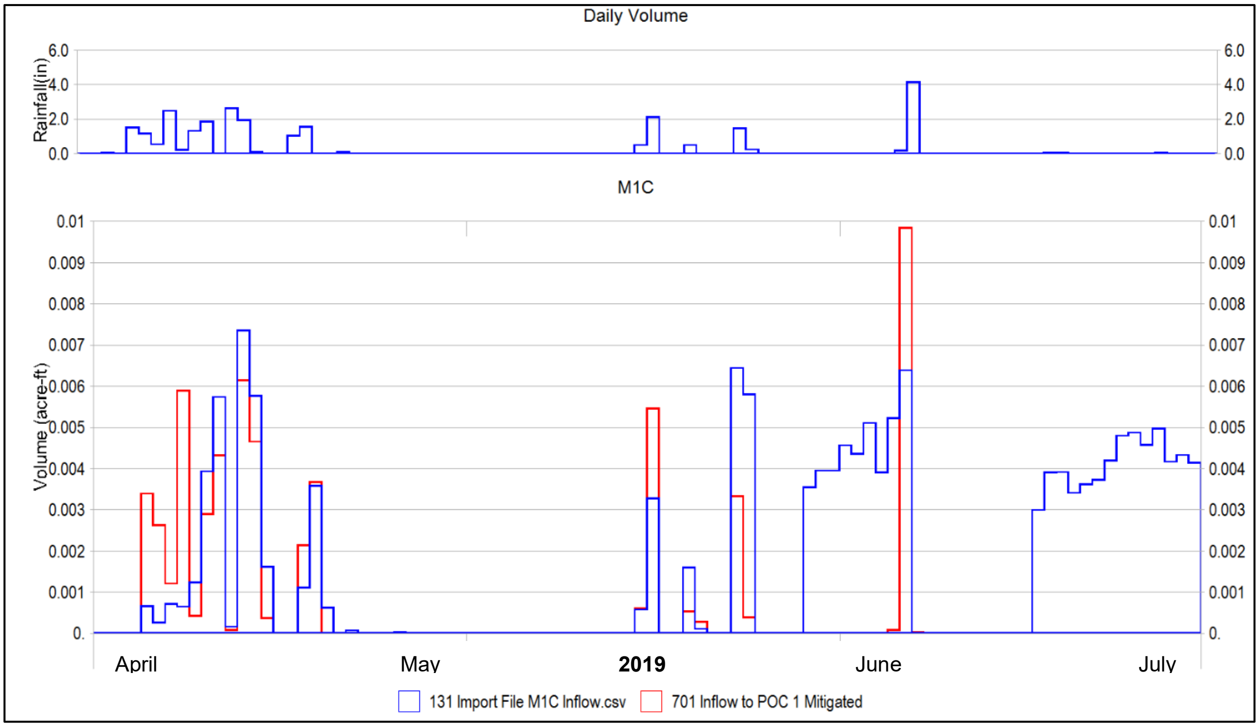



Figure M1C-1. M1C Daily Inflow Volumes

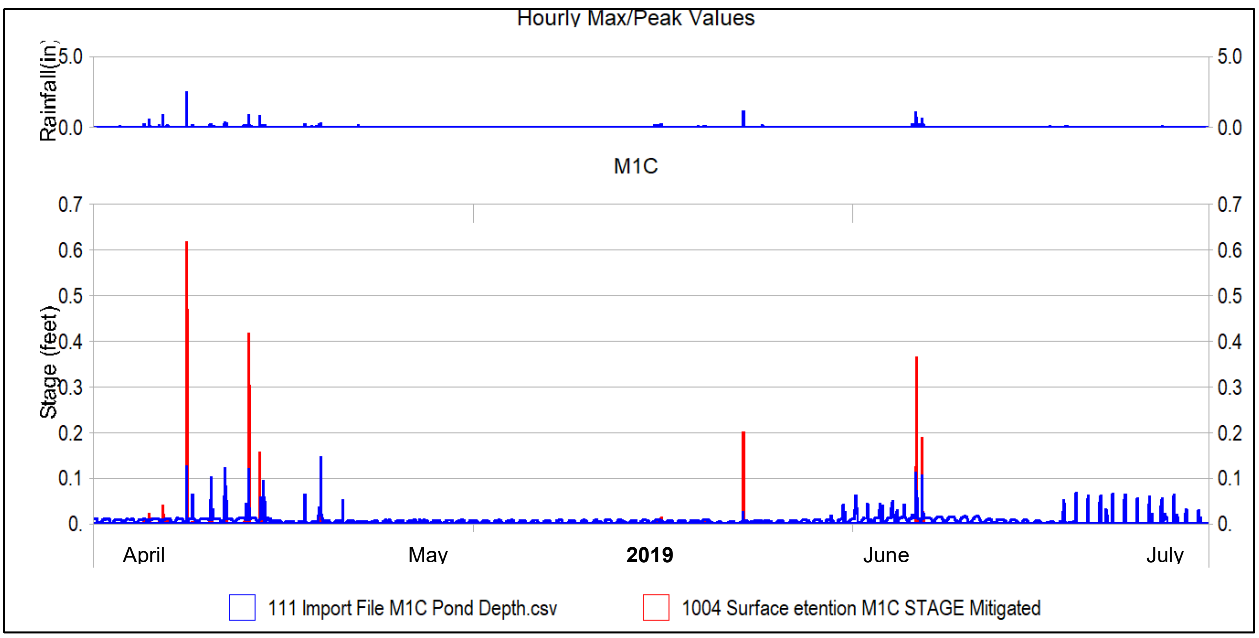



Figure M1C-2. M1C Hourly Surface Ponding Depths

Figure M1C-2 shows the simulated (red) and recorded (blue) hourly maximum 15-minute surface ponding (stage) values and, along the top of the figure, the M1C site monitored hourly maximum 15-minute rainfall data. The simulated ponding depths are larger than the recorded depths except for the periods when the addition of irrigated water produces ponding. This is observed to start in early June. The stormwater runoff onto the bioretention site appears to infiltrate better than the Ecology soil mix would indicate.

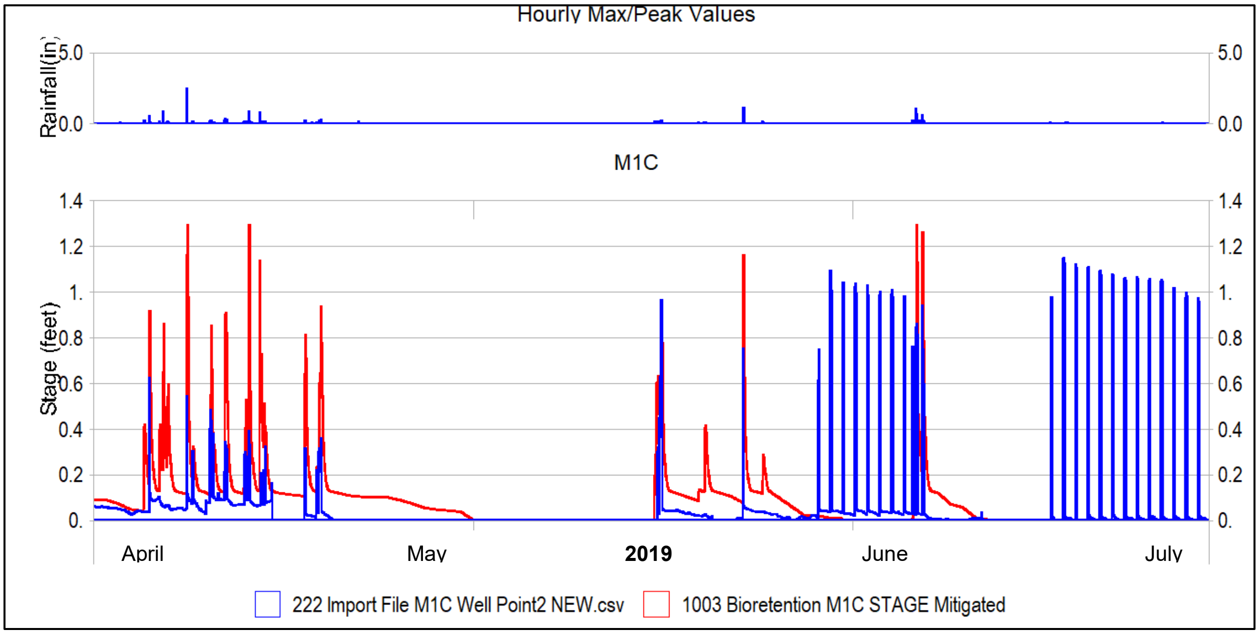
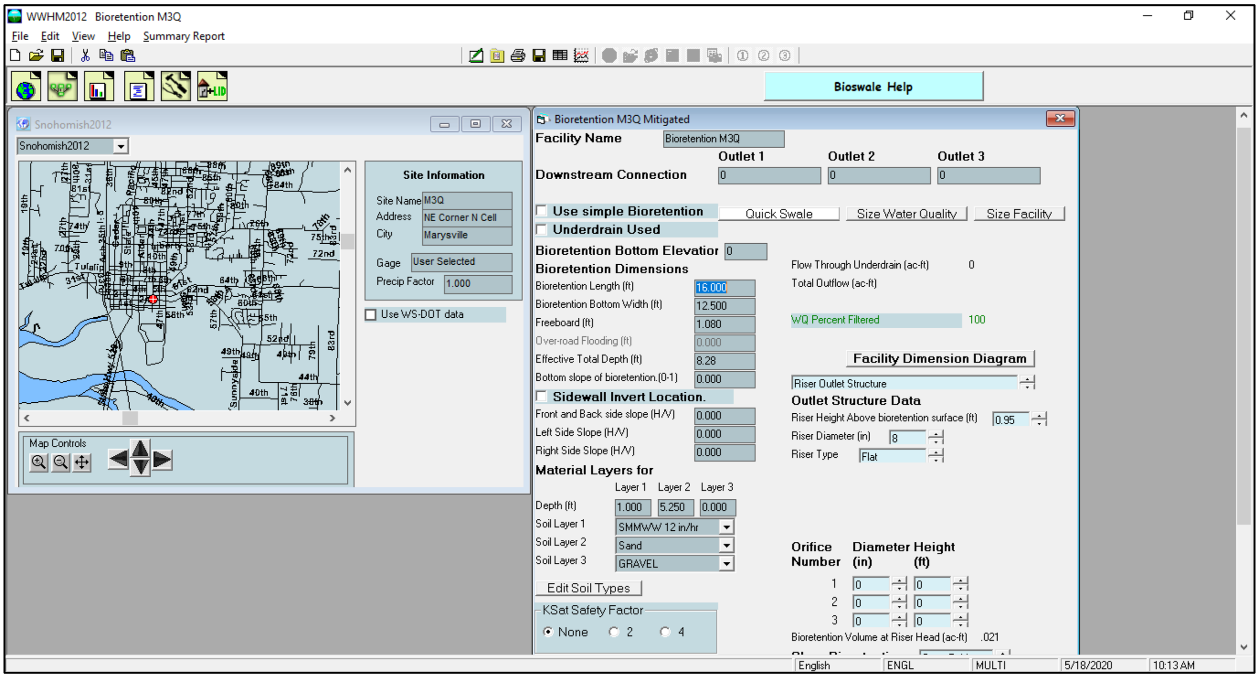



Figure M1C-3. M1C Hourly Soil Layer Well Point Elevations

Figure M1C-3 shows the simulated (red) and recorded (blue) hourly maximum 15-minute soil layer well point elevations (stage) values and, along the top of the figure, the M1C site monitored hourly maximum 15-minute rainfall data. The simulated and recorded ponding values match well when there is measured rainfall data. The simulated values show more fluctuation and faster drainage times than the recorded well point data. The recorded spikes in well point elevations starting in late May/early June appear to be the result of on-site irrigation of the bioretention facility. This is often done to water the bioretention plant community during dry periods. This artificial addition of water to the site is not included in the model results.

The long-term modeling results based on the Snohomish County Everett rain gage record show that M1C passes both MR #5 and MR #6. Ability to pass these two minimum requirements is due to infiltration of almost 100% of the total runoff volume. This was also true for the nearby M3Q site.

M3Q: Marysville, Snohomish County




The M3Q bioretention site is located in Marysville, Snohomish County, Washington. The drainage area to M3Q consists of 0.02 acres of road on a flat slope (0-5%). As discussed below, the design drainage area was specified as 0.08 acres of road, but the modeling results showed that that size of a drainage area to the bioretention site was highly unlikely due to the very large inflows and resulting pond depths that are computed using a drainage area of 0.08 acres of impervious surfaces when compared to the recorded (monitored) data. A drainage area of 0.02 acres produces more realistic results.

The M3Q surface area footprint is 200 square feet at top of overflow. This equals 23% of the 0.02-acre tributary drainage area to M3Q.

M3Q has a riser for surface discharge set at 0.95 feet above the surface bottom. All of the inflow to M3Q is infiltrated into the native soil beneath the bioretention soil layer.

A native soil infiltration rate of 15 inches per hour is based on the infiltration field test. The bioretention top soil layer of Ecology SMMWW 12 in/hr soil represents the soil found on the site.

Figure M3Q-1 shows the simulated (red) and recorded (blue) daily inflow volumes and, along the top of the figure, the M3Q -1 site monitored daily rainfall data. Even with the reduction in drainage area from 0.08 acres to 0.02 acres the simulated daily inflow volumes exceed the recorded inflow volumes. The error may be in the difficulty to accurately measure very small flow values that enter M3Q through the 12-inch curb cut on Quinn Avenue. Also, the June rainfall event that measured 4 inches at the rain gage does not appear to be representative of the actual amount that fell on the M3Q drainage area.

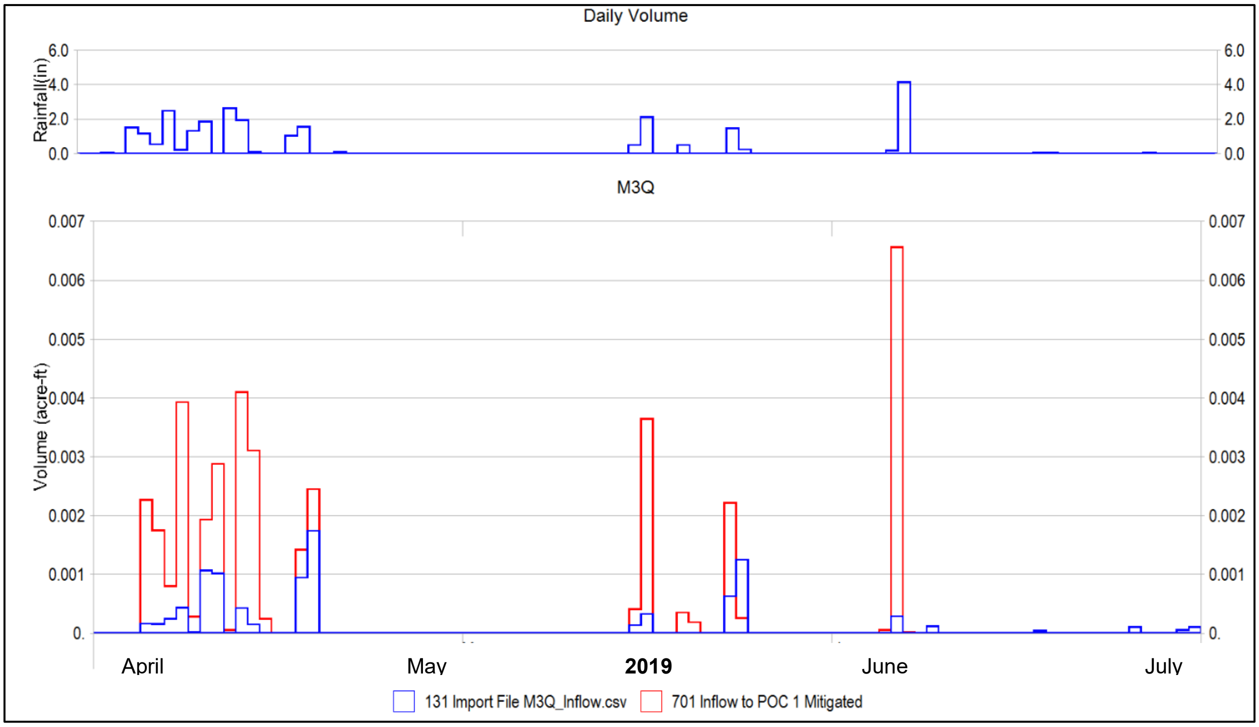



Figure M3Q-1. M3Q Daily Inflow Volumes

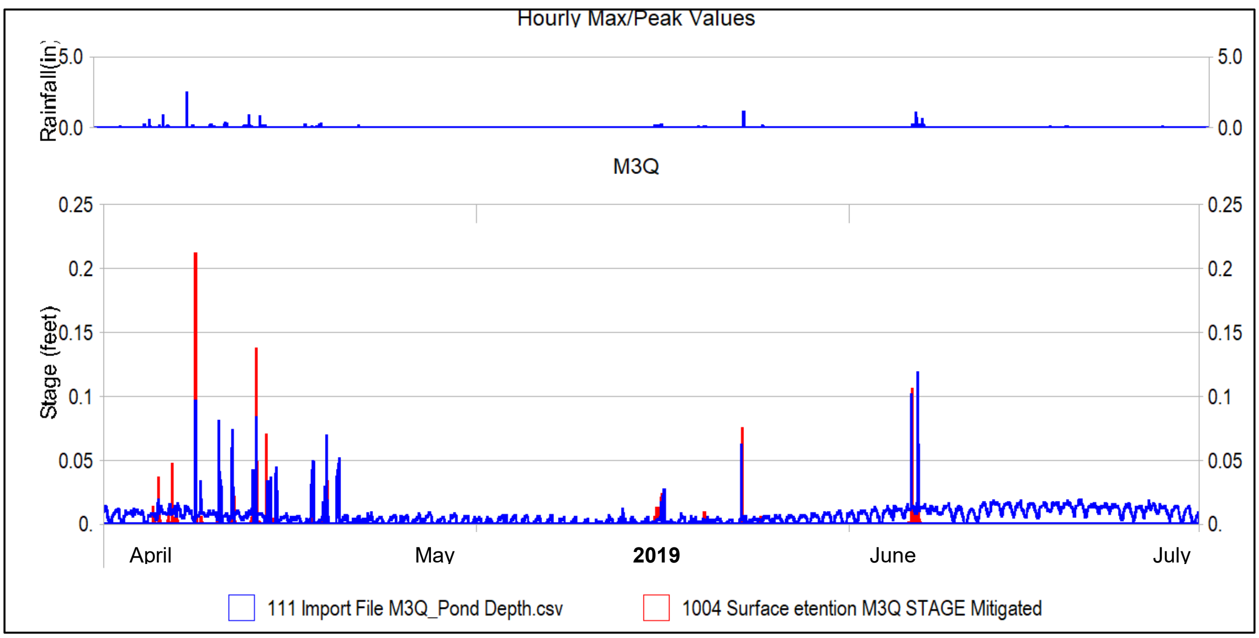



Figure M3Q-2. M3Q Hourly Surface Ponding Depths

Figure M3Q-2 shows the simulated (red) and recorded (blue) hourly maximum 15-minute surface ponding (stage) values and, along the top of the figure, the M3Q site monitored hourly maximum 15-minute rainfall data. The simulated ponding depths are close to the recorded depths for most of the storm events, although they are mixed (some higher and some lower) overall. The minor recorded depth fluctuations during the dry periods may either be due to monitoring equipment error resulting from daily air temperature fluctuations confusing the sensor. This phenomenon was observed at multiple sites.

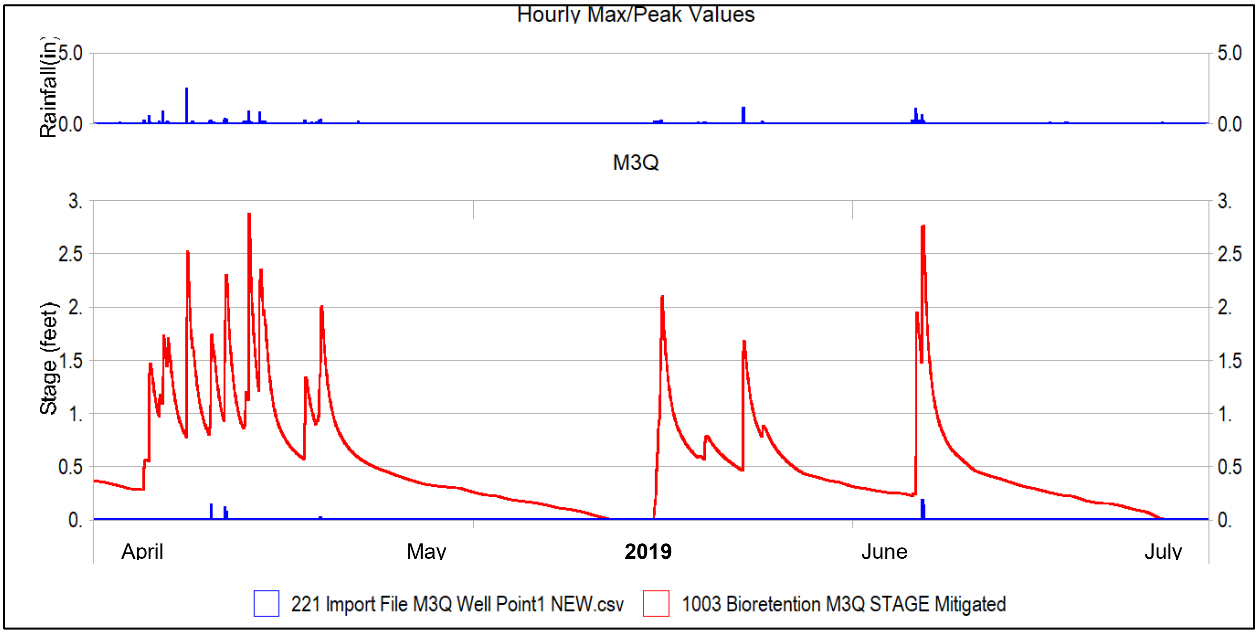
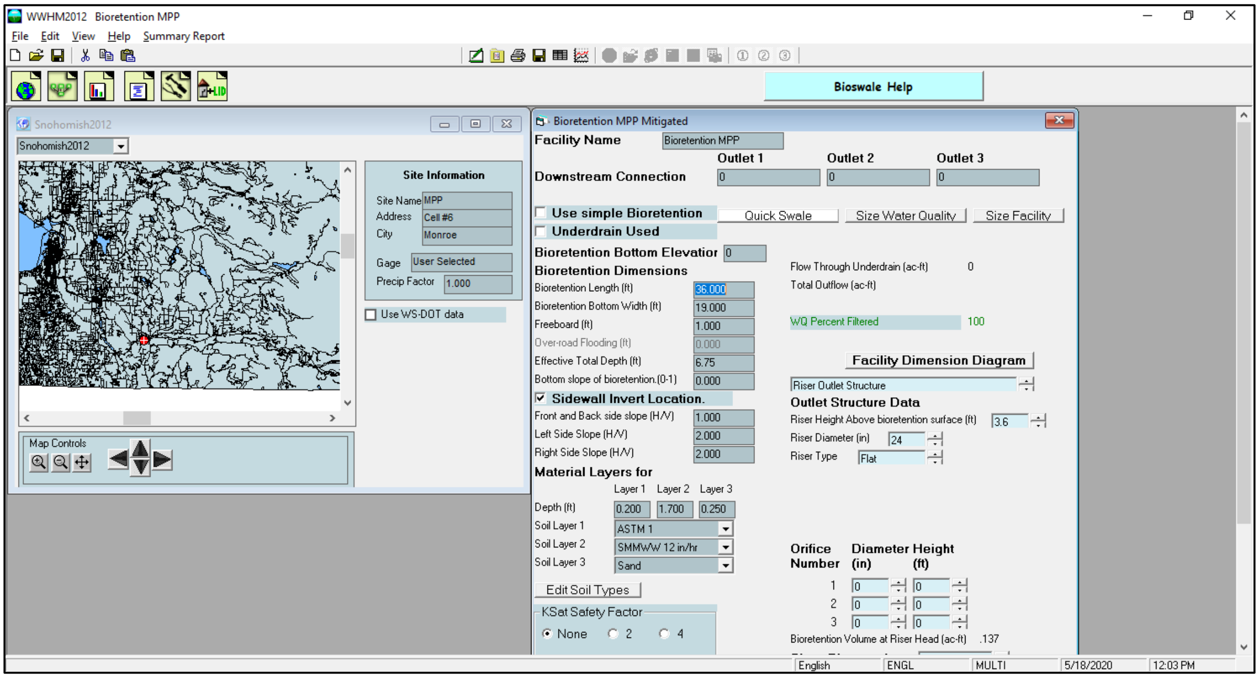



Figure M3Q-3. M3Q Hourly Soil Layer Well Point Elevations

Figure M3Q-3 shows the simulated (red) and recorded (blue) hourly maximum 15-minute soil layer well point elevations (stage) values and, along the top of the figure, the M3Q site monitored hourly maximum 15-minute rainfall data. The simulated values show more fluctuation than the recorded well point data. Similar results were seen at the nearby M1C bioretention site. The difference in simulated and recorded well point results may be due to faster drainage through the native soil than was modeled.

The long-term modeling results based on the Snohomish County Everett rain gage record show that M3Q passes both MR #5 and MR #6. Ability to pass these two minimum requirements is due to infiltration of almost 100% of the total runoff volume. This was also true for the nearby M1C site.

MPP: Monroe, Snohomish County




The MPP bioretention site is located in Monroe, Snohomish County, Washington. The drainage area to MPP consists of 0.19 acres of C soil, lawn vegetation, flat slope (0-5%) and 0.29 of road on a flat slope (0-5%).

The MPP surface area footprint is 1320 square feet at top of overflow. This equals 6.3% of the 0.48-acre tributary drainage area to MPP.

MPP has no surface outlet control structure but overtops the site at 3.6 feet above the surface bottom. All of the inflow to MPP is infiltrated into the native soil beneath the bioretention soil layers.

A native soil infiltration rate of 3 inches per hour together with a bioretention top soil layer of mulch or similar organic material (represented by ASTM1 soil), a second soil layer of Ecology SWWMM soil mix (12-inch per hour infiltration rate), and a third soil layer of sand best reproduced the monitored soil moisture and surface ponding conditions. The top organic layer appears to restrict infiltration of the inflow into the bioretention soil and was added to the model to reproduce monitored surface ponding depths.

Figure MPP-1 shows the simulated (red) and recorded (blue) daily inflow volumes and, along the top of the figure, the MPP site monitored daily rainfall data. The simulated daily inflow volumes are relatively consistent with the recorded inflow volumes.

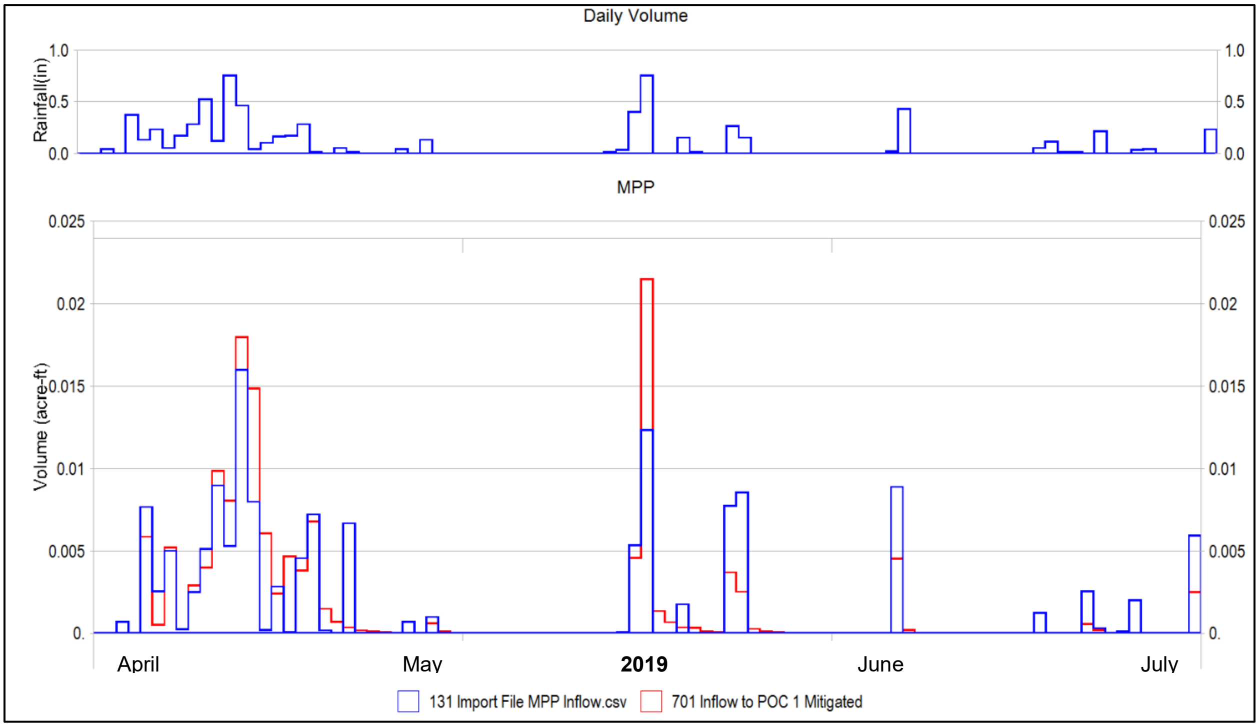



Figure MPP-1. MPP Daily Inflow Volumes

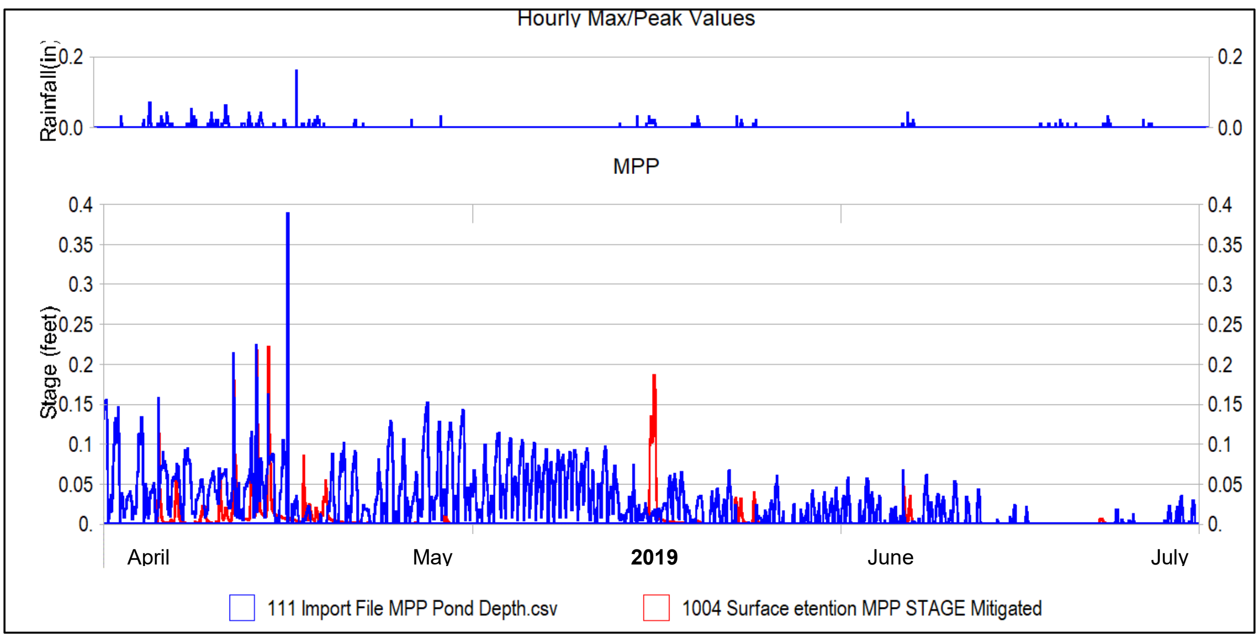



Figure MPP-2. MPP Hourly Surface Ponding Depths

Figure MPP-2 shows the simulated (red) and recorded (blue) hourly maximum 5-minute surface ponding (stage) values and, along the top of the figure, the MPP site monitored hourly maximum 5-minute rainfall data. The simulated and recorded ponding values show mixed results. As observed at some of the other sites, monitored ponding depth values fluctuate due to diurnal temperature changes.

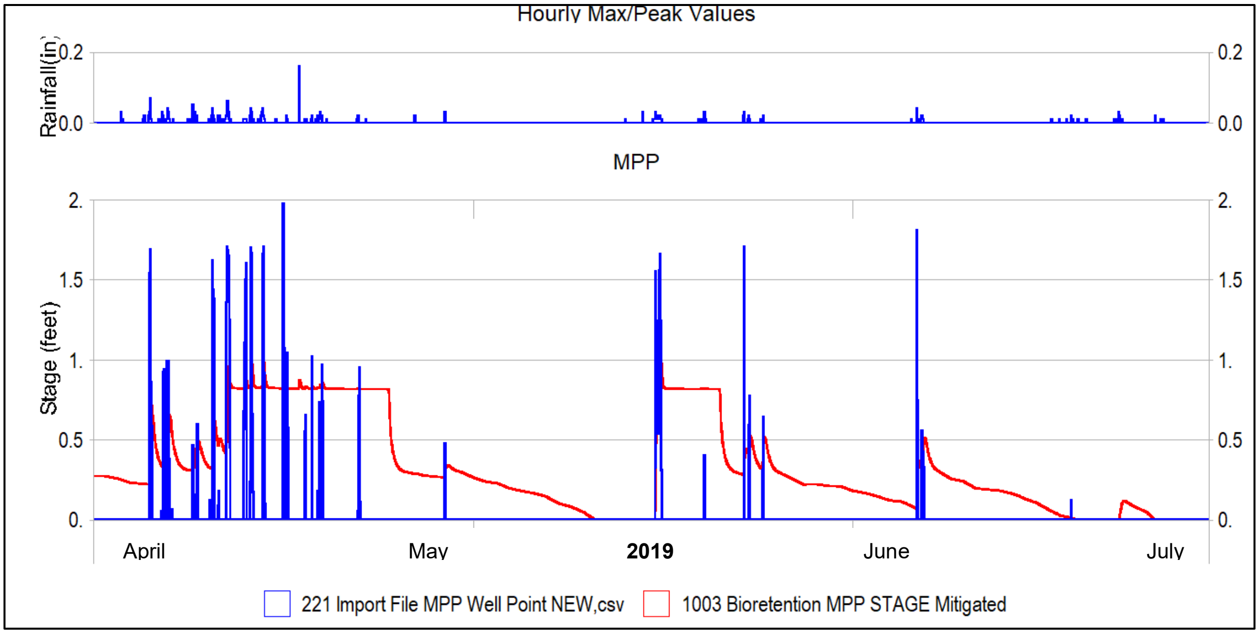
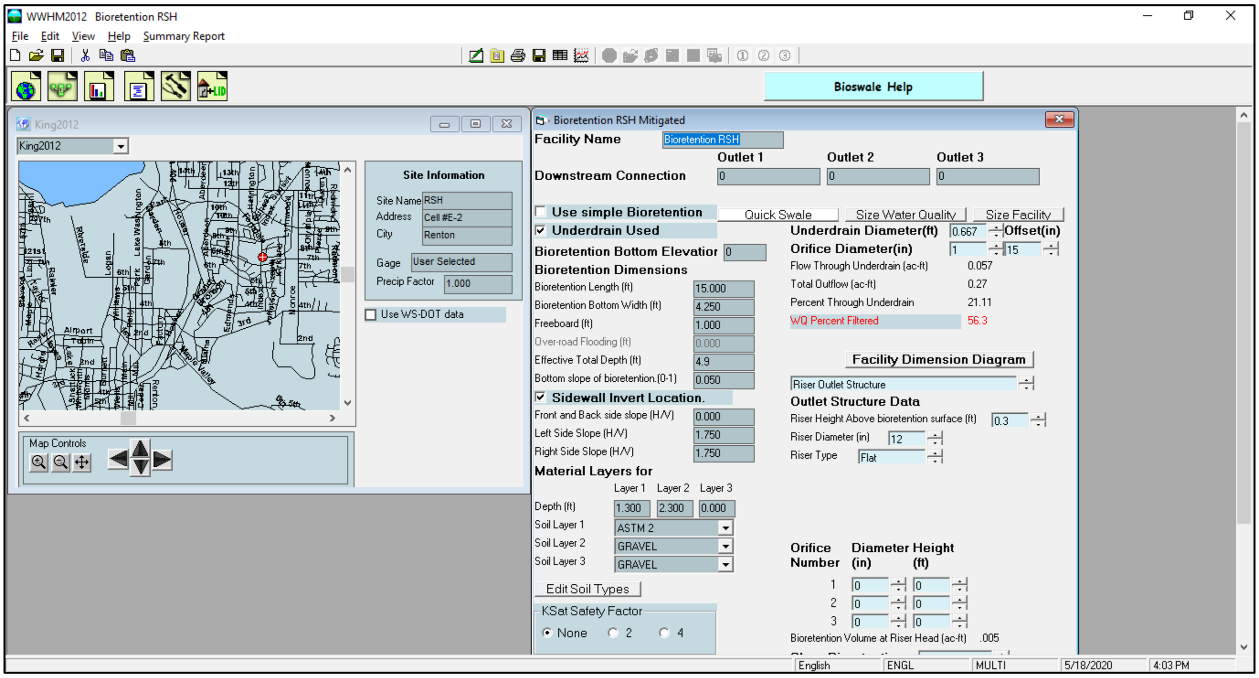



Figure MPP-3. MPP Hourly Soil Layer Well Point Elevations

Figure MPP-3 shows the simulated (red) and recorded (blue) hourly maximum 5-minute soil layer well point elevations (stage) values and, along the top of the figure, the MPP site monitored hourly maximum 5-minute rainfall data. The simulated values show less fluctuation than the recorded well point data. The reason for the very rapid discharge from the well points into the underlaying native soil is not clear based on the field-measured infiltration rate.

The long-term modeling results based on the Snohomish County Everett rain gage record show that MPP passes both MR #5 and MR #6. Ability to pass these two minimum requirements is due to infiltration of almost 100% of the total runoff volume.

RSH: Renton, King County




The RSH bioretention site is located in Renton, King County, Washington. The drainage area to RSH consists of 0.0283 acres of A/B soil, lawn vegetation, on a moderate slope (5-15%), and 0.1417 acres of roads on a moderate slope (5-15%).

The RSH surface area footprint is 68 square feet at top of overflow. This equals 0.9% of the 0.17-acre tributary drainage area to RSH.

RSH has a surface outlet at 0.3 feet above the surface bottom. RSH also has an underdrain. The underdrain is set at 15 inches above the bottom of the lowest bioretention soil layer. Approximately one-half of the inflow to RSH is infiltrated into the native soil beneath the bioretention soil layers. The underdrain is connected to an outlet pipe that connects to the municipal stormwater system.

AESI measured infiltration rate for the top bioretention soil layer to be only 2 inches per hour. For this reason the ASTM2 soil was used to represent this top layer. Below the bioretention soil layer is a gravel layer. Under the gravel layer is a native soil with a low infiltration rate. For modeling purposes, a native soil infiltration rate of 0.5 inches per hour was used.

Figure RSH-1 shows the simulated (red) and recorded (blue) daily inflow volumes and, along the top of the figure, the RSH site monitored daily rainfall data. The simulated daily inflow volumes generally match well with the recorded data for most of the April-June period.

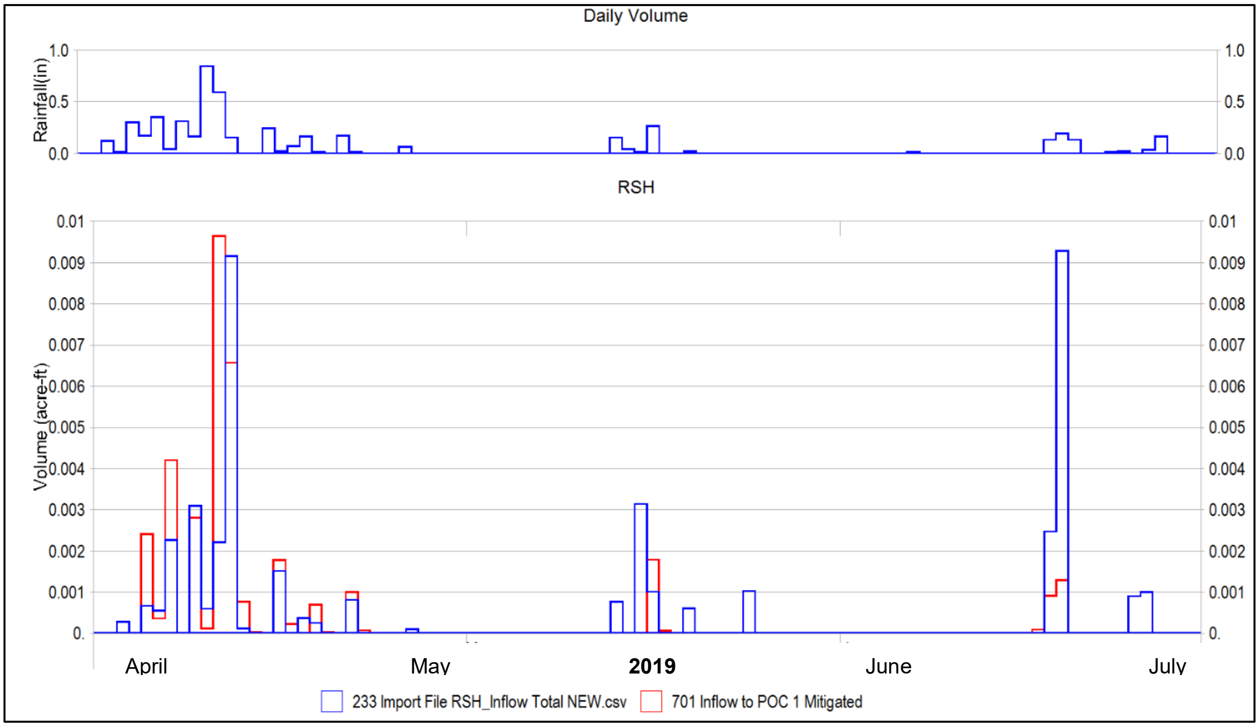



Figure RSH-1. RSH Daily Inflow Volumes

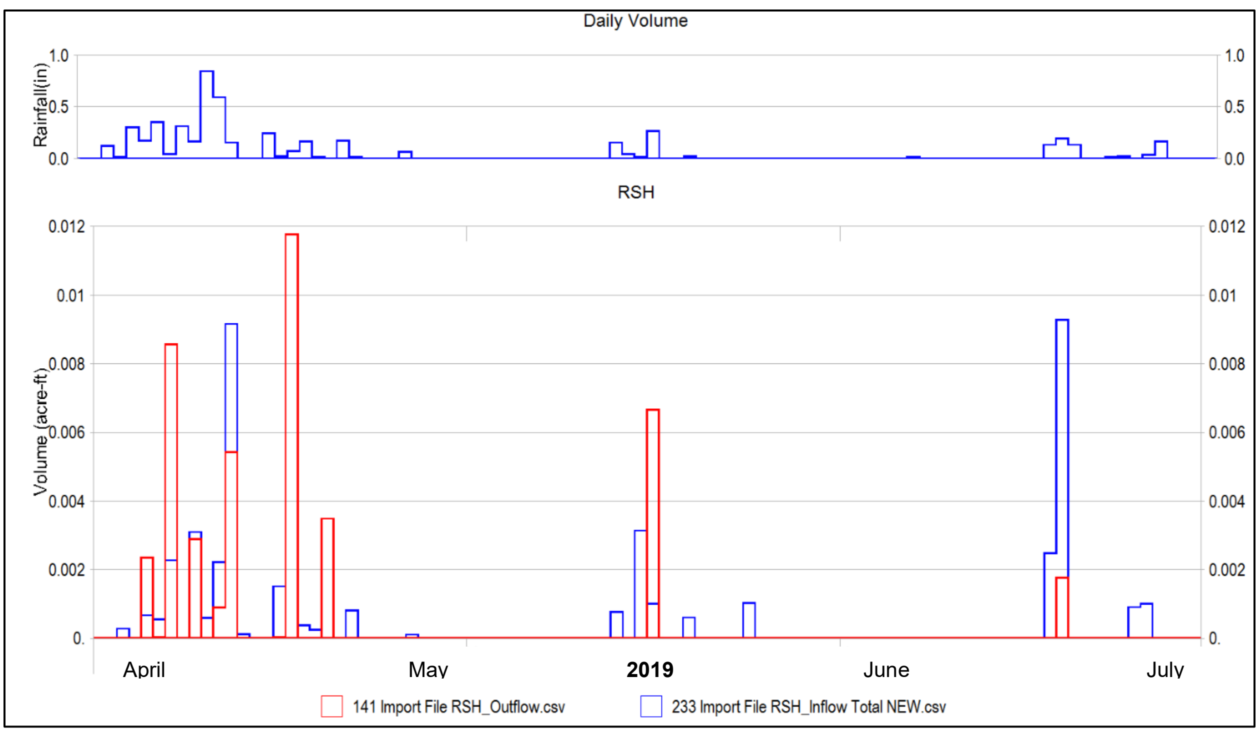



Figure RSH-2. Comparison of RSH Daily Inflow and Outflow Measured Volumes

In Figure RSH-2 the collection of measured outflow at the site made it possible to compare the RSH recorded inflow (blue) and the recorded outflow (red). It is expected that the inflow (blue) would be higher than the outflow (red) for each rainfall event. As shown in the figure, that expectation is often true, but there are some obvious exceptions in April and May 2019. These periods where the outflow volume is greater than the inflow volume are probably due to the errors inherent with the difficulty of measuring very small inflow and outflow rates from this small bioretention facility.

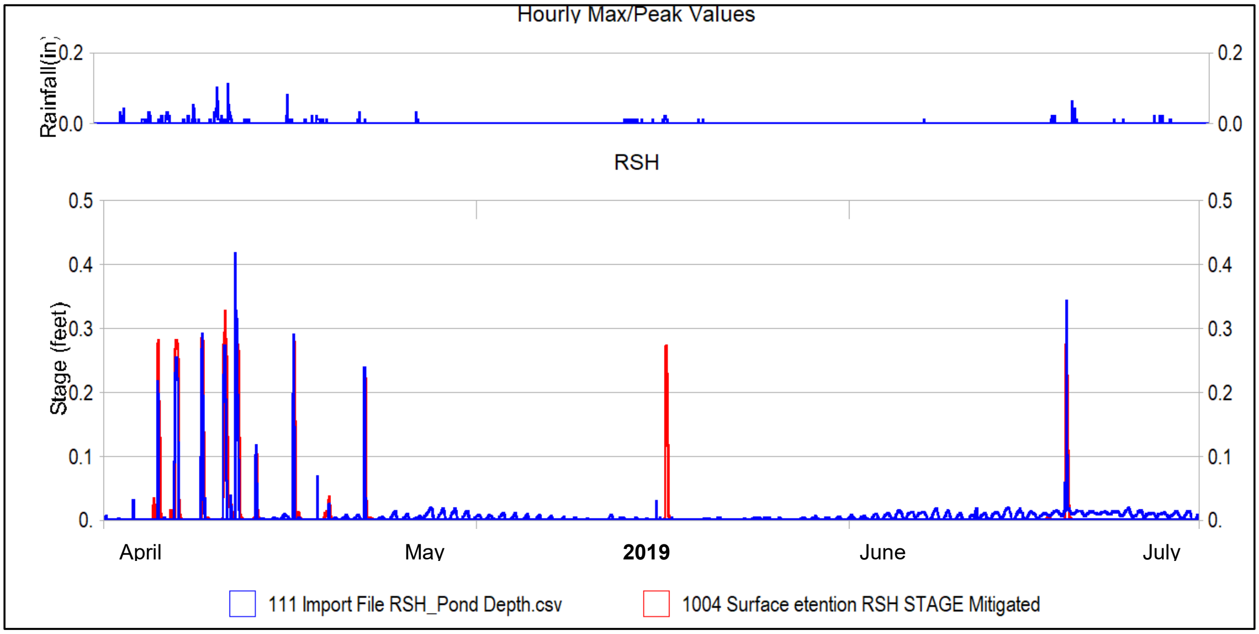



Figure RSH-3. RSH Hourly Surface Ponding Depths

Figure RSH-3 shows the simulated (red) and recorded (blue) hourly maximum 5-minute surface ponding (stage) values and, along the top of the figure, the RSH site monitored hourly maximum 5-minute rainfall data. The simulated and recorded ponding values show that the simulated ponding depths compare well to the recorded depths. Because of RSH's small size and limited ponding storage before overflow occurs the bioretention facility regularly fills to a depth of 0.3 feet and then overflows. That situation is observed in multiple storm events in the months of April, May, and June.

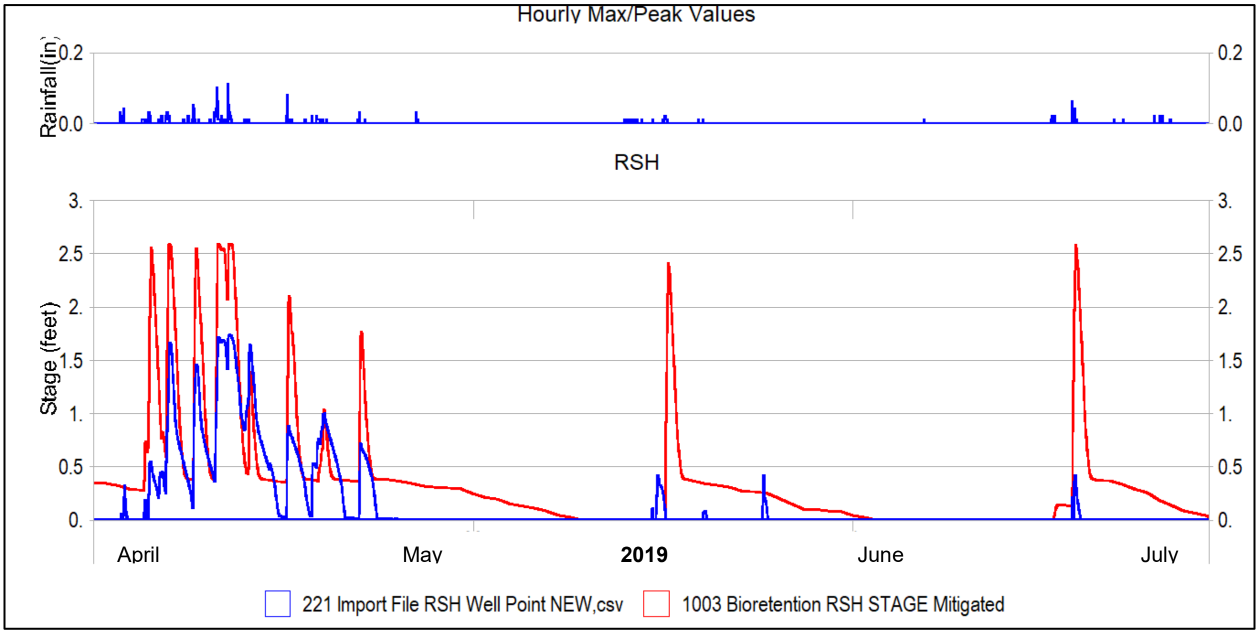



Figure RSH-4. RSH Hourly Soil Layer Well Point Elevations

Figure RSH-4 shows the simulated (red) and recorded (blue) hourly maximum 5-minute soil layer well point elevations (stage) values and, along the top of the figure, the RSH site monitored hourly maximum 5-minute rainfall data. The simulated values are larger than the recorded well point data, but in general both show a similar response to rainfall events.

RSH has an underdrain, but due to its location and how it was connected to the downstream outlet pipe to the municipal stormwater system it was impossible to measure the flow exiting the underdrain. Bryan Berkompas, the monitoring lead, described the situation as follows:

> "The underdrain at RSH was plumbed into a small plastic pipe with a sump and an outlet that discharged into the outlet/overflow catch basin. The outlet pipe was a couple of inches higher than the inlet within the plastic riser. We measured levels relative to the outlet invert figuring that the underdrain would not discharge until the level exceeded that invert so we declared that to be zero for our measurements.
>
> As for the flow, I had originally hoped that the orifice on the downstream end of the underdrain outlet was at an elevation that would allow us to measure flow out of the underdrain using the level in the sump. Unfortunately that pipe was steep enough that the water level acting on the orifice could not be related to the water level in the sump. Given that the water level in the discharge pipe could be either inlet or outlet controlled at any given moment I did not pursue further."

As a result of this situation, no underdrain outflow measurements are available.

The RSH simulated combined outflow was compared with the measured/recorded outflow to better understand the relative magnitude of the surface discharge and the underdrain outflow.

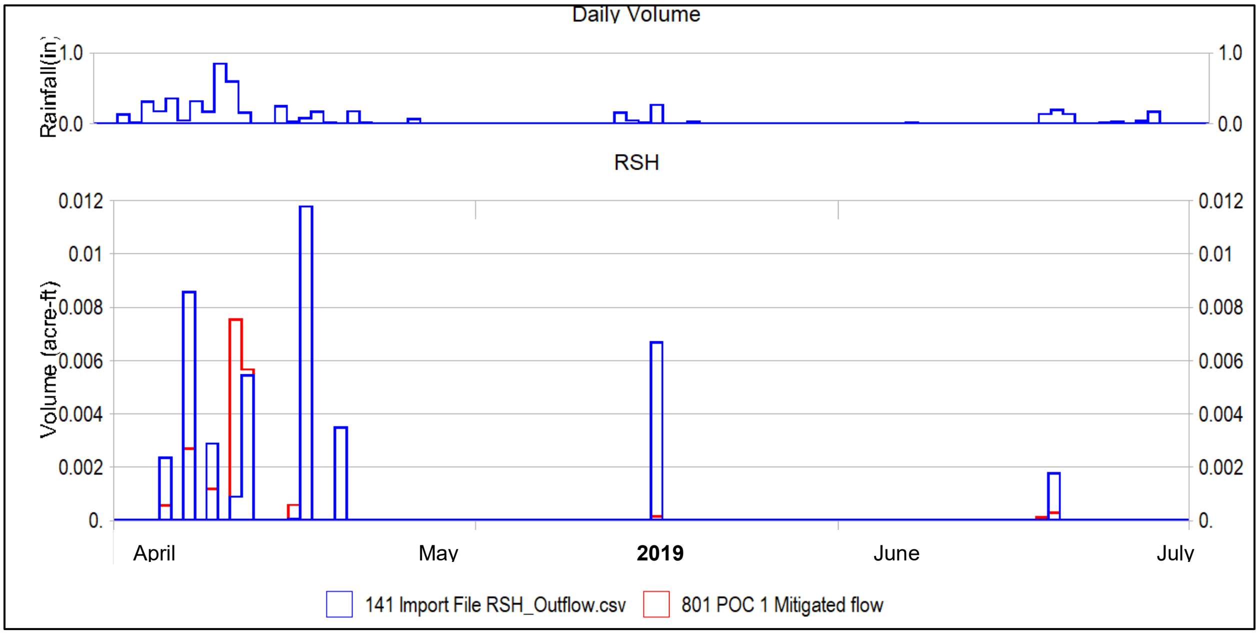
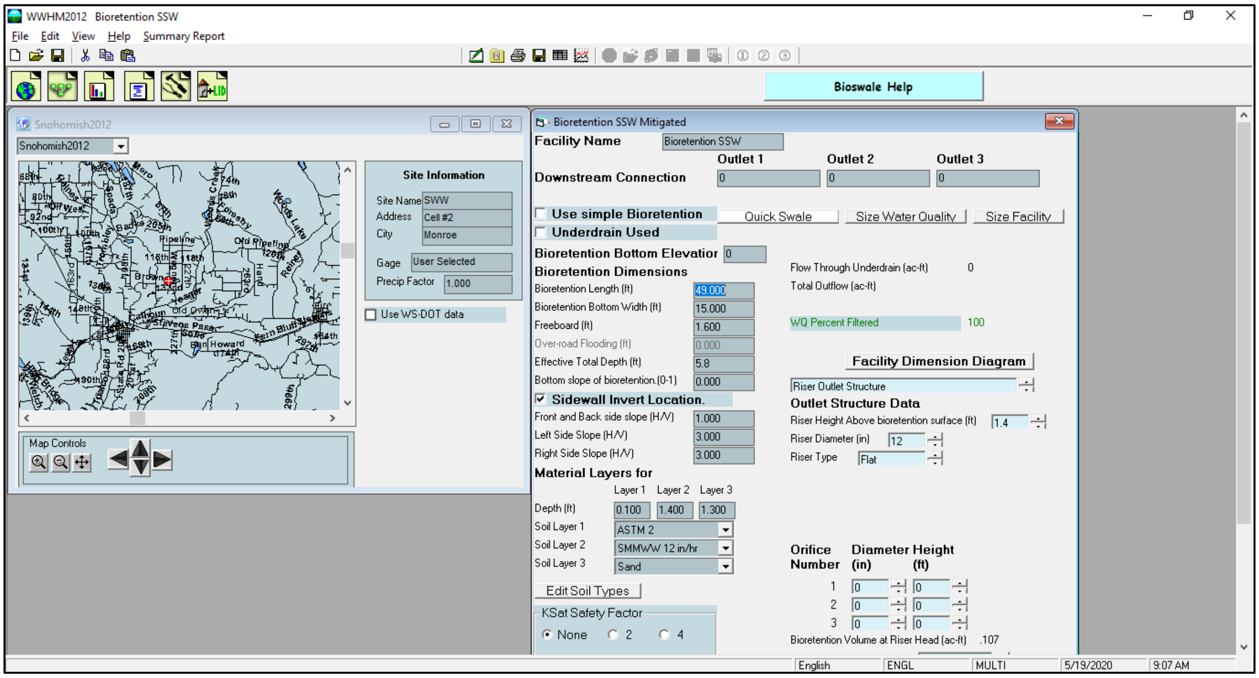



Figure RSH-5. RSH Daily Outflow Volumes

In Figure RSH-5 the RSH recorded outflow (blue) and the simulated outflow (red) daily volumes are shown. The simulated outflow is the sum of the surface discharge and the outflow from the underdrain. For most events the recorded outflow (blue) greatly exceeds the simulated outflow. As noted in the discussion above about recorded inflow and outflow, events when the outflow volume is unexpectedly large are probably due to the errors inherent with the difficulty of measuring very small outflow rates from this small bioretention facility.

The long-term modeling results based on the King County Sea-Tac Airport rain gage record show that RSH fails both MR #5 and MR #6. RSH's bottom area is only 0.9% of the drainage area to RSH. This site is too small to meet these minimum requirements and is overwhelmed by large runoff events.

SSW: Monroe, Snohomish County




The SSW bioretention site is located at Salem Woods Elementary School, just north of Monroe, Snohomish County, Washington. The drainage area to SSW consists of 0.4 acres of road on a moderate slope (5-15%). The original design assumed a drainage area of 0.22 acres of lawn vegetation, 0.03 acres of roof and 0.46 acres of road. However, site investigation work conducted by AESI and Aspect concluded that the roof and lawn area drainages were not connected to the bioretention site, as originally designed. A review of the drainage design also led to a small reduction in the roadway area draining to the site.

The SSW surface area footprint is 1022 square feet at the top of overflow. This equals 5.9% of the 0.40-acre tributary drainage area to SSW.

SSW has a surface outlet at 1.4 feet above the surface bottom. SSW has no underdrain. Overflow from the bioretention facility is discharged to an adjacent infiltration trench.

A native soil infiltration rate of 16 inches per hour together with a bioretention top soil layer of wood chips (represented by ASTM2 soil), a second soil layer of Ecology SWWMM soil mix (12-inch per hour infiltration rate), and a third soil layer of sand best reproduced the monitored soil moisture and surface ponding conditions. The wood chip layer was described in the geotechnical findings and added to reproduce monitored surface ponding depths.

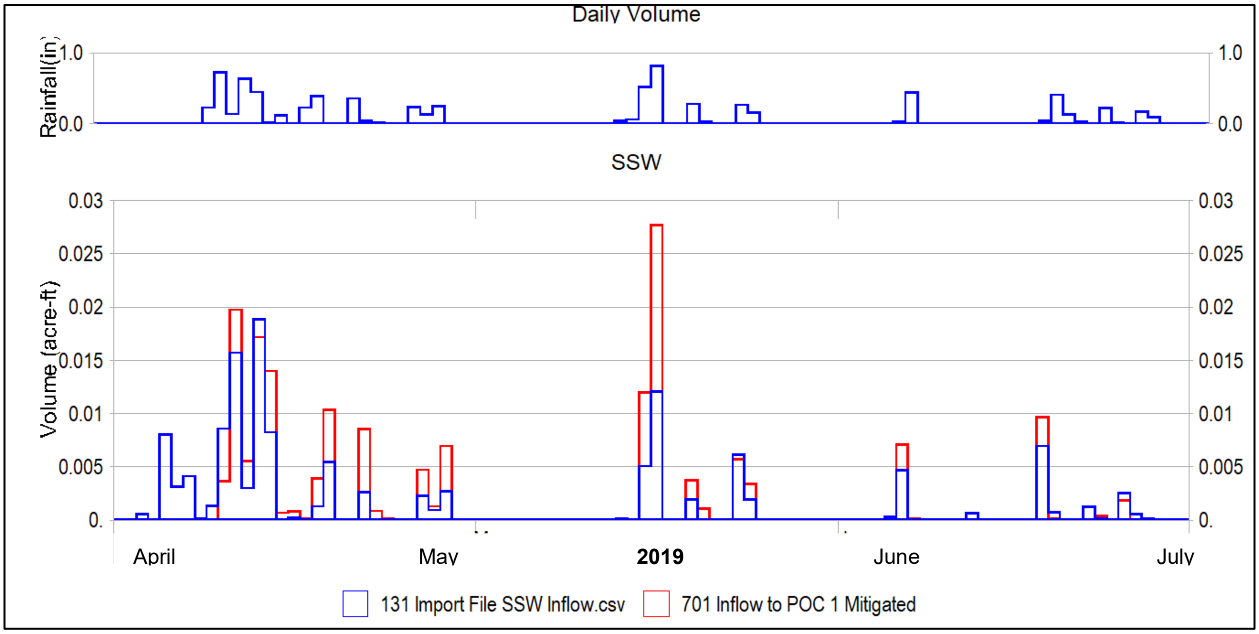



Figure SSW-1. SSW Daily Inflow Volumes

Figure SSW-1 shows the simulated (red) and recorded (blue) daily inflow volumes and, along the top of the figure, the SSW site monitored daily rainfall data. The simulated daily inflow volumes are larger than the recorded volumes. This difference may be caused by an over-estimation of the drainage area (even with the reduction noted above) or problems with measuring the actual inflow to the bioretention facility. The latter explanation is the most likely as the simulated and recorded ponding depths match well (Figure SSW-2).

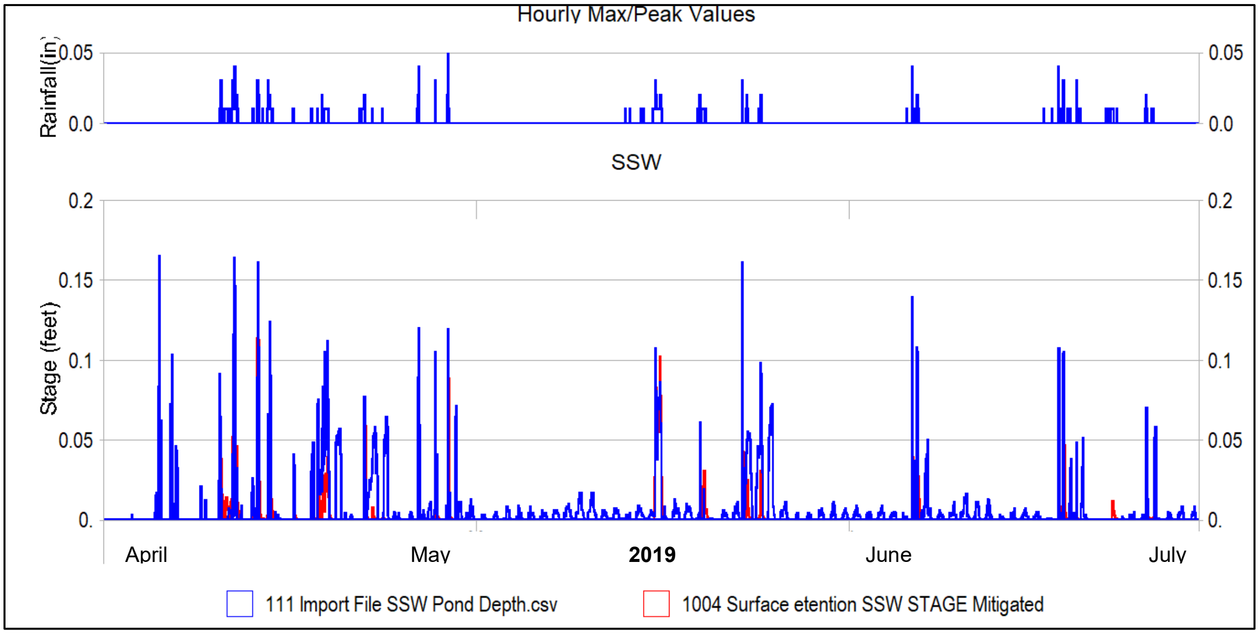



Figure SSW-2. SSW Hourly Surface Ponding Depths

Figure SSW-2 shows the simulated (red) and recorded (blue) hourly maximum 5-minute surface ponding (stage) values and, along the top of the figure, the SSW site monitored hourly maximum 5-minute rainfall data. The simulated and recorded ponding values match well (note that some of the simulated red lines are hidden by the recorded blue lines). As observed at some of the other sites, monitored ponding depth values fluctuate during dry periods due to diurnal temperature changes that affect the ponding depth sensor.

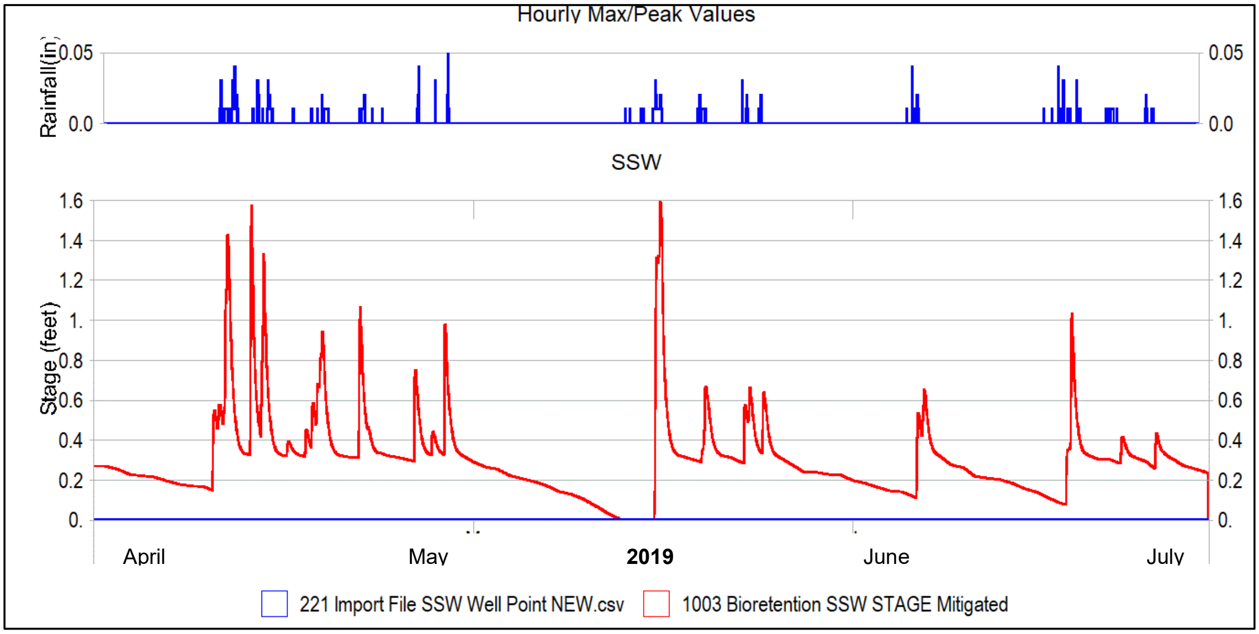
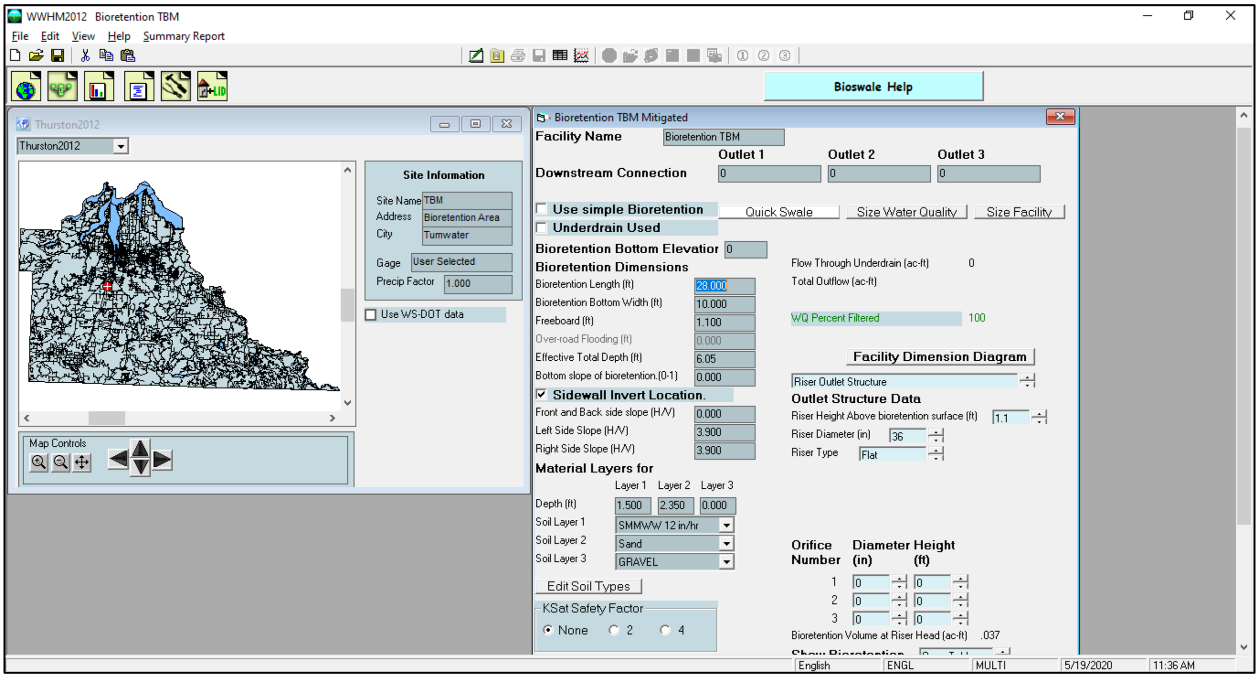



Figure SSW-3. SSW Hourly Soil Layer Well Point Elevations

Figure SSW-3 shows the simulated (red) and recorded (blue) hourly maximum 5-minute soil layer well point elevations (stage) values and, along the top of the figure, the SSW site monitored hourly maximum 5-minute rainfall data. The simulated values show higher water levels in the soil layer than the recorded well point data. The geotechnical report states that the underlying soil has a high infiltration. With the bottom of the monitoring well placed only 3 feet below the soil surface and the soil draining rapidly, it appears that the soil water levels never rose to the bottom of the monitoring well. Aspect reviewed the monitored data to doublecheck that there wasn't an error in the monitoring record,. No identifiable problems were found.

The long-term modeling results based on the Snohomish County Everett rain gage record show that SSW passes both MR #5 and MR #6. Ability to pass these two minimum requirements is due to infiltration of 100% of the total runoff volume (overflow from the bioretention facility was directed to an adjacent infiltration trench to ensure 100% infiltration was achieved).

TBM: Tumwater, Thurston County




The TBM bioretention site is located in Tumwater, Thurston County, Washington. The design drainage area to TBM consisted of 0.05 acres of A/B soil, lawn vegetation, flat slope (0-5%) and 0.13 acres of road on a flat slope (0-5%). Model inflows to the bioretention facility when compared to the monitored inflows were only approximately one-half of the monitored inflow volume. Monitored results led us to conclude that there must be additional drainage area contributing to TBM. Doubling the road drainage area from 0.13 acres to 0.26 acres produced more realistic model inflows, pond depths, and well point data.

The TBM surface bottom footprint is 366 square feet. This equals 2.7% of the tributary drainage area to TBM based on a total drainage area of 0.31 acres.

TBM has no surface outlet control structure but overtops the site at 1.1 feet above the surface bottom. All of the inflow to TBM is infiltrated into the native soil beneath the bioretention soil layers.

A native soil infiltration rate of 8 inches per hour together with a bioretention top soil layer of Ecology SWWMM soil mix (12-inch per hour infiltration rate), and a second soil layer of sand was observed on the site.

Figure TBM-1 shows the simulated (red) and recorded (blue) daily inflow volumes and, along the top of the figure, the TBM site monitored daily rainfall data. The simulated daily inflow volumes are low compared to the recorded inflow volumes. The water entering the bioretention facility apparently does not drain through the Ecology soil mix as quickly as calculated by the model.

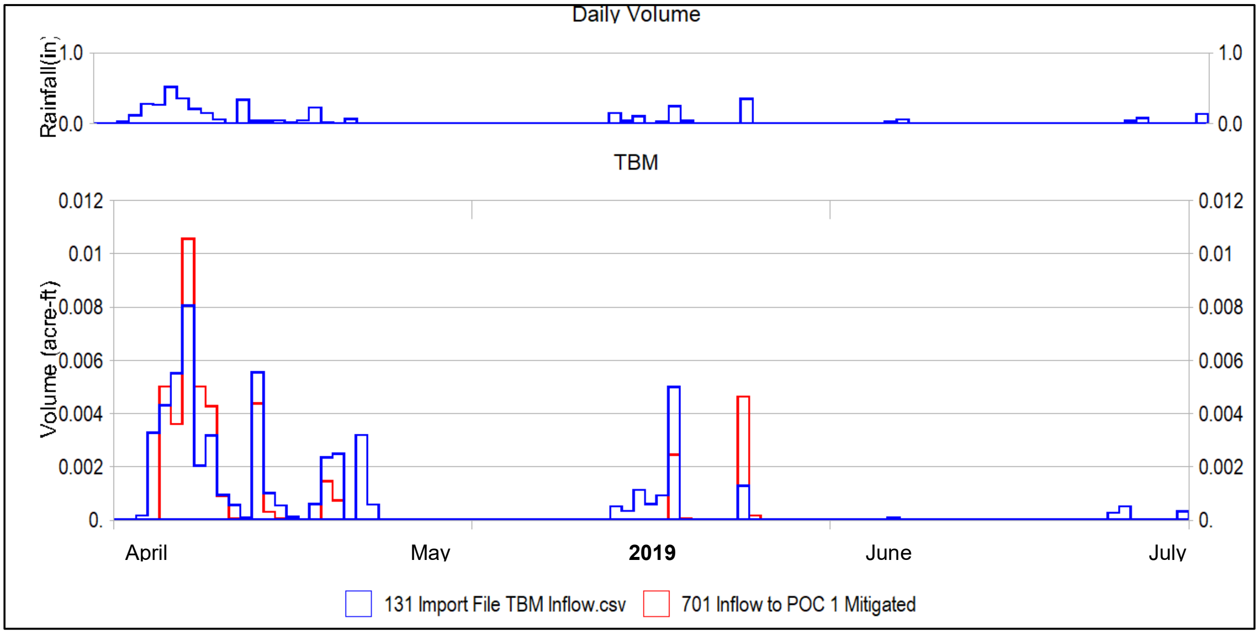



Figure TBM-1. TBM Daily Inflow Volumes

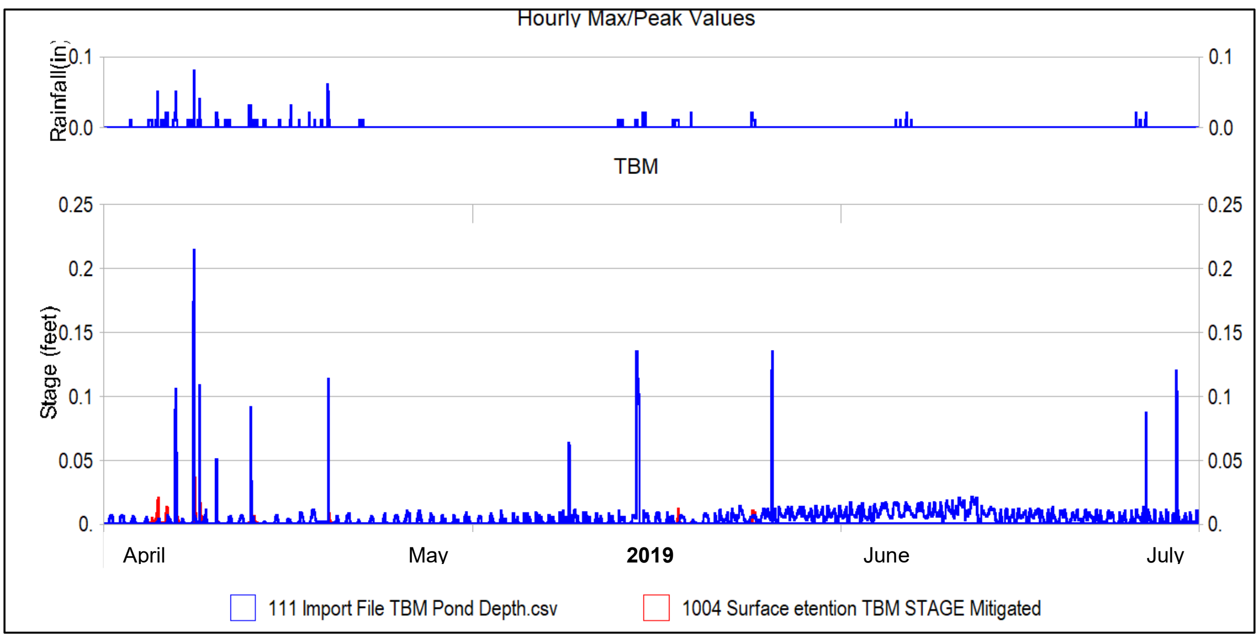



Figure TBM-2. TBM Hourly Surface Ponding Depths

Figure TBM-2 shows the simulated (red) and recorded (blue) hourly maximum 5-minute surface ponding (stage) values and, along the top of the figure, the TBM site monitored hourly maximum 5-minute rainfall data. The simulated ponding depths are consistently lower than the recorded ponding depths. As observed at some of the other sites, monitored ponding depth values fluctuate during dry periods due to diurnal temperature changes.

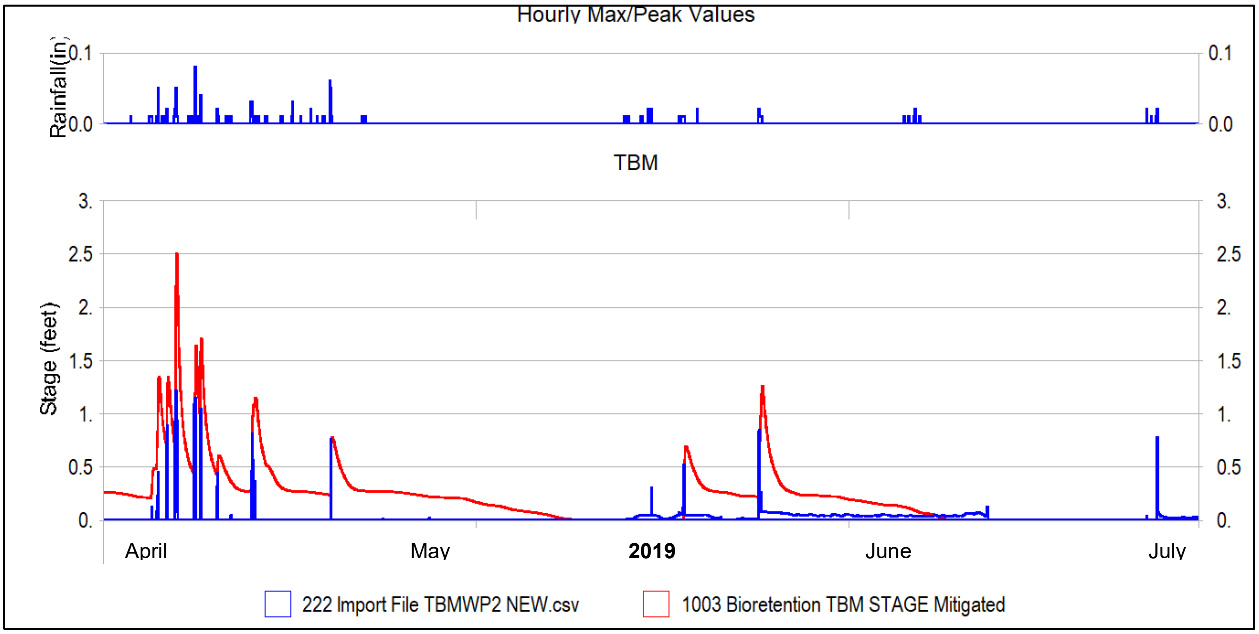
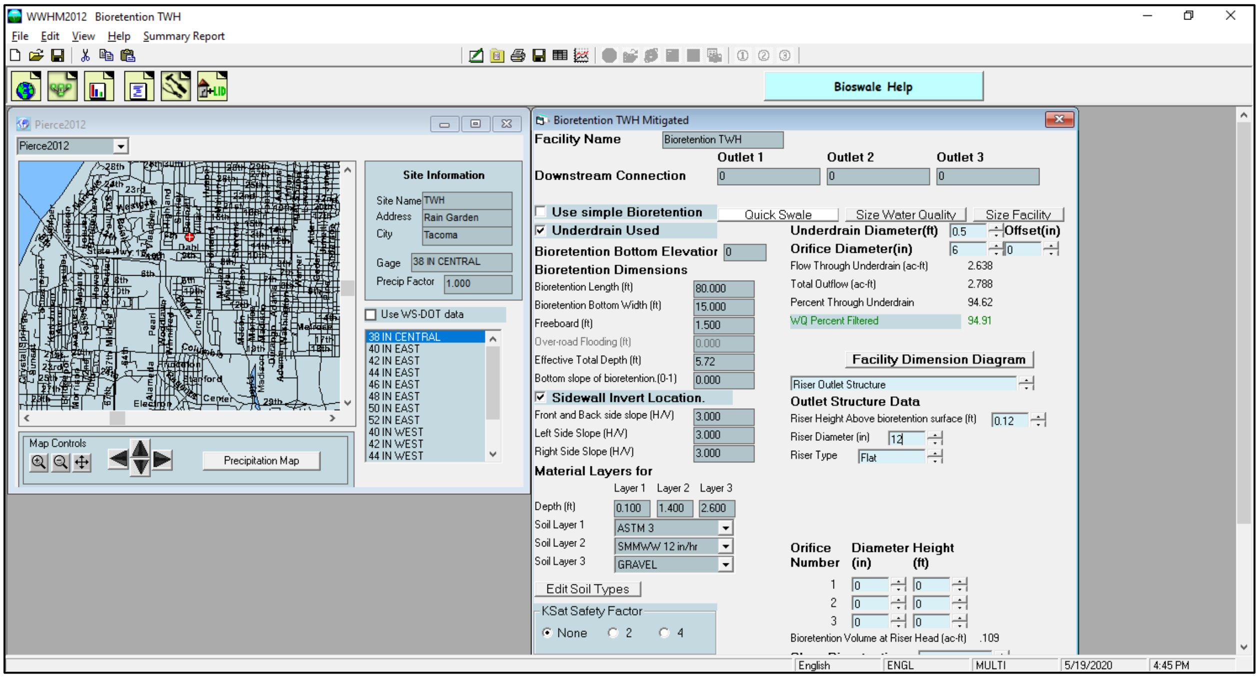



Figure TBM-3. TBM Hourly Soil Layer Well Point Elevations

Figure TBM-3 shows the simulated (red) and recorded (blue) hourly maximum 5-minute soil layer well point elevations (stage) values and, along the top of the figure, the TBM site monitored hourly maximum 5-minute rainfall data. The simulated values show longer drain times through the soil layers than the recorded well point data.

The long-term modeling results based on the Thurston County Olympia Airport rain gage record show that TBM passes MR #6 (water quality) but fails MR #5 (LID flow duration). TBM fails MR #5 because the surface overflow exceeds the flow duration standard for MR #5 (8% of Q2 to 50% of Q2) when ponding depths exceed 1.1 feet.

TWH: Tacoma, Pierce County




The TWH bioretention site is located in Tacoma, Pierce County, Washington. The drainage area to TWH consists of 0.19 acres of C soil, lawn vegetation, on a flat slope (0-5%) and 1.43 acres of road on a flat slope (0-5%).

The TWH surface area footprint is 1269 square feet at the top of overflow. This equals 1.8% of the 1.62-acre tributary drainage area to TWH.

TWH has a surface outlet control structure that is only 0.12 feet above the surface bottom. Most of the inflow to TWH is infiltrated into the bioretention soil mix beneath the top vegetative layer and then exits through an underdrain.

A native soil infiltration rate of 0.05 inches per hour together with a bioretention top soil layer of ASTM3 soil, a second soil layer of bioretention soil mix SMMWW (12 in/hr), and a third soil layer of gravel best reproduced the monitored soil moisture and surface ponding conditions. The top ASTM3 layer of 0.1 feet represents vegetative litter. This was added to reproduce monitored surface ponding depths.

Figure TWH-1 shows the simulated (red) and recorded (blue) daily inflow volumes and, along the top of the figure, the TWH site monitored daily rainfall data. The simulated daily inflow volumes are higher than the recorded volumes for some the rainfall events although overall the recorded peak inflows are larger than the simulated hourly inflow peaks (see Table 4).

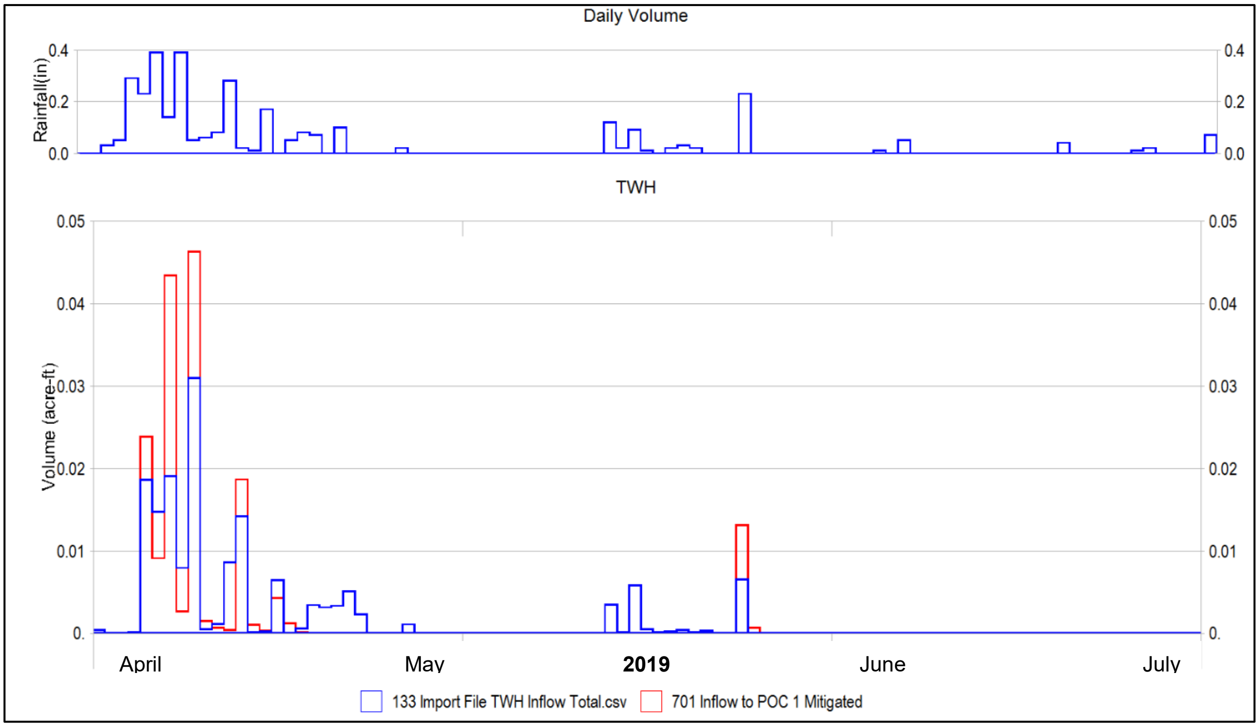



Figure TWH-1. TWH Daily Inflow Volumes

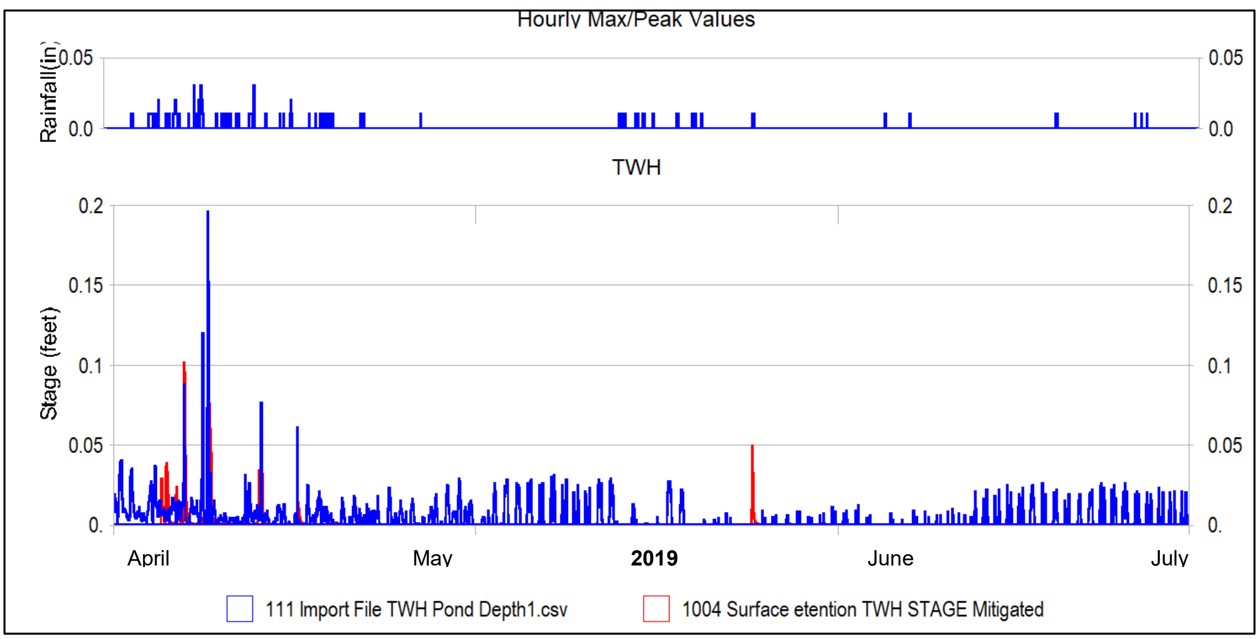



Figure TWH2. TWH Hourly Surface Ponding Depths

For TWH ponding depths were measured at two locations in the bottom of the bioretention facility. Figure TWH-2 shows the simulated (red) hourly maximum 5-minute surface ponding (stage) values; the recorded hourly maximum values for monitoring site 1 are shown in blue (monitoring site 2 values are less representative of the bioretention ponding depths than site 1). Along the top of the figure is the TWH site monitored hourly maximum 5-minute rainfall data. The simulated ponding values generally lower than the recorded values. As observed at some of the other sites, monitored ponding depth values fluctuate during dry periods due to diurnal temperature changes that affect the ponding depth sensor. These temperature changes are the source of the small daily recorded pond depths when there is no measured rainfall.

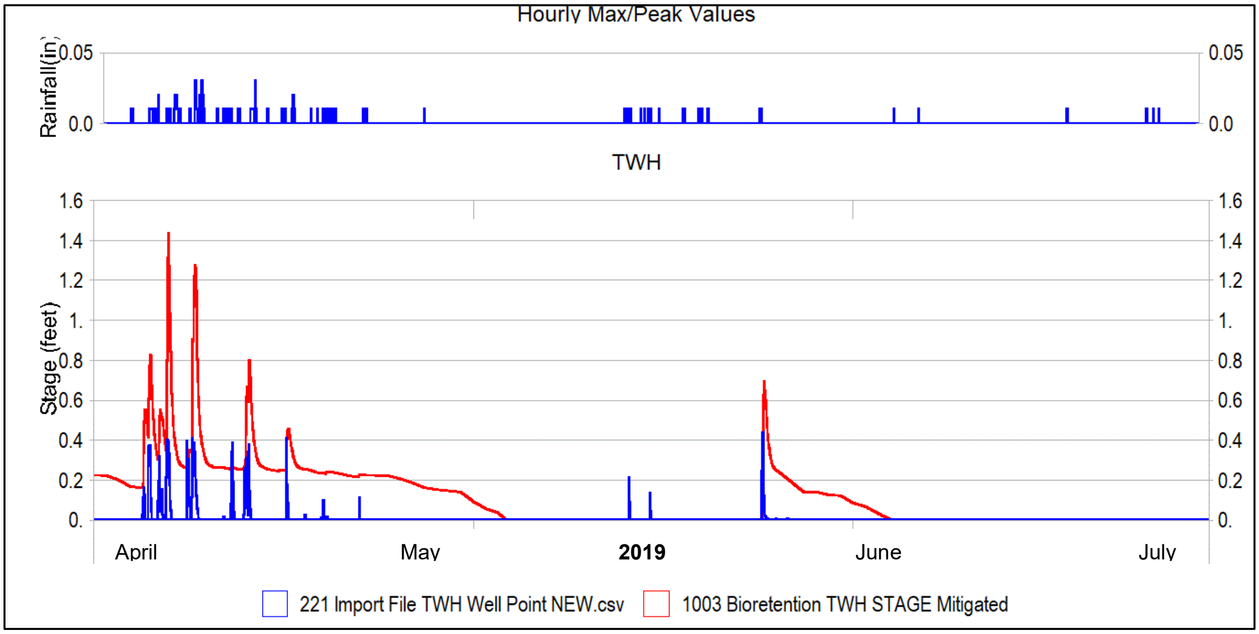



Figure TWH-3. TWH Hourly Soil Layer Well Point Elevations

Figure TWH-3 shows the simulated (red) and recorded (blue) hourly maximum 5-minute soil layer well point elevations (stage) values and, along the top of the figure, the TWH site monitored hourly maximum 5-minute rainfall data. The simulated values show longer drain times through the soil layers than the recorded well point data.

TWH has an underdrain, but there was no access to install monitoring equipment to measure the flow exiting the underdrain. As a result of this situation, no underdrain outflow measurements are available.

The TWH simulated combined outflow was compared with the measured/recorded outflow.

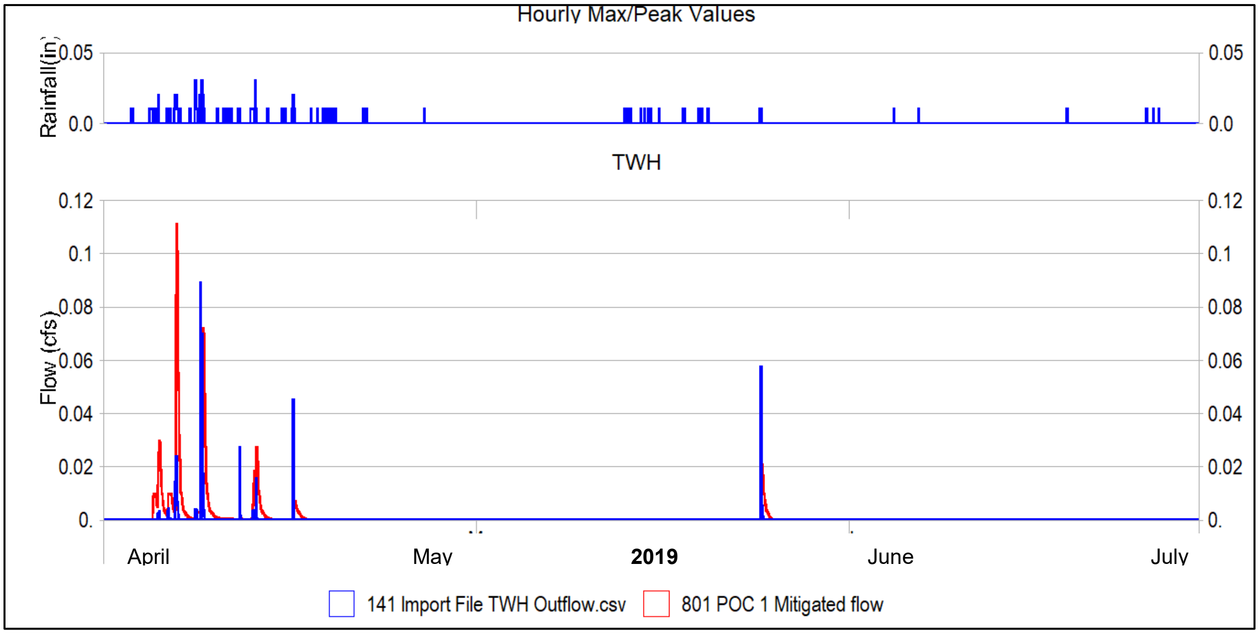



Figure TWH-4. Comparison of TWH Hourly Outflow Simulated and Measured Peak Flows

In Figure TWH-4 the TWH recorded outflow (blue and the combined simulated surface discharge and the underdrain outflow (red) hourly peak flows are shown. The recorded outflow (blue) and simulated outflow (red) results are similar. The surface discharge is very small compared to the underdrain outflow and is insignificant. For all practical purposes the underdrain produces all of the outflow. This same observation was made by AESI during the infiltration testing.

The long-term modeling results based on the Pierce County WSDOT 38-inch Central rainfall record show that TWH fails both MR #5 and MR #6. TWH's bottom area is only 1.7% of the drainage area to TWH. The relatively small size of TWH combined with its low riser height (0.12 feet) produces too much surface discharge to meet these minimum requirements and as a result TWH is overwhelmed by large runoff events.

**Summary**

In general the hydrologic performance of the ten bioretention facilities was well represented by WWHM2012. The range in performance in terms of ponding depths and well point elevations met or exceeded the expected WWHM2012 model graphical results comparison with the monitored data for many of the sites, although there was a frustrating lack of consistency from one site to another.

In general, the WWHM2012 models of the ten bioretention sites reproduced the monitored bioretention hydrologic performance data with accurate results when viewing the long-term graphical trends. Accurate results are defined as periods where the simulated results match closely with the recorded (monitored) data and other periods where the simulated results are sometimes high and sometimes low. Overall there is no obvious bias high or low.

As noted in our earlier study, it appears that there are two major model inputs that may be influencing the results. The vegetative litter cover can, at some sites, reduce the infiltration rate of the ponded water into the bioretention soil mix. At sites MPP, RSH, SSW, and TWM this vegetative litter cover was modeled using a limiting soil type (ASTM 1, ASTM 2, or ASTM 3). At the other six sites no vegetative litter cover was modeled.

The other major model input that may be influencing the results is the evapotranspiration (ET) from the bioretention soil mix. It is set in WWHM2012 to equal 0.5*PET (Potential ET). There is evidence from the well point data that the 0.5 multiplier factor should be higher. That will help to remove water faster from the bioretention soil mix layer.

As discussed above, Table 10 represents modeling for long term, and does not necessarily to match current hydrologic conditions of the sites at this current time. The long-term model results show the issues and problems that bioretention facilities are faced with in the real world. Some sites are undersized and do not meet MR#5 and MR#6, as a result. This may be due to retrofitting a site for stormwater control by adding a bioretention cell where space is limited. If the site is too small then the bioretention may not function as expected. As noted above, MR#5 failures are the result of either too much surface discharge (overtopping) or too fast underdrain discharge (due to the large diameter of the underdrain pipe and the absence of an underdrain orifice to restrict the underdrain discharge).

As a side note, sites with underdrains provide unique challenges. As was found by our field monitoring staff, underdrains are difficult and sometimes impossible to monitor. Without the ability to observe underdrain flows it is difficult to know where the underdrain water is going and at what rate.

MR#6 non-compliance is solely due to too much surface discharge. The limiting factors in meeting MR#6 are the surface area of the bioretention facility and the overflow height. The four sites that fail MR#6 (BCK, BUW, RSH, and TWH) all have small surface areas and low overflow heights. While some small sites met MR#6, no site with a surface area ratio percent less than 5% met both MR#5 and MR#6 standards.

The performance of the bioretention cells monitored in this study will be discussed as part of the final report.

At this time, based on the bioretention modeling completed for this study, we do not recommend any changes in the Ecology bioretention sizing criteria.

The complete set of WWHM2012 models for the ten sites has been provided to the Department of Ecology.