Bioretention Hydrologic Performance Study Final Report

Phase III
Assessment of Facilities Ten Years or Older

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Related Information

- Stormwater Action Monitoring projects aim to improve stormwater management. Learn about current and past studies at the SAM website[1].
- The Stormwater Work Group (SWG) oversees the SAM Program. Visit the SWG website.[2] to learn more.

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Table of Contents

List of Tables

List of Figures

List of Appendices

1.0 Executive Summary

1.1 Summary of Findings

The BHP III study examined bioretention facilities at least ten years post-installation and, consequently, provides us with new information on the long-term viability of facilities and how they may evolve over time. Overall, findings from the present BHP III study echoed findings from the previous BHP I and BHP II studies, further strengthening those conclusions. As a point of reference, recommendations from those previous studies are reproduced in Appendix A.

Representativeness of Sites Assessed

- Fifty sites selected for project assessment spanned a geographic range from Lynden, WA in the north and Olympia, WA in the south, and sites in Issaquah, WA and on the Kitsap Peninsula from east to west.
- All sites were constructed in 2013 or earlier to meet the project criteria of at least 10 years of operation.

Site Conditions Findings

- Sites remained generally identifiable as the original facility.
- Some non-engineered overflows and leaking overflow or containment structures allowed escape of flows before full infiltration.
- Surface flow paths across the facility were observed at times indicating potential effects on the lateral distribution of plant types and infiltration.
- Localized sediment accumulation and variation in plant species were observed near the facility points of inflow.

Vegetation Findings

- Approximately 45 of the 50 sites' original planting plans were located.
- Plant hydrophytic characteristics (described by the Wetland Indicator Status – WIS) shifted from original generally "wetter" planting plans toward "drier" plants observed today.
- The average number of herb species documented in the present conditions was 11.9 species across the 50 sites, while the average number of herbs in the original planting plans was only 2.9.
- Of the list of herbs in the original planting plans only 13.4% remained in the observed list indicating most of the original herbs died over the course of the site's operational life.
- Of the list of woody plants in the original planting plan 56% remained in the observed list indicating more than half of the original woody species survived over the course of the site's operational life.
- No correlation was apparent between the facilities' average weighted WIS and infiltration rates, suggesting other site characteristics were influencing the current plant composition.

Geotechnical and Hydrogeologic Findings

- Of the 50 sites evaluated 28 were typical design bioretention facilities (i.e., infiltrating to native subgrade) and 22 were underdrained.
- Sites were distributed across glacial outwash, recent alluvium and glacial till/drift geologic settings, with typical sites occurring generally on well infiltrating glacial outwash geology, while underdrained sites occurred more on the other less porous geology.
- Underdrained sites showed a generally higher distribution of infiltration rates than for typical sites.
- Infiltration rates overall remained high with no indication of clogging or sediment accumulation except localized areas near the point of inflow.

Modeling Review Findings

- Drainage reports from a total of 54 sites were reviewed; 28 of the 54 had useful bioretention modeling information.
- Of the 28 sites for which information is available, 11 used WWHM3 or its predecessor WWHM2 to model and size the bioretention cell. WWHM3 did not include a bioretention element so the modelers used either the pond element or the gravel trench element to represent the bioretention facility.
- Five sites were modeled and designed using MGS Flood, which does not have the bioretention algorithms required by Ecology for bioretention modeling. Two of the sites used KCRTS (King County Runoff Time Series); six used single-event models (Waterworks and SBUH); and one used the Pierce County LID Sizing Tool.
- Of the 28 sites which had bioretention modeling information, a total of 11 had sufficient information to compute the ratio of the bioretention base area to the contributing drainage area.
- Five of the 11 sites had basin area ratio values that were smaller than 5 percent, ranging from 1.4 to 4.7%. Of these five sites, infiltration rates ranged from 5.3 to 65 inches per hour, suggesting continued infiltration capacity even after 10 years or more of operation with large contributing areas.

Operations and Maintenance Findings

- Of the 50 sites more than half were maintained only 1-4 times per year.
- Most common maintenance activities were branch trimming, line trimming, and resulting debris and garbage removal.
- Sites in public view were maintained to a greater degree than non-public sites.
- Regular irrigation was primarily provided during the first two years of establishment followed by limited irrigation during dry periods or no irrigation.

1.2 Recommendations for Improved Designs and Performance

Recommendations from the present BHP III project are generally consistent with the findings from the previous BHP I and BHP II projects. As a point of reference, recommendations from these projects are reproduced in Appendix A.

Site Conditions Recommendations

- Monitor sites for non-engineered outflows, leaking overflow structures and buildup near the overflow that allow bypass of flows before full infiltration.
- Continue seasonal maintenance of inflow locations to prevent debris blockage.
- Conduct survey confirmation of site elevations of the bottom elevation and overflow elevations after construction.

Vegetation Planting Recommendations

- Document site environmental conditions (e.g., drainage ratio, aspect, shade, heat island, adjacent plant communities, meteorological, irrigation/maintenance conditions, infiltration rate, shallow ground water, underdrained or typical infiltration design) to inform the proposed planting plan to be consistent with these conditions.
- Consult the project administrative and operations and maintenance asset management plan for the site planting plan to be consistent with available management resources for site long term vegetation management.
- Revisit existing plant list guidance to recommend more facultative plants than obligate wetland plants for use throughout bioretention facilities.
- Provide a seed mix recommended specification as an option for sandy well drained soils for sites receiving low maintenance.

Geotechnical and Hydrogeologic Recommendations

- Locate typical bioretention cells in areas that can drain effectively.
- Monitor soil composition and texture to meet guidance specifications especially for organic matter and fine sand, silt and clay fractions.
- Monitor placement of bioretention soil media to avoid wet or compacting conditions.
- Monitor sites during large storm events to observe for non-engineered and leaking flows escaping the site.
- Monitor sites after large storm events to observe infiltration rates after discontinuation of rainfall inflows to confirm ongoing sufficient infiltration.

Modeling Recommendations

- Use current bioretention modeling recommendations from the SWMMWW.
- Conduct sensitivity analysis of modeling design bioretention areas using higher infiltration rates.

Operations and Maintenance Recommendations

- Maintain inflow locations to remove obstructions seasonally or in anticipation of storm events.
- Have site O&M and capital management staff participate in reviewing planting plan designs to ensure consistency with O&M level of service and budget planning.

2.0 Introduction

Bioretention facilities are generally recognized for their hydrologic detention and infiltration capabilities (Hoban and Gambirazio 2021). Until recently, however, little data existed to verify the hydrologic performance of these facilities in the Puget Sound region (Taylor et al. 2018, 2020). Even without confirming performance, the use of bioretention remains widespread in the Puget Sound region and is used as a stormwater management option to meet the requirements of the National Pollutant Discharge Elimination System (NPDES) Municipal Permits and the 2019 SWMMWW (Ecology, 2019). Indeed, the use of bioretention is anticipated to accelerate with the findings that the toxic compound 6-PPD was potentially removed from road surface stormwater runoff after draining through bioretention facilities (Navickis-Brasch et al. 2022).

With the ongoing use of bioretention, State and local government officials are looking for design guidance and validation to ensure that bioretention facilities constructed under previous versions of the design guidance in the SWMMWW attain their desired performance. Meeting expected infiltration and overflow conditions from bioretention facilities helps ensure downstream receiving waters are hydrologically protected. The downstream cumulative benefit of bioretention facilities on receiving waters will depend on the hydrologic performance of each of the individual facilities within a basin.

To assess the performance of existing bioretention facilities in the Puget Sound Region, Taylor et al. (2018, 2020) conducted intensive hydrologic performance monitoring of twenty bioretention facilities (BHP Studies I and II). Monitoring of these facilities included measuring infiltration rates and continuous inflows and overflows to compare observed field performance with their engineering design model. While some of the constructed facilities dimensions and bioretention soil media (BSM) composition did not meet design specifications, results nonetheless indicated the facilities provided infiltration capacity for most of the inflows and generally matched the modeled design flows.

A major unknown remaining in the performance of bioretention facilities, however, is the life span of a facility's infiltration performance. Do bioretention facilities continue to infiltrate the inflows as the BSM is exposed to stormwater loading over time? The hydrologic performance of bioretention facilities may affect the survival, composition, health and maintenance of the facility vegetation, which may, in turn, have an influence on the infiltration of the facility over time. Conducting a performance assessment of older bioretention facilities represents another point-in-time assessment to help ensure bioretention facilities perform well in the Puget Sound region.

The current BHP Study III is intended to assess the performance of ten-year-old or older constructed facilities through assessing each facility's infiltration rate, soil composition, vegetation community and maintenance practices. The objectives of this study were to:

- Assess bioretention potential lifespans of different sites through facility infiltration rates, soil composition, vegetation, and maintenance practices.
- Conduct a point-in time checkup on up to 50, 10-year-old or older bioretention facilities. The key field data collected were:

- Field infiltration rates using standardized, repeatable procedures;
- Overall condition including evidence of inlet efficiency, erosion, deposition, clogging, debris accumulation and overflow;
- Geotechnical data including bioretention media thickness and composition (grain size, organic content); mulch layer presence, extent, and thickness; relative soil compaction; and subsurface geologic and groundwater conditions using hand-augered boreholes.
- Vegetation community data including vegetation composition and structure, stem density of woody plants, and estimating the percent cover of herbaceous plants using quadrats;
- Maintenance practices and frequency through interviews with maintenance personnel or managers; and
- Site and facility design information as available including estimated cell size, drainage basin area, impervious acreage, and facility design specifics (age, BSM surface area, inlets, underdrains, outlets, ponding depth, assumed design rate).

In addition to the above data collection objectives, the goals of the project were to:

- Communicate the long-range bioretention effectiveness to a broad base of NPDES permit holders.
- Gather a large dataset on different systems to understand the possible influence of the above factors on facility hydrologic performance.
- Use the bioretention site documentation generated from this study as a baseline for potential follow-up studies in another ten years (or so) to see how the sites continue to age over time.
- Provide guidance from an engineering, maintenance and capital management perspective on what lessons can be learned from these older sites; identify the factors to help ensure bioretention sites perform well in future designs; and build confidence in the longevity of properly designed and constructed bioretention systems.

2.1 Literature Review

Recent scientific literature has begun to address the longevity of bioretention infiltration rates in general, and the role of vegetation and BSM composition in the infiltration rates observed in older facilities. The following summary of findings for infiltration and associated vegetation communities is largely for field scale sites. Past laboratory column studies have been conducted to simulate the hydraulic and particulate loading that bioretention soils may experience over time. However, recent authors of field-scale studies suggest that field-scale conditions are substantially different than column studies leading to caution being recommended in the direct application of column results to expected field conditions (Dagenais et al. 2018; Hoban and Gambirazio 2021).

Environmental site conditions can affect the evolution of infiltration rates at bioretention sites in addition to vegetation root growth and decay. These include hydrologic and particulate loading rates, wetting drying cycles, and soil compaction among others. Additionally, some authors recognize that changes in infiltration rates are spatially variable because of greater deposition of particulate matter and frequency of inflows near the facility inflow location leading to lower infiltrations rates in the immediate vicinity of the inlet (Willard et al. 2017; Klug et al 2018). These spatially variable infiltration rates and the location of inflows further influence the spatial distribution of vegetation types.

Several recent review articles summarize the findings of multiple field scale studies. These review articles provide good discussions and conclusions on the interactions of hydrology, soil, and vegetation that contribute to the observed performance of bioretention facilities. Notable review articles include Dagenais et al. (2018), Hoban and Gambirazio (2021), Kluge et al. (2018), Muerdter et al. (2018), Skorobogatov et al. (2020), and Techer and Berthier (2023).

Infiltration Rates Affected by Vegetation and Facility Age

In a literature review article Dagenais et al. (2018) compared empirical evidence from studies with the claims of the role of plants in stormwater design guidelines from around the world and addressed whether the literature supported these claims. Based on review of literature these authors found that the claim that "growth, senescence, death and subsequent degradation of plant roots create pores which help maintain soil porosity," is supported in the literature and that this mechanism is an "important" role of plants on the hydraulic performance of bioretention facilities. They note that "Several studies have demonstrated an influence of vegetation on the evolution of permeability over time in stormwater bioretention systems." However, "the potential for plant-created preferential flow paths, leading to pollutant migration, has not been adequately studied in the bioretention context."

Hoban and Gambirazio (2021) reviewed literature for continuous flow results through 15 bioretention facilities of 1 to 10 years of age and found large reductions of flow volumes over time. While direct infiltration rates were not measured, the observed field scale reduction of flows indicated "capacity of bioretention systems to attenuate peak flows and runoff volumes through detention and retention." The role of plants in the sites was not documented but the authors concluded that "Bioretention filter media specifications should be revised with an increased emphasis on plant health and water retention," and that "In terms of overall performance, increased organics are likely to be beneficial . . ."

Kluge et al. (2018) evaluated infiltration rates of 22 constructed bioretention facilities aged from 11 to 22 years in operation in Germany. Of the 32 individual double ring infiltrometer tests conducted in "sand - loamy sand" media, results ranged from 130 to 7.9 inches per hour. Results of 16 tests conducted from a set of finer grained "sandy loam – silty loam" ranged from 10.6 to 0.1 inches per hour. It should be noted that the double-ring method has been documented to mis-represent infiltration rates (both over- and under-estimate, particularly in sandy sediments (Ecology, 2019; Phillips and Kitch, 2011).

These findings indicated that "Most of the sampled systems correspond well with the recommended hydraulic conductivity of the technical guidelines in Germany" (1.4 to 14.1 inches per hour) for these systems aged 11 to 22 years. Additionally, results from corresponding metals accumulations in the facilities showed higher concentrations near the inflow points. The location of these higher pollutant concentrations near the inflows was used to infer that inflowing water infiltrated heterogeneously across the facility soil surface with a greater hydraulic load on the soils near the inlets due to being exposed to more small storm inflows. A greater extent of infiltration near the inflow points was one of the findings of the local studies by Taylor et al. (2018, 2020).

Muerdter et al. (2018) investigated the role of vegetation in bioretention and reviewed numerous articles to "describe plant traits and species that improve pollutant removal and hydrologic function." In the role of stormwater infiltration:

> *"The roots of bioretention vegetation create macropores and root channels that enhance media hydraulic conductivity and prevent clogging. Specifically, more extensive, thick roots and vigorous vegetation growth rates increase infiltration over time and are recommended for clogging prevention."*

However, "less-effective pollution removal performance may sometimes be a tradeoff of the increased infiltration and clogging prevention created through root density."

Skorobogatov et al. (2020) reviewed bioretention studies to "highlight data that challenge the importance of media as being the dominant design parameter and argue that the long-term performance is shaped by the interactions between media and the living components of a bioretention system, especially vegetation." The findings of their review emphasize "the impact of plant roots on media pore structure, which has implications on infiltration, storage capacity, and treatment." This emphasis on the soil structure rather than texture alone has been noted in several literature articles (cf. Johnston et. al. 2020 summarized below). Skorobogatov et. al (2020) note from their review of articles that:

> *Multiple studies demonstrated markedly different infiltration rates for systems of the same texture due to the impact of vegetation (Gonzalez-Merchan et al., 2014; Selbig and Balster, 2010; Virahsawmy et al., 2014). It has even been argued that living organisms may have a greater impact on infiltration capacity than the intrinsic properties of soil itself (Funai and Kupec, 2017). Le Coustumer et al. (2012) demonstrated that plants with thick roots show promise at maintaining the infiltration capacity of bioretention systems and counteracting clogging.*
>
> *A recent study conducted by Hart et al. (2017) concluded that there is a positive correlation between root morphology and infiltration rates in bioretention systems as well as seasonal variability in infiltration associated with root traits. The notion that plant roots can create macropores and thus enhance infiltration in as short of time as 1 to 2 years has been thoroughly reviewed by Beven and Germann (1982, 2013), yet a working understanding and appreciation of the phenomena is still lacking.*

Techer and Berthier (2023) reviewed literature on bioretention "to clarify the vegetation influences on bioretention media hydraulic conductivity, with the ultimate goal of improving guidance on plant choice for system durability." In general, their literature review found depth of rooting, root size, and density positively influenced water infiltration and percolation. Following these root characteristics, in most cases, vegetation selection had a determining role in maintaining initial media infiltration rates, with in terms of improvement: turfgrass < prairie grass < shrubs < trees. Furthermore:

results confirmed that among the herbaceous species, "prairie grass" (wild type, "rustic" species mixtures) or more "hardy grass" type covers are to be preferred over more commercial or "domestic" grass type like turfgrass (which have very shallow roots) in order to efficiently prevent surface clogging or media compaction phenomenon, especially in clay-type or fine-textured media. In fact, species with thick/fleshy and tap root/deep root systems are generally to be favored if infiltration is intended to be the dominant runoff management process.

Among these plants "spontaneous" (aka volunteer) vegetation may quickly become a significant portion of the vegetation community, and "proves to be better adapted to the local media hydrological regime, its compaction level as well as the overall quality of receiving urban runoff.

Finally:

Indeed, this literature synthesis confirmed that vegetation could play a determining role in maintaining bioretention performances, especially infiltration (and drainage) flows at levels comparable to those observed at the early beginning of the device implementation, or in ranges ensuring proper hydrological functioning by limiting the effects of naturally occurring compaction or clogging (i.e., sediment deposits). This overall positive effect of vegetation on infiltration is generally observed in fields and can be explained by their root functional traits.

Willard et al. (2017) monitored changes in flows between the 2007 – 2008 wet season and 2013 – 2014 in a bioretention cell in Raleigh, North Carolina. While only one cell was monitored and infiltration rate was not directly monitored, results of the flows comparing the two storm seasons indicated "that performance of a bioretention cell after seven years of use is not significantly different than performance immediately postconstruction . . ." Greater degrees of sediment again accumulated near the inlet as seen by Kluge et al. (2018). The authors note that vegetation root structures and initial high sand content may have led to long term infiltration capacity, but "media should contain enough sand to prevent clogging, yet enough organic matter and iron and aluminum hydroxides to promote denitrification and sorption of nutrients and metals to the media." Vegetation recommended for the facility was turfgrasses for easy maintenance with minimal (i.e., yearly) mowing.

Johnston et al. (2020) conducted a study of controlled hydrologic loading in replicated bioretention field test beds treated with turfgrass, prairie plants, shrubs, and controls lacking vegetation. Hydrologic response measured beneath the test beds showed the turf grass and prairie plant treatments facilitated more rapid hydrologic response through the soil beds than the shrubs and no vegetation treatments, indicating flow paths through the soils were facilitated by the root paths and otherwise associated soil structure. The authors conclude that:

"Here, we find supportive evidence that the textural domain of soil porosity was unchanged, but after four years, plants altered the structural domain of the soil mixture by changing Ks, infiltration, and soil water retention. These findings

signify how plant roots can be the catalysts for the alteration of soil porosity and connectivity."

In a study of ten bioretention facilities conducted in the Pacific Northwest, Hart (2017) compared infiltration rates during winter and late spring months. This study found seasonal differences in infiltration rates correlated with sampled root density, depth and surface area in plant roots, with higher rates occurring during late spring months. Rates observed in this study were measured as a rate of decline in ponded stage observed after cessation of rainfall events.

While infiltration rates were observed to differ seasonally, average rates were relatively low overall compared to rates reported in some other studies and in this study. "The average infiltration rate for all 10 facilities was lowest during the winter months (Oct-Feb) averaged around 3.7 cm/hr, increased Feb to Mar, averaged around 5.7 cm/hr from Mar - May, peaked at 8 cm/hr in Aug, decreased Sept to Oct, and averaged around 3.7 cm/hr in the winter (Dec 2014 – Feb 2015)." This range corresponds to approximately 1.45 to 3.15 inches per hour. These infiltration rates were determined from declining pool stages over time, in facilities without underdrains, so represent the overall infiltration rate into the subsurface. Vegetation composition in these sites was very narrow (the study "compared five larger-root facilities (*Juncus patens* dominant + tree) with five smaller-root facilities (*Carex species* dominant)". Soil texture was not reported.

In many of these literature sources reviewed the authors note the potential tradeoff between the influence of the growth of root structures on maintaining infiltration rates and the potential development of preferential flow paths that could circumvent contact with soil particles for pollutant removal. The degree to which preferential flow paths appears to be a factor in pollutant removal remained uncertain in the opinion of some of the authors reviewed here (Dagenais et al. 2018; Funai and Kupec 2017; Muerdter et al. 2018;). However, "preferential flow paths" alone would not pose a water quality concern at typical (non-underdrained) systems that fully infiltrate into the subgrade.

A number of these literature sources evaluating infiltration rates and the role of vegetation in maintaining those rates also noted there was a likely feedback loop of the influences between the placed soil media mix (sandy texture and organic composition), plant success, root growth, and senescence. This feedback loop results in the evolution of a more porous soil structure that is then the actual basis for sustained infiltration in older bioretention facilities. Indeed, factors other than plant roots such as maintenance, irrigation, compaction, soil fauna, etc. will also likely affect the outcome of bioretention infiltration rates in such a feedback loop.

Finally, many of these papers recognize the likely tradeoff between the relatively high sand composition of most soil mixes for bioretention (Funai and Kupec 2017), successful vegetation root growth and the development of potential "preferential flow paths." Sandy textured bioretention soil may constrain the types of vegetation and their associated root growth that thrive but may remain highly porous, nonetheless. Funai and Kupec (2017) suggest greater attention to the sand and fine soil textures may allow a greater range of successful plant selection for aesthetic or ecological reasons while recognizing greater maintenance will also be required. Greater pollutant removal may then also result from relatively higher portions of fine grain materials in the BSM.

Overall, potential site-specific influences on plant development and infiltration rates suggested in this literature include:

1. Soil texture of the bioretention media
2. Vegetation rooting depth and size and density of roots
3. Particulate loading rate
4. Hydraulic loading rate
5. Storm size distribution and seasonal distribution
6. Wetting and drying cycles
7. Compaction
8. Frequency of maintenance and irrigation
9. Horizontal variation in vegetation related to inflow and travel paths
10. Site aspect, solar exposure, temperature ranges and evapotranspiration
11. Replanting and mulching

Overall, these literature reviews support the idea that these systems are open dynamic systems with feedback processes that evolve over the life of the facility. The resulting long-term hydrologic and vegetation performance of these facilities will be in response to a few primary site-specific influences that ultimately drive the evolution of the site conditions such as the original soil media texture, maintenance activities (or lack thereof), and local aspect. As such each site's design will have factors that influence the overall final outcome. The more these influences are identified initially during facility design the more likely the long-term outcome will be reached quickly and in a stable manner.

3.0 Study Design and Site Selection and Study Design

This study is about bioretention facility lifespans, and the intent is to conduct a point-in-time checkup on up to 50, 10 years or older bioretention facilities, and then communicate the long-range bioretention effectiveness to a broad base of jurisdictions holding NPDES permits. The results would be based on measuring on how well bioretention continues to perform (especially infiltration rate) and identifying what site characteristics are common for well performing or under-performing systems. It is not a study of hydrologic model parameters, continuous hydrologic performance, or water quality/chemistry.

This study provided controlled field measurements of infiltration rate, assessment of the vegetation community composition, and related site conditions to evaluate maintenance thresholds for bioretention facilities and provide key performance information on stormwater control measures.

Site selection was conducted through direct communication with regional stormwater managers to inquire about their existing bioretention facilities that may qualify for the age and bioretention design criteria for the study. After receiving nominations for site inclusion, design reports and site visits were conducted to affirm the design conditions qualified and that available access and water supply were sufficient for the infiltration test.

3.1 Project Goals

Information on infiltration rates, design, age, vegetation conditions, maintenance practices and other hydrogeologic data can provide baseline information for better understanding of bioretention lifespans and considerations for benefit and tradeoffs in assessing stormwater treatment alternatives. Assessing bioretention lifespans can address practical questions about how quickly different sites age and thus help judge the capital investment and asset management value of alternative sites and even alternative technologies in providing water quality treatment.

Goals for this project were to:

- Gather a large dataset on different systems to understand the possible influence of the above factors on performance.
- Use the bioretention site documentation done in this study for use as a baseline for a potential follow-up study in another ten years (or so) to see how the sites continue to age over time.
- Provide guidance from an engineering perspective on what lessons we can learn studying these older sites; what are the critical factors to prevent bioretention site performance failure in future designs; and build confidence in the longevity of properly designed/ constructed bioretention systems.

Previous field assessment of installed facilities in the BHP Studies I and II demonstrated variability in infiltration rates, plant community (composition, density), bioretention media composition, and soil compaction between facilities. However, these previous assessments did not assess the longevity of the hydrologic performance of the sites or how sites change over time.

3.2 Project Objectives

There are many regional bioretention facilities that are over 10 years old and some more than 20 years old. Performance and condition measurements after a decade or more of performance will provide valuable lifespan information. The objectives of this study are to:

- Conduct a point-in-time checkup on up to 50 older (10 years or older) bioretention facilities. The key field data to be collected were:
    - Field infiltration rates using standardized, repeatable procedures;
    - Overall condition including evidence of inlet efficiency, erosion, deposition, clogging, debris accumulation, and overflow;
    - Geotechnical data including bioretention media thickness and composition (grain size, organic content); mulch layer presence, extent, and thickness; relative soil compaction; and subsurface geologic and groundwater conditions using hand auger boreholes.
    - Vegetation community data including vegetation composition and structure, stem density of woody plants, and estimations of the percent basal cover of herbaceous plants using quadrats;

- Maintenance practices and frequency through interviews with maintenance personnel or managers; and
- Site and facility design information where available including estimated drainage basin area, impervious acreage, facility design specifics (age, BSM surface area, inlets, underdrains, outlets, ponding depth, assumed design rate).

- Communicate the long-range bioretention effectiveness to a broad base of NPDES jurisdictions.

3.3 Site Selection Criteria and Selection Process

The site selection process was simply to contact local jurisdiction NPDES permit managers to inquire of their interest to nominate a bioretention facility built in 2013 or earlier for participation in the study. Numerous candidate sites were identified and an initial review of site plans was conducted to confirm the site was old enough and that the facility was constructed as a bioretention facility. Age of the facility and construction as a bioretention facility were the only firm criteria for site selection, with other flexible criteria included such as access and geographic distribution.

4.0 Results and Discussion

During the earlier BHP studies, we heard anecdotal concerns from jurisdictions, engineers, and in the literature about bioretention lifespan, particularly due to the possibility of (1) clogging of the systems over time, and (2) soil compaction, both of which can result in an overall reduction in permeability. Slow draining facilities can also cause problems of stagnant water and aesthetic problems and vegetation failures, leading to difficulties in acceptance of bioretention as a drainage or stormwater solution.

Following are results of the data collection and a discussion of these data in relation to issues identified in the literature review and in relation to potential guidance recommendations for future site designs. Site methods and raw data are available in the discipline reports (Raedeke Associates, Inc. 2023a, b; Associated Earth Sciences, Inc. 2024).

4.1 Geotechnical and Hydrogeologic Assessment

Geotechnical and hydrogeologic assessments included physical assessment of each site's infrastructure compared to design plans, multiple shallow hand borings, shallow well points, controlled field infiltration tests, geotechnical T-probe for compaction, and laboratory testing for BSM grain size and organic matter. A detailed description of methods is provided in the Quality Assurance Project Plan (Raedeke Associates, Inc. and Associated Earth Sciences, Inc. 2023). The findings from these investigations were intended to characterize the overall site conditions related to infiltration results and potential interrelated factors influencing vegetation success and composition.

Cell Condition Relative to Plans

Overall cell constructed conditions were consistent with plans in 38 of the 50 sites. Some variations included non-engineered overflows and bypasses such as leaking overflow structures and landscape modifications such as incorporating the facility into a residential lawn. Sites often had micro-topographic flow pattern as described above that resulted in variable infiltration across the facility. Figure 1 provides an example of observed standing water, non-uniform surface flow path and variable infiltration conditions at one test site.

Hydrogeologic Setting, BSM Soils, and Infiltration Rates

Hydrogeologic setting provides an important backdrop to understanding the design selection of whether a site was a “typical” design (no underdrain and infiltrating flows through the BSM then infiltrate into the native subgrade) or was an “underdrain” design (where infiltrating flows through the BSM are collected in a perforated underdrain pipe that diverts flows away from the bioretention facility and into a conventional street stormdrain system).

Table 1 provides a summary of the geologic setting of the sites studied. Distributions of the typical infiltrating and underdrained design types are separated appropriately between more highly infiltrating subgrades and less permeable subgrades that would not infiltrate waters well. Still, some lower permeability subgrades were established as typical designs.

The BSM installed at the various sites was sampled to evaluate the grain size distribution and organic content of all 50 sites. Grain size distributions are plotted compared to the current envelope of grain size specifications presently provided in the Stormwater Management Manual for Western Washington (WDOE 2019).

Results indicate many of these 50 older sites had fines content higher than that specified in the Ecology manual (Figure 2). As a point of comparison, this same grain size analysis of the previously studied 20 younger sites (Taylor et al. 2018, 2020) had fine fractions generally within or lower than the specified Ecology range. Even with this higher proportion of fines the overall site infiltration rates ranged over three orders of magnitude (Figure 3). These samples were collected at a depth suggesting they represented the original BSM material and not from accumulated fines from inflows.

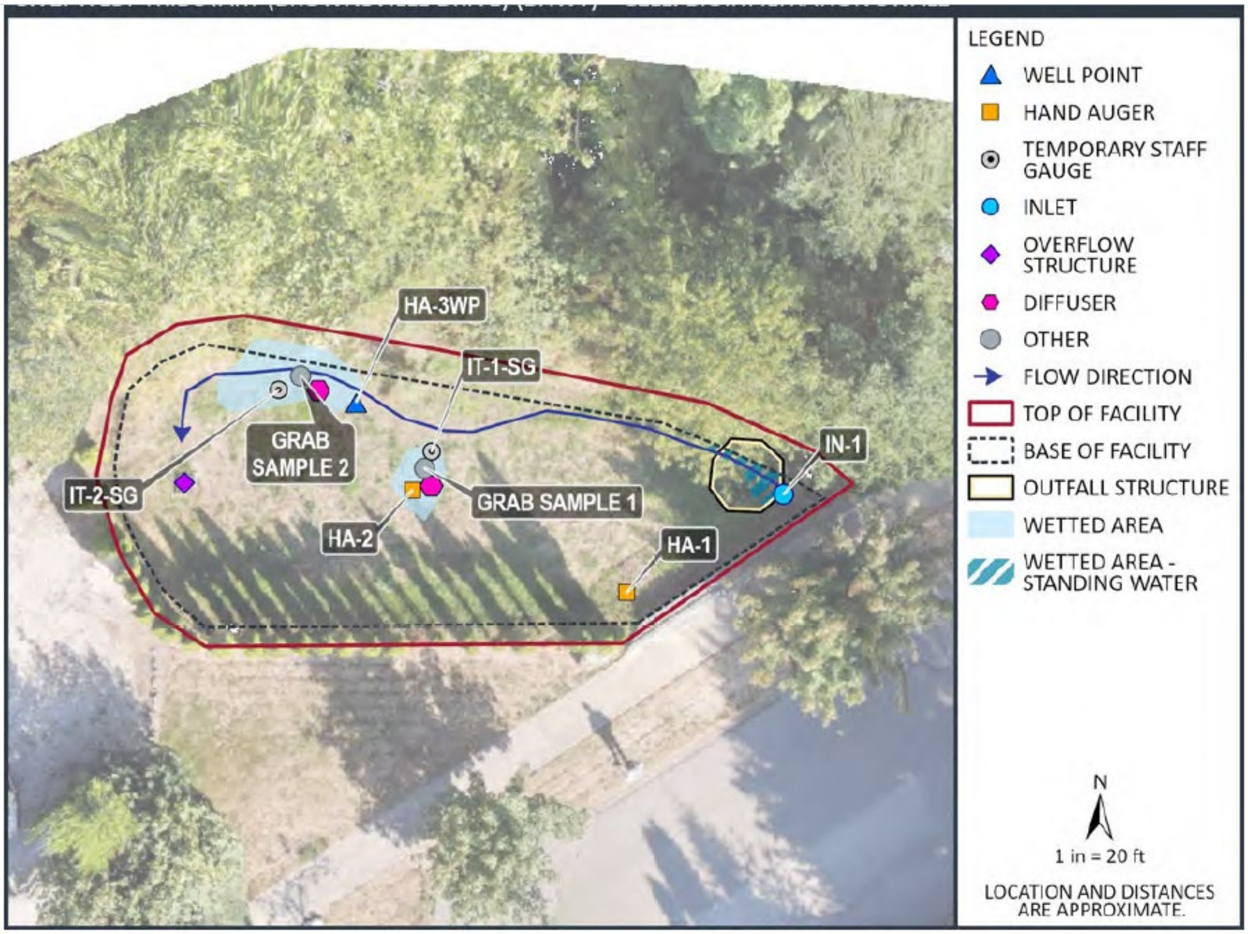


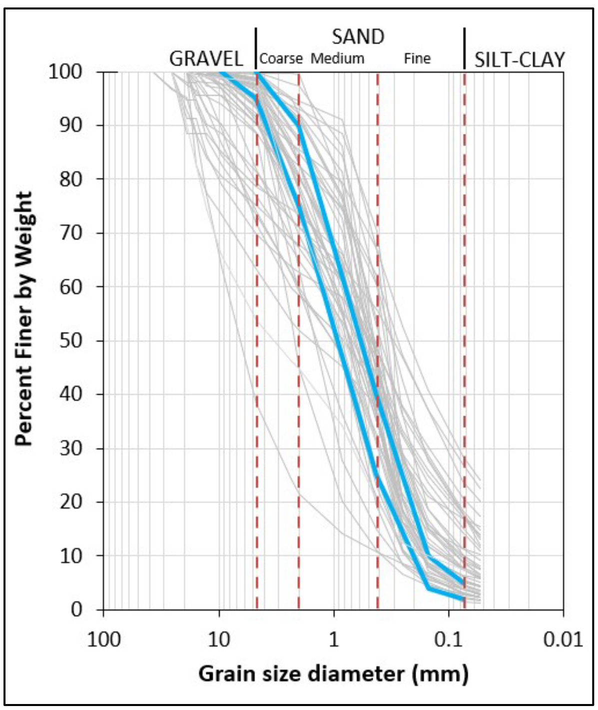
Figure 1. Example site variable flow path, wetted area distribution, and differential infiltration rates in different test locations (see infiltration test "diffuser" locations). Measured infiltration rates at the two wetted area infiltration flow test locations were 76 and 22 in/hr, respectively.

Infiltration rates for the typical and underdrained sites are presented as box whicker diagrams in Figure 3. These results illustrate the differences between lower native subgrade infiltration rates in the typical facilities, and the higher rates in the underdrained facilities that represent the BSM prior to collection and discharge through the underdrain.

Correlation was seen at a few sites between infiltration and percent fines over 10 percent (Figure 4). However, the conclusions from these infiltration rates suggest widespread accumulation of inflowing sediment is not reducing infiltration rates, except in some localized areas immediately adjacent to the inflow point as previously discussed.

Table 1. Geologic Unit and Geomorphic Setting Compared to Facility Type

Geomorphic and Geologic Setting	Total	Typical Infiltrating Facility	Underdrain Facility	Large Storage Sump Facility
Glaciated Upland	**33**	**15**	**16**	**2**
Fill/Unknown	2	1		1
Glaciomarine Drift	3		2	1
Till	15	3	12	
Advance Outwash	12	10	2	
Fill/Pre-Fraser Silt	1	1		
Outwash Delta	**1**		**1**	
Recessional Outwash	1		1	
Outwash Plain	**10**	**10**		
Recessional Outwash	10	8		
Valley	**6**	**3**	**2**	**1**
Recent Alluvium	6	3	2	1
Grand Total	**50**	**28**	**19**	**3**



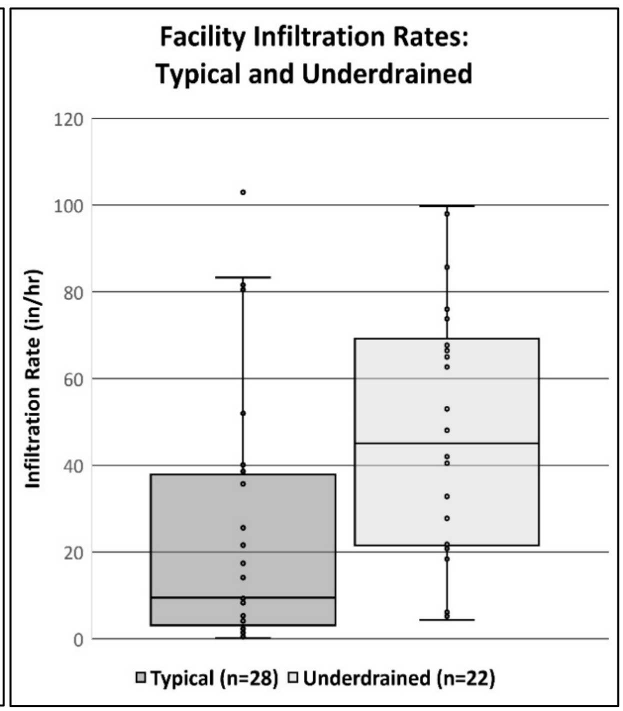


Figure 2 (left). Bioretention soil grain size distribution curve. The light blue lines illustrate the current specification guidelines for the Default Bioretention Soil Mix (WDOE 2019). Grey lines are the individual site grain size distribution results.

Figure 3 (right). Boxplot of facility infiltration rates for typical and underdrained facilities. For this plot, facilities with a large storage sump were grouped with underdrained. The plot used an exclusive median. The two highest typical infiltrating rates were on sites with highly pervious native subgrades.

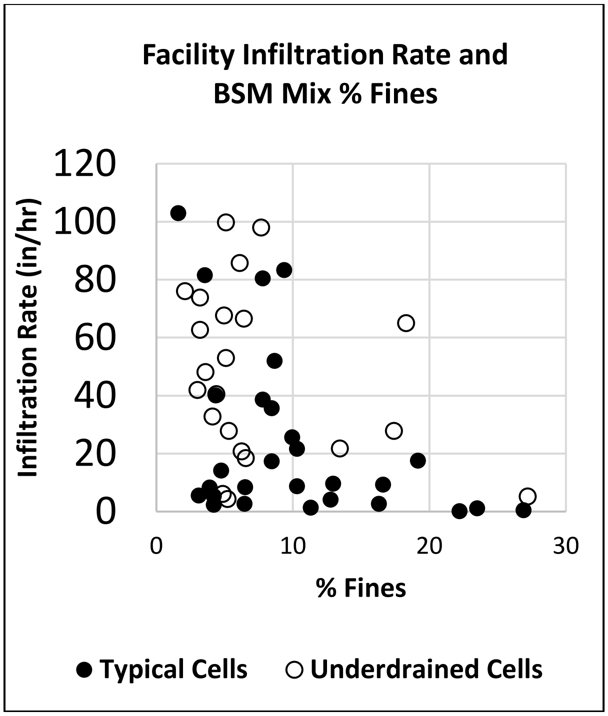


Figure 4. Facility infiltration rate (y-axis) compared to percent fines content (x-axis). Fines content refers to sediment finer than the #200 sieve and consists of silt and clay particles.

4.2 Vegetation Assessment

Vegetation transects and quadrat sampling was conducted in each of the sites to cover at least 25% of the facility bottom area and following the methods described in the Quality Assurance Project Plan (Raedeke Associates, Inc. and Associated Earth Sciences, Inc. 2023). Plants identified during the survey were then categorized by their Wetland Indicator Status (WIS) and grouped to evaluate the number of species remaining in each WIS group compared to the original planting plans when located. The WIS plant classifications were also used in combination with percent cover of all the plant species documented in the field to calculate a weighted average WIS value (i.e., the WIS Prevalence Index).

The principal findings of the vegetation communities compared to the original planting plans were that:

1. Plant species present in the observed plant list have generally shifted from a predominance of wetter WIS category plants in the original planting plans to drier WIS value plants presently seen.
2. Very little correlation was seen between the WIS Prevalence Index and site infiltration rates for either typical or underdrained facilities.
3. Frequency histograms of the WIS prevalence index indicate greater range in variation between the typical and underdrained sites.

Plant species list observed compared to original planting plans.

A consistent pattern was observed in a shift in the distribution of the percent of the original planting list to the current list from a greater set of wetter plants to drier plants in approximately 70% of the 50 sites. Some were similar between the original plant list and the observed, while a few shifted from drier plants to wetter.

These results suggest a preconception in the planting plan that the facilities will support wetter hydrophytic plants more than drier species. However, over time and the application of maintenance practices, most of the sites shifted to a larger set of drier WIS value plants. Figure 5 summarizes these findings across all 50 sites.

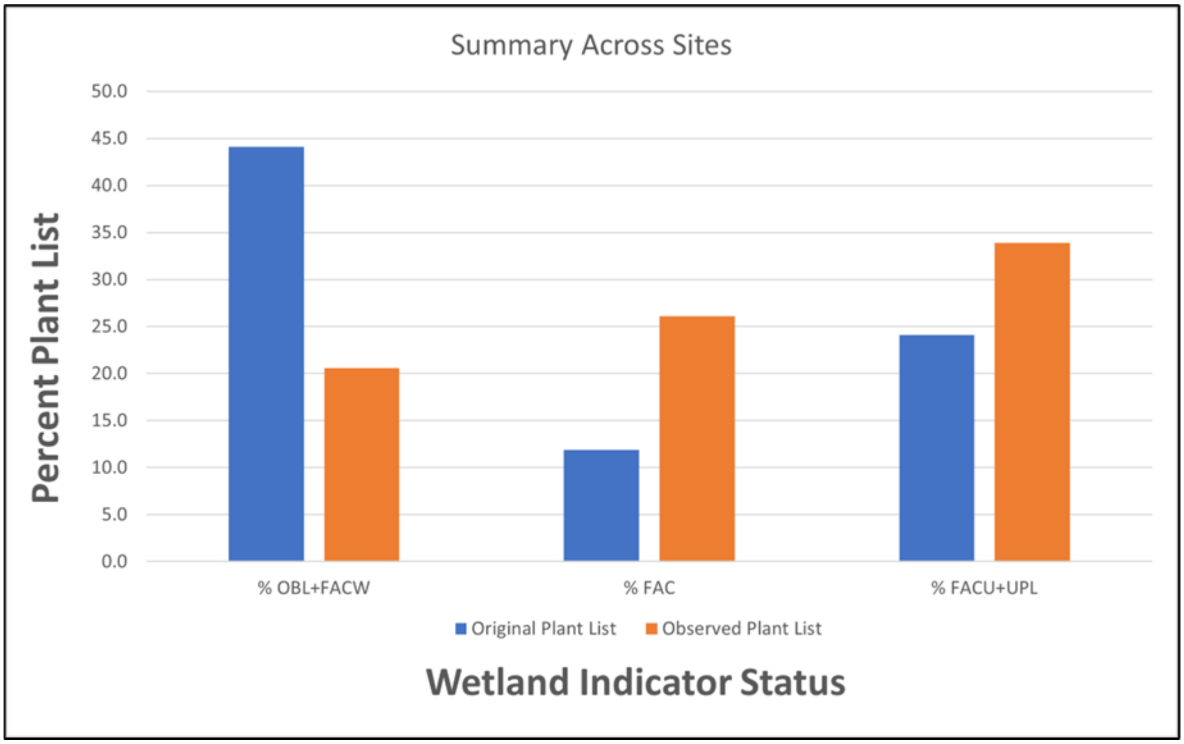
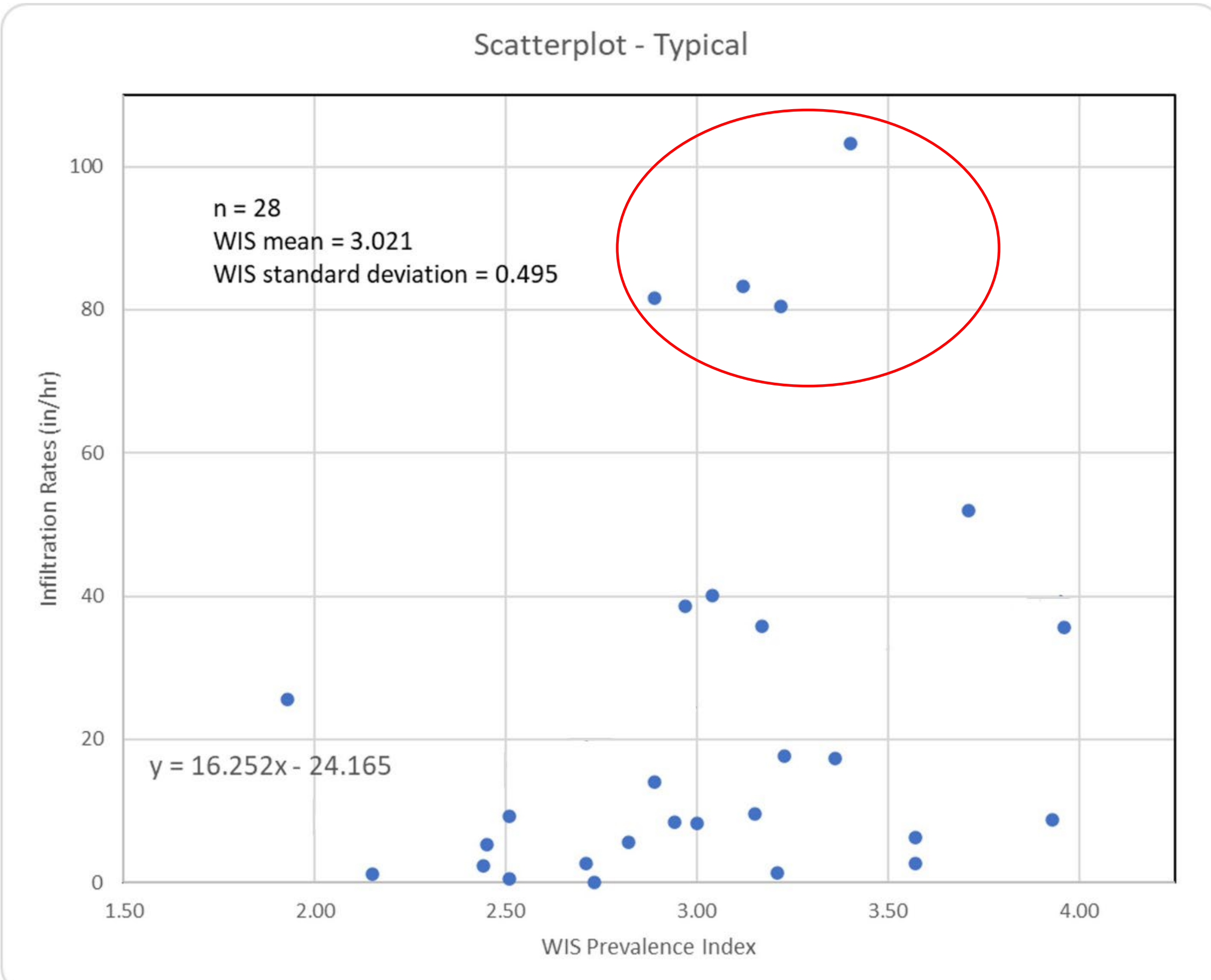


Figure 5. Observed shift in overall percent of plant list from wetter to drier plants across all 50 bioretention sites surveyed.

Comparison of WIS prevalence index with infiltration rates.

One comparison to address in the vegetation data is between plant community WIS prevalence index and observed infiltration rates. The thought is that hydrophytic characteristics of the observed plant community could be tied to the infiltration rate, with the possibility that slower infiltrating sites could influence the subsurface moisture conditions thereby supporting more hydrophytic plant communities. Plotting of the WIS prevalence index and infiltration rate showed very little correlation between these parameters. Figure 6a and Figure 6b present scatter plots of the WIS prevalence index versus infiltration rates separated by typical and underdrained sites. Calculated regression lines are provided for reference only to indicate a trend but were not statistically significant.

Some descriptions of outliers in these charts can provide greater detail to the condition observed. The outliers identified in the typical design scatterplot were sites located on exceptionally high infiltrating subgrade soils. In these “typical” (non-underdrained) sites, such high infiltration rates may suggest rapid pass-through of the BSM followed by high infiltration rates into the subgrade. These may indicate the influence of infiltration through the BSM mediated by large shrub root systems for example.



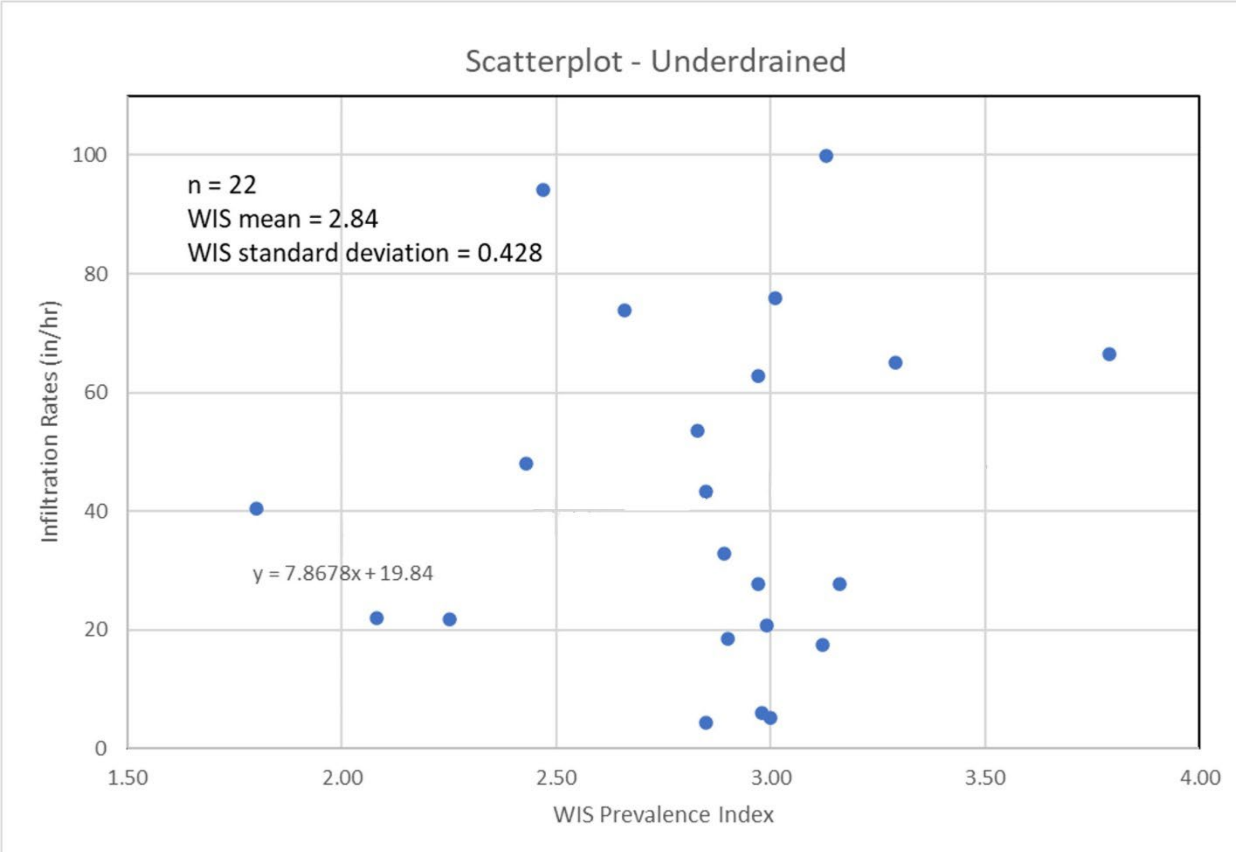


Figure 6a. and Figure 6b. Scatter plot distribution of infiltration rate versus WIS prevalence for typical and underdrained sites. Highlighted results in the typical scatter plot are sites with very high subgrade infiltration rates suggesting similarly high BSM filtration rates.

WIS prevalence index for typical and underdrained sites.

While little relationship between WIS prevalence and infiltration rates was indicated above, the simple distribution of WIS prevalence values of typical and underdrained facilities was plotted to possibly reveal trends between these two site designs.

The average WIS of underdrained facilities was (maybe counterintuitively) associated with a slightly wetter plant community than that of the typical facilities. However, there was a somewhat broader spectrum of WIS coded plants in typical facilities when compared to underdrained facilities. Figure 7 provides histogram frequency distributions of WIS values for typical versus underdrained sites.

It is likely that a combination of other factors separate from simply the typical versus underdrained design are the main influences on the final plant community WIS prevalence (and infiltration rates). As noted in the list provided above from the literature review many factors or a combination of factors could be the main influences on the vegetation community, infiltration rates, and resulting moisture conditions.

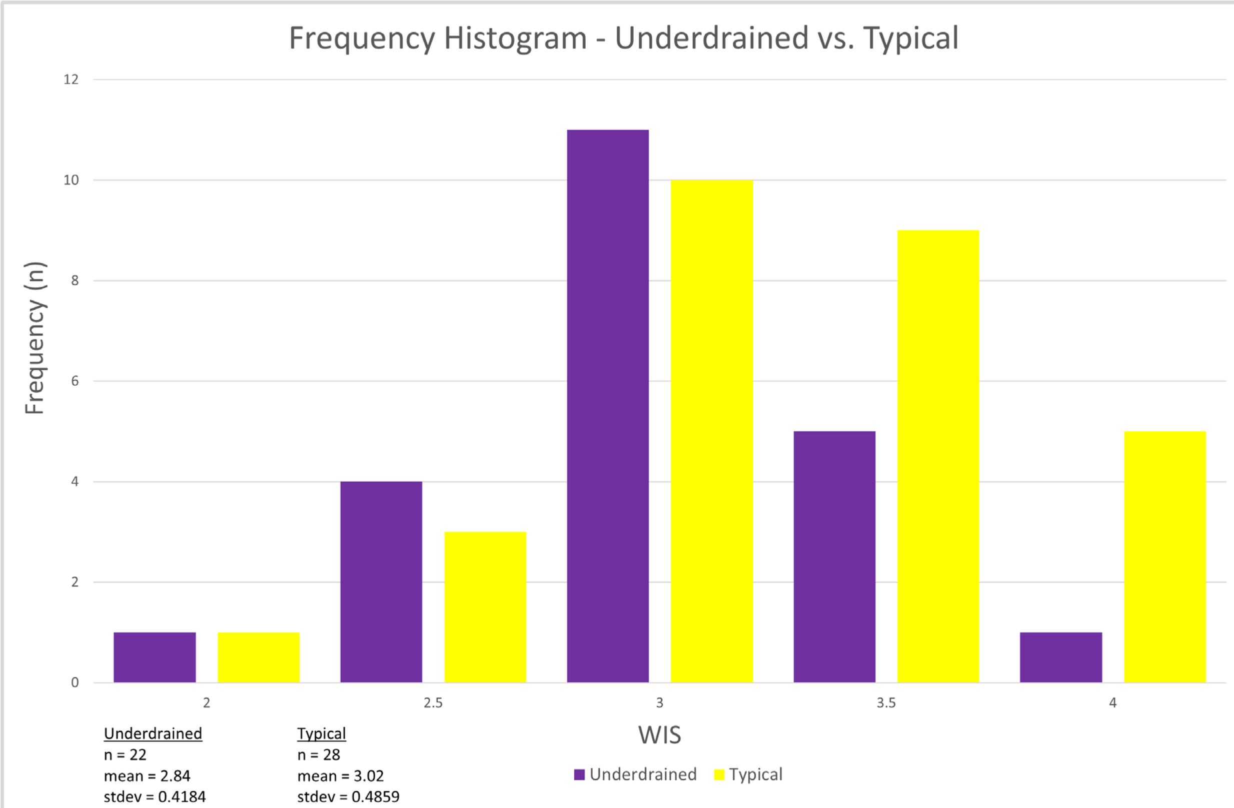


Figure 7. Frequency distribution of WIS prevalence values seen typical versus underdrained sites studied.

Vegetation design recommendations

Our vegetation sampling and measured infiltration rates indicate much of the vegetation community experiences extremely dry soil conditions with limited hydrophytic plant species remaining after ten years' time. Additionally, maintenance operations may further limit the success of many originally specified plant species where regular maintenance is intensive or infrequent and irrigation is lacking.

While current plant species selection guidance suggests plants with a narrow range of hydrologic tolerance (i.e., wetter conditions) are suitable in the lowest portions of a facility ("zone 1"), our findings indicate that moisture loving plant species may only be appropriate near the facility inflow locations and where heterogeneous flow paths and flow concentrations may occur. Site specific subgrade infiltration rates for "typical" site designs (without an underdrain) may create localized shallow moisture conditions that support a wider range of plant species.

Nonetheless, if a site is intended to present a landscaped aesthetic quality for public appearance, a broader range of plants may be selected but will likely require additional maintenance in the form of weeding, irrigation, and mulching to sustain desired plant species survival. Sites intended to provide plant cover with a priority for minimal maintenance and sustained infiltration capacity may otherwise suffice with a selection of self-maintaining native plants and even prairie – type grasses that have a wide range of hydrologic tolerance. Facility asset management planning that identifies the facility purpose and maintenance budgets should be consulted to specify planting plans that fit the expected goals and management conditions. (See the Maintenance discussion below).

Hinman and Wulcan (2012) provide a discussion and lists of potential plant selection and maintenance considerations for bioretention facilities. Our findings suggest the zone 2 plants in that document are more likely to be the species that persist long-term based on the study. Especially if the site is underdrained, the Zone 1 herbaceous species will likely not persist and will be replaced by species more typical of the Zone 2 list.

4.3 Review of Site Engineering Designs

Original drainage reports, previously collected by the AESI team, were reviewed for bioretention modeling information. Drainage reports from a total of 54 sites were reviewed; 28 of the 54 had useful bioretention modeling information.

All of the drainage reports, except for two, were produced prior to 2012 when Washington Department of Ecology's revised stormwater manual for Western Washington first included bioretention modeling specific information to assist in the design of bioretention facilities. Prior to that date, the guidance for stormwater design engineers was to use continuous runoff modeling but the ability to model bioretention cells varied between the available modeling software programs. This is evident in the different modeling software that they used. Of the 28 sites for which information is available, 11 used WWHM3 or its predecessor WWHM2 to model and size the bioretention cell. WWHM3 did not include a bioretention element so the modelers used either the pond element or the gravel trench element to represent the bioretention facility. The modelers for three of the sites used WWHM3 PRO or WWHM4, both of which did have the bioretention element that was later added to WWHM2012. This was the most accurate way to model bioretention facilities but note that both WWHM3 PRO and WWHM4 were proprietary software which had to be purchased from Clear Creek Solutions while, in contrast, WWHM3 was free.

Five sites were modeled and designed using MGS Flood, which did not have the bioretention algorithms required by Ecology for bioretention modeling at the time. Two of the sites used KCRTS (King County Runoff Time Series); six used single-event models (Waterworks and SBUH); and one used the Pierce County LID Sizing Tool. None of these modeling methods are consistent with the current bioretention model capability .

An attempt was made to compute the ratio of the bioretention base area to the contributing drainage area. The contributing drainage area value was taken from the drainage report where it was possible to identify the specific cell in the drainage report corresponding to the infiltration test cell.

The bioretention base area of the test cell was taken from the measurements made by AESI in the field during the infiltration testing. These measured areas were the area of the facility circumscribed by where the flatter bottom slopes transition to the steeper side slopes. These areas did not necessarily correspond with the wetted areas found during the infiltration test nor with the facility overflow elevation.

Of the 28 sites which had drainage reports, a total of 11 had sufficient information to compute the ratio of the bioretention base area to the contributing drainage area in terms of a percentage value. The general recommendation is that the size of the bioretention surface ponding area be at least 5 percent of the size of the contributing drainage area. Of the 11 sites for which there are numbers, six sites exceeded that recommendation. Five of the 11 sites had percent size values that were smaller than 5 percent.

These five sites that had bioretention base area to the contributing drainage area ratios of less than 5 percent are shown in Table 2. Without further investigation one would automatically assume that these sites would fail in large storm events, as they would not be able to successfully infiltrate all or most of the stormwater flowing into the bioretention cell. However, a review of the measured infiltration rates for each of these apparently under-sized facilities indicates otherwise.

As shown in Table 2 below, the small ratio bioretention cells have very large infiltration rates. Some also have underdrains, which facilitate the movement of water through and out of the bioretention facilities.

Table 2. Ratio of Cell Base Area to Drainage Area for Cell Ratios of Less than 5 Percent

Bioretention Cell	**Base Area to Drainage Area Ratio**	**Measured Infiltration Rate (in/hr)**
145th Pl RG#2 U	2.3%	40.5
Tyee Middle School Bioretention Pond A U	3.3%	62.7
Rainier Boulevard T	1.4%	35.8
Rosehill Community Center North Rain Garden UNK	4.7%	5.3
Decatur Raingarden U	3.2%	65.0

Note: T = Typical (no underdrain)
U = Underdrain
UNK = Unknown

The high measured infiltration rates offset the low cell base area to drainage area ratios and make these facilities viable stormwater solutions. However, using today's WWHM2012 bioretention software it is unlikely that any of these facilities would meet either Ecology's Minimum Requirement #5 (LID Flow Duration) or Minimum Requirement #6 (Water Quality).

It should also be noted that the current Ecology bioretention soil mix standard is for a soil mix with an infiltration rate of 12 inches per hour. For sites with higher native subgrade infiltration rates, as most of those noted above, the bioretention soil mix infiltration rate should be limiting the site's actual measured infiltration rate. In these early bioretention facilities that is obviously not the case.

4.4 Maintenance Survey Results

Methods and Approach

We developed a telephone survey of 13 questions reviewed by the City of Olympia and the Washington Department of Ecology to be used as a combined quantitative and qualitative approach to documenting the maintenance activity at as many of the facilities studied as possible. The survey questions utilized for this study are listed below. The facility owners were contacted to identify the appropriate maintenance manager with whom to conduct the survey.

Many of the owners had multiple facilities involved in the study and in almost all cases where multiple facilities were involved the same maintenance activities were generally applied.

While some of the questions posed were intended to be quantitative (e.g., as a yes/no or frequency of activity) with explanatory comments, many of the questions required qualitative explanations (e.g. what type of maintenance?; or what challenges have you observed?). As such the following description of the survey findings incorporates a discussion of both the qualitative and quantitative data that was obtained during our investigations.

Participation

For this study, fifty different bioretention cells were assessed in the field for plant community composition and infiltration rates and were included in the project survey sample size. The fifty bioretention facilities studied were owned and maintained by 23 jurisdictions or private owners (many of the site owners had more than one facility in the study). Two additional site owners were surveyed but their facilities subsequently disqualified. Their survey results were nonetheless included in the survey results for a total of 25 survey participants.

Appendix B provides the full list of the jurisdictions interviewed, and a summary of the responses provided by each. The following discussion provides a list of the questions and a question-by-question summary of the findings and identifies apparent themes and direct quotes to help provide overall survey conclusions.

In virtually all cases (22 of 25) the survey respondent was a grounds maintenance supervisor or stormwater maintenance and/or operations supervisor responsible for assigning work crews that conduct the maintenance activities in the bioretention facilities. Three of the respondents were professional project managers responsible for oversight of the facility or residential owners of the facility. Completion of the telephone survey generally took between 15 to 30 minutes.

The following summary presents the individual questions posed to the survey participants. Appendix B provides a summary of individual responses and tallies of quantitative replies.

Maintenance Survey Questions

1. Is there a planting plan goal for the cell to be sustained? If so, what is the source of the plan?
2. Is maintenance conducted in the bioretention cell/s and do you keep maintenance records?

3. What type of maintenance? (e.g., weeding, mowing/weed-whacking, trash removal, irrigation, replanting).
4. How frequently?
5. What challenges have you observed in maintenance?
6. Have you observed plant mortality or volunteerism?
7. Which plant species?
8. Have you replanted?
9. Have you done anything to the bioretention soil? (Mulching, aerating, etc.)
10. Do you observe extended periods of ponding in the cell?
11. Do the inlets into the cell get clogged or backup?
12. If there are underdrains, do those get clogged or the cell backup with water?
13. Any other issues observed or addressed at the site?

Maintenance Survey Findings

The maintenance survey results revealed a few relatively consistent responses especially in the frequency and the nature of the maintenance. Most of the sites were maintained two to four times per year and largely limited to weeding, trimming, and garbage collection, with little replanting. Irrigation of the cells was less common than no irrigation. The greatest differentiator of sites from a maintenance perspective appeared to be whether the site had public exposure and priority for aesthetic presentation. The surveys responses state that little maintenance was conducted on the soil itself, indicating the soil was principally composed of the original BSM.

Table 3. Frequency of maintenance conducted by grounds staff at 23 responding bioretention facility owners.

Frequency of Maintenance	Number of Respondents
0	1
1 - 2x / mo.	6
1 - 4x/ yr.	15
1/5 years.	1

Possible results of these maintenance conditions could be related to the degree of spreading of planted or volunteer plants into weeded areas and avoiding potential compaction of soil during foot access for maintenance. The BSM may also have reduced inputs of organic matter as weeded and trimmed material is raked and removed. Overall, a vast majority of the respondents found the sites are otherwise "self-maintaining" and successful for the purpose of stormwater treatment. Respondents' recommendations for future bioretention design largely revolved around selecting plant palates representing low growing and native vegetation that needs little maintenance or irrigation.

One conclusion in planning bioretention facilities maintenance is apparent when recalling the vegetation community composition and the shift in vegetation seen from the original planting plans to generally drier plants. Maintenance supervisors' comments noted the budgetary and staffing challenges for maintenance of many of the sites. Clearly planting plans can benefit from understanding the long-term asset management expectations of the facilities. Facility owners' management and maintenance departments should be consulted about the intended goals and budget conditions for their management.

If facilities are expected to be maintained through minimal budgets and largely self-sustaining growth without irrigation, as most of the facilities here were, planting plans should reflect those long term organizational and practical management terms of the facilities. If sites are intended to provide an aesthetic display with regular maintenance (and budget) the corresponding plant pallet and frequency of maintenance and plant replacement the initial planting plan can match those long-term conditions.

5.0 Conclusions and Discussion

A sampling of 50 ten-year-old or older bioretention facilities across the Puget Sound Region for infiltration, soil composition, structural conditions and vegetation community has provided a broad-based assessment of the performance of these aging facilities. The findings suggest that infiltration rates of these sandy BSM bioretention facilities remain high. Past literature and other suggestions of sediment accumulation, pore clogging and reduced infiltration rates are generally not seen in this study. Low infiltration rates appear to be in localized areas near the point of inflow or at sites where infiltration rates are limited by the underlying subgrade rather than the BSM.

One of the main conclusions of this study is that the visual flow paths and infiltration assessments suggest that these sites are not homogeneous in their lateral distribution of inflows and may have differing infiltration rates in different locations. Rather they appear to infiltrate much of the inflows near the point of inflow and can generate surface flow paths across the facility during larger storms. This contrasts with the facility theoretically filling in a pooling fashion starting at the low point of the cell for all storms.

The size and geometry of the facility and relative size of the contributing area will certainly influence the extent of these generalizations. However, these heterogeneous infiltration and flow conditions should not be entirely surprising for a relatively open hydrologic system as bioretention facilities are, as water will seek or develop a path of least resistance vertically and laterally in such a system.

Related to these laterally heterogeneous flow paths and infiltration conditions is also the question of "preferential vertical flow paths" that has been discussed in the literature as well. Such preferential infiltration paths may bypass the intention of broad-based filtration and pollutant removal especially in underdrained systems. Fully infiltrating "typical" systems would pose less of a concern for this issue than underdrained facilities as they do not discharge directly to conventional stormdrains and receiving waters.

The findings in this study of localized high infiltration rates themselves could be seen as a form of "preferential flow path" based on the coarse BSM texture alone. Whether vegetation creates another form of soil porosity that leads to preferential flow paths in addition to the coarse BSM texture is uncertain. In a dynamic way, highly infiltrating sandy BSM, vegetation root growth, development of soil structure related to vegetation roots and exudates, organic matter and wetting and drying cycles exposed to differing hydraulic and sediment loads and other factors identified in the literature review likely together create conditions unique to each facility.

The vegetation community composition results and their contrast with the original planting plans are a further important point of the findings of this study. While the actual plant community composition will likely influence the textural development of the BSM, selecting plants that will have a high survival and growth patterns for the infiltrating life of the facility will greatly reduce planting and maintenance costs. The overall findings of the vegetation surveys indicate that many of the sites were planted with plants having wetter preferential growing conditions. These original species tended to not survive and were supplanted by vegetation having greater tolerance to changing wet to dry conditions. As a result, planting plan recommendations provided here are largely focused on selecting plants adapted to both wet and dry conditions and other site growing conditions such as extreme heat or shading.

Overall, the present study indicates that aging bioretention facilities have a wide range of, but acceptable infiltration rates, and a more moisture-adaptable vegetation community than wet or dry plant communities. To best design and monitor these sites, site-specific conditions should be carefully assessed for structural, contributing drainage area, hydrogeologic, geotechnical and meteorological conditions, and organizational management commitments for each facility.

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APPENDIX A

A1.0 Recommendations from BHP I Report

Given the findings from this study, major recommendations intended for engineers, geologists, and landscape architects, as well as development reviewers at local jurisdictions for each of the design elements include:

A1.1 Design Features

- Provide inspectors' confirmation of constructed contributing areas and overflow elevations.

A1.2 Geotechnical and Hydrogeologic Recommendations

- Collect site-specific data to understand shallow soil, geologic and groundwater conditions affecting subsurface infiltration rates.
- Consider potential for lateral flow, and the ultimate path of the infiltrated water, particularly for sites with low or spatially variable infiltration rates.
- Provide soil media that is consistent with the specifications provided in the Ecology 2012 Stormwater Management Manual for Western Washington, as amended in December 2014 (2014 SWMMWW; Ecology, 2014).
- Conduct geotechnical plan review by the permit applicant and jurisdiction staff of permit plan set so that plans adequately incorporate geotechnical recommendations (i.e., are bioretention cells located near infiltration test locations or at different elevations or does the grading plan remove the permeable horizon).
- Conduct observations during construction by permit applicant and jurisdiction staff to observe whether the subsurface geologic and groundwater conditions are consistent with the basis of design (e.g., if site design is based on outwash soils being present, do not overexcavate into consolidated glacial till).

A1.3 Vegetation Recommendations

- Select plants that reflect the expected subsurface moisture and dry season conditions, and the solar exposure expected for the site.
- Select plant species that are consistent with each other for growing success (e.g., select shrubs that are not excessively shading the herbaceous plants).
- Select a planting plan that is consistent with the institutional or residential owner's design needs and commitment to maintenance.
- Install woody species at lower density to allow for plant growth and spreading.
- Select native herbaceous plant species that are more likely to survive in both wet and dry conditions.
- Maintenance plans and contingency plans should be part of the bioretention design specifications provided by the project design consultant.
- Conduct an assessment of how BSM infiltration rates change as the bioretention site ages and whether or not vegetation has an effect on the BSM infiltration rate.

A1.4 Modeling Recommendations

- Ecology should instruct the WWHM2012 software engineers to investigate how to more accurately represent the soil layer depths in the model development, including possibly a leaf litter layer.
- Ecology should instruct the WWHM2012 software engineers to investigate more appropriate default evapotranspiration rates based on vegetation types.
- Ecology should instruct the WWHM2012 software engineers to conduct sensitivity analyses of the magnitude of effect of infiltration rate variability, contributing drainage area, and use of regional rainfall records on facility performance.

A2.0 Recommendations from BHP II Report

Given the findings from this study, major recommendations intended for engineers, geologists, and landscape architects, as well as development reviewers at local jurisdictions for each of the design elements include:

A2.1 Design Features

- Maintain large (>5 percent) bioretention top area to drainage basin ratios including field confirmation of contributing areas.
- Maintain a minimum 6-inch riser height above the cell bottom elevation.
- Maintain a minimum 18-inch BSM depth and meet Ecology (2014) media particle-size criteria.
- Conduct as-built surveys of inlets, overflows, contributing areas, and bioretention surface area.
- Conduct a field inflow test to confirm positive drainage into the cell inlets.
- Include a capped underdrain as a back-up discharge management option in jurisdictions that encourage infiltration in soils that have low infiltration rates.
- Evaluate and incorporate in the design approach the effects of uneven infiltration (see same issue regarding planting plans below).
- Provide careful review of the TIR, design plans, and models before permitting for construction. This review should include contributing area calculations and reviewing the design model to determine the appropriate minimum facility size as a percentage of drainage area and accurate BSM filtration and native infiltration rates.
- Review retrofit facilities for limiting site conditions and the expected performance absent meeting new development facility criteria.

A2.2 Geotechnical and Hydrogeologic Recommendations

- Collect data specific to the facility location to understand shallow soil, geologic and groundwater conditions affecting subsurface infiltration rates.
- Use pilot infiltration testing at the facility location for estimating long-term design infiltration rates.

- Consider potential for lateral subsurface flow, and the ultimate path of the infiltrated water, for sites with low or spatially variable infiltration rates.
- Consider potential for utility corridor capture of infiltrated waters, particular in retrofit applications.
- Provide testing of the bioretention soil media for consistency with the specifications provided in the Ecology Manual, especially the #40, #100, and #200 grain-size fractions.
- Conduct geotechnical plan review of permit plans and during construction so that plans adequately incorporate geotechnical recommendations (e.g. are bioretention cells located near infiltration test locations or at different elevations; does the grading plan (improperly) remove the permeable horizon?).
- Conduct observations during construction to observe whether the subsurface geologic and groundwater conditions are consistent with the basis of design (e.g. if site design is based on outwash soils being present, and subsurface conditions are consolidated glacial till, a design change is required).
- Look for evidence of soil compaction. We speculate based on limited observations that soil compaction impacts are more common for narrow facilities. Evidence for surface compaction was exhibited in five of the ten facilities.
- Remediate compacted soil prior to acceptance. Soil compaction can occur during bioretention soil placement, irrigation installation, placement of inlet protection, or energy dispersion elevation, or from planting.
- Conduct a study of “aging” of facility infiltration rates over time, whether those rates are decreasing, increasing, or staying the same.

A2.3 Vegetation Recommendations

- Use shrubs as they tend to compete better with noxious weeds and therefore should be used more frequently in units to reduce maintenance. Cells that were planted with only herbaceous species, or where the woody plants had been heavily browsed by deer, tend to grow a greater density of noxious weeds.
- Plant with a variety of shrubs and herbs. Herbaceous species tend to have poor survival rates in bioretention cells compared to shrubs. Where large shrubs may be inappropriate due to limited sight lines, consider using smaller shrubs such as Kelsey Dogwood (Cornus sericea ‘Kelseyi’) and shinyleaf spirea (Spiraea betufolia var. lucida).
- Specify water-tolerant plants in bottom areas near the inflow, and fan out to more facultative, facultative upland plants farther away from the inflow.
- Do not use plants that commonly occur in wetlands. Wetland soils are anaerobic, waterlogged, and poorly draining; bioretention soil is very well draining. Wetland species that require constant water-logged soil will not grow well in bioretention cells and should be avoided (except for Carex obnupta).

- Develop maintenance plans and contingency plans with the planting designs to allow adaptive changes. Designers should follow up on the effectiveness of the design a year or two after installation.

A2.4 Modeling Recommendations

- Use a limiting "leaf litter layer" surface modeling layer in the model where non-wood mulch will be applied.
- To help assess design for retrofit and new facilities, Ecology should conduct a sensitivity analysis of the magnitude of effect of the variability of safety factor infiltration rates, contributing drainage area, and use of regional rainfall records on facility performance on long-range ability to meet MR #5 and MR #6.
- Double check the accuracy of the BSM and native soil infiltration rates input in the WWHM 2012 model and in the TIR for the site. Then reviewers should analyze results for compliance with MR #5 and MR #6 before approving new development site design.