Chapter 4. Stormwater Control Measures

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Chapter 4. Stormwater Control Measures

1.0 Overview

MHFD has established design criteria, procedures, and details for stormwater control measures (SCMs) providing treatment of post-construction urban runoff. SCMs provide treatment through a variety of hydrologic, physical, biological, and chemical processes. Functions provided by SCMs include runoff volume reduction, treatment, and slow release of the water quality capture volume (WQCV) in keeping with Steps 1 and 2 of the Four Step Process discussed in Chapter 1 of Volume 3. These SCMs can be designed to meet design standards in the Colorado Municipal Separate Storm Sewer System (MS4) General Permit related to runoff reduction, WQCV, and pollutant removal. Some SCMs may be capable of meeting permit standards as stand-alone practices, while others can help to satisfy the standards through a treatment train approach.

SCMs in Volume 3

Runoff Reduction

- Receiving Pervious Areas including Grass Swales and Buffers
- Roof Systems (Green Roofs/Blue Roofs)

Filtration and Infiltration

- Bioretention Systems
- Sand Filters
- Permeable Pavement Systems
- Manufactured Treatment Devices (Filtration)

Sedimentation

- Extended Detention Basins
- Retention Ponds and Constructed Wetland Ponds
- Manufactured Treatment Devices (Sedimentation)

This chapter builds on concepts and procedures introduced in Chapters 1 through 3 and provides design procedures for treatment SCMs. Table 4-1 provides a qualitative overview of key aspects of the post-construction treatment SCMs included in this chapter. The table includes the degree to which the SCMs provide various functions, general effectiveness for treating targeted pollutants, and other considerations such as life-cycle costs. The table indicates which functions are provided by different types of SCMs. This distinction is important because not all SCMs provide the same functions, and some are best used as a component of a treatment train rather than as a stand-alone practice. In general, designers should first evaluate and maximize opportunities for runoff reduction SCMs followed by treatment of the Water Quality Event (WQE) using infiltration, filtration or sedimentation processes. SCMs such as ponds that store and release runoff as surface discharges can provide effective treatment and are appropriate on many sites, especially when combined with upgradient runoff reduction measures and full spectrum detention.

Terminology

The term “stormwater control measure” (SCM) refers to any practice or method used to prevent or reduce the discharge of pollutants to waters of the State. SCMs include, but are not limited to, best management practices (BMPs), green infrastructure (GI), green stormwater infrastructure (GSI), and low impact development (LID).

Wherever practical, use combinations of SCMs in a treatment train approach. For example, SCMs that provide sedimentation functions can potentially improve the lifespan and reduce the maintenance frequency of filtration-based SCMs when the two SCMs are paired in series. Table 4-1 is based primarily on the International Stormwater BMP Database (www.bmpdatabase.org) and is intended for general guidance only. Specific SCM designs and site-specific conditions may result in performance that differs from the general information provided in the table. SCM performance and monitoring results can also vary widely depending on the monitoring protocols, analytical methods, and many other variables. In some cases, SCMs may be able to reduce pollutant concentrations, but this does not necessarily mean that the SCMs are able to treat runoff to numeric stream standards. For example, various studies have indicated that bioretention systems, media filters, and retention ponds may be able to reduce fecal indicator bacteria concentrations and loads in urban runoff, but not necessarily meet instream primary contact recreational standards based on concentrations at the end of pipe.

After reviewing physical site constraints, the surrounding environment, treatment objectives, master plans, and other factors, the designer can select the SCMs for implementation at the site and complete the engineering calculations and specifications for the selected SCMs. Where feasible, distribute SCMs throughout the site to maximize opportunities for infiltration and enhance community values rather than funneling all of the runoff from a site to a single SCM.

This chapter is intended to provide guidance and criteria that can be used by engineers to develop innovative designs. The chapter is organized by first presenting Components and Elements for Designing SCMs, which provides an overview of the major components that must be addressed in planning and design. This section also includes guidance and criteria for key components of SCMs that are common to many different SCM types and addresses topics related to how the SCM fits into its surrounding land uses (e.g., adding community value), site evaluation, SCM inflows, section development (aggregate sizes, media, underdrains, and related concepts), and SCM outflows. These foundational concepts are followed by fact sheets that provide guidance, design procedures, and criteria for specific SCMs. Designers should look for creative ways to incorporate SCMs into the overall landscape of the site by striving to achieve the intent of the criteria in a way that works well with site constraints. This chapter provides SCM guidance and criteria that can be used in conjunction with the WQCV and runoff reduction calculations in Chapter 3 to properly size and design an SCM based on a site's unique conditions to manage the 80th percentile runoff-producing event and satisfy MS4 permit standards for post-construction water quality treatment. For sites that drain to impaired or sensitive receiving waters or that include onsite industrial operations requiring additional treatment, implementation measures that go beyond the minimum criteria provided in the fact sheets in this chapter may be required. Additionally, local governments may have additional or different design standards than those presented in this chapter.

Tips for Using this Chapter in Conjunction with SCM Fact Sheets

- Use Chapters 1-3 and site assessment guidance in this chapter to select SCM type(s) for a site.
- After SCM selection, begin design process to size the SCM. For design volumes and flow rates, cross-reference to:
    - Chapter 3 for WQCV and WQE calculations
    - Chapter 12 *Storage*, Volume 2 for EURV designs that integrate water quality and flood control
- Use MHFD design workbooks to complete calculations, if applicable to the SCM.
- For filtration/infiltration systems, use Section 4 of this chapter to select section type (full infiltration, partial infiltration, no infiltration)
- Use this chapter to design SCM components:
    - Section 5 Inflow Features
    - Section 6 Outflow Features
- For vegetated SCMs, see Section 7 of this chapter for soil, vegetation and irrigation guidance.
- See Chapter 6 *Maintenance* to understand long-term maintenance commitments for selected SCMs.

Table 4-1. General Overview of SCMs included in Volume 3

SCM Applicability	Runoff Reduction SCMs			Filtration SCMs					Sedimentation SCMs			
	RPAs, Grass Buffers & Swales	Green Roofs	Blue Roofs	Bioretention	Sand Filters	Permeable Pavement Systems	High Rate Media Filtration	High Rate Biofiltration	Extended Detention Basins	Retention Ponds	Const. Wetland Ponds	Hydrodynamic Separators
MS4 Permit Applicability (design dependent)												
Meets Runoff Reduction Standard	Potential[1]	Potential[1]	Potential[1]	Potential[1]	Potential[1]	Potential[1]	No[2]	No[2]	No	No	No	No
Meets WQCV Capture Standard	No	Yes[1]	Potential[1]	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No
Meets Pollutant Removal Standard	No	No	No	Yes[3]	Yes[3]	Yes[3]	Yes[4]	Yes[4]	Yes[3]	Yes[3]	Yes[3]	No[4]
Typical Effectiveness for Targeted Pollutants[5]												
Sediment/Solids	Medium	Low	Low	High	High	High	High	High	Medium-High	High	High	Medium
Total Phosphorus	Low-Medium[7]	Low	Low	Low-Medium[7]	Medium	Medium	High[6]	High[6]	Medium	Medium-High	Medium-High	Low
Total Nitrogen	Low[7]	Low	Low	Low-Medium[7]	Low	Medium	Medium	Medium	Low	Medium	Medium	Low
Total Metals	Medium	Low	Low	High	High	Medium	High	High	Medium	Medium-High	Medium-High	Low
Bacteria	Low	Low	Low	Medium[1]	Medium	Medium	Low-Medium	Low-Medium	Low	Medium	Medium	Low
Common Applications												
Runoff Reduction (General "Step 1")	Yes	Yes	Yes	Yes	No	Yes	No	No[2]	No	No	No	No
Used as Pretreatment (in Treatment Train)	Yes	Yes	Yes	No	No	No	No	No	No	No	No	Yes
Primary Treatment	Potential[1]	Potential[1]	Potential[1]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Integration with Flood Control	No	No	Potential[1]	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No
Costs												
Life-Cycle Costs	Low	High	Medium	Medium	Medium	Medium[8]	Medium-High	Medium	Medium	Medium	Medium	Medium

[1] Design dependent.

[2] The Runoff Reduction Standard is not typically met with HRBF or HRMF devices sold as-is. HRBFs and HRMFs can be designed/retrofitted with additional appurtenances, such as extra underdrain pipe(s) or a chamber on the downstream side of the device, which will detain and regulate the release of treated stormwater and allow for infiltration.

[3] Meets Pollutant Removal Standard when designed to provide the WQCV.

[4] Typical effectiveness for HDSs is based on New Jersey Department of Environmental Protection laboratory testing protocol for HDSs (NJDEP 2021), with testing requirements for specific composition and gradation, average particle size, influent concentration, required inflow rates, and other parameters. Filtration MTD performance varies based on proprietary media/filter designs and targeted pollutants. "Typical" effectiveness descriptions are based on a combination of Washington Ecology's approved treatment technologies based on the Technology Assessment Protocol–Ecology (TAPE) use designation and the International Stormwater BMP Database 2020 Summary Statistics.

[5] Based on experience in Colorado supported by analysis of concentration data from the International Stormwater BMP Database (www.bmpdatabase.org) (Clary et al. 2020). Performance for particulate forms of pollutants is typically higher than for dissolved forms.

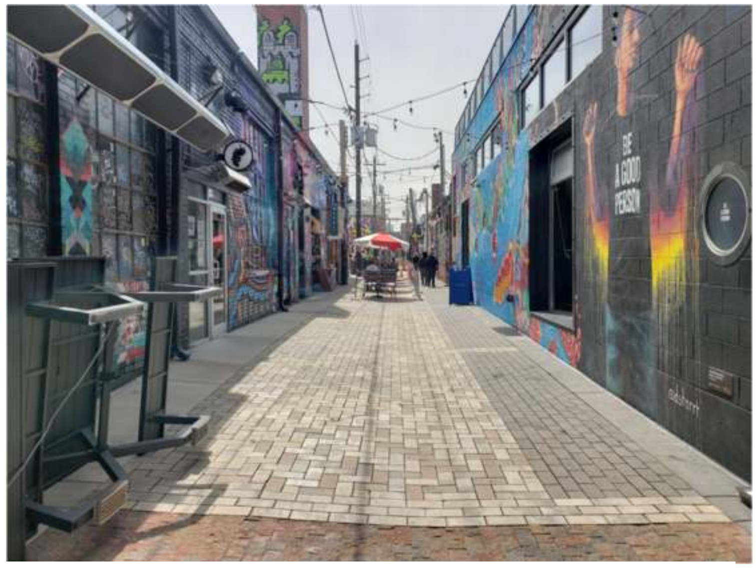
[6] Total phosphorus removal is typically high when it is specifically targeted for removal with proprietary media.

[7] When runoff volume reduction is considered, nutrient loads can be reduced. Nutrient concentrations may increase or not be reduced at discharge, depending on maintenance practices, soil conditions, and other site-specific factors.

[8] Relative to the life-cycle cost of conventional pavement.

2.0 Community Values

SCMs are beneficial for protection of public health, safety, and welfare and are required by local governments that are MS4 permittees; however, these types of facilities also have significant visual and experiential impacts on their surrounding environments. These impacts can be negative or positive depending on planning and design factors including selection of the most appropriate types of SCMs for the site; proper siting of features; design details, materials, and finishes of major elements; grading/landforms; vegetation; scale; and user experience. As SCMs become more commonplace in urban and suburban environments, it is important to understand the influence these features have in the landscape and how important good design is to a positive outcome. It is important to consider how investments in water quality treatment can provide value to the community beyond the primary treatment objectives.



Photograph 4-1. Permeable pavement in an alleyway provides infiltration in a space-constrained environment and provides a multi-functional area valued for more than just stormwater treatment.

Photograph 4-2. Full spectrum bioretention system at River Run Park creates a natural area that complements the manicured upland turf grass areas and provides a transition from the urban environment to the river.

Some important aspects of design to achieve broader community values include:

- **Context:** The surrounding environment should greatly influence the design of associated SCMs. Aesthetics, complementary uses or opportunities, and existing features including trees, walkway widths, adjacent buildings characteristics and other factors should play a primary role in SCM selection and design. For instance, if an SCM is in a dense, bustling commercial area dominated by buildings and hardscape, a more ordered and structured approach may be suitable given the surrounding urban fabric and need to fit into more constrained spaces. If an SCM is in a less-dense, suburban context dominated by open vegetated landscape areas, a softer approach is likely more compatible. Contextual influences determine which designs appear to “fit-in” versus clash with their surroundings. Exercise extra care when designing in unique settings such as underserved communities and historical/special districts, or when adjacent to parks and open spaces, pedestrian zones, and important civic and cultural landscapes. An incompatible SCM placed into a high value landscape can greatly diminish human experiences and civic value within the entire area.

- **Scale:** The mass and scale of an SCM can have a significant influence on its compatibility with a site. In the planning and design of SCMs, take cues from the surrounding context - avoiding large monolithic forms (such as walls, pipe features, etc.) that dominate the site/space unless there is a purposeful design objective to be achieved by emphasizing the structure’s architecture. When large features/SCMs are necessary, consider breaking up large masses of walls or structures into multiple smaller elements, steps, levels, or sections to reduce the scale of the feature. Incorporating vegetation into or adjacent to the SCM can help to modify the apparent scale of these facilities in the environment by screening and breaking up the visual mass of large structures.

- **Materials:** Materials and finishes play an important role in how infrastructure is integrated with its setting. Early in the design process, make decisions about whether an SCM should blend into its surroundings, complement nearby features, or be prominently visible. If blending into the setting is a desired objective, think about the effect of the feature’s colors, texture, and material qualities in relation to its surroundings. In a more naturalized setting, using neutral colors, natural materials, and irregular textures helps a feature to blend in. For cast-in-place concrete structures, consider form liners, exposed aggregate finishes, and sand blasting to help add texture and tactile qualities, soften hard edges, and reduce stark contrasts between manmade and natural site elements. Conversely, in highly urban areas, the look of smooth concrete with crisp forms may be a more appropriate way to integrate the feature into the architectural context. Thoughtful use of tones and color is important to complement material choices. Color variation can be achieved in many ways via material or finish selection, or with the use of stains and/or integral coloring agents. In public areas, graffiti is common and should be considered when making material decisions. Heavy

Photograph 4-3. Choice of materials for bioretention system is compatible with landscaping and aesthetics of neighborhood.

textures and specialized coatings can help reduce graffiti or make regular removal easier.

- **User Experience:** SCMs can be designed to enhance the experiences of people by way of appearance from near or afar, the sounds and aesthetic qualities of moving water, interpretive and educational opportunities, integration into landscapes, providing trails and gathering areas, or simply by not diminishing an otherwise nice place. This can often be achieved by considering ways to engage the curiosities of people, their movement near or on surfaces, seating, shade, or any other way to create a positive experience fora passer-by. A well designed SCM can become a popular destination for people to sit, walk across, learn something from, or be near water and interesting vegetation. Tree canopy can provide shade that enhances the user experience and also helps to mitigate urban heat island effects. Additionally, vegetation can provide ecosystem services (e.g., insects, birds). An experiential program can help create community values in many ways. This objective always needs to be balanced with safety-first design, and designers must avoid designs that invite people to access places where there are inherent hazards (high velocities, entrapments, drop-offs, etc.).

Photograph 4-4. Retention pond with trails and picnic shelters creates an open space amenity in multi-family development.

The SCM fact sheets that follow in this chapter provide information related to community values for design opportunities and recommendations specific to each type of SCM.

3.0 Site Assessment

Site assessment is the first step in developing a stormwater management strategy for a project or development site. As discussed in Chapter 1, consider stormwater quality needs early in the development process based on site conditions typically leads to better stormwater management. Site conditions related to existing and proposed topography and drainage patterns, hydrology, soils, groundwater, bedrock geology, vegetation and ecological resources, utilities, and other factors must be known to determine which SCM or combination of SCMs will be most effective. Planners and designers must conduct investigations to characterize site conditions and constraints to understand the surface and subsurface characteristics of a site. Whether the SCMs selected for a site rely on infiltration or rely on storage and slow release of runoff, diligent site assessment is needed to evaluate site conditions that affect SCM selection, design, and performance. Typical site assessments and data may include, among others:

- Topographic surveys of the project site, upstream areas draining onto site and downstream conveyance systems or overland flow paths.
- Natural Resource Conservation Service (NRCS) soils mapping.
- Geologic mapping from Colorado Geologic Survey (CGS) and other sources.
- Geotechnical exploratory borings and soils characterizations.
- Topsoil texture and agronomic properties.
- Infiltration test measurements for surface and subsoil characterization.
- Groundwater elevation data.
- Floodplain/floodway mapping from the Federal Emergency Management Agency and/or MHFD.
- Fluvial hazard zones and areas of geomorphic or geotechnical instability.
- Vegetation assessment including wetland and aquatic resources delineation.
- Evaluation of presence/absence of habitat for threatened or endangered species and other regulated species such as migratory birds.
- Studies of potential areas of contamination.
- Mapping of subsurface utilities including utility locates.
- Mapping of existing or proposed above-ground utilities and infrastructure in the vicinity of the SCM.
- Review receiving water quality conditions such as impairment listings on Colorado's 303(d) List and total maximum daily loads (TMDLs) for receiving waters. Local governments may have specific pollutant reduction targets due to TMDLs.

For SCMs that rely on infiltration as a primary outflow mechanism, such as bioretention, permeable pavements, grass buffers, and swales, subsurface investigations must be conducted to ensure that the soils will be suitable for infiltration of stormwater runoff over the life of the SCM. These investigations and design aspects of different types of infiltration sections are addressed in Section 4.0 Filtration and Infiltration Systems. Section 7.0 of this chapter addresses site assessment and design considerations for topsoil, vegetation and irrigation.

Figure 4-1 provides a flow chart that explains how the initial site assessment leads to decisions that affect SCM selection and design (additional guidance on SCM selection is provided in Chapter 2 of Volume 3). The numbering on Figure 4-1 is provided to indicate an order of preference for the various types of SCMs, focusing first on infiltration-based SCMs that provide a high level of treatment and runoff reduction, then on filtration-based SCMs that are lined, and finally on store-and-release SCMs such as ponds when these other approaches are not feasible. Runoff reduction practices that direct runoff from impervious surfaces to receiving pervious areas (e.g., Step 1) should be implemented on all projects whether the primary SCM uses an infiltration, filtration, or store-and-release approach.

FSD and Infiltration/Filtration SCMs

FSD can be combined with a variety of SCMs and is not restricted to ponds. When FSD is integrated with a filtration- or infiltration-based SCM such as bioretention or a sand filter, design the outlet to release the additional volumes associated with the EURV and 100-year storage via surface outlets consisting of orifices and/or weirs. The surface release of the EURV and 100-year volume helps to manage the hydraulic loading on the filter material and/or infiltration surface, which is primarily intended for treatment of the WQCV.

Use the data from the initial site assessment to first consider if the site is suitable for infiltration-based SCMs because these types of SCMs provide the most runoff reduction and high levels of treatment for many types of pollutants. If infiltration-based SCMs are not feasible on a site, next consider filtration-based SCMs that are lined to prevent infiltration. The physical and biochemical processes in these SCMs provide higher levels of treatment than sedimentation-based SCMs. If infiltration or filtration-based SCMs cannot be implemented or are incompatible with community design objectives, sedimentation-based SCMs including extended detention (dry) basins (EDBs), retention ponds, or constructed wetland ponds can be considered. When designed in a way that connects the SCM with surroundings, ponds can be valuable landscape features and provide good levels of treatment, particularly retention ponds and constructed wetland ponds.

Depending on the results of the site assessment and the types of SCMs selected, different sections of Chapter 4 will be needed for design. Figure 4-1 lists the key sections of this chapter used for design of different types of SCMs. To design an SCM, the engineer should use the sections of this chapter listed in Figure 4-1 in conjunction with the fact sheets specific to the types of SCMs selected.

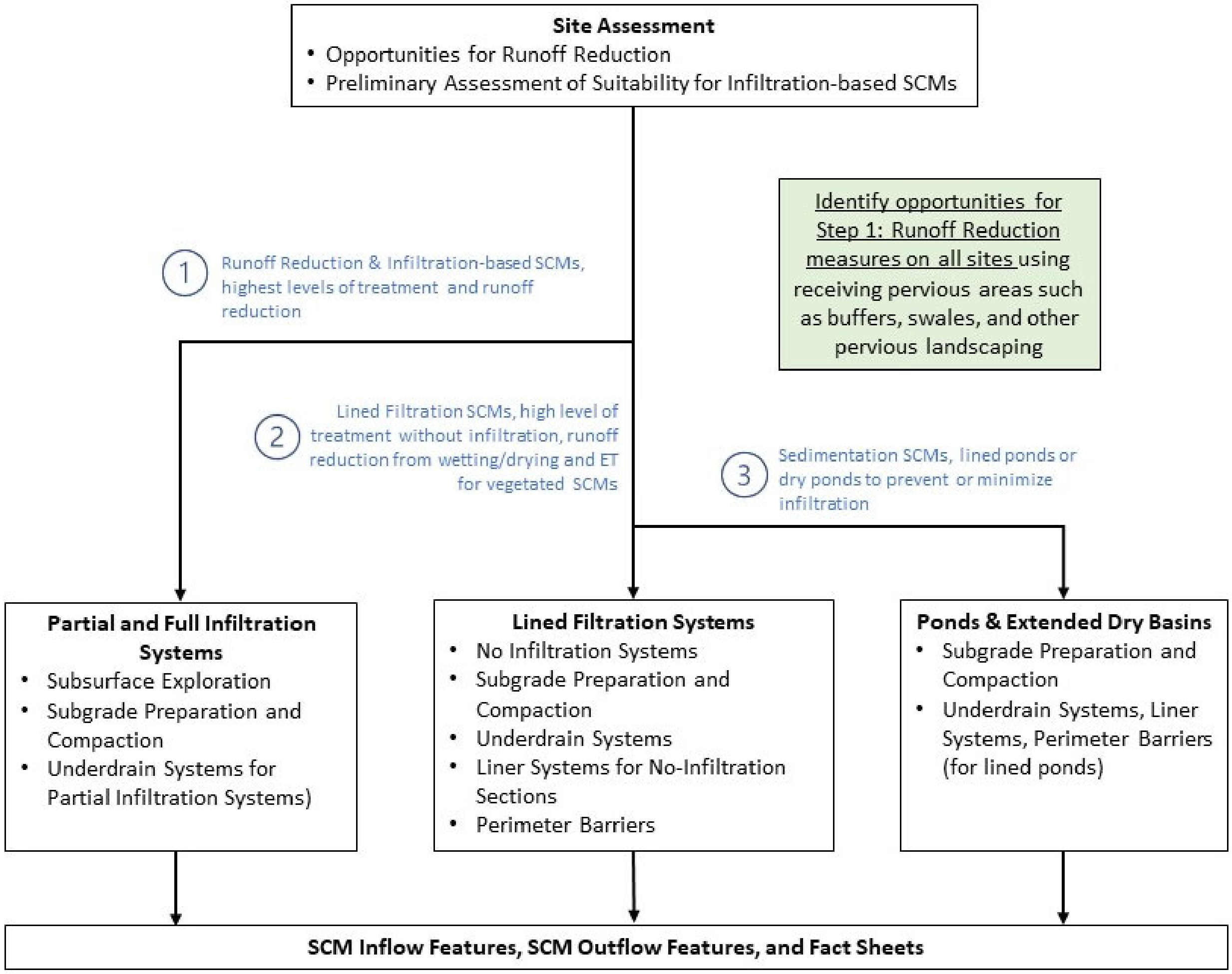


Figure 4-1. Applicable SCM Types Based on Site Assessment and Relevant Sections of Chapter 4 for SCM Design

3.1 Opportunities for Runoff Reduction

Site assessments should include evaluation of opportunities for infiltration-based SCMs because these types of SCMs reduce the *rate, volume, and frequency* of runoff, while SCMs that store and release the WQCV primarily affect *the rate*. Additionally, SCMs that provide runoff reduction help to reduce pollutant loads (considering volume reduction in addition to concentration reduction). Vegetated SCMs reduce the volume of stormwater runoff through infiltration, depression storage, and evapotranspiration. Permeable pavements and sand filters reduce runoff through infiltration without the vegetative component. To reduce the volume of runoff, impervious areas are "disconnected" to drain to receiving pervious areas (RPAs) such as buffers, swales, and other pervious areas instead of directly to gutters and storm drains. Runoff reduction practices described in this chapter may be used to meet the Runoff Reduction Standard in MS4 permits or to reduce the size of the WQCV required for other SCMs in a treatment train.

Suitability for Infiltration-based SCMs

Infiltration-based SCMs can be used in many settings; however, the effects of infiltration on surrounding structures and infrastructure must be carefully evaluated. Generally, infiltration is undesirable immediately adjacent to roadways, building foundations or near steep slopes. Consult with a geotechnical engineer when designing infiltration-based SCMs.

Some infiltration can be achieved even on low permeability sites by using a partial infiltration section. A no infiltration section with a liner and underdrain may be used in situations where infiltration into underlying soils must be avoided, providing treatment by filtration.

Runoff reduction is the first step of the Four Step Process for minimizing adverse impacts of urbanization as detailed in Chapter 1, *Stormwater Management and Planning*. Minimizing directly connected impervious areas (MDCIA) by allowing runoff from impervious areas to sheet flow through vegetation reduces pollutant loading to the receiving waters and helps mimic predevelopment hydrology. Runoff reduction approaches include conserving natural features such as trees, riparian corridors, and areas with permeable soils, as well as avoiding unnecessary impacts by not adding more impervious areas than necessary. These practices enhance site aesthetics and can be amenities that connect the built and natural environments when integrated with landscaping.

During a site assessment, it is important to identify areas that can be preserved to provide canopy interception, depression storage, and infiltration and to identify areas with soils that are most suitable for infiltration-based SCMs. This information should be gathered and analyzed as a part of the layout of roads and buildings so that features that reduce the volume, rate, and frequency of stormwater runoff can be preserved to the extent practical and created where these types of SCMs will be most effective.

3.2 Preliminary Assessment of Suitability for Infiltration-based SCMs

Perform assessments in the early planning stages of site development to determine if the site is suitable for infiltration-based approaches that reduce the volume of runoff reaching receiving waters. Because infiltration-based SCMs provide many benefits in terms of reducing runoff, providing a high level of treatment, and adding value to the surrounding community, among others, MHFD strongly encourages planners and engineers to integrate these types of SCMs into the early planning stages of a project, so that a project is not forced into using a less functional SCM, due to site layout constraints that could have been avoided with earlier coordination between site planners and stormwater designers.

Prior to conducting subsurface explorations, review geologic and geotechnical information to assess near-surface soil, bedrock, and groundwater conditions that may be encountered, along with anticipated ranges of infiltration rates for those materials. Obtain available hydrologic and geologic information on the near-surface soils and bedrock from published NRCS data, USGS maps, CGS maps, and other sources (Hart, 1974; Himmelreich, 1999; Noe et al., 1995; White et al., 2008). Identify any areas of known or suspected contamination on or near the site that may have the potential to affect water quality either through soils that are exposed during construction of the site or from infiltration of runoff into soils with existing contamination. Review any Environmental Site Assessments (ESAs) conducted for the site and consider hiring an environmental professional to perform a Phase I ESA if a recent one is not available. Potential resources for screening for known or suspected contamination are provided in Table 4-2. This information aids in planning detailed site investigations which may include geotechnical borings, soil testing, and infiltration measurements.

Table 4-2. Resources for Identification of Known or Suspected Contamination on Project Sites and within a 1-mile Radius[1]

Map/Database	Description
CDPHE Environmental Records Map	Colorado Department of Public Health and Environment (CDPHE) Database and map including solid waste facilities, Voluntary Cleanup (VCUP) sites, sites with institutional controls such as covenants required by the state, brownfield sites, National Priority List (NPL) sites, Resource Conservation and Recovery Act (RCRA) sites, Uranium Mill Tailings Remedial Action (UMTRA) program sites.
OPS Petroleum Release Events in Colorado	Underground Storage Tank (UST) system and Aboveground Storage Tank (AST) system petroleum release events, with their associated locations, contacts for remediation, and status in relation to currently being investigated, assessed, remediated, obtaining closure, or closed, dating back to 1986. Data provided by the State of Colorado, Department of Labor and Employment, Division of Oil and Public Safety (OPS).
Denver Area Historical Fill Areas	Database and mapping of historical fill sites in and near Denver, including portions of Commerce City, including historical dump sites.
Sanborn Fire Insurance Rate Maps of Colorado	The Sanborn Fire Insurance Maps of Colorado is a digital collection of Sanborn fire insurance maps of cities across Colorado. The collection contains 346 maps of 79 principal cities in 52 counties covering the years 1883-1922. These maps are useful for identifying historical land uses associated with potential contamination.

[1]These resources are provided for reference purposes only. This is not intended to be a comprehensive list of resources. Use these as an initial screening tool only. If there is known or suspected contamination on or near a site, identify such conditions through appropriate tools including the ones listed above, others, or an Environmental Site Assessment conducted by a qualified environmental professional and coordinate, as necessary, with appropriate regulatory agencies.

4.0 Filtration and Infiltration Systems

Filtration and infiltration systems reduce runoff volume and pollutants by filtering runoff through porous media and, when conditions are suitable, infiltrating the runoff into the underlying soils. In areas where infiltration is undesirable, systems can be located where more favorable conditions exist or designed with impermeable liners that provide a high level of treatment through filtration and runoff reduction through the wetting and drying of the porous media and evapotranspiration for vegetated systems.

High, Moderate, and Low Risks

Infiltration of stormwater has the potential to cause damages in some settings, and the potential for damages defines the level of risk. High risk is generally defined by the potential for major structural damage (i.e., swelling soils heaving foundations or roads). Moderate risk is defined by the potential for lesser damage that can be mitigated through the use of a lined system. Low risk areas are those where infiltration is acceptable and the risks primarily arise from uncertainty in actual infiltration rates rather than the potential for structural damage.

To evaluate the potential to use infiltration-based SCMs, consult with a geotechnical engineer during the initial site assessment and consider the risks of infiltration, even when an impermeable liner is used, based on subgrade conditions and potential structure impacts as described herein. Table 4-3 summarizes applicable SCM filtration and infiltration approaches for the three basic subsurface cross sections that are shown in Figure 4-2.

Table 4-3. Subsurface Conditions and Applicable SCM Filtration and Infiltration Systems

Subsurface Conditions and Risks of Infiltration[1]	**Applicable SCM Approach**			
	Full Infiltration System (no liner or underdrain)	**Partial Infiltration System** (underdrain, no liner)	**No Infiltration System** (liner and underdrain)	**Avoid** (locate SCM in an area with lower risk)
High infiltration rates and low risks	Must verify adequate subgrade infiltration rates	Acceptable		
Low to moderate infiltration rates and low risks		Acceptable		
Moderate risks			Requires careful QA/QC to ensure liner integrity	Consider an alternative SCM location
High risks				Find alternative SCM location

[1]Verify with geotechnical engineer.

4.1 Types of Filtration and Infiltration Systems

4.1.1 Full Infiltration Systems

Full infiltration systems can be used when the measured infiltration rate is at least 1 inch per hour and the subgrade of the SCM is approximately 3 feet or more above seasonal high groundwater or bedrock. When seasonal high groundwater is within 5 feet of the subgrade, consider more detailed monitoring of groundwater conditions before selecting a full infiltration system. Measure infiltration rates at the approximate depth of the proposed infiltration surface per Section 4.2 Subsurface Exploration. The minimum rate of 1 inch per hour accounts for some uncertainty in subsurface conditions and potential for some limited inadvertent compaction during construction. In some cases where the SCM has little run-on (e.g., a permeable pavement system with a low ratio of UIA:RPA), a full infiltration system may be used with lower measured infiltration rates at the discretion of the designer.

A conservative design of a full infiltration system could use the partial infiltration section with the addition of a valve or removable plate or plug at the underdrain outlet. If infiltration rates are lower than expected following construction or decline significantly over time, the valve could be opened, or plate/plug removed, to allow the system to operate as a partial infiltration section.

4.1.2 Partial Infiltration Systems

Partial infiltration systems are applicable in many settings when the conditions listed in Section 4.1.1 do not exist. Partial infiltration systems do not include impermeable liners and allow for infiltration but do include an underdrain system to collect and drain water that that does not infiltrate into the subgrade. MHFD recommends a partial infiltration system where infiltration rates do not meet the criteria for a full infiltration system and a no infiltration system is not warranted.

4.1.3 No Infiltration Systems

No infiltration systems include an underdrain and an impermeable liner intended to prevent infiltration of stormwater into the subgrade soils. Consider using a no infiltration system when any of the following conditions exist:

- The site is a stormwater "hotspot" (e.g., an area where pollutants may be highly concentrated such as an industrial storage area or drive-through lane) and infiltration could result in contamination of groundwater.
- The site is located above or adjacent to contaminated soils where infiltration could mobilize those contaminants, resulting in groundwater contamination.

- The facility is located over potentially expansive soils or bedrock that could swell due to infiltration, or potentially collapsible soils that could settle due to infiltration, potentially damaging adjacent structures including buildings and/or overlying hardscape areas or pavement.
- The facility is located above the foundation wall backfill placed against buildings with basements or below-grade levels. For this condition, a liner may only need to extend 10 feet beyond the wall before transitioning from a lined system to a partial or full infiltration system.
- The facility is located at the top of or on a slope steeper than 3 (horizontal):1 (vertical) that could become unstable when the soils are saturated. During the geotechnical investigation, evaluate the potential for landslides triggered by saturation of the site soils in such cases.

Depending on the severity of consequences of a no infiltration section liner leaking over time (i.e., structural damage, spreading of contamination, shallow groundwater conditions that may float the liner resulting in ground heave, etc.), even a no infiltration section may not be appropriate. In these cases, move the SCM away from the conditions of concern as indicated for high risks in Table 4-3.

Involve a Geotechnical Engineer

SCMs used for infiltration adjacent to buildings, hardscape, or conventional pavement areas can adversely impact those structures if protective measures are not provided. Oversaturated subgrade soil can cause structures to settle or result in moisture-related problems. Wetting of expansive soils or bedrock can cause those materials to swell, resulting in structural movements.

Consult with a qualified geotechnical engineer when planning an infiltration-based SCM. This is necessary to select the appropriate system type and establish minimum distances between the SCM and structures of concern or provide recommended measures to mitigate potential impacts. A geotechnical engineer also can assist in estimating the range of surface and subgrade infiltration rates to be used for design based on laboratory testing that identifies the hydrologic soil type and field infiltration testing that estimates in-situ rates of infiltration.

4.2 Subsurface Exploration

Subsurface exploration provides valuable site characterization for determining the appropriate type of subsurface filtration and infiltration system for a given location. If the location is constrained by shallow bedrock or shallow groundwater, a no infiltration, partial infiltration section, or store-and-release SCMs may be more suitable than SCMs that rely on infiltration into the subgrade as the primary outlet. Low permeability soils may also present challenges for infiltration-based SCMs; however, when properly designed, partial infiltration-based SCMs with underdrains can still provide significant runoff reduction, even in areas with less permeable soils.

Apply the following guidelines to characterize infiltration capabilities of a site and as a preliminary step in determining the appropriate type of filtration and infiltration system:

- Drill exploratory borings or excavate exploratory pits to characterize subsurface conditions beneath the subgrade and develop requirements for subgrade preparation. The borings or pits will identify changes in subsurface conditions spatially and with depth, particularly with respect to physical properties and hydrologic soil groups.
  - Drill or excavate at least one boring or pit for every 160,000 ft^2 of site area and at least two borings or pits for sites less than 160,000 ft^2.
  - Extend borings or pits to a depth of at least 5 feet into the subgrade below the bottom of the base of the SCM. Extend borings at least 25 feet below the bottom of the SCM in areas where there is a possibility of encountering potentially expansive soils or bedrock that could affect structures.
  - Additional borings or pits at various depths may be recommended by the geotechnical engineer in areas where soil types may change, in low-lying areas where subsurface drainage may collect, or where the water table is likely within 8 feet below the planned bottom of the base or top of subgrade of the SCM.
- Perform laboratory tests on samples obtained from the borings or pits to initially characterize the subgrade and use the information to recommend the possible infiltration section type. For permeable pavements, assess subgrade conditions for supporting traffic loads. Consider the following tests:
  - Moisture content (ASTM D2216), dry density (ASTM D2936), Atterberg limits (ASTM D4318), gradation (ASTM D6913), and hydrometer analysis (ASTM D7928) as needed to characterize the hydrologic soil type and engineering index properties of the subgrade soils.
  - Swell-consolidation (ASTM D4546) for assessing the swell potential of clayey soil or bedrock.
  - R-value (ASTM D2844) and/or 96-hour soaked California bearing ratio (CBR) (ASTM D1883) for assessing subgrade soils for permeable-pavement traffic loading.

Laboratory hydraulic conductivity tests may also be considered for assessing infiltration rates and hydrologic soil type, although field hydraulic tests generally will provide more accurate results.

A geotechnical engineer should determine the appropriate test method based on the soil type and the intended purpose of the SCM. Field infiltration tests or percolation tests can be considered for initial assessment. However, more definitive testing is necessary for final design of the SCM. Additional guidance follows for initial assessment and final design.

4.2.1 Initial Assessment

For initial assessment of filtration SCMs, a percolation test method such as that used by the State of Michigan (SEMCOG, 2008) can be performed in open boreholes or pits following exploration to initially assess the range of infiltration rates for the subgrade soils for facilities that will infiltrate water from engineered media to the subgrade soils. This is particularly useful for sites where the location of the SCM and the subgrade soil horizon beneath the SCM have not yet been identified and/or exposed by excavation.

Other infiltration testing methods (such as a Turf-Tec infiltrometer or similar device) may be used for preliminary characterization of comparative infiltration rates or to help determine the most appropriate lower-infiltration area to perform the more definitive ASTM D3385 or ASTM D8152 tests discussed below. These methods are suitable for runoff reduction practices infiltrating flows from the land surface.

4.2.2 Final Design

For final design of a full infiltration SCM, perform the Modified Philip Dunne infiltrometer test (ASTM D8152) or double-ring infiltrometer tests (ASTM D3385):

- Perform at least one test for every 10,000 ft^2 of SCM area and no fewer than two tests per SCM location.
- Locate tests within the footprint of the planned SCM at the elevation of the proposed subgrade, if possible. This may require excavation of test pits to reach the subgrade.
- When feasible, conduct tests near the locations of completed borings so the test results can be compared to the subsurface conditions encountered below the subgrade horizon in the borings.
- Locate at least one test near the boring or pit showing the most unfavorable subgrade conditions for infiltration. The boring or pit can be one of those completed as part of the initial assessment, or a boring or pit from supplemental exploration that may be needed for final design.

Consult a qualified geotechnical engineer to see if additional exploration is needed.

Infiltration rate for design should be based on careful assessment of the subgrade conditions, classification of the hydrologic soil groups based on exploration and laboratory testing, and field infiltration testing. Be aware that actual infiltration rates are highly variable dependent on soil type, in-place density, moisture content, and degree of compaction (including over-compaction that can occur during construction), as well as other environmental and construction influences. Actual infiltration rates can differ by an order of magnitude or more from those indicated by infiltration or permeability testing, and a reasonable degree of conservatism is necessary when selecting the design infiltration rate. Because of this and the potential for decay of infiltration rates over the life of a facility, the HSG-based final infiltration rates in the *Runoff* chapter are recommended for design. If site-specific measured final infiltration rates differ significantly from the HSG-based rates in the *Runoff* chapter, the measured rates may be used with a 50% reduction for clogging over time.

4.3 Filtration and Infiltration Section Development

4.3.1 General Considerations

General requirements, design considerations, and construction considerations for filtration and infiltration-based SCMs are presented below. See specific SCM fact sheets for additional guidance and criteria. To the extent that guidance in the fact sheets differs from the general guidance in this section, follow the more-detailed guidance in the fact sheet. General differences between sections developed for no infiltration, partial infiltration, and full infiltration types are shown on Figure 4-2 and summarized below. Further detail and material specifications are provided in the next section.

- A **no infiltration section** is designed to prevent infiltration into the subgrade and includes a liner and underdrain system designed to gravity-drain water captured by the SCM to an outfall or discharge point. In accordance with criteria below, use a PVC geomembrane with a minimum thickness of 30 mil for the buried liner, and place a protective, non-woven geotextile fabric (Mirafi 180N or equivalent) above the geomembrane to protect the geomembrane from punctures and tears during placement and construction of the overlying filter/drain system and SCM. Consider using a similar geotextile beneath the geomembrane if there are sharp rocks or objects beneath the liner that cannot be removed during subgrade preparation. Other liner systems may be approved by local governments.
- A **partial infiltration section** allows for infiltration into the subgrade but also includes an underdrain to slowly release water that does not infiltrate. This section includes a geotextile filter fabric (Mirafi 180N or equal) along the bottom and the sides of the drainage trench holding the underdrain pipe and drain gravel. The filter fabric is used to prevent finer subgrade soils that are not filter-compatible with the drain gravel from migrating into the gravel and eventually into the pipe. In the unusual condition that the subgrade soil below the base of the SCM consist of coarse gravels and cobbles that are not filter compatible with the overlying SCM materials, place a minimum 6-inch-thick transition filter between the SCM and the underlying layer. For example, in a localized area where the underlying subgrade is composed of gravel, cobbles, and boulders and there is a potential that bioretention growth media could migrate through the voids of the subgrade, consider placement of a 6-inch transition filter that is compatible with both the growth media and the subgrade. Filter sand like that used above the underdrain trench may be used, provided it is filter-compatible with the subgrade. If not, a coarser transition filter material may be needed. Procedures for assessing the filter-compatibility between soils for dams (USDA, 2017) can be used to design a proper transition filter if needed. Using a geotextile filter fabric in place of a minimum 6-inch-thick transition filter is generally not recommended because the fabric could bridge or “tent” over the underlying cobbles and boulders, resulting in voids beneath the fabric. This can cause the unsupported fabric to tear and result in settling of the overlying filter/drainage system and SCM.

- A **full infiltration section** is designed to infiltrate all of the WQCV into the subgrade and does not include an underdrain system or a liner. If there are localized areas of the SCM where the SCM material is not filter-compatible with the subgrade, place a minimum 6-inch transition filter in these areas. In some cases, a full infiltration section may be constructed with an underdrain that is plugged or controlled with a valve to allow the system to be converted to a partial infiltration system in the event that infiltration into the subgrade slows over the long term.

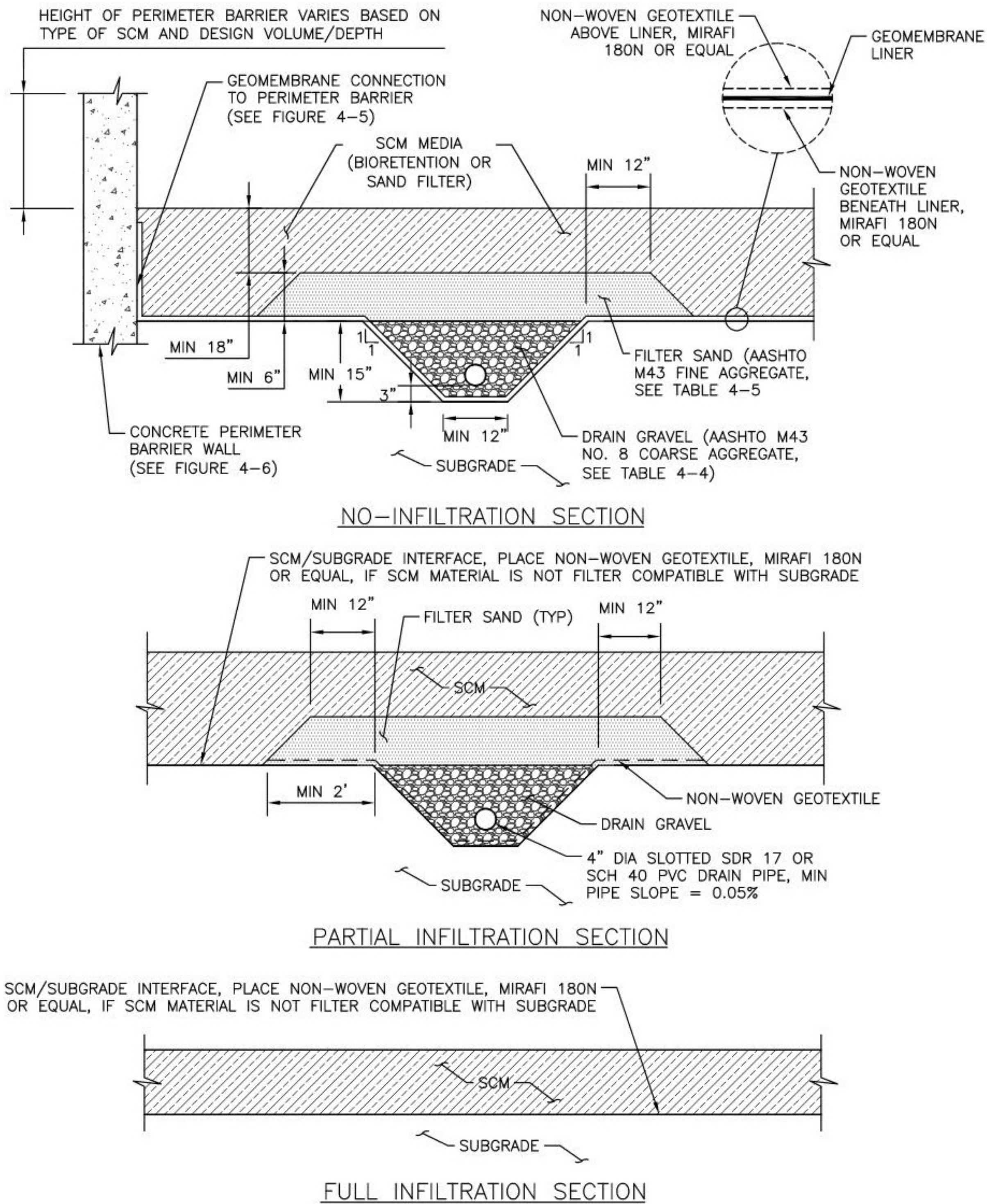


Figure 4-2. Conceptual Cross Sections for Full, Partial, and No Infiltration Systems

4.3.2 Subgrade Preparation and Compaction

Subgrade preparation and compaction are critical elements of SCM design and construction. Subgrade compaction is needed to prevent settling in no infiltration systems and in load bearing systems, but for partial and full infiltration systems that are not subject to vehicular loads, only limited compaction of the subgrade is recommended to preserve the infiltration characteristics of the subgrade. Different criteria apply depending on the type of filtration and infiltration system and the type of SCM.

For SCMs that require subgrade support (e.g., pavements), scarification and compaction should be provided in accordance with the pavement requirements. Scarification of the upper 6 to 8 inches of subgrade, moisture-conditioning, and recompaction of the subgrade are typically required for subgrade preparation prior to constructing any pavement section, including conventional flexible pavements, or permeable pavements. Scarification is beneficial in providing a more uniformly moisture-conditioned and densified subgrade. It also allows the engineer to observe a proof-roll of the compacted subgrade to identify local soft areas that deflect under compaction that need additional work.

No Infiltration Systems

For a no infiltration system, specify compaction to at least 95 percent of Standard Proctor Compaction (AASHTO T99) at a moisture content within 2 percentage points of the optimum moisture content. Alternatively, specify compaction of the subgrade with several passes of compaction equipment that provides a level of compaction equivalent to at least 95 percent of Standard Proctor. Consult with a qualified geotechnical engineer regarding the compaction equipment and number of passes. These criteria are also applicable for lined ponds.

Partial and Full Infiltration Systems

For partial and full infiltration sections, scarify the subgrade to a minimum depth of 12 inches and level the surface. Provide only limited compaction, where necessary, to limit settlement of the SCM.

For partial and full infiltration sections, place equipment outside limits of the SCM or use low-ground-pressure (LGP) tracked equipment for subgrade grading to limit subgrade compaction.

Refer to the SCM fact sheets in this chapter for specific compaction requirements for different types of SCMs. For SCMs such as permeable pavements that include coarse aggregates, those materials may not be testable for compaction using a method based on specified density (e.g., nuclear density testing). Consider a method specification (e.g., number of passes of a specified vibratory compactor) for those materials. The appropriate number of passes is dependent on the type of equipment and depth of the layer.

4.3.3 Underdrain Systems

An underdrain system is required for no infiltration and partial infiltration sections. An underdrain system consists of a slotted PVC pipe placed within a layer of drain gravel consisting of a crushed rock that satisfies gradations requirements for AASHTO M 43 No. 8 aggregate in accordance with Table 4-4. Specify that this be washed or otherwise ensure it contains minimal fines. Do not use rounded or sub-rounded aggregate, sometimes referred to as pea gravel, because it can move under compaction or when stepped on or loaded with construction equipment. Compaction of the drain gravel placed above the underdrain pipe in the confined trench shown on Figure 4-2 typically is not required because that confined material will be adequately densified by compaction of the material placed above it. Place a minimum 6-inch-thick layer of filter sand above the drain gravel and underdrain pipe and extend at least 12 inches beyond the limits of the drain trench. The filter sand must satisfy gradation requirements for AASHTO M 43 fine aggregate material based on the gradation limits in Table 4-5.

Table 4-4. Gradation Specifications for AASHTO M 43 No. 8 Coarse Aggregate (Drain Gravel)
(Source: CDOT Table 703-1)

Sieve Size	Mass Percent Passing Square Mesh Sieves
12.5 mm (1/2")	100
9.5 mm (3/8")	85 – 100
4.75 mm (No. 4)	10 – 30
2.36 mm (No. 8)	0 – 10
1.18 mm (No. 16)	0 - 5

Table 4-5. Gradation Specifications for AASHTO M 43 Fine Aggregate (Filter Sand)

Sieve Size	Mass Percent Passing Square Mesh Sieves
9.5 mm (3/8")	100
4.75 mm (No. 4)	95 – 100
2.36 mm (No. 8)	80 – 100
1.18 mm (No. 16)	50 – 85
600 µm (No. 30)	25 – 60
300 µm (No. 50)	10 – 30
150 µm (No. 100) [1]	0 – 10
75 µm (No. 200)[1]	0 - 3

[1] Slight variation from CDOT Table 703-1

Use factory-slotted pipe consisting of a minimum 4-inch (inside diameter) Schedule 40 or SDR 17 PVC pipe. Do not use perforated pipe or pipe that is hand-slotted. A slotted 6-inch inside diameter Schedule 40 or SDR 26 pipe can be used to allow larger access for video-inspecting the pipe. SDR pipe includes bell-and-spigot joints that provide more joint flexibility, whereas Schedule 40 pipe requires gluing the couplings, which provides less flexibility at the coupling. This may not be problematic provided that the pipe is well seated in the drain gravel.

Figure 4-3 and Table 4-6 provide recommended configurations of slot rows, widths, lengths, and spacing. Calculate the underdrain open area to verify conformance with the minimum and maximum values provided in Table 4-6. Recommendations aim to provide adequate open area to accept design flow rates while maintaining slot dimensions that retain pipe strength and are compatible with the No. 8 aggregate (USACE, 1984). Design interception rates are based on a slot velocity of 0.1 foot per second (fps) and a 50% clogging factor, which are criteria often used in well design.

Compact the filter sand above the underdrain using a walk-behind vibratory plate compactor in a single, approximately 8-inch-thick loose lift to achieve the minimum compacted thickness of 6 inches measured in place. Compact the filter sand to between 65% and 75% of relative density (ASTM D4253 and ASTM D4254). Do not over-compact the filter sand because this could cause the sand particles to break down, increasing the fines content (percent passing the No. 200 sieve) of the material.

Table 4-6. Recommended Underdrain Slot Configurations

Dimension	4-inch ID Underdrain		6-inch ID Underdrain	
	Minimum	Maximum	Minimum	Maximum
Number of slots per row (A)	4	6	4	6
Length of solid wall between slots at ID (B) (inches)	1.2	N/A	1.2	N/A
Slot width (C) (inches)	0.10	0.10	0.10	0.10
Slot spacing (D) (inches)	0.75	1.25	0.75	1.25
Open area per linear foot (square inches)	5.0	9.0	5.0	12.0 recommend

Note: ID = internal diameter

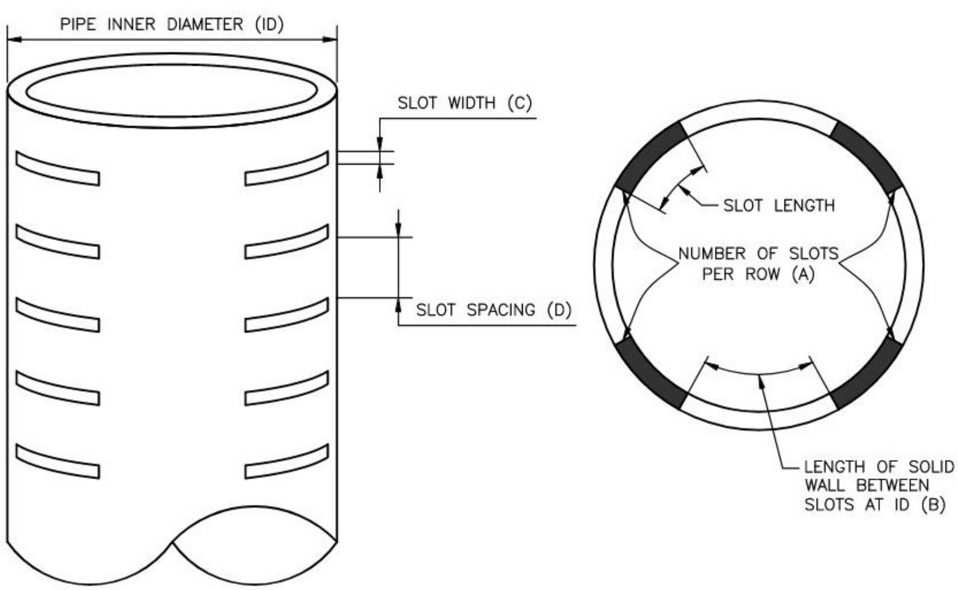


Figure 4-3. Configurations for Number of Rows, Slot Sizes, and Spacing for Schedule 40 Underdrain Pipe

When using an underdrain system, provide a control orifice sized to drain the design volume in 12 hours or more in accordance with the drain time criteria in the SCM fact sheets. Use a minimum orifice diameter of 3/8-inch to avoid clogging. When drilling orifices into a removable weir plate such as with an Agri-drain outlet, smaller orifice sizes may be used on a case-by-case basis to meet required drain times. The maximum spacing of the underdrain pipes should be determined by the designer based on the SCM fact sheets and the estimated flow rates but should not exceed a maximum spacing of 30 feet on center.

Provide clean-outs to allow camera inspection of the underdrain pipe system during and after construction to ensure that the pipe was not crushed or disconnected during construction and to allow for maintenance of the underdrain. For small systems, a single cleanout at the upstream end of the underdrain may be needed. For larger systems, multiple cleanouts may be required. Although a slotted 4-inch-diameter underdrain pipe can be video inspected, a slotted 6-inch-diameter Schedule 40 or SDR 26 pipe will allow for easier camera access for inspection and cleaning. The underdrain pipe should include vertical and horizontal bends using long-sweep elbows or elbows angled at 22.5 degrees to allow access for inspection cameras and cleaning equipment. Consider using a protective steel cover with a locking cap to protect the underdrain system from being damaged or vandalized.

Internal Water Storage (IWS) Zone (Brown et al. 2009)

An IWS zone can be created in bioretention systems using partial infiltration systems by adding a 90-degree elbow to the underdrain outlet to raise the elevation of the outlet and increase contact time with the media and infiltration into the subgrade. The top of the elbow should be at least 12 inches below the lowest elevation of the surface of the SCM in areas with HSG A soils and 18 to 24 inches below the surface for HSG B soils. An IWS may also be achieved by elevating the orifice in a flow control structure such as an Agri-drain.

In areas with lower permeability soils, an IWS zone must be carefully evaluated based on the site-specific permeability of the subgrade and the time it will take for water to drain from the IWS zone to avoid creating a permanently (or near permanently) saturated condition. The pore storage in the IWS zone may be counted as a part of the WQCV provided by the SCM, assuming effective porosity of 20% for sand and 30% for aggregate. In addition to benefits of increased infiltration and media contact time, the IWS zone promotes denitrification by creating an anoxic zone in the lower layer of the SCM where nitrate removal occurs.

4.3.4 Liner Systems for No Infiltration Sections

For no infiltration sections, install a minimum 30 mil PVC geomembrane liner on the bottom and sides of the SCM. Material specifications and physical requirements for the geomembrane liner are presented in Tables 4-7 and 4-8. Bury the geomembrane under at least 12 inches of cover material to protect the geomembrane from UV deterioration. Connect the geomembrane liner to a concrete perimeter wall, structure wall, or building foundation.

The geotextile used as a separator fabric or filter fabric should consist of a non-woven geotextile (Mirafi 180N or equal) satisfying the material specifications presented in Table 4-8.

Table 4-7. Geomembrane Properties

Properties	Test Method	Specified Value
Gauge (mils, nominal)	-	30
Thickness (mils, min.)	ASTM D1593 (Par. 8.1.3)	28.5
Specific Gravity (min.)	ASTM D792 (Method A)	1.20
Minimum Tensile Properties (each direction)	ASTM D882 (Method A or B)	
• Breaking Factor (lbs/in)		73
• Elongation at Break (%)		380
• Modulus at 100% Elongation (lbs/in)		32
Tear Resistance (lbs, min)	ASTM D1004 (Die C)	8
Low Temperature (deg F)	ASTM D1790	-20
Dimensional Stability (% change, max.)	ASTM D1204 (100 deg. C, 15 min.)	3
Water Extraction (% loss, max.)	ASTM D3083 (NSF 54 Modified)	0.15
Volatile Loss (% loss, max.)	ASTM D1203 (Method A)	0.7
Resistance to Soil Burial (% change, max.)	ASTM D3083 (NSF 54 Modified)	
• Breaking Factor		5%
• Elongation at Break		20%
• Modulus at 100% Elongation		20%
Hydrostatic Water Resistance (psi, min.)	ASTM D751 (Method A)	100
Water Vapor Transmission (cm/sec, max.)	ASTM D814	5.0×10^{-9}
Pinholes (number per 10 sq. yds. Geomembrane)		1
Seam Requirements		
• Bonded Seam Strength (lbs/in width, min.)	ASTM D882	58.4
• Peel Adhesion (lbs/in width, min.)	ASTM D882	15

Table 4-8. Material properties for Non-Woven Geotextile used for Separator or Filter Fabric

Properties	Test Method	Specified Value
Grab Tensile Strength (lbs, min.)	ASTM D4632	200
Grab Tensile Elongation (%)	ASTM D4632	50
Trapezoid Tear Strength (lbs, min.)	ASTM D4533	80
Mullen Burst Strength (psi, min.)	ASTM D3786	375
Puncture Strength (lbs, min.)	ASTM D4833	100
Apparent Opening Size (AOS) (U.S. Sieve)	ASTM D4751	80
Permittivity (sec^{-1})	ASTM D4491	1.4
UV Resistance (at 500 hours) (% strength retained, min.)	ASTM D4355	70
Weight (oz/yd^3, min.)	ASTM D5261	8

Figure 4-4 is a conceptual detail for the underdrain penetration of the liner. A detail for connecting the geomembrane to vertical concrete surfaces such as perimeter barrier walls and/or the concrete facing of buildings or other concrete structures is presented in Figure 4-5, and a detail for an example barrier wall is presented on Figure 4-6. Batten bars used to attach the liner to the concrete structure should consist of a 1/4-inch x 2-inch stainless steel bar with anchor holes at 6 inches on center and should be attached using 3/8-inch x 3-inch stainless steel anchor bolt, nut, and washer.

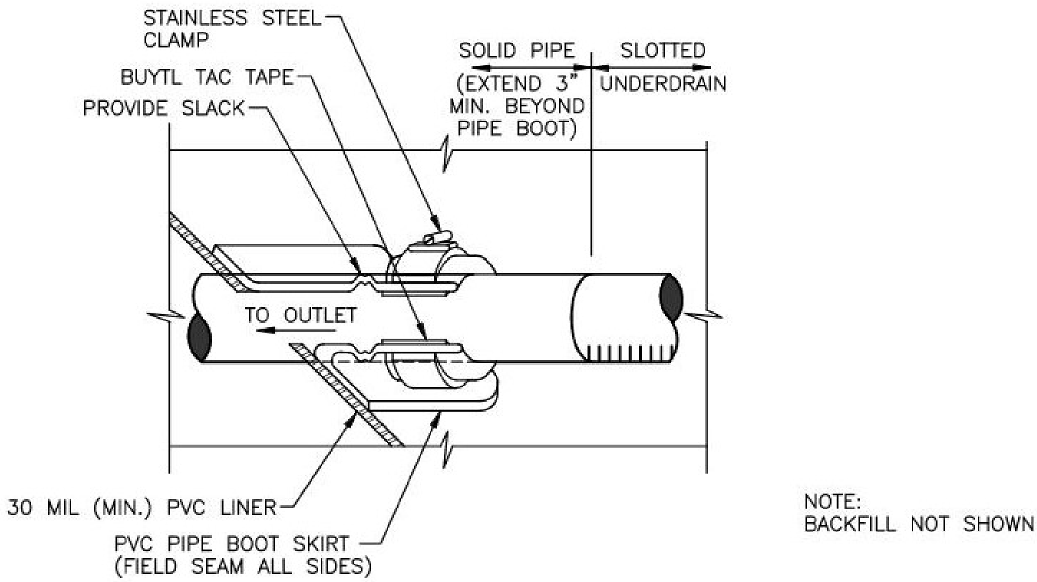


Figure 4-4. Conceptual Liner Penetration Detail for Underdrain

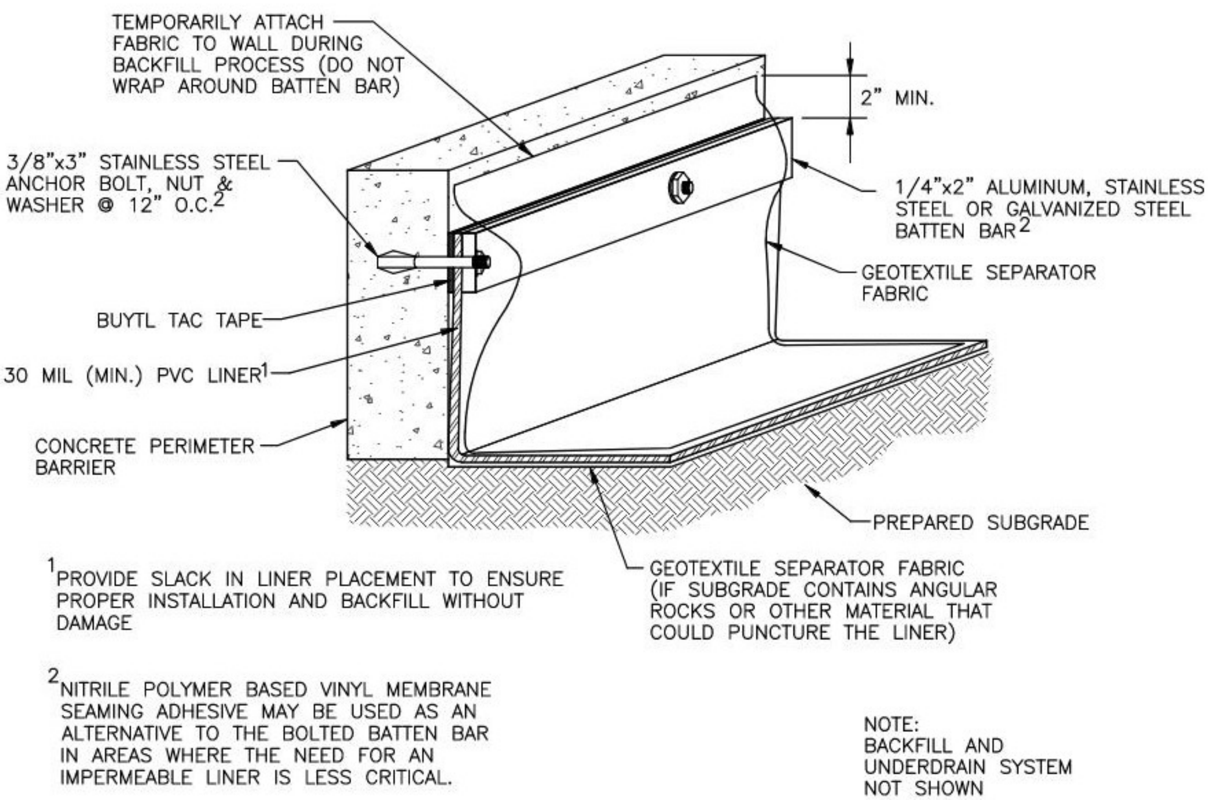
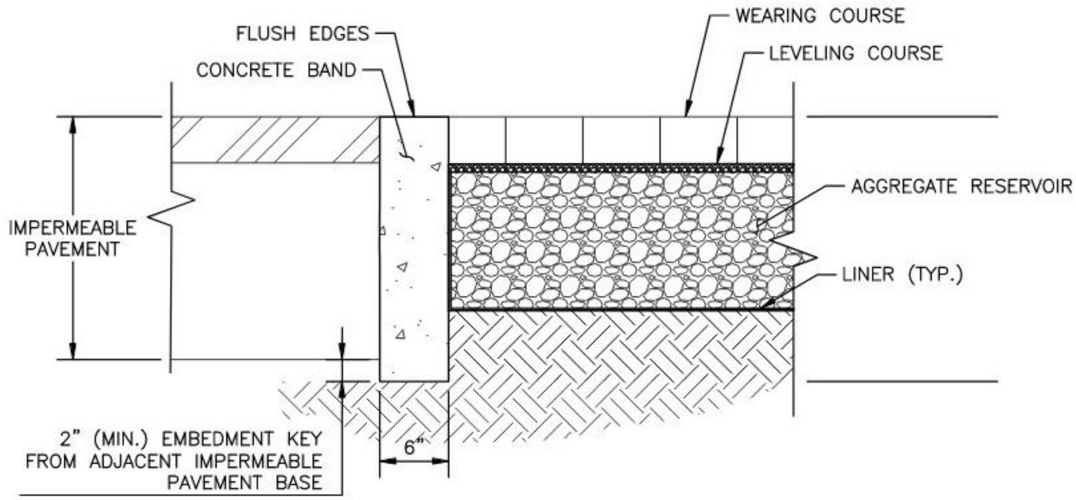
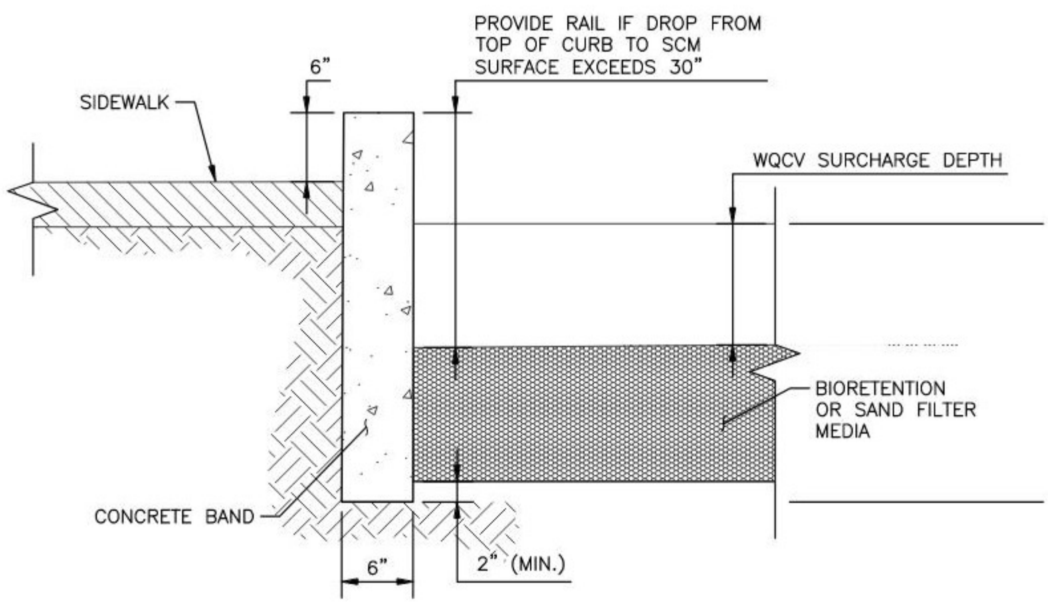


Figure 4-5. Conceptual Detail for Connecting Geomembrane to Vertical Concrete Surface



CONCRETE PERIMETER BARRIER FOR PERMEABLE PAVEMENT ADJACENT TO IMPERMEABLE PAVEMENT



CONCRETE PERIMETER BARRIER FOR BIORETENTION ADJACENT TO SIDEWALK

Figure 4-6. Conceptual Details for Concrete Perimeter Barriers

A perimeter anchor trench for the geomembrane may also be acceptable provided that at least 12 inches of cover material above the anchor trench is provided and that the top of the trench, marking the highest elevation of the geomembrane, provides adequate reservoir capacity for the SCM. Construction recommendations for geomembrane liner installations include:

- Field-seam the geomembrane using a single-track or double-track thermal fusion welder, and in accordance with the geomembrane manufacturer's requirements.
- Provide a 1.5-inch-wide seam for single-track welds and two nominal 0.5-inch-wide seams separated by an air test channel for dual track welds. Provide at least 6 inches of overlap between geomembrane panels for single track and dual track thermal fusion welding (PVC Geomembrane Institute [PGI], 2003).
- Install the geomembrane with some slack to prevent tearing due to backfill, compaction, and settling. Follow manufacturer's specifications related to acceptable weather conditions for installation. Do not install in the presence of standing water, mud, snow and excessive moisture, or frozen subgrade conditions.
- Prepare a smooth-rolled, level subgrade surface that is free of loose fragments greater than 2 inches in size and sharp rocks or objects that could potentially puncture the geomembrane. Both the SCM designer and geomembrane installer should inspect the subgrade for sharp rocks or objects prior to installing the geomembrane.
- Consider placement of a non-woven geotextile (Mirafi 180N or equivalent) beneath the geomembrane, in addition to the geotextile placed above it, if the subgrade surface cannot be prepared to remove sharp materials that could puncture the geomembrane. However, a bottom geotextile should only be when sharp materials are present. This is because geotextile placed under the geomembrane can allow lateral travel of leakage from local pinholes or other small defects to more permeable areas of the subgrade, potentially increasing seepage losses into the subgrade.
- Test all field seams, batten bar connections, pipe penetrations, and patches using a non-destructive air lance test. Perform destructive field seam tests to verify that the seam strength requirements of the specifications are met. Collect random samples at least every 500 linear feet (PGI, 2003) for field seams and conduct at least three tests regardless of the length of seams. Test coupons or samples cut out of the liner at selected seam locations for thickness, bonded seam strength and peel adhesion in accordance with minimum strength requirements presented in Table 4-7. Place and seam geomembrane patches used to repair the liner at each destructive sample location in accordance with the geomembrane supplier's requirements and test each patch with an air lance.

4.3.5 Lateral Flow Barriers

Lateral flow barriers are used in SCMs including permeable pavement systems, sand filters, and bioretention when the subgrade is sloped. These barriers prevent runoff that infiltrates into a upgradient portion of the SCM from re-emerging on the surface downslope and helps to reduce the potential for developing preferential subsurface flow paths due to piping. Lateral flow barriers are not needed for SCMs with flat or mildly slope subgrades. Construct lateral flow barriers using concrete walls or a 30 mil (minimum) PVC geomembrane. Place lateral flow barriers parallel to contours of the subgrade (normal to flow). See Figure 4-7 for typical steps in installing a geomembrane to create a lateral flow barrier. Provide separator fabric meeting the criteria in Table 4-8 between the geomembrane and all aggregate materials.

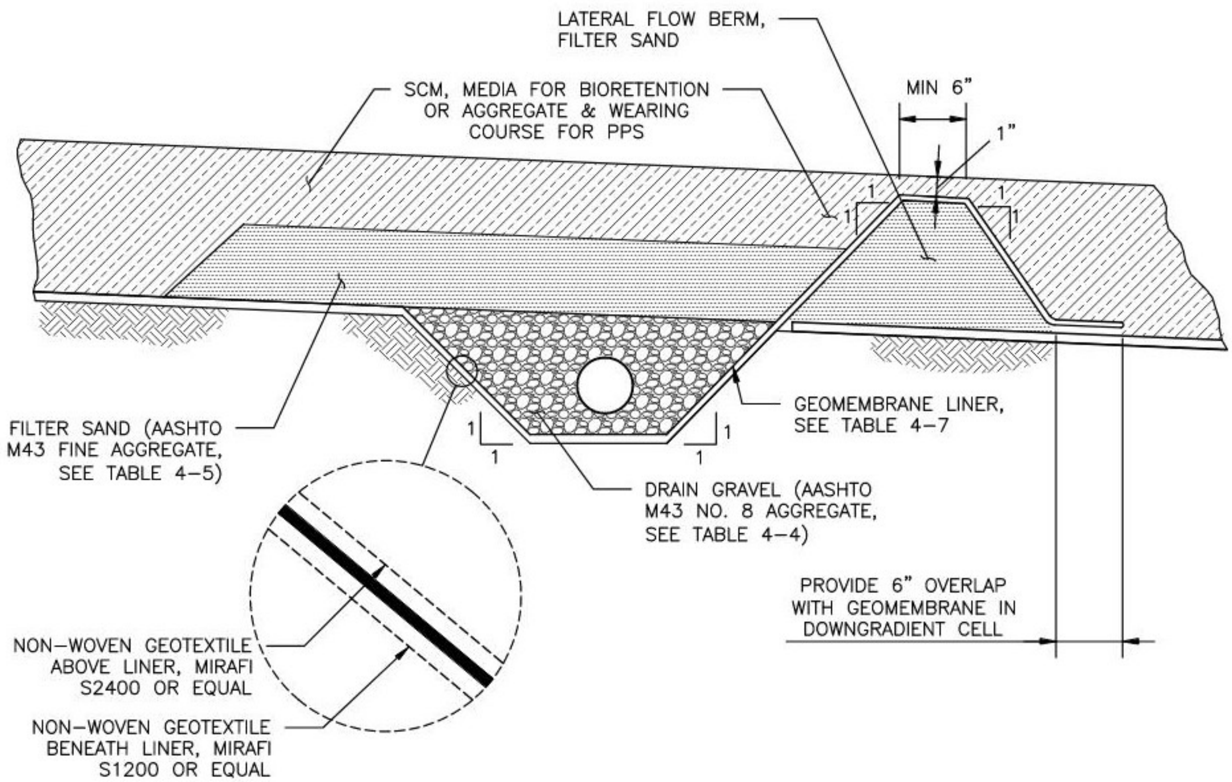


Figure 4-7. Lateral Flow Barrier Installation

4.3.6 Perimeter Barriers

A perimeter barrier is used to contain the subsurface media and aggregate layers of the SCM within the footprint of the SCM. For permeable pavement systems, a perimeter barrier also serves to contain the pavers and helps to reduce the potential for differential settling of the pavement. The perimeter barrier is typically designed to minimize or prevent the subsurface lateral migration of runoff and focus infiltration into the area underlying the SCM. The perimeter barrier also serves to minimize migration of fines from surrounding soils into engineered media and aggregate. Depending on the type of the SCM and the surroundings, a perimeter barrier may range from a geotextile fabric to an impermeable barrier such as a concrete wall or geomembrane. A perimeter barrier can be integrated with landscape edge treatments around the SCM.

Consider the area adjacent to the SCM when evaluating the perimeter design. Lateral flow can negatively impact adjacent structures and infrastructure. Consider construction of the interface between the permeable pavement and the adjacent materials and how the design will prevent adjacent materials from entering the SCM section. Depending on the soils, depth of SCM, and other factors, this may be achieved with fabric or may require a more formalized barrier. When the SCM section is adjacent to conventional pavement, a vertical liner may be required to separate the aggregate and media or the SCM from the dense-graded aggregates and soils within the conventional pavement. An impermeable liner can be used to provide this vertical barrier and separate the SCM from the adjacent street and utilities.

For a no infiltration section, the perimeter barrier also serves to attach the impermeable membrane. The membrane should extend up to the top of the filter layer and be firmly attached to the concrete perimeter barrier using batten bars to provide a leak-proof seal. A nitrile-based vinyl adhesive can be used when the need for an impermeable liner is less critical. Avoid attaching the liner to the barrier prior to placing aggregate as this often results in tears. See Figures 4-4 and 4-5 for installation details. For ease of construction, including the placement of geotextiles, extend the barrier to the bottom of the filter layer.

Photograph 4-5. Liner tear after aggregate placement (even with slack provided). To avoid this problem, delay attaching the liner to the perimeter barrier with a batten bar until after placing aggregate by temporarily anchoring the liner

For partial and full infiltration sections, the perimeter barrier for these sections restricts lateral flow to adjacent areas of conventional pavement or other structures where excessive moisture and/or hydrostatic pressure can cause damage. When this is of particular concern, extend the perimeter barrier to a depth 12 inches or more below the underdrain; otherwise, extend the barrier to the bottom of the filter layer.

5.0 SCM Inflow Features

The planning and design of inflow features must consider the flow distribution requirements of the SCM because many types of runoff reduction and filtration- and infiltration-based SCMs require sheet flow conditions to properly function and others can accept concentrated inflows. Once the designer determines whether sheet flow conditions are required or concentrated flows are permitted, evaluate different types of inflow features to select the approach that best fits the treatment objectives of the SCM and the surrounding environment. Sheet flow inflow features must be configured in a way that distributes the flows as intended to benefit vegetation and promote infiltration. For inflow features that convey concentrated flows, a sediment forebay is typically required to dissipate energy and provide an area for sediment and trash accumulation that is accessible for maintenance.

Table 4-9 summarizes a variety of options for inflow features based on the types of flow distribution along with common energy dissipation methods and forebay recommendations. There are many opportunities for creative design of inflow features provided that they meet the fundamental objectives of conveying runoff, dissipating energy, allowing for maintenance, and distributing flow in an appropriate manner for the SCM.

Maintenance Access

For sheet flow inflow features, access to the RPA along the downstream edge of curbless pavement, slotted curb, or level spreader is critical to allow for mowing to manage growth of vegetation and/or for sediment removal. Without this type of access and routine maintenance, the RPA can become densely overgrown and block drainage from the impervious area.

5.1 Sheet Flows

Sheet flow is uniform shallow surface flow that is evenly distributed, usually with a depth on the order of 0.1 feet of less. This typically occurs in the upper portions of watersheds and transitions to shallow concentrated flow over a distance of no more than a few hundred feet unless engineering measures such as level spreaders are used to redistribute the shallow concentrated flow as sheet flow. Some types of SCMs such as grass buffers and permeable pavements require sheet flow conditions to properly function. However, sheet flow conditions are not restricted to these types of SCMs. The banks of SCMs such as grass swales, extended detention basins, or other types of ponds can be designed as vegetated buffers to receive runoff from adjacent impervious areas. Bioretention systems and sand filters can incorporate level spreaders to evenly distribute inflows across the SCM, and level spreaders can be used to transition small, concentrated flows into shallow sheet flows. This section provides guidance and examples of different types of sheet flow inlets including curbless pavement, slotted curbs, and level spreaders.

Table 4-9. Summary of SCM Inflow Features

Typical Inflow Features	Energy Dissipation	Sediment Forebay	Typical Applicability to SCMs			
			RPAs, Buffers, Swales	EDBs, RPs, CWPs[2]	Permeable Pavements	Bioretention, Sand Filters
Sheet Flows						
Curbless pavement	Vegetation	No	✓	✓	✓	✓
Slotted curb	Vegetation	Curb acts as forebay	✓	✓		✓
Curb opening with level spreader	Level spreader	Blind swale[1]	✓			✓
Pipe outfall with level spreader	Level spreader	Blind swale[1]	✓			✓
Concentrated Inflows						
Downspout	Vegetation or hardscape	No	✓		✓	✓
Curb opening	Vegetation or rock	Yes	Swale only	✓		✓
Pipe outfall	Impact basin	Yes	Swale only	✓		✓
Grass swale	Vegetation	No		✓		✓
Stable ephemeral channel[3]	Vegetation and bed roughness	Case-by-case		✓		

Abbreviations: RPA: Receiving Pervious Area; EDB: Extended Detention Basin, RP: Retention Pond, CWP: Constructed Wetland Pond.

[1] A blind swale is a shallow area upstream of the crest of the level spreaders that allows for even distribution of flow across the length of the spreader. Additional information is provided in the Level Spreader section of this chapter.

[2] Level spreader applicable when side slopes act as RPAs.

[3] Locate SCMs offline when feasible, primarily applies to regional facilities, see *Storage* chapter.

5.1.1 Curbless Pavement

For parking lots, low-speed roads, and similar areas, sheet flow conditions can be created by foregoing a curb and gutter section. As shown in Photograph 4-6, curbless pavement can drain through a grass buffer and into an SCM such as a swale, bioretention system, sand filter, or pond as a part of a treatment train.

Photograph 4-6. Curbless pavement promotes sheet flow in adjacent grass buffers and swales for filtering and infiltration.

Use a concrete edger to create a stable edge for concrete or asphalt pavements. Provide a 3-inch drop from the edge of the impervious surface to the adjacent receiving pervious area to allow for growth of vegetation and accumulation of sediment over time. Some installations include a small gravel shoulder between the pavement and grass buffer. Because curbless pavement distributes runoff and creates sheet flow conditions, additional energy dissipation features and sediment forebays are typically not necessary. It is very important to include measures to discourage vehicles from driving off the pavement and rutting the SCM. In parking lots, wheel stops may be used. Sometimes markers, bollards, or fencing are used, or slotted curbs, described below, are selected instead of curbless pavement.

5.1.2 Slotted Curbs

Slotted curbs create sheet flow conditions in the adjacent RPA while also protecting the area from damage due to vehicles. In addition, slotted curbs provide for some trapping of litter and, in a sump condition, can act as a small sediment forebay. When functioning as a sediment forebay, design the slotted curb with access for a street sweeper for ease of maintenance similar to the City and County of Denver installation shown in Photo 4-7. The typical turning radius for a street sweeper is 25 feet but may be less depending on the specific type of sweeper used.

Photograph 4-7. Slotted or perforated curbs distribute pavement runoff and can function as a sediment forebay able to be maintained with a street sweeper.

As shown in Figure 4-8, design slotted curb with a 2-inch vertical drop to the concrete mowing strip. Similar to curbless pavement, the intent is to allow for the accumulation of sediment over time. The mowing strip facilitates maintenance and removal of sediment and overgrowth using a flat shovel. Space slots 2 feet on center or less to allow runoff to spread and form sheet flow conditions in the grass buffer. Compared to larger openings, sizing the slot openings at 1.5 inches will reduce potential damage from snowplowing. Provide a maintenance plan that specifies plowing of the area with a rubber tipped plow blade to further minimize damage.

Photograph 4-8. Typical slotted curb showing drop from slot to adjacent pervious area to allow for growth of vegetation and sediment accumulation. This area provides for mowing and maintenance access to keep positive drainage from the parking lot to the RPA.

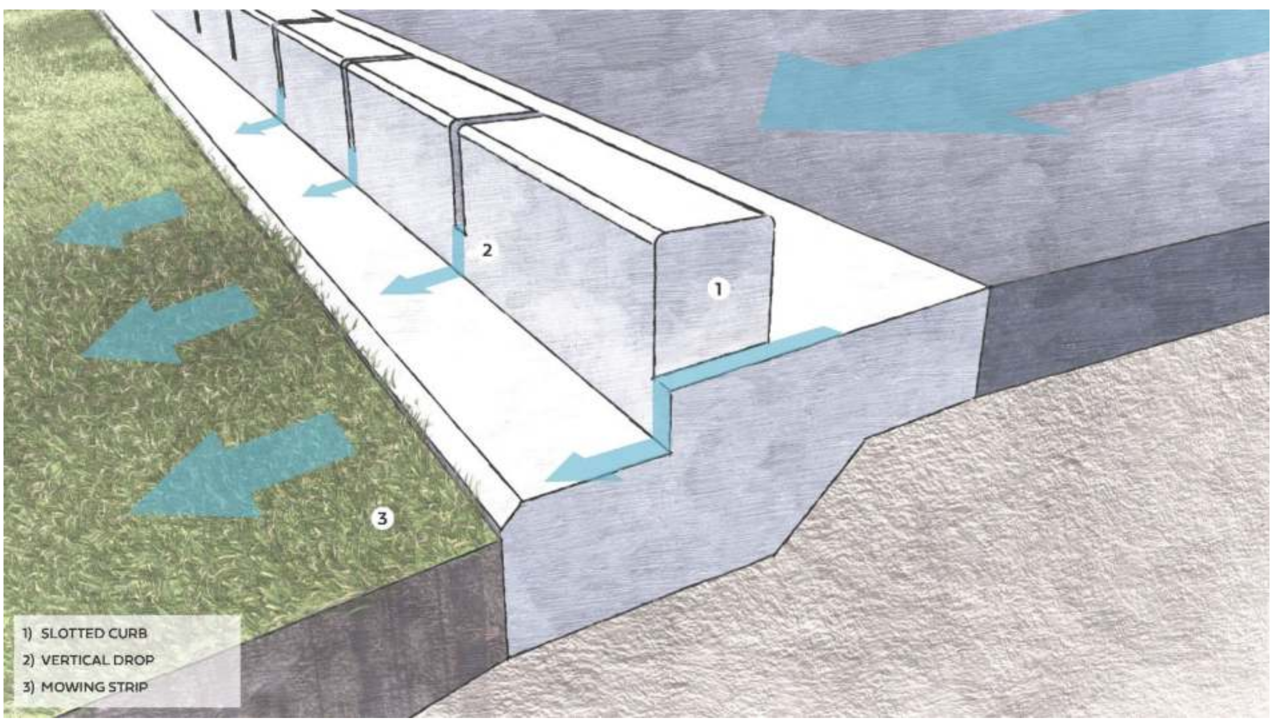


Figure 4-8. Slotted Curb Design Components

5.1.3 Level Spreaders

Level spreaders are features that capture shallow concentrated flows and flows from small diameter pipes and distribute them evenly over a level surface to create sheet flow conditions. Criteria for determining the required level spreader geometry are provided in the Receiving Pervious Area fact sheet. As shown in Figure 4-9, the primary components of a level spreader are a "blind swale" upstream of the spreader that distributes the concentrated flow along the upstream edge of the level surface, the level spreader surface (effectively a broad crested horizontal weir), a vertical or sloped drop of at least 3 inches immediately downstream of the spreader surface, and a maintenance access mowing strip downstream of the drop along the upper portion of the RPA.

For level spreaders designed for shallow concentrated inflows, such as at the edge of a parking lot, the curb and gutter may serve as the blind swale. For larger concentrated inflows from small pipes or channels, a vegetated swale with a flat longitudinal slope or depression may be used for the blind swale. When a blind swale is used to distribute flow to a level spreader, evaluate the potential for piping of runoff that infiltrates through the blind swale beneath the level spreader. If underlying soils are erosive, this type of piping can undermine the level spreader. The potential for this occurring can be minimized by providing good compaction beneath the level spreader and extending the foundation of the spreader deep enough to cut off potential piping beneath the level spreader. This is generally only a problem with very sandy soils.

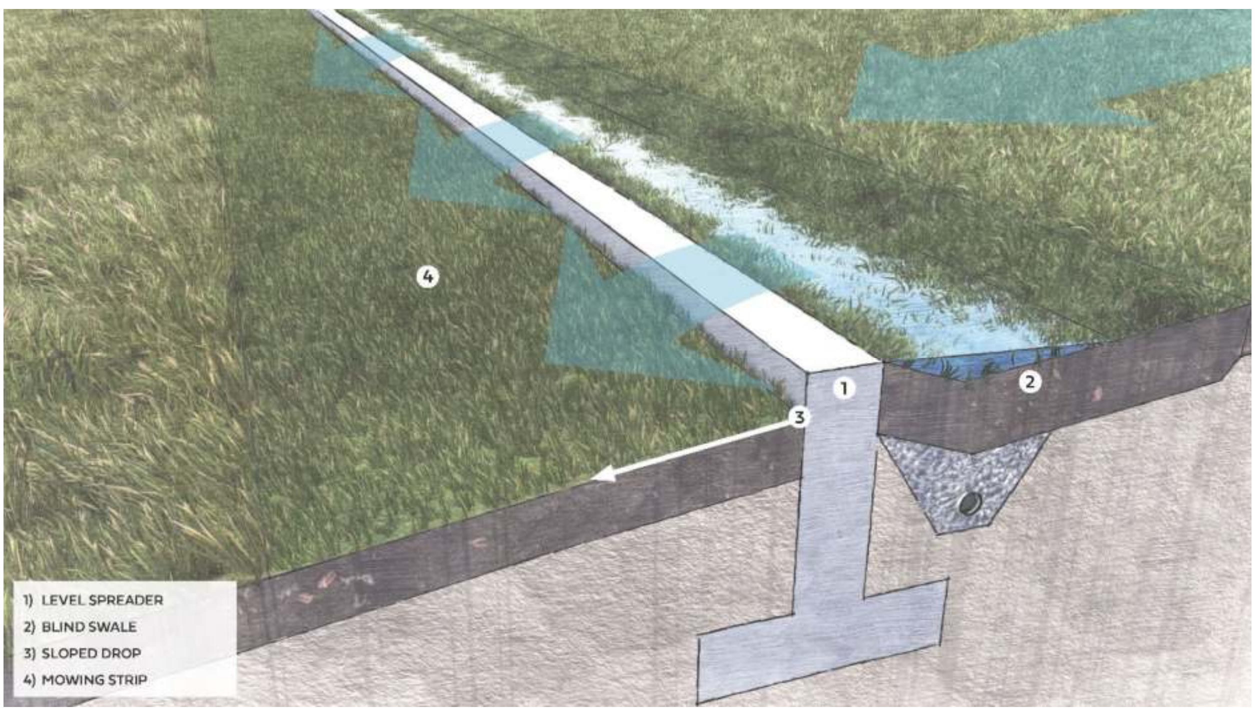


Figure 4-9. Level Spreader Components

Alternatively, shallow U-shaped concrete channels, rock-lined depressions, and other materials can be used for the blind swale provided that the configuration promotes even distribution of flow along the level spreader and is a surface that can be maintained without undue effort when sediment and trash accumulate in the area. Figure 4-10 illustrates a concept for using a level spreader for a curb opening inflow, and Figure 4-11 presents a concept for a level spreader to diffuse a small, piped inflow. Both show a narrow slot or slots in the level spreader to ensure they remain free draining. The intent is to not create standing water.

The spreader itself consists of a level surface that will not erode over time. Often a concrete sill is used, but other materials can be used to provide more visual interest and integrate the level spreader into the surrounding environment, provided that the surface is level and uniform. For larger drainage areas, variations of the slope of the impervious area draining to the level spreader may necessitate using tiered level spreaders along the slope at different elevations to effectively spread flows to the receiving pervious area below.

The 3-inch drop on the downgradient side of the level spreader and the mowing strip are critical features for long-term function of the level spreader. The 3-inch drop allows room for vegetation to grow and some sediment accumulation without impeding free flow over the level surface. The mowing strip provides access for maintenance of the level spreader and the RPA.

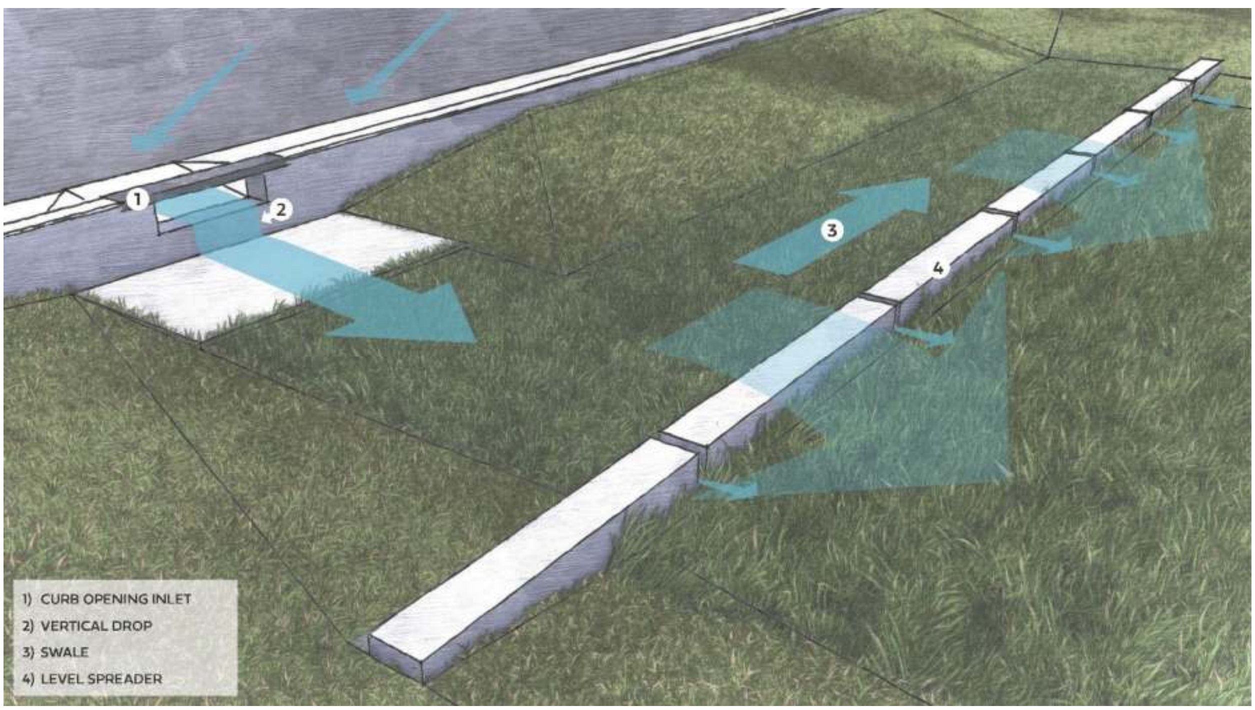


Figure 4-10. Level Spreader for Curb Opening Inflow

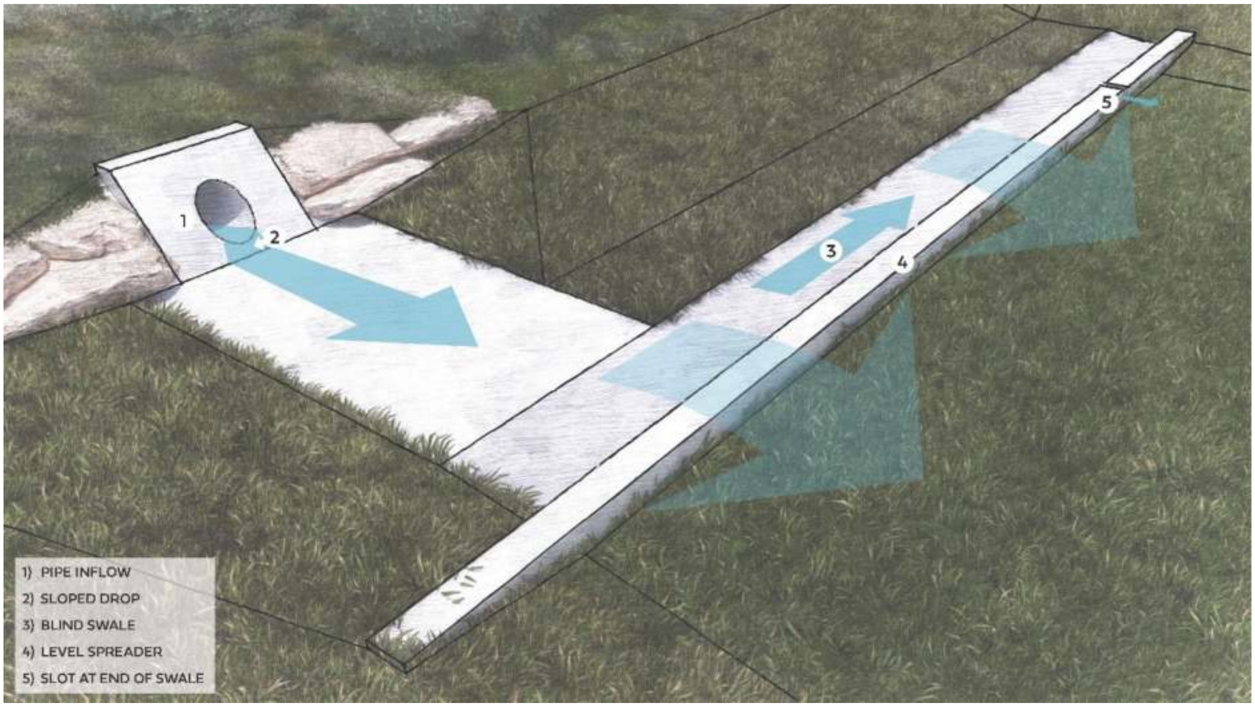


Figure 4-11. Level Spreader for Pipe Inflow

Photograph 4-9. Concrete edge acts as level spreader, distributing flow from parking lot as sheet flow to SCM.

Level spreaders can be effective as inflow features to SCMs including ponds and filtration and infiltration-based SCMs. In this case, hydraulic loading rates may be higher than when used to meet MS4 design standards as presented in the Receiving Pervious Area fact sheet. In this case, a level spreader functions as a broad-crested weir, and additional energy dissipation downstream of the level spreader may be needed.

When level spreaders are used to distribute runoff to long vegetated buffers, flow may begin to concentrate as it flows down the buffer. The distance along the buffer where flow begins to concentrate is known as the effective distance, which is a function of the slope and vegetative cover of the buffer. For long buffers, it may be necessary to use level spreaders in series to re-establish sheet flow conditions. Table 4-10 provides typical effective distances for grass buffers based on slope. If the length of the buffer exceeds the effective distance in Table 4-10, use level spreaders in series to maintain sheet flow conditions.

Table 4-10. Effective Distance for Level Spreaders in Series
(Source: Hunt et al., 2001)

Ground Cover	Slope	Effective Distance (feet)
Turfgrass, > 80% density	0 – 8%	50
	8 – 25%	25
	>25%	17

For SCMs that are designed to meet water quality requirements but do not incorporate full spectrum detention, design of a level spreader (or other type of inflow feature) must provide for bypass of larger flows to the receiving conveyance system. For piped systems, a maintenance hole with a weir or orifice can be used to capture and divert flows design flows to the level spreader, while allowing larger flows to overtop and bypass the treatment system. For channelized conveyances (e.g., swales) a check dam can be used to divert flows up to the design event to a level spreader and the SCM, while bypassing larger flows. In some cases, larger flows can be allowed to flow across the RPA, with collection at the downgradient end of the RPA; however, the designer must ensure that the larger flows will not cause erosion of the RPA.

Photograph 4-10. This level spreader distributes concentrated piped inflows from the road to the buffer to the right in the photograph. The concrete sill to the left is the level spreader, and the flat shallow channel with water is the blind swale. Photo: Wenk.

When using a level spreader for a piped inflow, velocities entering the level spreader will be higher than for shallow concentrated flows. Level spreaders are generally suitable for relatively small piped inflows. For large piped inflows, a stilling basin and forebay are more commonly used. When level spreaders are used, important design considerations include the angle at which the pipe enters the level spreader and the distance from the pipe opening to the level spreader. Piped inflows entering the blind swale perpendicular to the level spreader will not be distributed as effectively along the length of the spreader as flows that enter parallel to the spreader or at an angle that reduces the momentum of the inflow normal to the direction of flow over the level spreader. If enough space or sufficient energy dissipation is not provided between the piped inflow and the level spreader, the flow over the portion of the level spreader in the proximity of the pipe will be greater than portions of the spreader that are further away, resulting in an undesirable, non-uniform flow condition over the spreader. Use energy dissipation measures such as boulders, concrete blocks, or concrete deflection walls at the pipe outfall to dissipate high velocity inflows and create uniform flow conditions on the upstream side of the level spreader in space-limited situations or where the angle of the pipe inflow is not ideal.

Photograph 4-11. Concrete ramp provides maintenance access to blind swale. Photo: Wenk.

Photograph 4-12. Aurora Sports Park Level Spreader. This level spreader carries concentrated flows into a slotted pipe encased in concrete to distribute flows evenly to the RPA shown left in the photo. Photo: Wenk.

The concept of a level spreader (e.g., a level surface for uniform distribution of flow) can also be applied in SCMs such as bioretention or sand filters to achieve more uniform flow across the surface of the SCM. In these cases, a level spreader acts as a horizontal weir to distribute a concentrated inflow across the surface of a filtration- or infiltration-based SCM. The sill of the forebay can be designed as a level spreader. The sheet flow criteria in the Receiving Pervious Area fact sheet may not apply in this application as the depths of flow in the SCM will exceed sheet flow depths. In these cases, the intent of the level spreader is to distribute the inflows more evenly across a vegetated surface and/or minimize the visual impact of the forebay.

Photograph 4-13. Level spreader at Aurora Sports Park evenly spreads flow to the wetland area downstream.

Level spreaders are also useful features for avoiding rilling and gullying of slopes in areas that may not be designed to provide all of the functions of a vegetated RPA, such as a rock mulched areas or landscape areas that may not have the 80% density of turfgrasses required for water quality SCMs. These areas can provide valuable runoff reduction benefits and enhance the aesthetics and community value of a site, even if they are not considered SCMs for purposes of MS4 permit compliance.

5.2 Concentrated Flows

Concentrated flows commonly occur in urbanized areas to efficiently route stormwater while minimizing disruptions during frequently occurring runoff events. Concentrated flows include flows in downspouts, gutters, cross pans, curb cuts, pipes, and open channels. In some cases, concentrated flows can be transitioned to sheet flows through the use of level spreaders; however, for larger-diameter pipes and channels, this may not always be feasible. When designing a concentrated inflow feature to an SCM, important objectives include minimizing the potential for erosion and providing an accessible area where sediment and trash conveyed into the SCM can be maintained. These objectives are achieved through implementing energy dissipation measures and the use of forebays. The extent of energy dissipation and forebay requirements depends primarily on the magnitude of the inflow. For example, appropriate energy dissipation for a curb cut draining into a grass swale may consist of only a concrete pad set 3 inches vertically below the edge of the curb cut where sediment and trash can be maintained (essentially a small forebay), as shown in Figure 4-12.

Downspouts

Downspouts provide excellent opportunities to direct concentrated runoff to RPAs for infiltration. Do not pipe downspouts to underdrains or to the storm drain system where discharge to an RPA is feasible. Energy dissipation is typically provided via a concrete or rock splash pad that directs runoff away from the building's backfill zone. In some cases, downspout extensions are necessary to bridge the backfill zone.

For downspouts draining large roof areas, use a small level spreader to create sheet flow or shallow flow conditions to the RPA.

Decisions related to downspouts are often made by architects without significant input from engineers, so coordination between the engineer and the architect early in the design process is critical to maximize opportunities to disconnect impervious roof area.

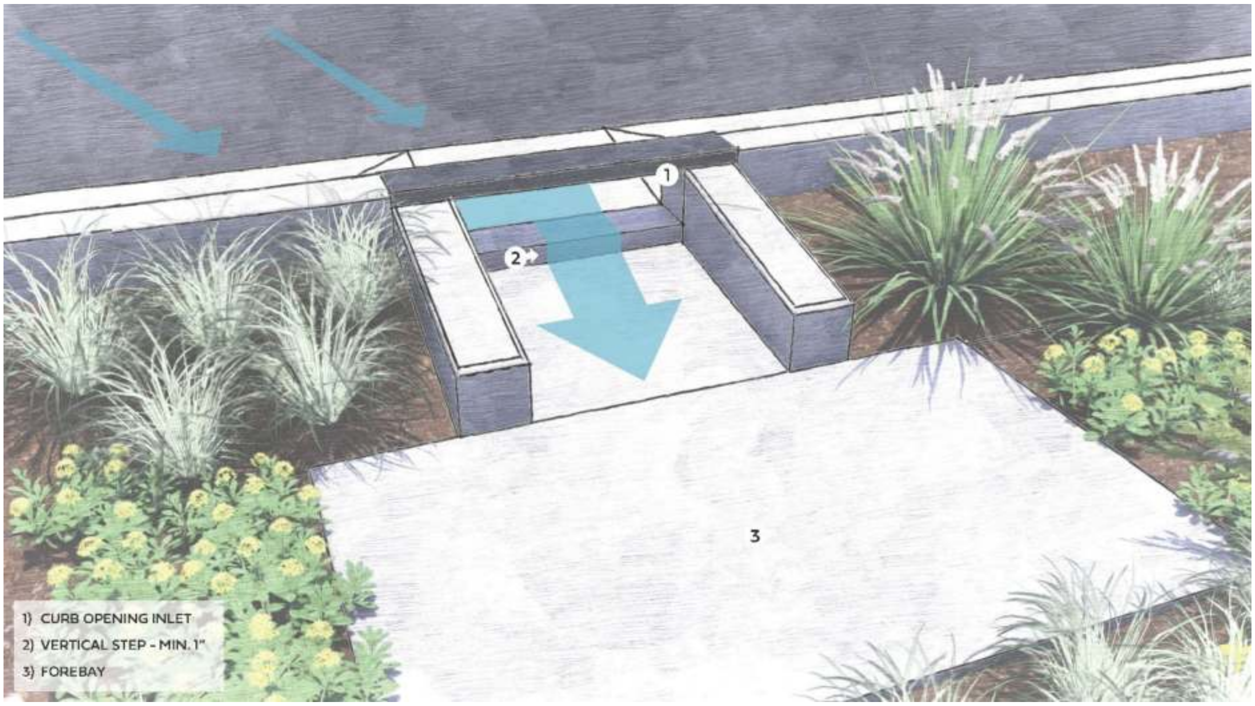


Figure 4-12. Curb Opening Inlet into Streetside Bioretention Area

Curb opening inlets like the one illustrated in Figure 4-12 are used to convey runoff into many types of streetside SCMs and are an effective type of inlet for small, highly impervious drainage areas. The curb opening must be located at the upstream end of the SCM, convey runoff from the curb and gutter across the step-out zone, and be sized to convey the water quality event assuming an appropriate amount of debris blockage. The inlet must be designed to function in concert with a forebay (often a concrete pad surrounded by vegetation) that captures coarse sediments, trash, and debris and aids in energy dissipation. The inlet features a 2-inch depression in the flow line of the gutter to help direct runoff into the opening and reduce bypass flow.

The inlet in Figure 4-12 is shown as a chase-type structure with a cover plate. Slope the interior portion of the inlet box (bottom slab of the chase drain) and provide a 3-inch drop-off from the invert of the chase drain to the sediment collection pad or filter surface (for tree trenches), which should be at least 4 inches below the water quality water surface. This allows for some amount of debris and sediment buildup without reducing stormwater conveyance through the inlet.

The opening length of the inlet varies depending on flow rate and longitudinal slope. Use Figure 4-13 to determine the length of inlet required for a given upstream area (assumed to be fully impervious).

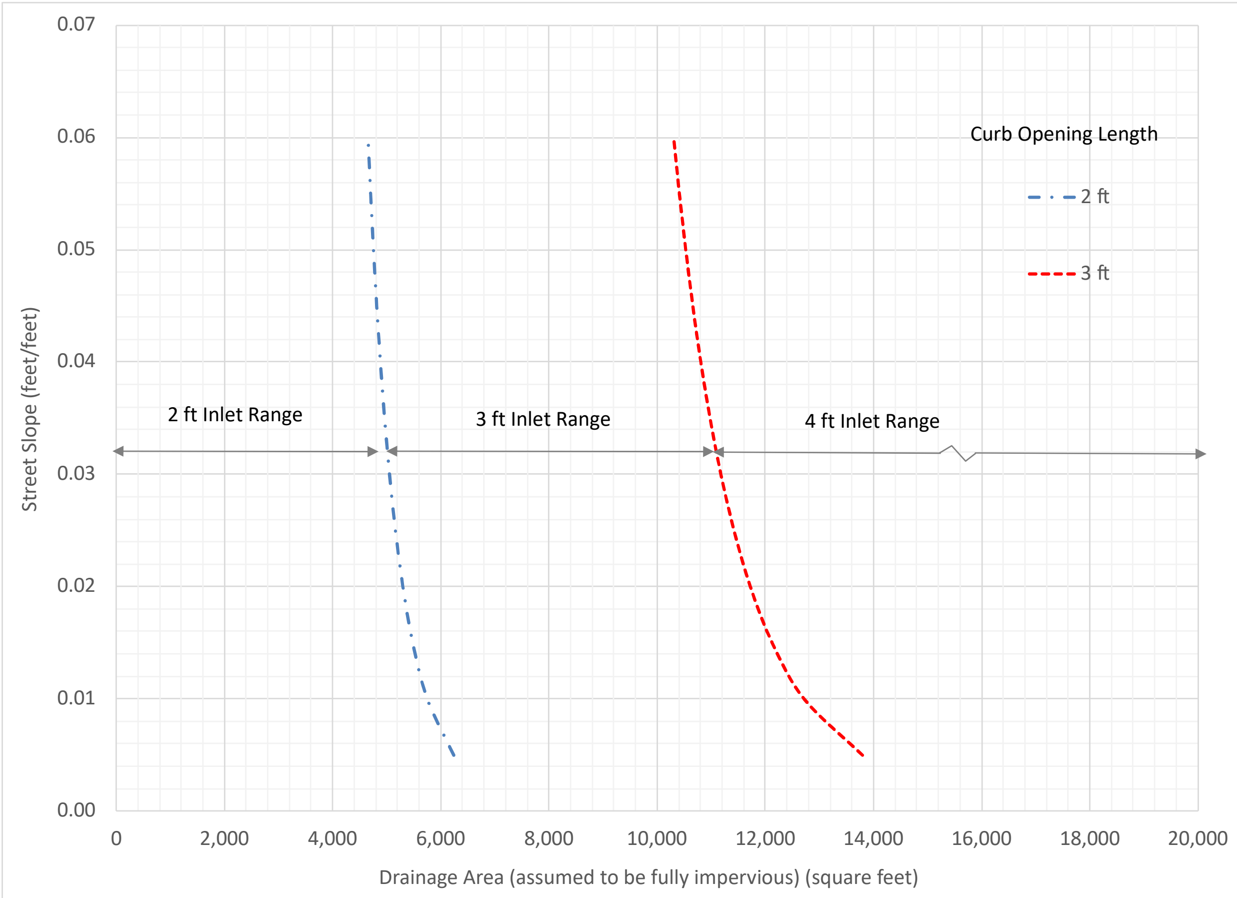


Figure 4-13. Curb Opening Inlet Width Based on Drainage Area[1]

[1] Figure 4-13 is derived from Equation 3 for continuous grade applications in Technical Memorandum Re: Hydraulic Efficiency of Inlets Common to the UDFCD Region (UDFCD, 2011). The figure accounts for a debris clogging factor of 10 percent (as recommended in the Technical Memorandum).

For larger inflows, engineered energy dissipation structures and formal forebays are required, as illustrated in Figure 4-14. These features are discussed below and in the *Hydraulic Structures* chapter.

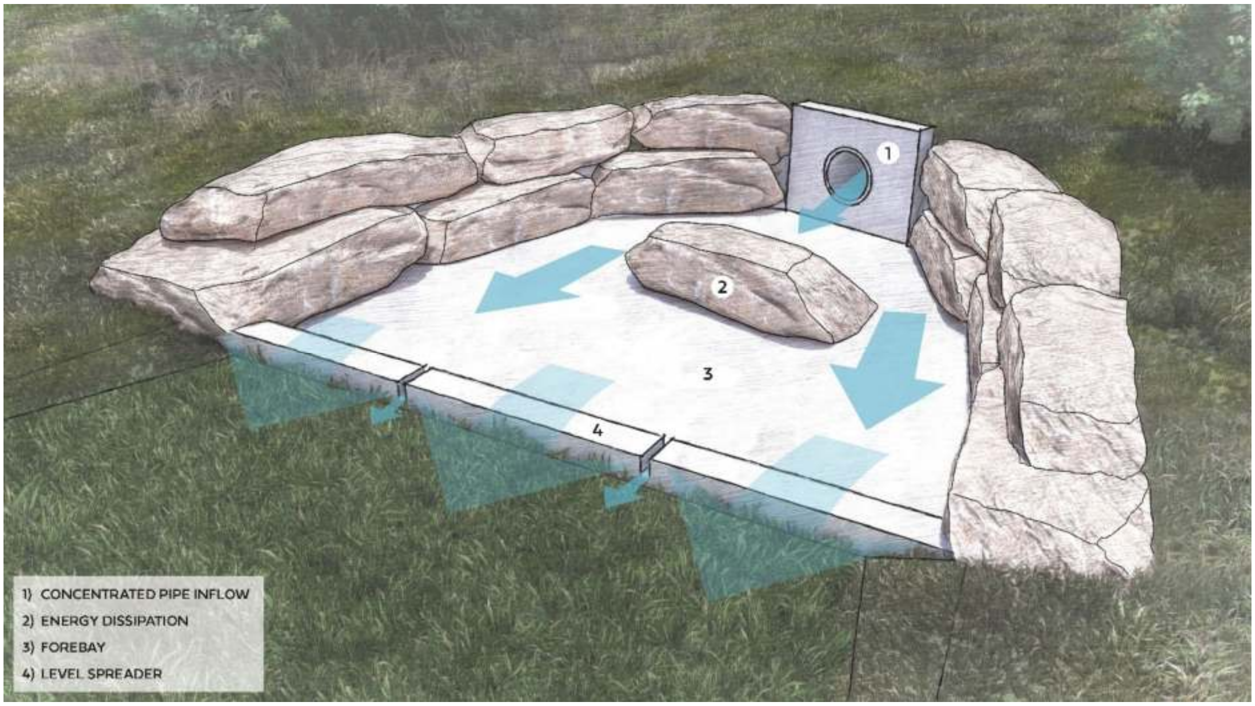


Figure 4-14. Energy Dissipation Structure and Forebay for Concentrated SCM Inflows

5.2.1 Energy Dissipation

Depending on the magnitude and configuration of the design inflow, energy dissipation may be provided through vegetative resistance or structural measures. For concentrated inflow features that are vegetated such as swales and ephemeral channels, the roughness provided by the vegetation and bed may be sufficient for energy dissipation. Perform hydraulic calculations of inflow velocities and tractive forces, considering seasonal variations in roughness coefficients, and compare with permissible velocities of the materials used in the SCM to verify if additional energy dissipation measures are needed.

Photograph 4-14. Disconnected downspouts discharge to grass swale to dissipate concentrated flows and allow for infiltration and filtration. Vegetation provides energy dissipation.

Photograph 4-15. Inlet to swale has small riprap forebay to collect trash. Riprap and dense vegetation in swale dissipate energy. However, sediment will be difficult to remove from the riprap.

Photograph 4-16. Morse Park forebay provides energy dissipation with placement of a boulder, and the dense vegetation helps encourage sediment to stay in the forebay. This is an easily accessible area to remove sediment and trash, and it provides even distribution of flow to the SCM.

For impervious conveyances including pipes, velocities are typically much higher, and structural energy dissipation in the form of riprap or an impact basin, sized in accordance with the *Hydraulic Structures* chapter, may be needed to avoid causing erosion in the SCM. Follow the design procedure in the *Hydraulic Structures* chapter to avoid over- or under-sizing energy dissipation structures and take care to install the structures at the appropriate elevation to achieve the intended function.

5.2.2 Forebays

A forebay provides an opportunity for coarse sediment and debris to settle out in an area that can be easily maintained. Forebays are recommended for all concentrated SCM inflow locations but vary in size and complexity of design based on the magnitude of the inflows and sediment loads anticipated. For tributary areas with high sediment loads (e.g., road sanding, developing watersheds), forebays are essential for ease of maintenance and to protect infiltrating surfaces.

Table 4-11 provides criteria for forebay sizing depending on the impervious area in the contributing watershed. Use this table as a guide as it does not consider the characteristics of the watershed and may not be appropriate for tributaries much larger than 20 acres. For small inflows (up to one acre of imperviousness) a concrete sediment pad may be used as a forebay, as illustrated in Figure 4-10 for a curb cut. Dense vegetation along the edge of the pad will help keep sediment on the pad where it can be maintained. When dense vegetation is not planned, another option is a 1-inch-tall metal lip with multiple 1- to 2-inch slots at the edge of the concrete pad, combined with a 1- to 2-inch drop from the pad to the media surface (Denver DOTI 2021). If the inflow is from a stable vegetated conveyance and the impervious area is less than 1 acre, a concrete sediment pad may not be necessary. For larger contributing drainage areas, the minimum volume of the forebay is determined as a fraction of the WQCV, and the maximum release rate via the forebay wall/notch configuration is determined as a fraction of the 100-year undetained peak flow rate.

Concrete forebays are often used in ponds and many sub-regional and regional SCMs due to the ease of maintenance. While these are effective at their intended function, they are not always attractive. Other alternatives for forebays for larger SCMs include constructing a vegetated berm with a pipe rather than a concrete wall to contain the forebay. For smaller drainage areas, a notch is recommended instead of a pipe to avoid small pipe sizes that cannot be maintained, but even for smaller SCMs, a vegetated berm with a notched concrete section in the middle could be an alternative to a concrete wall.

A primary reason the bottom of the forebay is often concrete is so that there is a well-defined surface to dig to or scrape when sediment removal is required. For a more natural appearance, and when sufficient energy dissipation is provided, the bottom of the forebay can be a reinforced grass pavement such as Grasscrete or other open-celled concrete. A vegetated surface such as Grasscrete also provides greater roughness that slows down runoff and helps with removal of sediment and trash.

Maximize the length of the flow path through the forebay and minimize the forebay bottom slope to encourage settling. When portions of the watershed will remain disturbed for an extended period, increase the forebay size to accommodate the potentially high sediment loads from the disturbed watershed.

Table 4-11. Forebay Sizing Criteria

Forebay Sizing Criteria	Watershed Impervious Area (IA, acres)				
	IA ≤ 1 ac	1 ac < IA ≤ 2 ac	2 ac < IA ≤ 5 ac	5 ac < IA ≤ 20 ac	IA > 20 ac
Forebay Release Rate and Configuration	Use concrete sediment pad	Release 2% of undetained Q_{100} via wall/berm/notch configuration			Release 2% of undetained Q_{100} via wall/notch or berm/pipe configuration
Minimum Forebay Volume		1% of WQCV	2% of WQCV	3% of WQCV	3% of WQCV
Maximum Forebay Depth		12 inches	18 inches	18 inches	24 inches

6.0 SCM OUTFLOW FEATURES

SCM outflow features provide two important functions: 1) release the WQCV over the drain time required for the SCM and 2) convey larger flows to the downstream conveyance system. Depending on the type of SCM, outflows may include infiltration into the subgrade, controlled release via an underdrain system, release through an orifice plate, and/or overflow via a weir. In many cases, these features are designed to be part of a single integrated outlet structure. Often, SCMs that provide the WQCV can be expanded to also incorporate the EURV and 100-year detention storage volumes with relatively simple modifications to the outlet.

Photograph 4-17. Outlet for bioretention system at River Run Park. The WQCV is filtered through media and infiltrates or discharges to the outlet via an underdrain. The outlet is also designed for detention of larger events with a weir control (i.e., top of outlet box) and overflow spillway. The spillway is provided as a low spot above the outlet near the rain gage.

The common types of outflow features associated with different types of SCMs are summarized in Table 4-12. Infiltration systems and underdrains are discussed extensively in Section 4.3. Therefore, this section focuses on types of outlets that release the WQCV over the drain times required for different types of SCMs and allow larger flows to pass to the downstream conveyance system. For guidance and criteria on outlet design for Full Spectrum Detention (FSD), see the *Storage* chapter.

Photograph 4-18. Although each site is different, most sedimentation SCMs have similar outlet structures. Each structure should include a partially submerged orifice plate with a screen (or grate) protecting the orifice plate from clogging, and an overflow weir for flows exceeding the WQCV or EURV when full spectrum detention is used.

Photograph 4-19. Retention pond outlet structure blends with the bank and is easily accessible for maintenance.

Table 4-12. Summary of Typical SCM Outflow Features

Typical Outflow Features	Typical Applicability to SCMs			
	RPAs, Buffers and Swales	EDBs, RPs, CWPs	Permeable Pavements	Bioretention and Sand Filters
Infiltration (unlined systems only)	✓	Limited	✓	✓
Underdrain (no and partial infiltration systems)	Some swales	Not typical	✓	✓
Orifice Plate		✓	✓ orifice on underdrain	✓ orifice on underdrain
Weir		✓	✓	✓
Trash Rack		✓		When combined with FSD
Safety Grate		✓		When combined with FSD
Spillway		✓		✓
Micropool		✓ EDBs		

Abbreviations: RPA: Receiving Pervious Area; EDB: Extended Detention Basin; RP: Retention Pond; CWP: Constructed Wetland Pond; FSD: Full Spectrum Detention.

6.1 Orifice Plates

Outlets that release the WQCV are most commonly designed as orifice plates. The fundamental design parameters are the head that the WQCV creates on the orifice, and the required drain time of the SCM. Table 4-13 provides required drain time for different types of SCMs.

Table 4-13. Required WQCV Drain Times for Different Types of SCMs

SCMs	WQCV Drain Time (hours)
Extended Detention Basins	40
Constructed Wetland Ponds	24
Permeable Pavements Systems, Bioretention, Sand Filters, Retention Ponds	12

To size the outflow orifice(s), use the MHFD-Detention workbook, available at www.MHFD.org, to route flow and calculate the required orifice sizes. Consider a total of two orifices to maximize the orifice size and the allowable openings in the grate while providing redundancy. Using fewer but larger openings allows for a grate with larger openings, which reduces potential for clogging of the orifice plate.

Orifice outlet features can be used for surface or subsurface release of the WQCV. For filtration and infiltration-based SCMs such as bioretention, sand filters, and permeable pavement systems that incorporate underdrains, an outlet structure often consists of a shallow structure with an orifice plate separating the underdrain from the downstream conveyance system. The top of the orifice plate may be configured as an overflow weir to limit the buildup of head over the orifice plate to the design depth of the WQCV so that larger events overtop and flow downstream. Outlets with removable weir plates such as Agri-drains (with or without an orifice drilled into one of the plates) have been successfully used in many applications in the MHFD region as outlets from small to medium-sized filtration and infiltration facilities with underdrains. Figure 4-15 shows a conceptual outlet configuration for an SCM that releases the WQCV via an orifice-controlled underdrain.

For extended detention basins and other basins that function based on surcharge and slow release of the WQCV, orifice plates are commonly used. In most applications, the orifice plate consists of ¼-inch-thick steel with circular or rectangular orifice openings. The span of the orifice plate should not exceed 2 feet for ¼-inch-thick steel. Figure 4-16 provides a detail and notes for a typical combination of an orifice plate and trash rack for a retention pond or wetland basin.

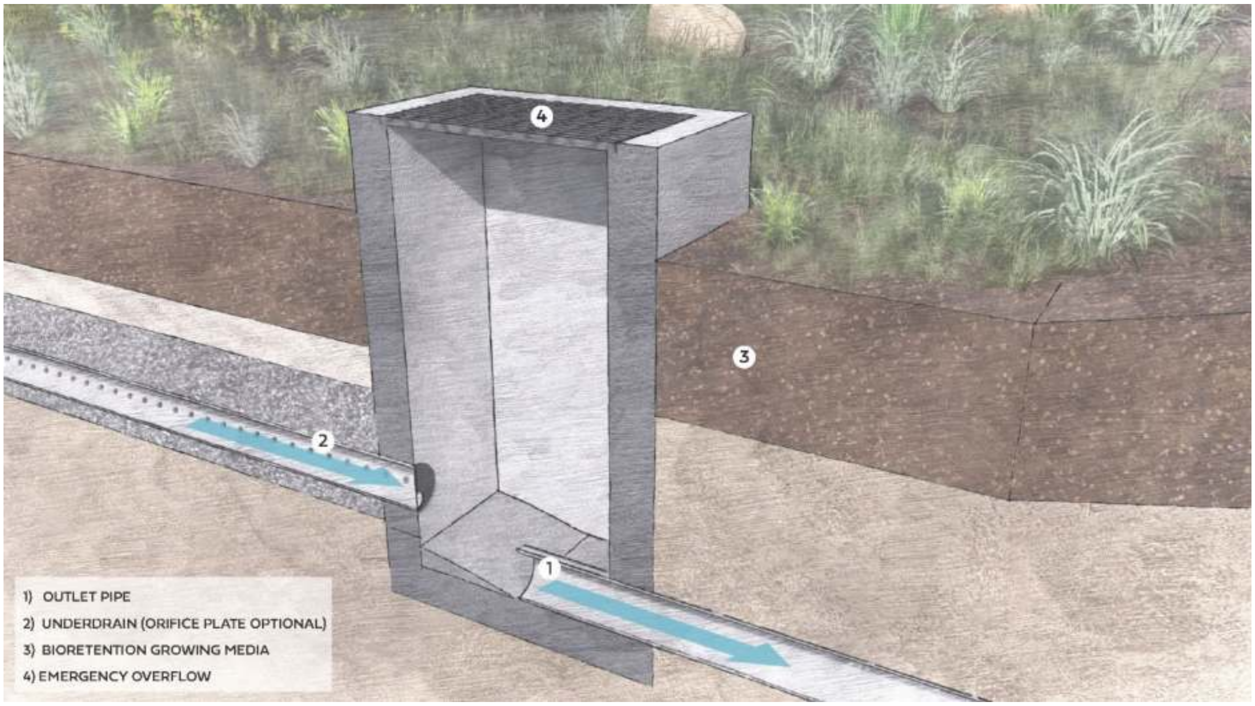


Figure 4-15. Conceptual Outlet Configuration for SCM that Releases the WQCV via an Orifice-controlled Underdrain

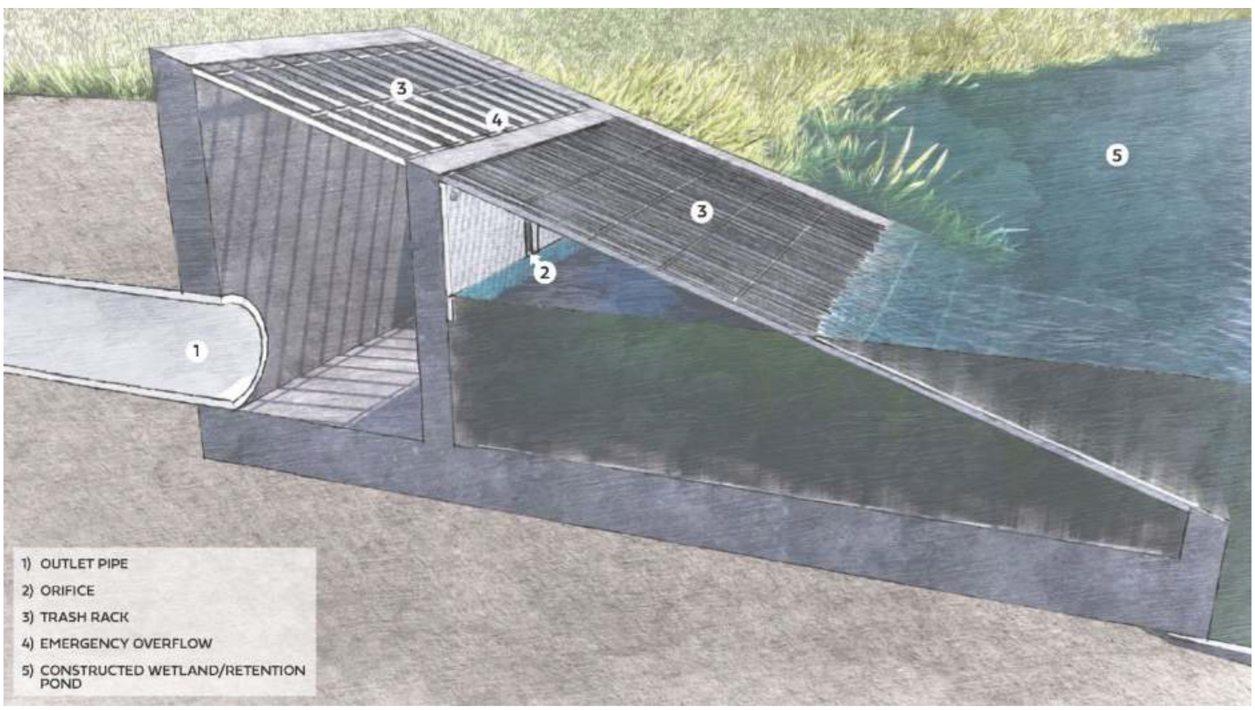


Figure 4-16. Conceptual Outlet Configuration for Retention Pond/Constructed Wetland Basin

6.2 Weirs

Photograph 4-20. Grate acts as overflow weir for bioretention systems located along street frontage. Very large events may spill over the sidewalk to the street with the sidewalk acting as the spillway.

Weirs come in many different shapes and sizes, depending on the size of the SCM and its overflows. For a bioretention system, the overflow may be an area inlet set at the maximum elevation of the WQCV to allow flows that exceed the WQCV to flow directly into the outlet structure downstream of the orifice plate. For permeable pavement systems, the overflow weirs may be area inlets within the pavement surface that prevent excessive ponding in the event that the runoff rate exceeds the pavement infiltration rate. For ponds, the overflow weir is commonly the perimeter of a drop inlet at the top of the outflow structure. Use the MHFD-Detention workbook to size overflow weirs.

6.3 Safety Grates and Trash Racks

Safety grates are intended to keep people and animals from inadvertently entering a storm drain. They are sometimes required even when debris entering a storm drain is not of concern. The grate on top of the outlet drop box is considered a safety grate and should be designed accordingly. The danger associated with outlet structures is the potential associated with pinning a person or animal to the structure. See Figure 4-17 for sizing of the opening area of the safety grate relative to the pipe size. The *Culverts and Bridges* chapter of Volume 2 provides additional information and criteria related to safety grates.

Trash Rack Design for Maintenance

Rather than using the minimum criteria for the trash rack width, maximize the width of the trash rack to match the geometry of the outlet. This will reduce clogging and frequency of maintenance of the SCM. If designing to the minimum criteria, consult with the owner and/or facility maintenance crew to understand how the site will actually be maintained and how frequently maintenance will occur. These site-specific factors may impact the design.

Trash racks are intended to keep trash and debris from plugging the orifice openings in the SCM outlet. For orifice openings with a diameter of 1.25 inches or less, a well screen is recommended for the trash rack. When the opening sizes are larger, use a bar-grate trash rack, which is less susceptible to plugging than a well screen. See the Extended Detention Basin fact sheet for more information including details.

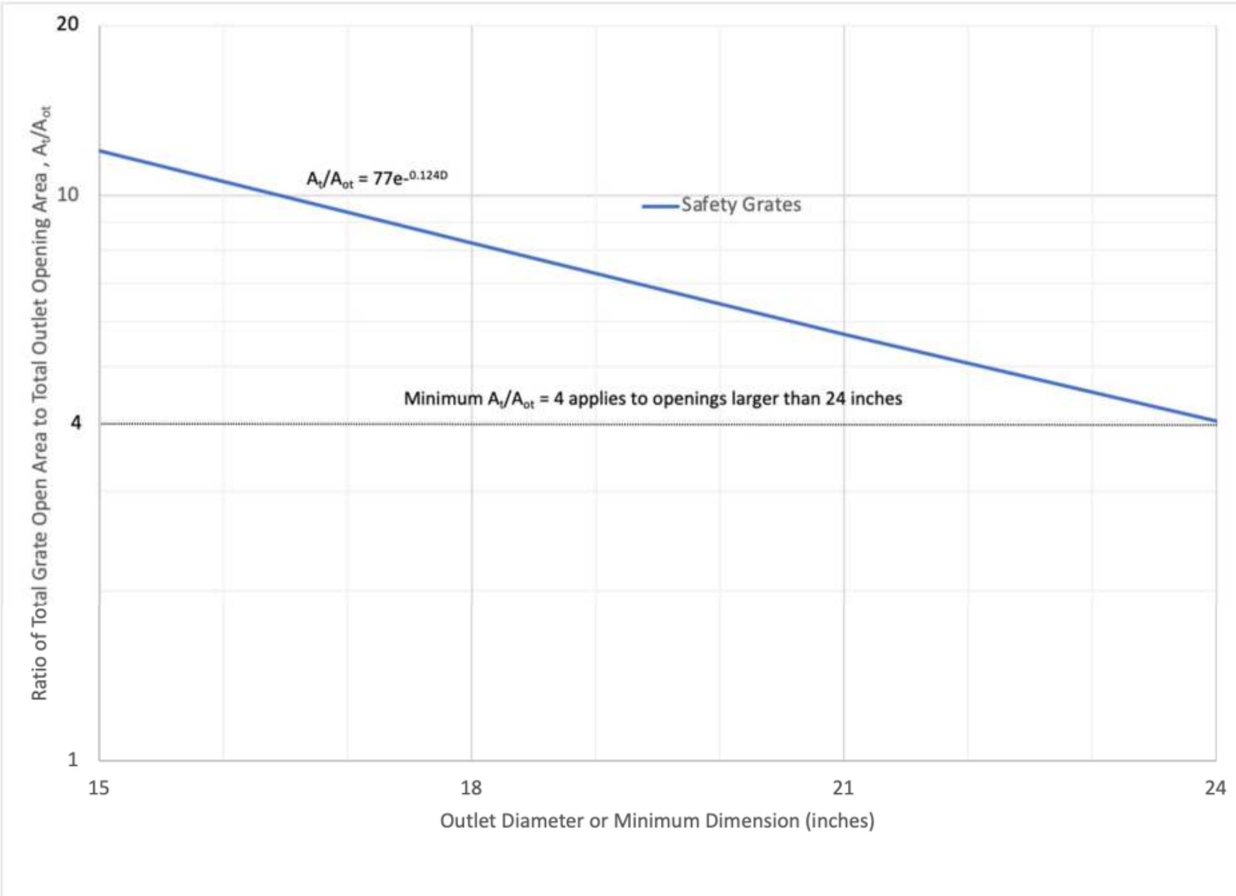


Figure 4-17. Safety Grate Sizing

(Note: see Extended Detention Basin fact sheet for trash rack sizing)

6.4 Spillways

When designing any type of SCM, consider what will happen when the SCM fills and must overflow. A spillway provides a stable overflow path to discharge runoff to the downstream conveyance system. For SCMs serving small drainage areas, the spillway may be a low spot around the perimeter of the SCM that redirects runoff back to a street or nearby inlet. The spillway can be vegetated or hardscaped depending on the surrounding context of the SCM. If spillway depths are shallow, little armoring other than vegetation is typically needed for SCMs serving drainage areas smaller than one impervious acre.

For SCMs serving larger drainage areas or SCMs that impound water using embankments, a more formal spillway consisting of a broad crested weir is recommended that is sized to pass the undetained 100-year peak flow rate from the drainage area contributing to the SCM. Depending on the size of the peak flows, velocities, and spillway geometry, spillways may consist of vegetated soil riprap, riprap, or concrete. See the *Storage* chapter for additional guidance and criteria for designing spillways.

6.5 Micropools

Micropools are a unique feature of extended detention basins and are designed in conjunction with the orifice plate and trash rack to allow water to flow through a submerged portion of the trash rack and reach the openings in the orifice plate even when floating vegetation and debris is matted against the portion of the trash rack that is above the water surface. The same effect can be achieved in wet ponds and constructed wetland ponds, which are designed to have open water in front of the outlet, by extending the trash rack below the water surface in front of the orifice plate. Because micropools are specific features of extended detention basins, guidance and criteria for micropool sizing and concepts for integrating the micropool with the extended detention basin outlet design are provided in the Extended Detention Basin fact sheet.

7.0 Soils, Vegetation, and Irrigation for SCMs

Vegetation is a key component of many types of SCMs and provides important functions that enhance treatment processes, aesthetics, ecology, and overall sustainability of the SCM. These functions include:

- Filtering (straining) of trash and sediment.
- Increasing surface roughness to reduce runoff velocity, broaden runoff hydrographs, and attenuate peak flows.
- Providing pathways into the soil through shoots and roots to promote and sustain infiltration over time.
- Enhancing soil ecology and biochemical processes in the SCM soils.
- Providing habitat and ecosystem services.
- Stabilizing the ground to reduce erosion in the watershed surfaces and along streams.
- Reducing weed growth by providing dense desirable vegetation.
- Mitigating urban heat island effects.
- Reducing heat gain and providing aesthetic value for green roof installations.

Vegetation transforms SCMs into multi-functional infrastructure that improves public acceptance and adds value to communities and the environment by enhancing the wildlife habitat, aesthetics, and user experience. Appropriately selected and well-established vegetation is fundamental to expanding the benefits of SCM functionality; in addition, vegetation is central to water quality treatment processes.

Sources of Vegetation Guidance and Criteria for SCMs

- RPAs – Fact Sheet and *Revegetation* Chapter
- Green Roofs – Fact Sheet
- EDBs, RPs, CWPs – *Revegetation* Chapter
- Bioretention – Fact Sheet

In addition to these resources, the Colorado Natural Heritage Program and the Colorado State University Extension Service have extensive guidance on plants suitable for Colorado's climate.

Because favorable topsoil conditions are critical for the successful establishment of vegetation, an essential resource to support development of revegetation plans is MHFD's Topsoil Management Guidance, which provides guidance for assessing and developing a plan for healthy topsoil to support newly planted or seeded vegetation in SCMs. Another important resource is the *Revegetation* chapter of this Manual, which provides revegetation guidance for SCMs and water resource-related project sites in the MHFD region. However, the *Revegetation* chapter is largely geared to the revegetation of natural areas, particularly stream corridors, which can present different hydrologic regimes and growing conditions than those found within SCMs. SCMs often occur in and around urban development, which ranges in character from ultra-urbanized sites with little or no natural context to suburban open space tracts that include relatively natural landscapes. The landscape plan for the SCM should reflect the specific characteristics and context of surrounding land use, as each situation presents different opportunities and constraints. The MHFD Topsoil Management Guidance and the *Revegetation* chapter provide information that can be applied to many different types of SCMs, and these documents are intended to be used in conjunction with the SCM-specific guidance provided in the fact sheets.

The primary objectives to address in SCM landscape plans include:

- **Create vegetation plans that support SCM water quality functions.** The specific roles that vegetation plays in the function/performance of each SCM vary. Vegetation design and establishment is especially critical to achieving sustained infiltration in SCMs such as bioretention and grass buffers, swales, and other RPAs. Refer to the SCM fact sheets for specific guidance for selection of vegetation appropriate to the type of SCM.

- **Develop landscape plans that stabilize SCMs and create sustainable facilities.** Landscape plans should address SCM stability issues such as steep slopes, overflow areas, problematic soils, and other areas with high erosion potential. Plans should include specific measures to establish resilient vegetation that will protect the SCM from erosion. Deep-rooted vegetation can out-compete weeds, providing a stable and attractive SCM. Drought-tolerant native plants are preferred over types of vegetation that require more irrigation. Landscape plans should address proper soil assessment/placement/preparation, seeding, plantings, erosion control measures, and weed control, among other items.

- **Create landscape plans that enhance the SCM's surrounding context and provide multiple benefits to the community.** SCM locations and contexts vary a great deal, from highly visible ultra-urban locations to remote suburban or rural sites surrounded by open space. In each case, the designer should consider the context and site-specific opportunities and constraints to develop an overall vision and strategy for what the vegetation should accomplish for the site. These strategies may range from "creating a functional landscape feature" in the case of a very visible and urban site to "maximizing habitat and plant diversity and integrating the SCM into the surrounding landscape" in remote open space sites. Objectives of landscape plans for SCMs should include:
    - Enhancing community benefits by employing a "place-making" approach (providing shade, reducing heat island effects, visual interest, etc.).
    - Improving biodiversity of the site with use of appropriate native species and including pollinator species in the plant palette.
    - Practicing environmental stewardship though conservation of water and other resources.
- **Develop landscape plans that are adapted to the ecology and environmental characteristics of the site *and the conditions created by the SCM*.** Consider site characteristics including solar aspect, soils, and water regime in developing a landscape plan for an SCM. Inundation frequencies and depths associated with temporary storage and/or infiltration of runoff affect planting conditions and potential for plant growth. Many SCMs have modified hydrologic regimes compared to streams and other natural areas. Consider the hydroperiod of the SCM, as well as the potential for extended periods of drought and how healthy vegetation will be maintained during very dry periods. In many settings, drought-tolerant native plants are preferred over types of vegetation that require more irrigation. Designers must evaluate the specific characteristics of each SCM and site and specify plant material that can survive and thrive under those specific conditions. "One-size-fits-all" vegetation design is not an acceptable approach for successful vegetation establishment for an SCM.
- **Consider maintenance requirements.** Maintenance of vegetation is necessary for all types of vegetated SCMs to maintain healthy vegetation, manage weeds, and prevent overgrowth of vegetation from interfering with the functions of the SCM. The level of maintenance required for vegetation is dictated by the conditions in the SCM and by plant selection and density. The planning and design of vegetation for an SCM that will be maintained frequently will be different than for an SCM that is intended to have low, infrequent maintenance requirements. In addition to the level of service anticipated for maintenance, understanding specific maintenance practices, such as how mowing and weed control will be performed, may influence plants that are selected and how plants are grouped and spaced. As part of the landscape plan, the designer must provide instructions on how the landscape is to be maintained over time and ideally who is responsible for various types of maintenance. Incorporate this information into the overall operations and maintenance plan for the SCM.

- **Determine SCM irrigation requirements.** Develop an irrigation plan in conjunction with the vegetation plan for the SCM, including irrigation system operation and maintenance requirements. Establishing vegetation, even drought-tolerant native species, in the semi-arid rainfall zone prevalent in the MHFD is difficult and may not be successful with natural rainfall alone, especially if optimum seeding periods are missed. In some cases, the natural hydrology may be sufficient for establishment of vegetation (for example, native seeding in an average or wetter-than-average spring); however, there is an equal chance that hydrologic conditions will be drier than average. Because of hydrologic variability, irrigation is necessary for all vegetated SCMs during vegetation establishment, including native plantings.

  For native species, irrigation may not be necessary once the vegetation becomes established, except in periods of extended drought. Given the potential for future climate variability with longer periods of drought, providing irrigation is prudent, even when using native species. The need for and extent of the permanent irrigation system will be dictated by plant selection. Once native, drought-tolerant species are established in an SCM, the long-term irrigation requirements may be eliminated or significantly reduced (with supplemental irrigation during periods of drought only). Given the need for irrigation during the establishment period for native species, installing an irrigation system that can be used during establishment and then intermittently during extended dry periods may be more cost-effective than installing and removing a temporary irrigation system and then having to secure another form of irrigation during a drought.

  For non-native vegetation and many ornamental species and trees, permanent irrigation is necessary for healthy vegetation. The irrigation plan should include guidance for water-efficient irrigation according to the needs of the established plants.

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T-1 Receiving Pervious Areas including Grass Buffers and Swales

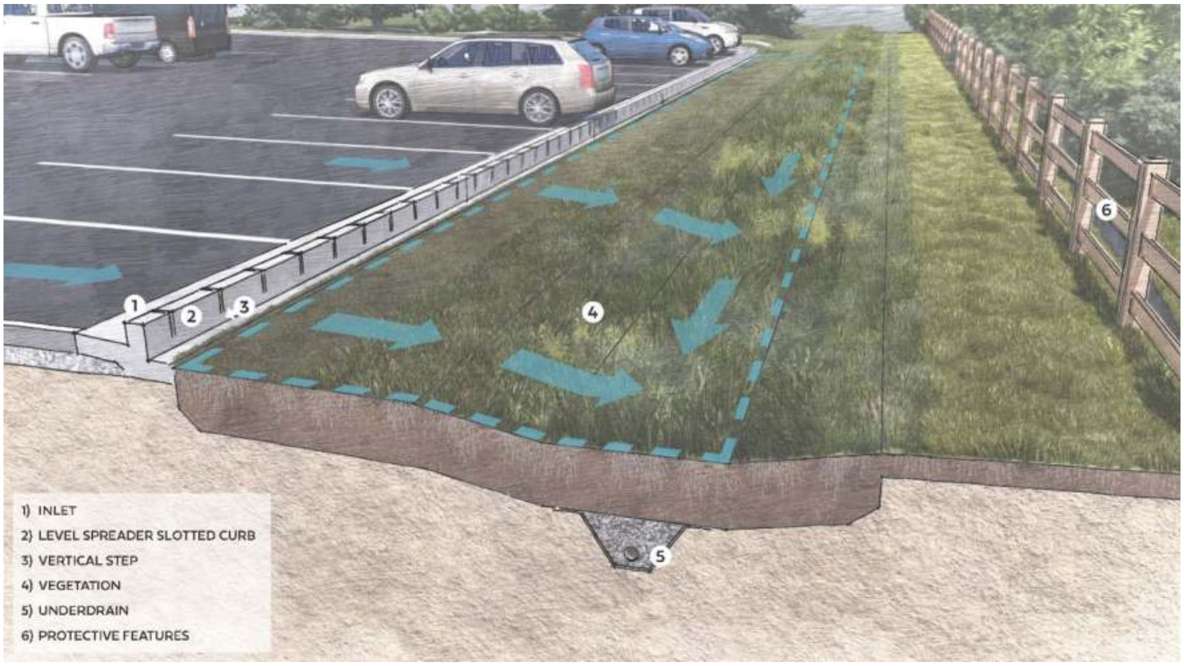

Figure RPA-1. Grass Buffer and Grass Swale Components

Description

Receiving pervious areas (RPAs) reduce the volume of runoff through infiltration and wetting of soils/media with subsequent evapotranspiration. RPAs are commonly used as the first step in MHFD's Four Step Process to disconnect impervious area and provide opportunities for filtration and infiltration of runoff, while conveying runoff to other SCMs. RPAs are integral to Low Impact Development and Green Infrastructure approaches. When properly sized, RPAs including grass buffers and swales can partially (as part of a treatment train) or fully satisfy the Runoff Reduction Standard in MS4 permits. These types of SCMs are not generally capable of meeting the WQCV or Pollutant Removal Standards in the MS4 permits due to the transient storage volumes and generally low hydraulic residence times of runoff in these SCMs.

MS4 Permit Applicability (Dependent on design and level of treatment)	
Meets Runoff Reduction Standard	Potential
Meets WQCV Capture Standard	No
Meets Pollutant Removal Standard	No
Typical Effectiveness for Targeted Pollutants	
Sediment/Solids	High
Total Phosphorus	Low-Medium[1]
Total Nitrogen	Low
Total Metals	Medium
Bacteria	Low
Common Applications	
Runoff Reduction (General)	Yes
Used for Pre-treatment	Yes
Integrated with Flood Control	No
Cost	
Life-Cycle Costs	Low

[1]Concentration reduction is typically low, but load reduction can be more significant due to volume reduction.

Photograph RPA-1. Grass buffers are often used in conjunction with grass swales as a treatment train. These pervious areas also help reduce heat island effects in urban areas. Photo: Muller Engineering.

While all of these practices rely on vegetation and soils to infiltrate runoff, design procedures vary depending on whether the SCM is a buffer, swale, or other type of RPA, such as a small landscaped area.

RPAs include grass buffers and swales and also small landscaped areas receiving runoff from roof or hardscape areas, vegetative strips not strictly meeting design requirements for grass buffers, and other areas in the landscape that promote infiltration of runoff and are wetted in the water quality design event.

Grass buffers are densely vegetated strips of grass designed to accept sheet flow from upgradient developed areas. Properly designed grass buffers enable infiltration and play a key role in slowing runoff. Grass buffers provide filtration (straining) of sediment. Buffers differ from swales in that they are designed to accommodate overland sheet flow rather than concentrated or channelized flow.

Grass swales have dense vegetation and broad cross-sections that convey concentrated flow in a slow and shallow manner, facilitating infiltration, sedimentation, and filtering (straining) while limiting erosion. Check dams may be incorporated into grass swales to flatten steep slopes and reduce velocities to encourage settling and infiltration.

Benefits

- Reduction in runoff rate and volume through attenuation and infiltration.
- Delay in time to peak by disconnecting impervious area.
- Potential reduction in the extent of storm drain systems in upper portions of a watershed while mimicking natural system with pervious conveyances.
- Removal of sediment and associated pollutants through filtering and reduced loading.
- Easily integrated into treatment train with other SCMs.
- Creation of aesthetic amenities with stormwater features integrated with landscaping.
- Modest maintenance requirements that can typically be accomplished as part of normal landscape maintenance practices.

Limitations

- Irrigation is typically required, although may be reduced for native grasses once established.
- May not be appropriate in areas with high sediment, trash, or debris loading without frequent maintenance.
- Adequate space and relatively low ratios of Unconnected Impervious Area (UIA) to Receiving Pervious Area (RPA) needed to fully meet the MS4 Runoff Reduction Standard.
- Damage from adjacent vehicular traffic may occur if adequate separation or protection is not provided.

Photograph RPA-2. RPAs including grass buffers and swales treat runoff by filtering and infiltration. For treatment to be effective, RPAs must receive runoff as sheet flow. Photo: WWE.

Photograph RPA-3. This grass swale provides treatment of runoff from a parking lot, portions of the building, and sidewalks at a healthcare facility. Photo: WWE.

SCM Components

The primary components of RPAs are the inflow distribution feature and the vegetated pervious area. Components of grass buffers and grass swales are illustrated in Figure RPA-1. Other RPAs are simply adaptations of buffers or swales and share the same general components.

Because RPAs are based on infiltration of runoff, distribution of the runoff from the upgradient watershed evenly across the vegetated surface is critical. Runoff must be able to flow freely into the SCM from the unconnected impervious area (UIA); therefore, the inflow distribution system must be designed to avoid excessive accumulation of sediment and allow for maintenance that includes removal of accumulated sediment. Level spreaders are commonly used to achieve uniform distribution of runoff to these types of SCMs and are discussed in detail in Section 5.0 *SCM Inflow Features* of this chapter.

Component	Intent	Grass Swale	Grass Buffer	Other RPAs
Inlet	Allows stormwater to enter the SCM.	✓	✓	✓
Level Spreader (Sheet Flow Inlet)	Spreads flow and maximizes infiltration and pollutant removal.	✓ (some cases)	✓	✓ (or similar function)
Vertical Drop	Provides a small drop to ensure that flow can enter the SCM, even when a buildup of sediment or vegetation is present. This is also the primary location for sediment removal.	✓	✓	✓
Vegetation	Provides pollutant removal through volume reduction, pollutant uptake and straining.	✓	✓	✓
Underdrain	Ensures desired vegetation is not stressed due to excessive moisture.	✓ (very mild slopes <2%)	Not typical	Not typical
Protective Features	Minimizes compaction and disturbance over time.	✓	✓	✓

The vegetated RPA must be planned and designed to allow for infiltration of runoff (in some cases, a significant fraction of the WQCV), while avoiding standing water for prolonged periods. A minimum vegetation density of 80% is required for RPAs to function as intended. Guidance on selecting vegetation is provided in Section 7.0 of this chapter. Healthy topsoil is critical for the dense vegetation needed for RPAs to properly function. See MHFD's *Topsoil Management Guidance* for information on soil management, testing, and amendments. In some cases, an underdrain may be needed to avoid prolonged standing water, depending on soils, depth to groundwater and topography of the RPA.

Photograph RPA-4. Grass buffers can be used to manage runoff from parking lots, multi-use paths, roadways, or roof areas, provided the flow is distributed in a uniform manner over the width of the buffer. Native grasses provide a more natural appearance. Photo: WWE.

Site Considerations

Photograph RPA-5. Grass buffers are well suited for use in riparian zones to assist in stabilizing channel banks adjacent to major drainageways and receiving waters.

Grass buffers, grass swales, and other types of RPAs can be integrated on many sites across the spectrum from low density to urban development. These SCMs are generally best suited for sites with low to moderate slopes but can be used on steeper sites when grade control measures are implemented such as terracing for buffers or check dams for swales. RPAs can be incorporated on almost any site by directing runoff to landscaped areas. For lower density sites, this could include directing downspouts to lawn areas, sloping hardscape areas to sheet flow to vegetated areas, and using buffers and swales. For more urban sites, RPAs may include vegetated planters. (Note: permeable pavements function as RPAs because they disconnect impervious area—these SCMs are addressed separately in the Permeable Pavement Systems Fact Sheet).

Grass swales can serve as an important part of the conveyance network for a development, while also promoting infiltration and filtration of runoff. Incorporating the existing ephemeral stream network of an undeveloped watershed into a development as a system of shallow stabilized swales can have significant runoff reduction benefits. In other cases where impacts to the low-order stream network cannot be avoided, the natural system can be mimicked by using swales rather than pipes for the minor drainage collection system.

Community Values

RPAs including grass buffers and swales are adaptable SCMs that can be integrated into many different landscapes in a distributed manner to provide runoff reduction benefits while also providing attractive, enjoyable, usable, and sustainable green space for the community. Key considerations for creating RPAs that provide value to the surrounding community include:

- **Design RPAs to complement the other functions of the site.** Consider how RPAs relate to viewsheds, pedestrian and bike circulation, social gathering areas, and other site uses and design RPAs to complement these uses. For example, a vegetated buffer strip on the downgradient side of a bike path can be designed as a linear RPA to infiltrate much of the runoff from the path from frequently occurring events.
- **Integrate drainage and landscape design to distribute RPAs across a site.** RPAs are distributed SCMs and are most effective when implemented throughout a site as a part of

integrated drainage and landscaping plans. Many types of RPAs can be designed to be indiscernible from the surrounding landscape, except during shallow, short-term ponding during rainfall events. Add interest to RPAs by creating dynamic landforms through the use of curves and variations in side slopes. Even slopes intended to drain by sheet flow can have subtle variations to create visual interest.

Photograph RPA-6. Dense vegetation in this 5% sloping swale provides the roughness to resist erosion and slow, filter, and infiltrate runoff.

- **Consider native vegetation for water conservation.** The selection of native versus non-native turf grasses for a RPA should be a conscious decision based on which type best meets objectives for the site usage and surroundings as well as runoff reduction and water quality objectives for the site. Irrigated turf, such as Kentucky bluegrass, is a more durable surface for areas where there is foot traffic or in recreational areas. Irrigated turf grass provides a manicured appearance that complements certain urban and suburban aesthetics. However, non-native, irrigated turf grasses require more water, frequent mowing, fertilizing, and weed control.

  Native grass turf areas provide wildlife habitat and create a 'regional' natural aesthetic. Pollinator plants can be seeded in with the native grasses to provide additional environmental benefit. Compared to irrigated bluegrass, native grasses and pollinator plants require much less water and have fewer maintenance, fertilizer, and weed control needs once established. During establishment, irrigation is required to achieve required vegetation density in a timely manner. In many settings, native turf grasses are a more sustainable option than non-native, irrigated turf grasses. See Section 7.0 of this chapter for additional considerations related to vegetation selection.

Maintenance

Grass swales, buffers, and RPAs require maintenance of vegetation and periodic removal of sediment. During design, identify where and how sediment will be removed. See Chapter 6 for detailed maintenance requirements for all SCMs. During design, consider the following to facilitate maintenance over the long-term:

- Incorporate a "blind swale," which can be a gutter section or a pervious linear depression running along the upgradient side of the level spreader, to distribute flow along the spreader and facilitate sediment deposition. This can enable collection and removal of sediment without impeding the ability of the level spreader to function between maintenance cycles. (See Figure 4-9 in Section 5.1.3 of this chapter for an example.)

- Consider an underdrain system if there are concerns about excessively wet areas that could cause rutting and damage to the vegetation during mowing operations. See Section 4.3.3 *Underdrain Systems* in this chapter for guidance and criteria on underdrains.

Photograph RPA-7. RPA in multi-family residential neighborhood. Sign warns of periodic flooding which helps establish expectations for periodic temporary ponding, while providing a safety warning. Photo: WWE.

- Provide suitable topsoil based on recommendations in MHFD's *Topsoil Management Guidance*. Good topsoil and healthy vegetation will reduce the extent of maintenance required for weed control and will avoid having areas with unhealthy vegetation susceptible to erosion.

- Design and adjust the irrigation system (temporary or permanent) to provide water in amounts appropriate for the selected vegetation at the appropriate irrigation frequencies. Irrigation needs will change from month to month and year to year. For RPAs with native vegetation, temporary irrigation is typically required to establish suitable vegetation density. Avoid over-irrigation, which can result in ponding and limit infiltration capacity. See Section 7.0 of this chapter for more information on irrigation requirements.

Photograph RPA-8. Post signage to protect RPAs from vehicular traffic if there is not a barrier between the parking or roadway and the RPA. Photo: Nancy Styles.

- Provide access for mowing equipment and design side-slopes flat enough for the safe operation of equipment.

- Consider the use and function of other site features so that the SCM fits into the landscape in a natural way. This can encourage upkeep of the area, which is particularly important in residential areas where a loss of aesthetics and/or function can lead to homeowners modifying SCMs.

- Protect pervious areas from vehicular traffic when implemented adjacent to roadways. This can be done with a slotted curb (or other type of barrier) or by constructing a reinforced grass shoulder as discussed in Section 5.0 *SCM Inflow Features* in this chapter. Signage can also be provided in lieu of a physical barrier.

- Consider impacts of snow storage on vegetation and designate an area for snow storage outside of the RPA. Additional maintenance of vegetation is often required when vegetation receives runoff from snowmelt containing salt and sand in the winter.
- Consider providing pet waste disposal stations and signage in areas frequented by dog owners.
- If the RPA is used to meet post-construction MS4 permit requirements, local governments may have specific requirements for RPAs to be covered by drainage easements or other legal agreements so that these areas are not modified over time.

Design Procedures and Criteria

Table RPA-1 provides a summary of design criteria, and the following steps outline the procedure for quantifying stormwater runoff reduction associated with RPAs. The criteria in Table RPA-1 and steps below are applicable to all types of RPAs including grass buffers and swales. Additional criteria specific to buffers and swales are provided following the criteria applicable to all types of RPAs.

Design Procedure and Criteria for All RPAs

The following steps provide design criteria and procedures applicable to *all* RPAs:

1. **Apply Four-cover Land Use Model to Site Layout:** Identify areas of directly connected impervious area (DCIA), separate pervious area (SPA), UIA, and RPA as stormwater management plans are developed for a site in accordance with Chapter 3. Look for opportunities to direct impervious areas to vegetation and to integrate RPAs with landscaping.
2. **Delineate the RPA and determine the UIA:RPA ratio:** Only include pervious areas receiving flow from the UIA in the calculated RPA. For swales, only include the flat bottom width as RPA. For buffers and other types of RPAs, only include the area receiving stormwater in a distributed manner such that stormwater wets the entire width of the RPA for this calculation. Do not include pervious areas that have concentrated flow as RPA. These criteria assume uniform sheet flow across the wetted portion of the RPA. A level spreader should be used when flows from the UIA are concentrated. Section 5.0 SCM *Inflow Features* in this chapter provides guidance and criteria for design of level spreaders.

Table RPA-1. Design Parameters for RPAs including Grass Buffers and Swales

Design Parameters	Description, Guidance, and Criteria
Area of UIA	UIA should be approximately 1 acre or smaller, although larger areas may be applicable with proper grading and flow distribution to the RPA. Multiple level spreaders may be needed for larger areas.
Wetted Area of the RPA and Flow Characteristics	RPA must receive evenly distributed flow (sheet flow) from the UIA. Consider only the wetted area when delineating the RPA. Only the area that is directly within the flow path should be considered RPA. For swales, only the bottom width is considered RPA. See the design procedure for additional criteria and considerations for swales and buffers.
Vegetation of RPA	RPA vegetation (from seed, sod, or plugs) should form a turf with a uniform density of at least 80%. Non-native turf grasses such as Kentucky bluegrass are often used in manicured areas but require more irrigation than native turf grasses. Where a more natural look is desired, use dense native turf-forming grasses. Depending on anticipated flows, consider erosion control measures until vegetation is established. Mulch, gravel, and any materials that can be washed away easily should not be used for the RPA.
Interface between UIA and RPA	The RPA must be protected from vehicle traffic, and the interface between the UIA and the RPA must provide a vertical drop to allow runoff to flow freely from UIA to RPA as sediment and grasses build up over time.
Length-to-Width of UIA:RPA pair	SWMM modeling for the development of this Fact Sheet was limited to a length-to-width ratio of the UIA:RPA pair between 0.06 and 16.0. When using these criteria outside of these limits, results may vary.
Slope of RPA	The slope of the RPA should be no greater than 3:1 (H:V). For native turf grass RPAs, consider using more mildly sloped buffers to reduce the potential for erosion while the native grasses are becoming established.
UIA:RPA ratio	The recommended maximum UIA:RPA ratio is 10:1. Ratios greater than this may be appropriate if pretreatment and level spreaders in series are provided. Pretreatment should also be considered as the ratio of UIA:RPA increases.
Soil Type and Preparation	The topsoil and underlying soils of the RPA affect infiltration characteristics and the density and health of vegetation. Perform a gradation test to ensure assumptions are accurate, especially when quantifying runoff reduction in HSG A and B soils. See MHFD's *Topsoil Management Guidance* for information on soil types, soil management, testing, and preparation.
Underdrains	Underdrains are often used to avoid soggy bottoms in swales that have mild slopes. Using an underdrain may increase outflows from the RPA, which may reduce the effectiveness of the SCM for runoff reduction to varying degrees. The Runoff Reduction worksheet in the MHFD-BMP workbook is not suitable for quantifying runoff reductions of RPAs with underdrains because it does not account for underdrain outflows.
Irrigation	Provide temporary or permanent irrigation systems, depending on the type of vegetation selected. Adjust irrigation application rates and schedules throughout the establishment and growing season as appropriate to meet the needs of the selected plant species. Initially, native grasses have similar irrigation requirements to bluegrass. After the grass is established, irrigation requirements for native grasses can be reduced.

3. **Calculate Runoff for the UIA and RPA Pair:** In the MHFD region, the precipitation depth associated with the WQCV event is 0.6 inches. For areas outside of the Denver Metro

region, the precipitation depth for the WQCV event may differ. The Runoff Reduction worksheet in the MHFD-BMP workbook is not applicable for precipitation depths less than 0.25 inches or greater than 0.95 inches. For evaluating greater rainfall depths, CUHP and SWMM should be applied. Calculate the total runoff from each UIA:RPA pair using Equation RPA-1 (Piza and Rapp 2018):

$$Q = C_0 + C_1(0.95 - P_2) + C_2(A) + C_3(L{:}W) + C_4(S) + C_5(I) + C_6(I^2) \qquad \text{Equation RPA-1}$$

Where:

Q = Runoff from the UIA:RPA pair (watershed inches)
P_2 = Precipitation for 2-hour WQCV event (inches)
A = Total Area of UIA:RPA pair = Area of UIA + Area of RPA (ft^2)
L:W = Ratio of total flow length to interface width
S = Average overland slope (ft/ft)
I = Imperviousness of UIA:RPA pair = UIA/(UIA + RPA), expressed as a decimal
C_x = Regression coefficients, see Table RPA-2.

Table RPA-2. Coefficients for Quantifying Runoff from UIA:RPA Pair for Runoff Reduction Analysis (Piza and Rapp 2018)

Hydrologic Soil Group	Constant C_0	Precip, P_2 (in), C_1	Area (ac), C_2	L:W, C_3	Slope (ft/ft), C_4	Imperv., C_5	Imperv., C_6
A	0.581	-0.779	-3.34×10^{-07}	-0.00193	0.0703	-2.49	2.64
B	-0.0777	-0.925	-2.45×10^{-07}	-0.00145	0.00502	-0.0136	0.924
C/D	-0.0113	-0.899	-2.68×10^{-07}	-0.00157	0.0545	0.355	0.464

Calculate the volume of runoff from the UIA:RPA pair by multiplying the watershed inches determined in Equation RPA-1 by the total area of the UIA:RPA pair as shown in Equation RPA-2:

$$V_{UIA:RPA} = \left[\frac{Q}{12}\right] A_{UIA:RPA} \qquad \text{Equation RPA-2}$$

Where:

$V_{UIA:RPA}$ = Volume of runoff from UIA:RPA pair (ft^3)
$A_{UIA:RPA}$ = Area of UIA:RPA pair (ft^2)

4. **Compare Runoff from UIA:RPA Pair to Runoff from UIA Only:** Calculate the runoff from the UIA by assuming impervious area depression storage of 0.1 inches:

$$V_{UIA} = \left[\frac{P_2 - d_{store}}{12}\right] A_{UIA}$$

Equation RPA-3

Where:

V_{UIA} = Volume of runoff from UIA (ft^3)
P_2 = Precipitation for 2-hour WQCV event (in)
D_{store} = Impervious area depression storage (in), assume 0.1 inches for most impervious surfaces
A_{UIA} = Area of UIA (ft^2)

The difference between this value (V_{UIA}) and $V_{UIA+RPA}$ from Equation RPA-2 is the runoff reduction associated with the UIA:RPA configuration. The percentage reduction in runoff can be calculated as:

$$\%Runoff\ Reduction = \frac{V_{UIA} - V_{UIA:RPA}}{V_{UIA}}$$

Equation RPA-4

Within the MHFD region (where the WQCV precipitation depth is 0.60 inches), the runoff reduction percentage is equivalent to the WQCV reduction percentage. However, outside the MHFD region, these percentages may differ based on the relationship between the 2-hour WQCV precipitation depth and the average runoff-producing storm's precipitation depth, d_6 (Figure 3-1 in Chapter 3) which is used to adjust the calculated WQCV.

The Runoff Reduction worksheet in the MHFD-BMP workbook can be used to quantify runoff reduction from the WQCV rainfall depth and for conceptual sizing of the interface width and buffer length needed to achieve specific runoff reduction objectives.

Table RPA-3. Quick Reference Sizing for RPAs, including Grass Buffers

HSG	Required UIA:RPA Ratio[1]	
	60% WQCV Reduction	100% WQCV Reduction
A	7.2:1	3.7:1
B	3.4:1	1.9:1
C/D	2:1	1:1

[1] Based on WQCV precipitation of 0.6 inches and slopes up to 33%.

How much is enough?

When using RPA as stand-alone treatment for the WQCV, the MS4 Phase 2 General Permit requires reduction of 60% of what the calculated WQCV would be if all impervious area for the applicable development site discharged without infiltration. However, some municipalities may have more stringent requirements. In either case, downstream SCMs may still be required to meet permit conditions and the MHFD-BMP tool can help size those while accounting for volume reduction utilizing this method. Use Table RPA-5 for a quick reference when initially sizing RPAs to reduce 60% or 100% of the WQCV.

5. **Provide a Vertical Drop:** Provide a minimum vertical separation of 3 inches between the UIA and RPA at their interface. Where pedestrian or vehicular traffic is of concern, the drop can be sloped from the edge of the impervious surface to the buffer using #57 stone underlain with geotextile separator fabric. Limit the drop to no more than 6 inches. The drop is required to ensure positive drainage from the UIA to RPA as vegetation becomes established.
6. **Protect the RPA from Traffic:** The RPA must be protected from vehicular traffic. A slotted curb can be used for this purpose. See Section 5.0 *SCM Inflow Features* in this chapter for guidance and criteria on inflow configurations for RPAs.

> **Flexibility to Fit Site Constraints**
>
> Grass buffers, swales, and other types of RPAs provide some benefit in volume reduction and pollutant removal even when the geometry of the SCM does not meet the criteria provided in this Fact Sheet. These criteria provide a design procedure that should be used when possible; however, when site constraints are limiting, grass buffers, swales, and RPAs designed for stability are still encouraged.

7. **Characterize On-site Topsoil and Determine Suitability for the RPA:** The NRCS Web Soil Survey is a good resource for an initial investigation of site soils. However, only soil sampling and testing will confirm the actual NRCS Hydrologic Soil Group (HSG). Inexpensive laboratory tests quantify particle size based on sieve and hydrometer analyses to determine sand gradation and percent sand, silt, and clay for texture determination, and include agronomic tests for organic content, pH, salinity, and nutrients. MHFD recommends onsite topsoil sampling and testing as a standard of practice on every project. It is essential to characterize soil conditions to identify locations that are well suited to serve as RPA and to determine appropriate amendments where RPA is planned (some local governments may also require proof of soil conditions/amendment in landscaped areas for water conservation reasons).

   Soil characterization is also required to ensure use of the proper coefficients in Equation RPA-1. Plot the percent sand, silt, and clay of each sample on a USDA soil triangle and use this to confirm soil texture and HSG. Table RPA-4 and Figure RPA-2 indicate HSG based on percent sand, silt, and clay according to the NRCS National Engineering Handbook (USDA 2009). Based on the results of on-site soil sampling and testing, refer to Table RPA-4 to select the most suitable soil from the site for use in the RPA. See MHFD's *Topsoil Management Guidance* for additional information on preserving topsoil and providing amendments as needed to create a healthy medium for vegetation to grow.

Table RPA-4. Percent Sand, Silt, and Clay for HSG A through D

HSG	% Sand	% Clay	% Silt
A	> 90	< 10	0 – 10
B	50 – 90	10 – 20	10 – 50
C	< 50	20 – 40	0 – 100
D	< 50	> 40	0 – 60

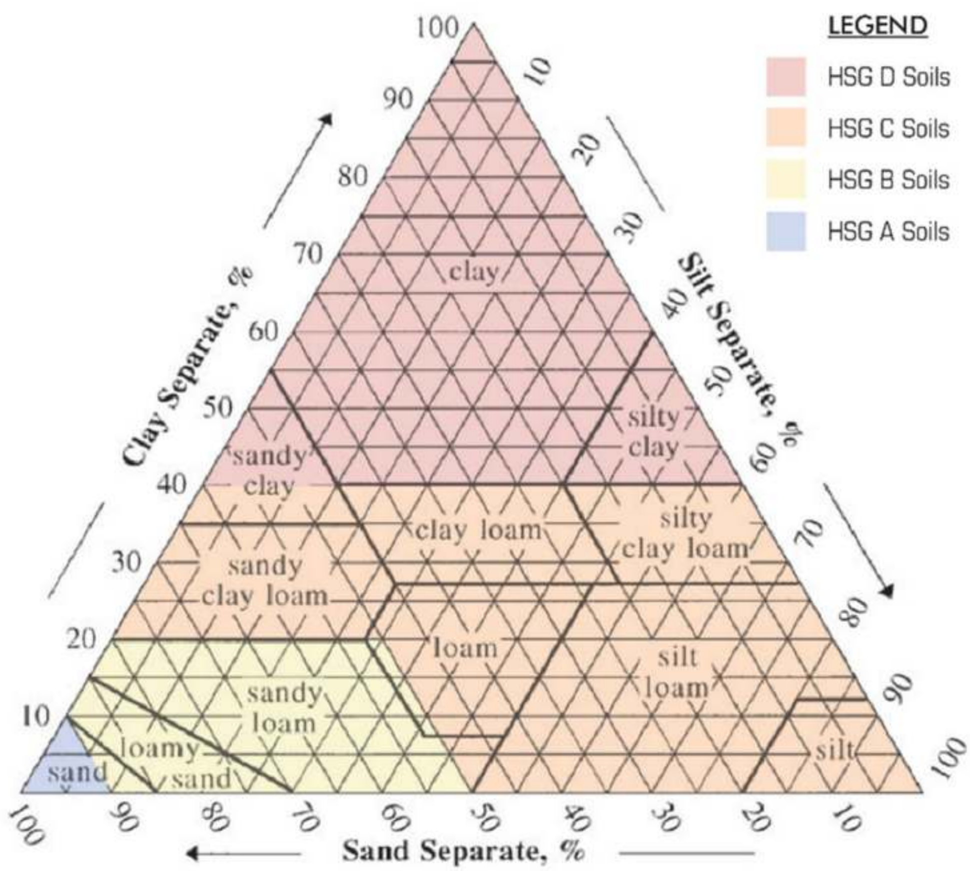

Figure RPA-2. USDA Soil Triangle with USDA NRCS Soil Texture Classes overlain by USDA Hydrologic Soil Groups

8. **Select Appropriate Vegetation:** Modeling supporting the calulations in this fact sheet assume all RPA is vegetated. RPA vegetation should be turf grass with a uniform density of at least 80%. Seed or sod is acceptable and plugs may provide quicker establishment compared to seed. When selecting a seed mix, consider using all turf grasses or a combination of turf and bunch-forming grass to produce uniform density of 80%. Grass buffers can be dryer than grass swales so selecting the appropriate seed mix is important. See the *Revegetation* chapter in Volume 2 for guidance and consult with a qualified landscape architect or ecologist to confirm the appropriate mixes and seeding locations of the mixes in natives areas. Irrigation is required for establishment of

vegetation, and supplemental irrigation may be necessary during extended dry periods once vegetation is established and to maintain a healthy turf.

Grass Buffer Additional Design Procedure and Criteria

Previously described criteria outlined above for RPAs are required for grass buffers when quantifying runoff reduction. Procedures and criteria specific to designing grass buffers for water quality include:

Photograph RPA-9. Grass buffer provides an opportunity for filtration and infiltration of roof runoff and disconnects impervious area of roof from inlet to storm drainage system.

1. **Design Discharge:** Calculate peak flows to the buffer using the methods in the *Runoff* chapter for a 2-year event. While the objective of the buffer design is to infiltrate some or all of the runoff from an 80^{th} percentile runoff-producing event, the 2-year event is used to evaluate velocities to reduce the potential for erosion of the buffer. If a level spreader and buffer system are used to treat runoff from a concentrated discharge from a larger drainage area, it may be necessary to design an upstream bypass system for flood flows to avoid creating velocities that would erode the buffer.

2. **Flow Conditions:** Assess the need for a level spreader using Equation 4-1 in Section 5.1.3 *Level Spreaders* of this chapter. Grass buffers require sheet-flow conditions to be effective at infiltrating runoff. Concepts for level spreaders to diffuse concentrated flows are also presented in Section 5.1.3.

3. **Buffer Interface Width:** Limit the maximum flow to the buffer to no more than 1 cfs per 20 feet of buffer width at the interface between the edge of pavement or level spreader and the buffer (distance measured perpendicular to the direction of flow). This is necessary to avoid hydraulic overloading and/or erosion of the buffer as flows begin to concentrate on lower portions of the buffer. Based on the calculated 2-year peak flow rate, determine the required buffer width (Hunt et al. 2001, assuming a permissible velocity of 3.5 feet per second):

$$W = 20 \cdot Q_2 \qquad \text{Equation RPA-7}$$

Where:

Q_2 = 2-year peak runoff (cfs)

W = width of buffer (feet)

4. **Buffer Length:** The length of the buffer is the measure of the vegetated surface in the direction parallel to flow. While there are no minimum length requirements for buffers, the runoff reduction and pollutant removal benefits of buffers increase as the total wetted area increases. For very long buffers and/or for buffers on steep slopes, additional level spreaders may be needed along the buffer length to avoid concentration of flow.

Tiered Level Spreader-Buffer Systems

If the calculated buffer width is more than 100 feet, tiered level spreader-buffer systems can be used to design wider buffers, while still providing for even sheet-flow distribution across the width of the buffer.

4. **Minimum Buffer Slope:** The design slope of a grass buffer in the direction of flow must be mild enough to avoid erosion and to allow for infiltration, while still allowing for positive drainage to avoid problems with standing water. Generally, a minimum slope of 2% or more is adequate to facilitate positive drainage for turf grasses. For slopes milder than 2%, consider including an underdrain system to mitigate nuisance drainage. See Section 4.3.3 *Underdrain Systems* of this chapter for additional information on underdrains

Grass Swale Additional Design Procedure and Criteria

Grass swales are important SCMs for conveying runoff from a site through a vegetated, pervious flow path. Swales slow down runoff, promote infiltration, and extend the time of concentration of the watershed, thereby reducing the rate, volume, and frequency of runoff produced by a watershed. When designed for shallow depths with dense vegetation, grass swales may aid in achieving the MS4 Permit Runoff Reduction Standard for a site. Even when designed primarily for conveyance purposes (e.g., somewhat higher velocities and depths), swales help to dampen the runoff response and filter and infiltrate runoff. Swales provide the types of benefits envisioned by Step 1 of MHFD's Four Step Process.

Criteria outlined above that apply to all RPAs are required for grass swales when quantifying runoff reduction. Additional procedures and criteria specific to designing grass swales for water quality include:

1. **Design Discharge:** Calculate peak flows for the swale using the methods in the *Runoff* chapter. For water quality design, use a 2-year event. Larger events such as the minor storm event also may be conveyed in swales; see the *Open Channels* chapter for design of conveyance swales.

2. **Swale Inflows:** Provide a sediment pad at the entrance to the swale to facilitate maintenance as shown in Figure 4-10 of Section 5.1.3. Locating the vertical drop described in Step 5 of the design procedure for all RPAs where inflow meets the sediment pad allows for sediment accumulation where it is intented without impeding inflow. See Section 5.0 *SCM Inflow Features* for more ideas at the inlet.

3. **Swale Cross Section:** The swale cross section should be trapezoidal with side slopes not exceeding 4:1 (horizontal: vertical), preferably flatter. Fit the swale into the site by varying the swale alignment and side slopes and avoid linear, prismatic designs to the

extent practical unless the application is in a highway environment. Trapezoidal swales with wide bottoms maximize the wetted perimeter. Per Table RPA-1, it is only the bottom area of the trapezoid that is considered RPA in quantifying volume reduction.

4. **Longitudinal Slope:** Establish a longitudinal slope that will maintain positive drainage while limiting velocities in the swale to non-erosive levels. Typically positive drainage for a swale can be achieved with a minimum longitudinal slope of 2%. MHFD recommends using an underdrain when swales have longitudinal slopes less than 2% to minimize the potential for standing water and nuisance conditions. See Section 4.3.3 *Underdrain Systems* of this chapter for additional information on underdrains for grass swales. Use check dams as needed to accommodate steeper site constraints. Commonly used check dam materials include rock, riprap, concrete, and vegetated earth (MPCA 2023; Davis, Hunt and Traver 2022). Provide energy dissipation downstream of each check dam when using these grade control structures.

5. **Hydraulic Residence Time:** The hydraulic residence time is the average amount of time it takes for runoff to move through the swale in a specified design event. Increased hydraulic residence time in a grass swale improves water quality treatment. Maximize the length of the swale when possible to increase hydraulic residence time. If the length of the swale is limited due to site constraints, the slope can also be decreased or the cross-sectional area increased to increase hydraulic residence time. Adjusting the cross section to increase the wetted perimeter and reduce velocities is another way to increase hydraulic residence time. Lower velocities result in improved pollutant removal efficiency and greater volume reduction.

Photograph RPA-10. Sediment forebay at the entrance to a grass swale leading to an EDB concentrates maintenance needs at entrance of swale. This is an example of a three-step treatment train: forebay, swale, pond.

Bioswales

In some cases, engineers may design "bioswales" that incorporate more diverse, often hydrophytic, vegetation and enhanced landscaping features. These types of swales can provide an enhanced level of water quality treatment and in many applications serve as a hybrid of a swale and a bioretention facility. These types of swales are encouraged when they can be incorporated into the landscaping and provide benefits beyond water quality treatment. The same fundamental procedures apply for designing a bioswale; however, the vegetative retardance coefficient must be adjusted to reflect the mature state of planned vegetation for evaluation of depth. The "E" curve (very low vegetal retardance) should be used to evaluate velocities, representing conditions prior to establishment of dense vegetation.

6. **Design Velocity:** The maximum flow velocity in the swale should not exceed 1 foot per second. Higher velocities up to 3 to 5 feet per second (depending on the soil type and swale lining) for the 2-year event are permissable for swales that are intended primarily for conveyance rather than infiltration, provided that the Froude number does not exceed 0.5. Even if velocities exceed 1 foot per second, swales can still play an important role in disconnecting impervious area and will provide some infiltration benefits. Use the Natural Resource Conservation Service (formerly the Soil Conservation Service) vegetal retardance curves for the Manning coefficient (Chow 1959). Determining the retardance coefficient is an iterative process that the MHFD-BMP workbook automates. When starting the swale vegetation from sod, use curve "D" (low retardance). When starting vegetation from seed, use the "E" curve (very low vegetal retardance) to evaluate potential for erosion during initial establishment and the "D" curve for evaluating depths and velocities for the established condition.
7. **Design Flow Depth:** The maximum flow depth should not exceed 1 foot at the 2-year peak flow rate if the swale will provide runoff reduction benefits as a part of a system intended to satisfy a MS4 permit treatment standard. Depths up to 3 feet may be allowed in the 2-year event for swales that are intended only to satisfy Step 1 of the Four Step Process, provided that the Froude number does not exceed 0.5. Check the conditions for the 100-year peak discharge to ensure that drainage is being handled without flooding critical areas, structures, or adjacent streets.
8. **Swale Outflows:** Provide a means for downstream conveyance for the range of flows that may be conveyed through the swale. For swales that drain to inlets or culverts, perform analysis of headwater depth for the 2-year design flow rate to be sure that the headwater depth is contained within the swale with an allowance for a minimum of 6 inches of freeboard. Greater freeboard requirements may apply depending on road classifications adjacent to swales.

Construction Considerations for RPAs

Success of RPAs, including buffers and swales, depends not only on a good design and long-term maintenance but also on proper construction so that the RPA functions as designed. Construction considerations include:

1. Fence off areas to avoid over-compaction of soils to preserve infiltration capacities.
2. When using an underdrain, ensure no filter sock is placed on the pipe. This is unnecessary and can cause the slots or perforations in the pipe to clog.
3. Perform fine grading, soil amendment, and seeding only after upgradient surfaces have been stabilized and utility work crossing the SCM has been completed. The final grade of the RPA, once sod has been placed or seeded vegetation has become established, must accept sheet flow from adjacent impervious surfaces without impeding flow.
4. Inspect the RPA prior to placement of seed or sod to check that inflows are not concentrated and that the final grade, including the vegetation, will not impede sheet flow onto the vegetated pervious area.

5. When using sod tiles, stagger the ends of the tiles to prevent the formation of channels along the joints. Use a roller on the sod to ensure there are no air pockets between the sod and soil.
6. If the area where the SCM will ultimately be constructed will be used as an SCM during construction (e.g., sediment trap, drainage ditch), the area must be restored prior to constructing the permanent SCM by removing all accumulated sediments and ripping the soils to a depth of 12 inches. Do not install underdrains or place topsoil in the SCM until the watershed is stabilized and the SCM is no longer acting as a sediment trap.
7. Erosion and sediment control measures on upgradient disturbed areas must be maintained to prevent excessive sediment loading to the SCM. Implement final grading, soil amendments, seeding, and related activities once the contributing watershed has been effectively stabilized.

Photograph RPA-11. Signage and construction fencing can help protect the RPA as vegetation becomes established.

8. Provide irrigation appropriate to the type of vegetation. Note that irrigation will be needed for native grasses to establish the root system (typically one or two growing seasons).
9. Weed the area during the establishment of vegetation by hand or mowing. Mechanical weed control is preferred over chemical application.
10. Consider signage and barriers to prevent use of the RPA while the vegetation becomes established.

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T-2 Rooftop Systems (Green Roofs & Blue Roofs)

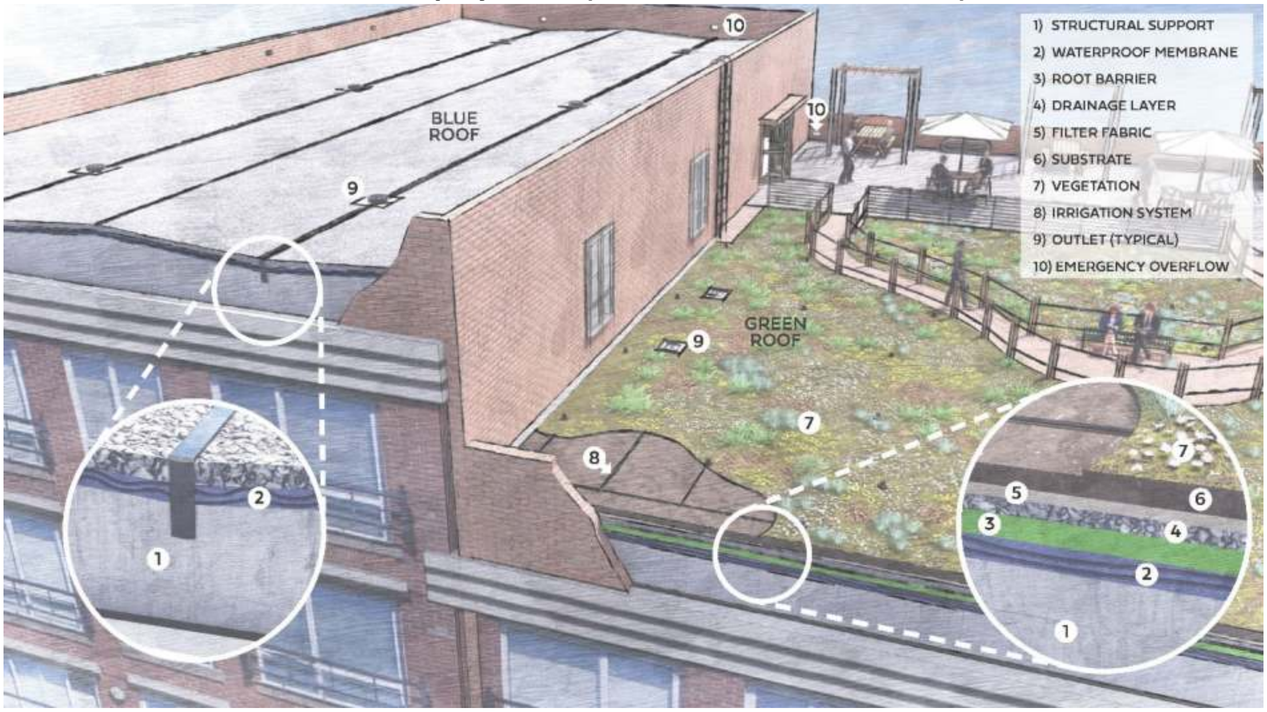

Figure GR-1. Green Roof and Blue Roof Components

Description

Rooftop systems for stormwater management include green roofs and blue roofs. Green roofs are vegetated systems grown in substrate that helps to reduce runoff volumes and rates. Blue roofs are unvegetated rooftop stormwater detention areas. Blue-green roofs combine these two systems.

There are two main types of green roofs: extensive and intensive. Extensive green roofs are shallow, usually with up to 6 inches of substrate, and do not typically support a large diversity of plant species because of root zone limitations. Intensive green roofs are more like rooftop gardens with deep substrate (from 6 inches to several feet) and a wide variety of plants. Most buildings are not designed to withstand the additional weight loading for intensive roofs unless accounted for in the original design of the building. For this reason, intensive green roofs are typically limited to

MS4 Permit Applicability (Dependent on design and level of treatment)	
Meets Runoff Reduction Standard	Potential
Meets WQCV Capture Standard	Yes
Meets Pollutant Removal Standard	No
Typical Effectiveness for Targeted Pollutants[1]	
Sediment/Solids	Low
Total Phosphorus	Low
Total Nitrogen	Low
Total Metals	Low
Bacteria	Low
Common Applications	
Runoff Reduction (General)	Yes
Used for Pretreatment	Yes
Integrated with Flood Control	No[2]
Cost	
Life-Cycle Costs	Medium
[1]Primary benefit is volume reduction. [2]May vary by jurisdiction for blue roofs.	

new construction. Extensive green roofs are shallower, less expensive and generally much better suited to the structural capabilities of existing buildings and therefore, are installed more often.

Blue roofs are a rooftop system that provides rooftop detention without vegetation or substrate. Roof drain orifices regulate the rate of runoff from the roof to release the WQCV and/or EURV. Combining blue roof and green roof systems on the same rooftop is increasingly becoming more common.

Photograph GR-1. Extensive Green Roof. Photo: Jennifer Bousselot.

Photograph GR-2. Denver Botanic Gardens intensive green roof over parking garage. Photo: Michael Guidi.

Benefits of Green Roofs

- Reduces runoff rates and volumes.*
- Reduces heat island effect in urban areas.
- May qualify for multiple green building credits and/or help satisfy local green building codes.
- May extend roof lifespan by reducing daily temperature fluctuations and providing shading from ultraviolet light.
- May provide energy savings from additional insulation and cooling from evapotranspiration.
- Provides an additional protective layer over the rooftop that may extend the lifespan of traditional roof membranes relative to impacts from hail and UV degradation.
- Provides aesthetically pleasing open space in ultra-urban areas.
- Provides habitat for pollinators and birds.
- Reduces (or eliminates) stormwater quality management footprint on the ground surface.*

Limitations of Green Roofs

- Initial installation costs are greater than conventional roof (although lifecycle costs are lower).*
- Supplemental irrigation is required in semi-arid climate.
- Maintenance during vegetation establishment (first two years) may be significant.

* = *Also applies to blue roofs.*

SCM Components

The primary components of green roofs include a waterproof membrane, a root barrier, drainage layer, filter membrane, the substrate (growing media), vegetation, an irrigation system and outlets to drain the roof. In the case of blue roofs, components include structural support, a waterproof membrane, and orifice-controlled outlet(s). Before installing a green roof or blue roof on an existing structure, a structural engineer must verify that the roof structure can support the load associated with the rooftop system.

Some systems may also incorporate a water retention layer, if Colorado water rights constraints are addressed. Insulation layers may also be incorporated into the design based on building heating/cooling objectives. For new buildings, the building design should include the rooftop system load.

Component	Intent
Structural Support	Roof structure that supports the substrate, vegetation, and live loads associated with rainfall, snow, people, and equipment.
Waterproof Membrane	Prevents water from entering the building.
Root Barrier	Protects the waterproof membrane by preventing roots from reaching the membrane. (Note: In some proprietary products, root barriers may be integrated into the product with the drainage layer.)
Drainage Layer	Drains the rooftop system to the outlet. This is sometimes an aggregate layer or a proprietary product.
Filter Fabric	This prevents fine soil and substrate from being washed out into the drainage layer.
Substrate (Growing Media)	Provides a growing media for the rooftop vegetation. Although the substrate is typically not "soil," the terms *soil matrix*, *soil media* and *growth substrate* are sometimes used.
Vegetation	Provides evapotranspiration to reduce runoff volumes, aesthetic appeal, ecosystem services and a cooling effect for the building. Native/adapted, drought-tolerant grasses, perennials, and shrubs with relatively shallow root depths are possibilities for roof plantings.
Irrigation System	Supports vegetative health of green roofs. Even vegetation with low water requirements will require supplemental irrigation in the metro Denver area.
Outlet(s)	Provides outlet for detained flows to drain from the rooftop. Orifice controls are not required for green roofs designed to treat the WQCV. Orifice controls are required for blue roofs or if the green roof is designed to detain storms larger than the WQCV.

Site Considerations

Green roofs can be installed on commercial or residential buildings as well as on underground structures such as a parking garage (Photo GR-2). Green roofs may be particularly well suited for ultra-urban areas where development is typically lot-line-to-lot-line and garden space is at a premium. Green roofs are particularly valuable when their use extends to a place of enjoyment with visual or physical access for those that inhabit the building.

For existing buildings, verify the structural integrity of the building prior to consideration of retrofitting the building with a green roof. For both existing and new construction, a multi-disciplinary design team is essential. This team may include a structural engineer, stormwater engineer, architect, landscape architect, and horticulturist. Involve all members of the design team early in the process to ensure the building and site conditions are appropriate for green roof installation.

Several factors contribute to the success of green roofs in a semi-arid environment. Access to permanent irrigation is required, even if it is only used in drought conditions once the green roof is established. Wind scour is a major concern for rooftop systems (particularly taller buildings), so it is important to keep the slope consistent throughout the green roof and avoid vegetating high wind areas at building corners. In a dry climate, the aspect of the green roof is important: south or west-facing sloped applications may require more irrigation and maintenance; therefore, north and east-facing installations are preferred when feasible. Scale is also important – it is challenging to maintain a thriving green roof in a small space or disconnected pattern. When the planted area of the green roof does not cover the entire roof, design the green roof to aggregate the planted area of the roof.

Blue roofs have similar site considerations to green roofs, but without vegetation and irrigation-related factors. Blue roofs are not typically designed for public access or to serve as multi-purpose amenities.

Community Values

Green roofs, blue roofs, and blue-green roofs improve the quality of the urban environment by using rooftop areas that are infrequently used for other purposes for stormwater management. In the case of green roofs and blue-green roofs, this SCM also provides valuable green space in an urban environment. To decide between a green roof or blue roof, assess the overall objectives of the project and the opportunities and constraints presented by the roof area and surroundings. Green roofs and blue roofs have distinct characteristics that must factor into this choice, as described below.

Green Roofs: Even in the semi-arid climate of the Denver metro area, green roofs can be a good choice for an SCM, particularly in ultra-urban environments. When evaluating applicability of this SCM, consider whether the community benefits (beyond the stormwater management objectives) merit the higher construction costs, irrigation system, and water required to sustain the plants, and evaluate costs of maintenance required to establish the green roof and sustain the plants for the long term. The value of green roofs to the community can be significant, particularly when safe, public and semi-public access to the green space is allowed. These "gardens in the sky" can provide valuable outdoor spaces that might otherwise not be available in dense urban environments. These spaces benefit not only those who have direct access to the space, but also people in upper building floors and in adjacent buildings who are able to look down at the green roof. Other benefits provided by green roofs include enhanced habitat for pollinators and birds, improved air quality, building energy efficiency, and reduction in the urban heat island effect. In some cities, green roofs are also used for rooftop vegetable and herb gardens, supporting restaurants in the building.

Key design objectives to consider in efforts to maximize the community value of green roofs include:

- Take design cues from the architectural and landscape architectural design and materials of the building on which the green roof is located. The green roof should either blend with the architecture's forms and materials or be intentionally designed to contrast and stand out as a special feature.
- Create spaces for people. Ensure that the rooftop area open to public use is universally accessible (refer to ADA Standards for Accessible Design) by providing adequate doorways, walkways, ramps and seating. Provide shaded areas if possible, and lighting if evening/night use is a possibility.
- Design for safety. Green roofs that provide physical access will need appropriate safety features to ensure that visitors cannot endanger themselves.
- Design the green roof for viewing from all possible vantage points (including upper floor windows and adjacent buildings).
- Provide diverse plant material that can withstand harsh rooftop growing conditions and that enhances the urban ecosystem, including flowering plants for pollinators. (Follow the plant selection guidance provided later in this Fact Sheet.)
- Create more favorable environments for plants and people by siting planting and use areas away from prevailing winds and harsh southwestern sun exposures. Use wind screen panels or solar panels to deflect the wind if the green roof must be located in windier areas. Also be aware of the potential for the sun to reflect off of upper story building windows and other reflective surfaces, intensifying heat (i.e., magnifying glass effect) that can kill plants.

Blue Roofs: Blue roofs have lower construction and maintenance costs than green roofs, have no irrigation requirements (relative to green roofs), and are well suited for rooftop areas when the potential for community benefits is low (e.g., the building rooftop has limited physical or visual access). In these cases, blue roofs may be more economical choices for rooftop SCMs, making use of an otherwise underutilized area. Blue roofs benefit the community by eliminating or reducing the need for SCMs elsewhere on the site, allowing more of the site to be dedicated to community-oriented uses, thereby enhancing the urban environment.

Maintenance

Photograph GR-3. Intensive green roof over parking garage is readily accessible for mainteannce.

Recommended ongoing maintenance practices for all SCMs are provided in Chapter 6. When designing a rooftop system, the designer and owner must understand both the initial establishment and long-term maintenance requirements for rooftop systems. Prepare a written maintenance plan at the time of design that clearly describes the legal means of access, types of equipment required for maintenance and maintenance requirements, including the various components of the rooftop system. Rooftops are a challenging location to grow vegetation, so maintenance is essential, especially during establishment. Address the unique characteristics of the green roof including: irrigation system, shading, microclimates (shade, temperature, and wind), nutrient/fertilizer management, plant debris removal, maintenance access, and vegetation design (i.e., keeping plants in specific areas). During design, consider the following to ensure ease of maintenance for green roofs over the long-term:

- Provide access for equipment and inspections following construction.
- Carefully design and install the irrigation system, substrate, and appropriately selected plants because these are critical factors determining long-term maintenance requirements and survival of the green roof vegetation under hot, dry conditions. Otherwise, vegetation may have to be repeatedly replanted and/or the irrigation system replaced.
- If an underdrain system is used, provide cleanouts for inspection and maintenance. There is potential over the long term for the roof underdrain system to become clogged with substrate that migrates down beneath the plant root zone. The ability to access the underdrain system for cleanout is important. See Section 4.3.3 *Underdrain Systems* of this chapter for guidance and criteria on underdrains.
- Provide signage for orifice-controlled outlets to prevent modification of the orifice.
- Consider winter maintenance access requirements such as breaking up ice formation around outlets and overflows (particularly for blue roofs).

Design Procedures and Criteria

Design considerations include:

1. **Structural Integrity**: For green roofs, blue roofs and combination green-blue roofs, a structural engineer must ensure the load-bearing capacity of the roof is adequate for the system to be installed. Account for the load of the green roof plus any ponded water below the overflow weir or scupper. For new buildings, green roofs require a multi-disciplinary team and coordination throughout all phases of design.

2. **Water Quality Capture Volume:** Intensive green roofs and extensive green roofs with a substrate of 4 inches or more typically meet the WQCV Capture Standard of the MS4 permit for the green roof area (not including run-on) without orifice-controlled flow-release. The WQCV is stored within the pore space of green roof the substrate and drainage layer.

   In Colorado, green roofs are allowed without a water right provided that they intercept only precipitation that falls within the perimeter of the vegetated area of the green roof and do not intercept or consume concentrated flow or store water below the root zone (DWR 2016). In cases where a portion of the roof is a green roof and a portion of the roof is a traditional roof, the WQCV for the green roof area can be deducted from the stormwater quality treatment requirement for the overall site.

   For blue roofs, a 12-hour drain time is used to calculate the WQCV. The 12-hour drain time differs from the 40-hour extended detention basin drain time due to the lower pollutant loads of roof runoff compared to runoff from roads, landscaped areas, and other ground-level land uses. The 12-hour drain time also is intended to allow the SCM to drain fully before another storm occurs to avoid storing excessive runoff for structural reasons. Determine the required WQCV using Figure 3-2 of Chapter 3 of this manual. Design the orifice controls for blue roofs (or other roof conditions requiring orifice control) to release the WQCV over the required drain time.

Green Roofs and the WQCV

Stormwater performance monitoring data collected by EPA from the Region 8 office green roof in Denver, Colorado demonstrated that green roofs can be effective at detaining and reducing runoff volume. This is especially true for snowmelt events and for smaller precipitation events (generally $<1"$ rainfall in a 24-hour period). EPA's monitoring showed that the green roof retains and evapotranspires 98 to 100% of the WQCV, even without a restriction on the outlet for drain time control. This is largely due to wetting and subsequent evapotranspiration in the substrate. The data showed few exceptions to this finding, which were attributed to successive rain events.

Based on these findings, MHFD recognizes green roofs as a volume-based SCM, able to capture the WQCV for the area of the green roof, without constructing a controlled release at the outlet. This finding applies to green roofs that meet or exceed the EPA building's green roof section, which is a modular system using trays with a minimum of 4 inches of substrate. An intensive roof, which typically has greater substrate depth, also meets the WQCV Capture Standard in the MS4 permit.

3. **Impermeable Membrane and Waterproofing**: For green and blue roofs, an impermeable membrane is required. Install roof membranes in accordance with the manufacturer's specifications to provide proper waterproofing. The system must have a waterproof seal along all seams in the roof membrane and in areas where mechanical devices, equipment, or other structures are affixed to the roof surface. Attach the waterproofing system to the roof surface using adhesives or other methods approved by the system manufacturer. Adhesives that may corrode or otherwise compromise the performance of the membrane or roof system should be avoided. If a green roof will be used as ballast for the membrane, provide temporary ballast until the green roof is installed (NYDEP 2012).

   For existing buildings, check waterproofing warranty and consult the warranty company to ensure the policy will not be voided by a green roof application. A leak test is required following installation of the impermeable membrane, and a leak detection system is recommended for long-term operations, especially in systems with permanent irrigation.

4. **Root Barrier:** All green roofs require protection against root penetration. The waterproofing system should be able to resist even the most aggressive plant roots. Only plastic or rubber membranes are acceptable as root barriers. If waterproofing is used without a supplemental root barrier, obtain and evaluate test data for root resistance of the waterproofing materials. Seams should provide the same level of root resistance as the root barrier membrane. Acceptable seaming methods are hot-air welding (thermoplastic membranes) or overlaps of at least 5 feet combined with an adhered seam. Sealing the root barrier seams also provides additional waterproofing for the system and may extend the life of the roof (NYDEP 2012).

5. **Granular Drainage Layer and Drainage System:** For green roofs, granular mineral drainage media can be used to provide a drainage layer that slows flow toward roof drains and lengthens the time of concentration. Granular drainage layers may be as thin as 1 inch but are typically 2 to 4 inches thick. This type of drainage layer can be used to supplement assemblies that include reservoir sheets and fill in some void space to reduce shock to the root system. Layers that incorporate drainage media become part of the root zone of the plants, and the materials should be chosen accordingly. Granular drainage layers should contain as little silt and clay as possible and should have high

Substrate and Drainage System Technology and Research

In Colorado and nationally, research continues on various types of substrate and drainage technology for green roofs. Green roof substrate characteristics that are lightweight, drain well, and provide nutrients for plants without exporting nutrients are ideal. Additionally, some vendors have developed technologies that use water retention mats or wicking technologies to access water stored below the root zone or to retain water in the root zone. When evaluating emerging technologies, factors to consider include treatment of the WQCV and compliance with Colorado water law, which does not currently allow storage of water below the root zone (without a water right).

permeability and porosity. See FLL Guidelines for recommended granular drainage layer recommendations (NYDEP 2012).

Provide a filter fabric above the drainage layer to keep the substrate from clogging the drainage media. Although roots may pass through the filter fabric, roots should not pass through the waterproof membrane below the drainage layer. Roof outlets, interior gutters, and emergency overflows must be kept free from of debris and plant material in order to convey drainage properly (NYDEP 2012).

Provide vegetation-free zones such as gravel with stainless steel edging between the green roof and outlets and at the roof border with the parapet wall and for any joints where the roof is penetrated or joins with vertical structures. Vegetation free zones serve as both material separation and root barrier.

Photograph GR-4. The metal edging has perforations near the bottom to allow flow into the drain.

Photograph GR-5. Metal edging separates substrate from rock that surrounds the roof drain. It also serves to facilitate regular maintenance by limiting plant and root growth near the drain.

6. **Substrate**: The substrate serving as the growing media for green roof plants is a key component for plant health, irrigation needs, proper drainage, and stormwater benefits. The substrate is not the same thing as "soil." Most extensive green roof substrates consist primarily of expanded slate, expanded shale, expanded clay, or another lightweight aggregate such as pumice. Such lightweight aggregates have some limitations such as draining very quickly and leaving little water or nutrients available to plants. To prevent filter fabric clogging and loss of permeability, substrate should not contain more than 15% particles in the silt-size fraction, nor should it contain more than 3% in the clay-size fraction (NYDEP 2012). Substrate criteria are not explicitly defined in this Fact Sheet; see the FLL Guidelines for recommendations. Additional research is ongoing related to substrate mixes appropriate for use on extensive green roofs in Colorado. For intensive green roof applications where weight is explicitly factored into the structural design, the substrate can include materials with higher water retention characteristics such as organic matter (e.g., compost), provided the structural design accounts for the saturated load. The substrate is the most critical

element to the success of a green roof system and should therefore be purchased from reputable suppliers or specified by green roof experts.

7. **Planting Method**: In general, the planting method will be either "continuous" (planted *in situ*) or "modular" (tray approach):

   - Continuous systems are "built in place" on the roof with layers designed to work together to provide a healthy environment for plants. Examples of continuous roof approaches range from rolled sedum mats to hand-planted buffalograss plugs. Due to the variations in green roof designs, it is important to consult with a multi-disciplinary team to determine the type of roof design most appropriate for the short-term and long-term conditions expected at the site.

   - Modular systems are self-contained trays, which can vary in size, and have relatively shallow depth (2 to 8 inches deep). When modular trays are planted with groundcover and placed close together, the roof often has the appearance of a continuous system once the vegetation is established. Modular systems, without substrate or vegetation, are also used for blue roofs in some retrofit situations.

8. **Plant Selection:** While there are several species that could potentially adapt to extensive green roof systems along the Colorado Front Range, the most commonly used species are stonecrops or sedums because of desirable characteristics such as prostrate growth form, shallow root systems, and drought tolerance. Another favorable attribute of sedums is that the foliage tends to remain greener than grasses throughout the entire year, even in northern climates. However, drawbacks to a monoculture for green roofs are the same as for a monoculture in agricultural applications – risk of widespread vegetation loss if conditions (e.g., drought, disease, temperature, etc.) change from the anticipated range.

   Characteristics of plants that tend to work well on green roofs in a semi-arid climate include:

   - Self-seeding.
   - Perennial.
   - Low or compact growth format.
   - Diffuse or fibrous root system.

Considerations for Plant Selection for Colorado Green Roofs

General categories of potentially viable plants for Colorado green roofs include native, alpine (grows in shallow rocky soils), and xeric plants (e.g., sedum). Plants must meet certain criteria to optimize their chance of survival on a green roof. Due to the shallow, well-drained materials in extensive green roof systems, plants must be drought resistant. However, not all drought resistant plants are well-suited for green roofs. For example, some plants avoid drought by rooting deeply to access a more stable supply of water. Such plants are not suitable for a shallow green roof. Grasses with strong rhizome growth such as bamboo and varieties of Chinese reeds should be avoided because these have the potential to compromise the roof membrane.

- Low water use.
- Cold hardiness. For rooftops, two zones lower than the assigned U.S. Department of Agriculture (USDA) Plant Hardiness zone is recommended (e.g., Denver is in Zone 5b, so select plants suitable for Zone 3b or 4a).
- Cressulacean Acid Metabolism (CAM), which is common in sedums (stonecrops) where plant stomata are closed during the day to conserve water.

Extensive green roof plant species suggestions are provided in Table GR-1. Intensive green roof species can be as diverse as gardens at grade. Research findings from a mixed extensive and intensive green roof at Denver Botanic Gardens (Schneider et al. 2021) is a good source of information on plants to consider or avoid for green roofs.

Table GR-1. Extensive Green Roof Plans Species Suggestions

Common Name	Scientific Name	Requirements/ Conditions	Notes
Stonecrops	*Sedum* spp.	Dry, full sun, spreading	Most common genus of plants on green roofs
Buffalograss	*Buchloe dactyloides*	Full sun, spreading	Native grass
Blue grama	*Bouteloua gracilis*	Upright, spreading	Native grass
Pineleaf penstemon	*Penstemon pinifolius*	Full sun, good for pollinators	Also many other *Penstemon* relatives
Prickly pear	*Opuntia* sp.	Dry, full sun, spreading	Colorful flowers, fruit
Pussytoes	*Antennaria* spp.	Spreading	Silvery; some reseeding
Wormwood	*Artemesia* spp.	Spreading	Silvery; sage-like scent

9. **Irrigation:** Irrigation is required for successful green roofs in Colorado. Colorado State University green roof research has shown that shallow green roofs in Colorado can survive on a minimum of 5 inches of irrigation over the growing season (about ¼ inch of irrigation per week spread across 3-4 small irrigation events). The decision to use drip or overhead spray irrigation is determined based on substrate characteristics and plant needs. Overhead irrigation, particularly large droplet rotor systems, is recommended for shallow depth applications rather than drip irrigation, which may not spread laterally when applied over a rapidly draining substrate. Drip irrigation may be considered for intensive roof applications. Where drip irrigation is used, it is more efficient when installed below the vegetation layer to avoid heating of the drip line and to more effectively transfer water to the roots. When overhead spray systems are used, exposed mainline and distribution pipe should be UV-stabilized and rated for sun exposure. Additionally, winter watering is required in the relatively warm and dry winter days if precipitation has not occurred in three weeks. Typically, winter watering is done by using the irrigation system and blown out the same day (ideally with an inline air compressor) or through use of a temporary/mobile irrigation product.

10. **Site-Specific Design Considerations:** When designing a green roof, various site-specific factors must be considered. Examples include:

    - **Wind:** Select substrate and install material layers in a manner to withstand expected average and storm wind conditions, especially for taller buildings (e.g., greater than four stories). Maintaining a consistent slope throughout the green roof will prevent excessive wind scour in steeply sloped areas. When designing for wind, make sure that high wind areas at the corners of buildings are fully vegetated at the time of installation or otherwise screened for wind protection. In some cases, solar panels can serve as wind screens.

    - **Roof Microclimates**: Consider the effect of roof microclimates on the vegetation, including factors such as shading, temperature fluctuations, localized strong winds, and reflected solar radiation from surrounding buildings. Solar panels can provide partial shade to vegetation that may not perform well when exposed to full sun.

    - **Sloped Roof Applications**: Green roofs may be installed on flat, low slope, or steep roofs. For flat roofs (e.g., roof slopes less than 2%) a deeper drainage course is recommended to avoid water logging. For steep roofs (e.g., slopes greater than 30%), structural anti-shear protection will normally be needed to prevent sloughing of materials. There are many products available for substrate stabilization on slopes, which may include baffles, cells, meshes, or fabrics.

Combining solar panels with green roofs is mutually beneficial (Irga et al. 2021). Solar panels stay cooler, and vegetation receives partial shade, reducing irrigation requirements.

11. **Outlets (for Blue Roofs)**: Controlled-flow roof drains for blue roofs are designed based on a 12-hour release rate of the WQCV. Provide these design parameters to a specialized drain manufacture to design the roof drain(s) to achieve the desired release rates in place of conventional roof drains. Settings on the drains must be fixed prior to installation to prevent future modification. Flood tests should be conducted after installation of the controlled flow drains to verify that they function as intended. To prevent clogging of the drains, each orifice should be equipped with a screen or strainer that completely encloses the inlet. Attach screens to the roof with tamperproof screws or bolts (NYDEP 2012).

12. **Emergency Overflow/Bypass**: Both green and blue roof designs must include a bypass/overflow mechanism to allow rapid discharge when the storage volume of the roof system is exceeded. The overflow structure determines the maximum ponding depth for the roof.

13. **Signage**: Post signs on doors that provide access to the roof and near drainage inlets to inform building owners, maintenance staff, and others that the roof is designed for storing stormwater. Signs should indicate that several inches of water may pond after storm events

and that roof drains require specific maintenance procedures and should not be altered. Signage increases awareness of the rooftop system and is intended to prevent future modifications, which may be incompatible with the roof design (NYDEP 2012).

Construction Considerations

Success of green roofs depends not only on a good design and maintenance, but also on construction practices that enable the SCM to function as designed. Construction considerations include:

- **Load-bearing Inspection:** Before any construction for the rooftop system begins, construction of all major components of the building's structural system must be complete, and a construction inspection by a licensed professional must be conducted to verify that the building, as constructed, has the capacity to support roof loads from the rooftop system (NYDEP 2012).
- **Permit Requirements, General Coordination, and Warranties:** Investigate permitting requirements for green roofs in the local jurisdiction. Significant coordination between architects, engineers, roofers, and landscapers is needed. Contractually, it is common to have the roofer warranty the impermeable membrane, whereas the landscaper is typically responsible for the growing media, vegetation, and other landscaping. Typically, irrigation systems have warranties, but plants do not, with the exception of situations where a maintenance contract is in place. Where a maintenance contract is in place, some landscapers or greenhouses will provide plant warranties.
- **Roof Membrane:** Inspect the roof membrane (the most crucial element of both green roofs and blue roofs) and conduct a leak test prior to installing the remaining layers of the roof. Leak testing involves closing the roof drains and filling the roof with water (flood testing) to determine if there are leaks present following the membrane installation process. Flood testing requires at least 24 hours (ASTM D5957-98).
- **Plant Protection During Establishment:** Where wind scour is a concern, protect plants during establishment using fabrics (secured mesh wind blanket) or other techniques.
- **Installation Safety:** Most landscapers are accustomed to working on the ground, so safety training is important. If the green roof will be accessible to the public, safety at roof edges must be a paramount objective and are required per OSHA standards.

Additional Design Resources

Because green roofs are an emerging practice area in the Denver metropolitan area relative to other commonly used SCMs, designers should consider additional resources for green roof designs in addition to the guidance provided in this Fact Sheet. Examples include:

- **FLL Guidelines**: The FLL Guidelines are green roof standards developed by the German Research Society for Landscape Development and Landscape Design. (FLL is derived from the German title: "Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.") These guidelines include the planning, execution and upkeep of green roof sites. The 2008 edition of these widely consulted guidelines is available for purchase in English through http://www.greenrooftechnology.com/fll-green-roof-guideline.

- **ASTM Book of Standards, v. 04-12, 2005:**
  - ASTM E2396-E2777: ASTM has developed a set of standards for green roofs; however, it is important to recognize these standards were developed outside of Colorado.
  - ASTM E2396-05: Standard test method for saturated water permeability of granulated drainage media (falling-head method) for green roof systems.
  - ASTM E2398-05: Standard test method for water capture and media retention of geocomposite drain layers for green roof systems.
  - ASTM E2397-05: Standard practice for determination of dead loads and live loads associated with green roof systems.
  - ASTN E2777-20: Standard guide for vegetative (green) roof systems.
- **BOCA Codes**, International Code Council (ICC): Building Officials and Code Administrators International Inc. (BOCA), now known as the International Code Council (ICC), publish codes that establish minimum performance requirements for all aspects of the construction industry. BOCA codes at the Library of Congress are located in the Law Library Reading Room. Some state codes are available at no cost through the eCodes sections of the ICC Website, while others must be purchased http://www.iccsafe.org/.
- **Various Green Building and Sustainable Infrastructure Programs:** Over the past few decades, a variety of green building and sustainable infrastructure programs have emerged that provide credit for green roofs and rooftop stormwater management systems. Credit may be available in areas such as runoff reduction, stormwater treatment, reduced heat island effects, and energy efficiency.
- **City and County of Denver Green Building Ordinance**: The City and County of Denver City Council passed a Green Building Ordinance in October 2018 after a public vote in 2017. Green roofs are one of the options for compliance for 5+ story commercial and residential buildings larger than 25,000 square feet indoors: https://www.denvergov.org/content/denvergov/en/denver-development-services/commercial-projects/green-roof-initiative.html
- **Green Roofs for Healthy Cities:** Green Roofs for Healthy Cities website (www.greenroofs.org) provides a variety of resources related to green roof design. Green Roofs for Healthy Cities - North America Inc. is a non-profit 501(c)(6) professional industry association. Their mission is to develop and protect the green roof market by increasing the awareness of the economic, social, and environmental benefits of green roofs, green walls, and other forms of living architecture through education, advocacy, professional development, and celebrations of excellence.
- **New York City Guidelines for the Design and Construction of Stormwater Management Systems:** This guidance provides detailed design, construction and maintenance information on both green and blue roofs, as well as combining rooftop systems with other

treatment systems. Although climate and vegetation recommendations in New York differ from Colorado, the remainder of the guidelines may be useful for designers in Colorado.

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T-3 Bioretention Systems

Figure BR-1. Bioretention System Components

Description

Bioretention systems are vegetated, engineered, depressed landscape areas designed to capture and filter and/or infiltrate the water quality capture volume (WQCV). Engineered media and vegetation facilitate filtration, adsorption, absorption, and biological processes that retain stormwater pollutants and enhance infiltration capabilities. The terms porous landscape detention (PLD), rain garden, and bioretention are often used interchangeably in the MHFD region. The term rain garden is sometimes used to describe smaller engineered bioretention systems or non-engineered installations and when describing this SCM to the public. Bioretention can be configured in several ways in urban areas and may be described as streetside planters, curbside bioretention, bump-out stormwater

MS4 Permit Applicability (Dependent on design and level of treatment)	
Meets Runoff Reduction Standard	Potential
Meets WQCV Capture Standard	Yes
Meets Pollutant Removal Standard	Yes
Typical Effectiveness for Targeted Pollutants	
Sediment/Solids	High
Total Phosphorus	Low to Medium[1]
Total Nitrogen	Low to Medium[1]
Total Metals	High
Bacteria	Medium
Common Applications	
Runoff Reduction (General)	Yes
Used for Pretreatment	No
Integrated with Flood Control	Yes
Cost	
Life-Cycle Costs	Medium
[1]Concentration reduction is typically low, but load reduction can be significant due to volume reduction.	

planters. Ultra-urban adaptations of bioretention can also include tree trenches and tree pits (although not described in this fact sheet). Local jurisdictions may have additional or different requirements for various types of bioretention systems.

MHFD strongly encourages use of bioretention as a stormwater control measure (SCM) because properly designed, constructed and maintained bioretention systems provide effective stormwater treatment, reduce runoff volume and erosive flow rates, and provide community connection benefits and green space in the urban environment.

Bioretention areas can be designed to provide detention for events exceeding the WQCV by incorporating storage of the Excess Urban Runoff Volume (EURV) and 100-year detention storage volumes above the WQCV, with drain times and release rates in accordance with the *Storage* chapter.

Photograph BR-1. This bioretention area treats runoff from the roof and lot, while serving as an aesthetically pleasing landscape feature. Photo: Wright Water Engineers.

Component	Intent
Inlet	Allows stormwater to enter the SCM.
Forebay	Facilitates removal of trash and coarse sediments, providing pretreatment for the SCM. (Other pretreatment may also be beneficial in a treatment train prior to flows entering the SCM.)
Energy Dissipation	Minimizes potential for erosion of media surface.
Storage Volume	WQCV or additional flood storage volume provided above the media to ensure capture of the design volume. Also referred to as surface storage or "storage bowl."
Engineered Media	Supports plant growth and reduces pollutants by filtering and through other biological treatment processes.
Vegetation	Helps maintain infiltration over time through root penetration of media, increases evapotranspiration and biological uptake of pollutants, aerates media, catalyzes soil ecology, and creates an attractive SCM.
Underdrain with Orifice Release	Collects and slowly releases the WQCV over 12 hours to reduce erosion in the receiving stream and enhance treatment by increasing contact time with the media.
Outlet Structure	Safely conveys stormwater flows that exceed the design volume. For bioretention systems that detain the EURV and/or 100-year flow, surface outlet structures will have additional orifice controls for surface discharge rather than infiltration through the media.

SCM Components

The primary components of bioretention include inlet(s), energy dissipation and forebay(s), a surcharge volume, engineered media, vegetation, an underdrain (for no- or partial-infiltration designs), and an outlet structure (Figure BR-1). The primary outflow for the WQCV is typically an underdrain or infiltration into the underlying soil. When bioretention is designed to provide full spectrum detention, design the outlet to release the EURV and 100-year volumes in accordance with the EURV drain time and 100-year release rates. Even if the bioretention system is only designed to treat the WQCV, an emergency overflow (outlet or spillway) is necessary to safely convey flows from larger events.

Photograph BR-2. Bioretention system treating urban stormwater during runoff event. Photo: Wright Water Engineers.

See Section 3.0 *Site Assessment* and Section 4.0 *Filtration and Infiltration Systems* of this chapter for guidance and criteria on determining the appropriate type of bioretention system and designing underdrain and liner systems as needed based on site-specific conditions. Section 5.0 *SCM Inflow Features* and Section 6.0 *SCM Outflow Features* of this chapter provide guidance on creative ways to drain runoff into the SCM and release the treated runoff.

Bioretention media sourcing and composition, component design, and associated specifications must be followed and checked closely in the field during installation to prevent failures and/or frequent maintenance requirements. The engineered media and vegetation are the core water quality treatment elements of bioretention. The media must balance good infiltration capabilities with properties needed to support vegetation. MHFD has conducted significant testing of different mixes for bioretention media to develop the recommended specifications in this fact sheet. Additionally, national research has included media amendments targeting specific pollutants (Tirpak et al. 2021, Pitt and Clark 2010, Clark and Pitt 2012, Erickson et al. 2012 & 2021, Hunt et al. 2012, Chandrasena 2014, Mohanty and Boehm 2015, O'Neil and Davis 2012a&b, Mohanty et al. 2018, Hinman 2021, among many others). This fact sheet focuses on a basic engineered media design suitable for broad use in the MHFD jurisdiction, but does not preclude consideration of media amendments designed to target specific pollutants, provided that they maintain the intended functions of MHFD's media.

Other bioretention design variations in the underdrain configuration, such as use of an upturned underdrain elbow to create an internal water storage zone (Brown et al. 2009) to reduce nitrogen, are discussed further in Section 4.3.3 of this chapter.

Site Considerations

Bioretention is an excellent choice for small sites because it treats the WQCV and serves as a landscape feature. It is typically a much better choice for small sites than an extended detention basin (EDB) because EDBs treating small drainage areas have outlet structures with small orifices that are prone to clogging. Bioretention can also be incorporated into larger sites and can be designed to provide full spectrum detention.

Bioretention systems typically are installed in locations such as:

- Plazas
- Parks
- Parking lot islands
- Street medians
- Landscape areas between the road and a detached walk
- Planter boxes that collect roof drain flows.

To avoid clogging of media, bioretention requires a stable watershed. When the watershed includes phased construction, sparsely vegetated areas, or steep slopes, consider another SCM that is less susceptible to clogging or provide pretreatment to facilitate sedimentation before runoff from these areas reaches the bioretention media surface. Additionally, bioretention is intended to dry out between runoff events; therefore, it should not be used when a baseflow is anticipated.

Benefits

- When designed and constructed correctly, routine maintenance is relatively straight-forward and consists of removing sediment and debris from the forebay and vegetation management.
- Bioretention incorporates multiple treatment processes including sedimentation, filtering, adsorption, evapotranspiration, and biological uptake of constituents.
- Stormwater treatment occurs within attractive landscaped areas and decreases urban heat island effects.
- Bioretention can be integrated into space-constrained urban areas in a variety of shapes and sizes such as a series of linear curbside planters or as larger landscape features.
- Avoids problems with clogging of small orifices common with extended detention basins on small sites.

Limitations

- Vegetation requires proper and sometimes specialized management.
- Requires additional steps when placement is near or upgradient from a building foundation and/or when expansive soils exist.
- In a developing or otherwise erosive watershed, high sediment loads can clog the bioretention system.
- Trash and sediment can clog inlets along roadways causing bypass of flows, if not regularly maintained. Additional measures may be needed in high-use areas to manage trash.

The surface of the bioretention media should be flat or at a mild slope. For this reason, bioretention can be more difficult to incorporate into steeply sloping terrain; however, terracing can be used to create flat areas suitable for bioretention even with sloped topography.

Photograph BR-3. Terraced bioretention SCM in recreation center parking lot. Photo: MHFD.

When bioretention areas are located adjacent to structures or infrastructure that could be adversely affected by infiltrating runoff or in areas with expansive soils, consult with a geotechnical engineer. A geotechnical engineer can evaluate the suitability of soils, identify potential impacts, and establish minimum distances or other physical barriers to implement between the bioretention system and structures. See Section 3.0 *Site Assessment* and Section 4.0 *Filtration and Infiltration Systems* for guidance and criteria on geotechnical considerations and testing requirements, underdrain and filter layers, perimeter barriers, and other aspects common to infiltration-based SCMs including bioretention.

Community Values

Bioretention provides opportunities to provide a high level of treatment for stormwater while also creating landscape features that add value to a site by enhancing the landscape aesthetics and experience. Bioretention areas that are an integral part of the site's landscape provide far more benefits than areas dedicated solely to stormwater treatment, such as small EDBs, because bioretention areas are multifunctional and can serve other purposes including meeting landscape area requirements, providing attractive pockets of interesting plants, aesthetic screening of parking lots, and others.

It is important to establish pre-design planning objectives to facilitate a successful design. At an early stage, determine the aesthetic design approach that best meets the overall project objectives. There are many opportunities for creativity in grading, plant selection, and design of inflow and outflow features for bioretention. Design approaches typically endeavor either to integrate the SCM into its surroundings with a "contextual design," or consciously contrast with the surroundings to highlight the SCM as a "stand-alone element," providing a counterpoint to the context of the site.

In a contextual design, the design responds to and builds on the character of the surroundings. Forms and shapes are related to and harmonious with surrounding structures and site improvements and fit into their environment through use of similar or complementary materials, scale, and design detailing. Materials used in this approach may directly reflect materials used in the surrounding architectural and engineering improvements. Coordinate design details for the bioretention area, such as concrete or stone edgers and retaining walls, with the surrounding site improvements to provide a unifying effect with the surroundings.

Plant materials should also relate to surrounding landscape in overall character, massing, and degree of formal or naturalistic arrangement, while selecting drought-tolerant plants that will also thrive in the periodically wet environment.

A "stand-alone" or counterpoint design aims to create a feature that contrasts with its surroundings through uses of form, scale, materials, color, and other features. A counterpoint design can create a strong dramatic effect, but to be successful, it must be done in a way that creates an overall balanced site design.

Of these two approaches, contextual design is more common and is generally easier to accomplish. With either approach, the emphasis should be on creating a feature that adds value to the site while effectively treating the WQCV. Maintenance is critical for ensuring long-term function of bioretention and community acceptance, so planning for maintenance and selecting plants that are suitable for the hydrologic conditions in the SCM are important design aspects to avoid burdensome maintenance.

Appropriate plant selection enhances the community value of bioretention systems. Considerations for plant selection from a community-values perspective include:

- Select plants that thrive and perform over the long-term without excessive maintenance. For bioretention to be accepted by the community, it should be attractive (Davis, Traver and Hunt 2022), which requires healthy plants and routine maintenance.
- Select plants appropriate for the site's unique micro-climatic conditions and bioretention design features, construction techniques, and expected maintenance levels of service. Microclimate, including solar aspect, exposure to wind, and shading or sun reflections from adjacent buildings, can have a significant effect on the conditions that plants must tolerate. Visiting the site during different times of the day in summer months prior to design is very informative for understanding sun and shading as well as urban heat island effects.
- Small trees can provide significant added value to bioretention areas, including runoff reduction and mitigation of urban heat island effects. When considering trees for bioretention systems, assess the compatibility of different species with the hydrologic, soil, and solar aspect of the SCM. Healthy trees also require adequate above and belowground space (Davis et al. 2021). (See additional considerations for trees in the Design section of this fact sheet.)
- Use natives plant species when feasible. Native species tend to tolerate the region's hot summers and cold winters better than most non-natives. Native grasses have deep roots that can reach residual moisture in the bioretention media during times of drought.
- Select plants that are drought tolerant but that can also tolerate prolonged periods of inundation or media saturation, particularly during sequential storms.
- Consider planting vegetation in groupings or masses of single or similar species. Generally, large masses of plants grouped relatively close together create dense stands of vegetation that grow together to out-compete weed growth, while enhancing infiltration through root penetration that creates macropores as roots die and decay.

Maintenance

Routine maintenance of bioretention is similar to landscape maintenance, consisting of trash and sediment removal from the forebay and care for vegetation. Chapter 6 of this manual provides recommended maintenance practices for all SCMs. During design, consider the following during design to ensure ease of maintenance over the long-term:

- Consider how the SCM will be accessed for routine and restorative maintenance, what equipment will be required, and how routine maintenance activities can be performed in a way that minimizes impacts to vegetation.
- Understand the level of maintenance that will be needed over the long term. Bioretention features designed as aesthetic amenities in public areas may require more frequent maintenance than those with more naturalized designs in suburban settings. Do not select plantings that require frequent maintenance if the owner does not have the resources to perform such maintenance. Poorly maintained bioretention areas can become weedy eye sores that contribute to poor public acceptance.
- Make the bioretention surface area (bowl) as shallow as needed. Increasing the depth unnecessarily can create erosive side slopes and complicate maintenance. Shallow bioretention areas are also more attractive.
- The best surface cover for bioretention is full vegetation, in part because it reduces weeding and various mulch-related maintenance issues. Use rock mulch sparingly because it limits infiltration, is more difficult to maintain and can also increase urban heat island effects. Wood mulch handles sediment build-up better than rock mulch; however, wood mulch floats and can settle unevenly or clog the overflow depending on the configuration of the outlet. Some municipalities may not allow wood mulch for this reason. When specifying mulch, look for shredded varieties. Also, increase density of grasses at the interface of the forebay and vegetation to slow flows entering the basin.
- Provide pretreatment when it will reduce the extent and frequency of maintenance necessary to maintain function over the life of the SCM. Provide a forebay for any concentrated inflows. For small inflows, the forebay may consist of a pad for sediment accumulation and removal surrounded by grasses to help keep sediment from migrating onto the filter area.
- Note that research shows that deicers can cause reduced infiltration rates in media and soils with clay content (Sileshi, Pitt and Clark 2017). Understand the composition of the media and the underlying soils in this respect and develop the planting plan accordingly. Deicers in runoff can stress vegetation, which may result in increased maintenance and vegetation replacement requirements. Conifers are particularly sensitive to salt.
- Establishing healthy vegetation is critical for this SCM to properly function. Design and adjust the irrigation system (temporary or permanent) to provide appropriate water for the establishment and maintenance of selected vegetation.

- Consider maintenance access and requirements for tree pruning and frequency of raking, if trees are included in bioretention systems. Do not operate heavy equipment on the media surface (e.g., cherry picker lifts) for tree pruning.
- Do not put a filter sock on the underdrain. This is not necessary and can cause the underdrain to clog.
- Never use bioretention systems for snow storage. Designate a location for snow storage elsewhere.

Design Procedures and Criteria

Criteria and guidance for bioretention components including inlets, forebays, underdrains, liners, and outlets are provided in the front section of this chapter. Reference this section for design of these specific features.

The MHFD-BMP workbook, available at www.mhfd.org, is an Excel-based workbook that steps through the criteria listed below and performs design calculations for bioretention. Use this workbook to ensure designs meet criteria for treating the WQCV. Use a separate tool, MHFD-Detention, to develop and route storm hydrographs for a range of events through bioretention systems.

The following steps outline the design procedures and criteria for designing bioretention for water quality:

1. **Subsurface Exploration and Determination of a Full Infiltration, Partial Infiltration or No-Infiltration Section.** See Section 3.0 *Site Assessment* and Section 4.0 *Filtration and Infiltration Systems* of this chapter to determine the most appropriate type of filtration and/or infiltration system for the bioretention area based on site conditions.
2. **Inlet Design and Pretreatment.** See Section 5.0 *SCM Inflow Features* of this chapter for guidance and criteria for inlets, energy dissipation, and forebays. Provide pretreatment with a properly designed forebay or other device designed to remove coarse sediment, trash, and debris. Pretreatment of roadway runoff to remove sediment is especially critical for bioretention systems receiving roadway runoff.

   While not always feasible, if inlets to the SCM can be designed to enter the SCM above the WQCV elevation, this will reduce maintenance requirements for the inflow pipes related to sediment deposition due to backwater conditions.
3. **Design Storage Volume**: Provide a storage volume equal to the WQCV[1] based on a 12-hour drain time, after accounting for runoff-reduction SCMs in the contributing watershed. Determine the required WQCV (watershed inches of runoff) using Equation 3-2 of Chapter 3 of this manual (for WQCV). Always size SCMs based on their tributary

[1] MHFD's standard design procedure is based on treatment of the WQCV, which corresponds to the Colorado's MS4 WQCV design standard. In some cases, bioretention systems may be designed to meet a volume reduction target, particularly where underlying soils allow for infiltration. In this case, conduct site-specific analysis to determine whether the volume reduction target can be met for site conditions.

area. When sizing the basin for EURV or larger detention volumes, see the *Storage* chapter of Volume 2. Where needed to meet the required volume, also consider the available void storage capacity of the media at 15 percent.

4. **Bioretention System Basin Geometry:** Basin geometry considerations include surface area, filter surface slopes and ponding depth.

   - **Media Surface Area:** Equation BR-1 provides a minimum media surface area for the WQCV allowing for some of the volume to be stored beyond the flat area of the media (i.e., above the side slopes of the bioretention basin). Additional surface area beyond this minimum may be necessary to meet the maximum recommended ponding depth.

     $$A_F = 0.02 \cdot A \cdot I$$ Equation BR-1

     Where:

     A_F = minimum filter area (ft^2)

     A = area tributary to the SCM (ft^2)

     I = imperviousness of tributary area draining to the SCM (percent expressed as a decimal)

     Use vertical walls or slope the sides of the basin to achieve the required volume. Side slopes should be no steeper than 4:1.

   - **Ponding Depths:** Maximum ponding depths vary depending on the bioretention design, with a maximum recommended WQCV ponding depth of 12 inches stored above the surface to minimize stress to vegetation for frequent inundation and to manage the hydraulic loading. When the bioretention basin is designed for the WQCV only, locate the overflow spillway crest at or above the elevation associated with the maximum ponding depth for the WQCV measured vertically from the flat filter media surface.

   - **Media Surface Slopes:** The media surface of the bioretention area typically should be flat. The exception to this is when a mild slope (e.g., < 1%) from the inlet to the outlet will help distribute runoff to the vegetation and reduce sediment deposited at the inlet. Linear systems, such as streetside stormwater planters, may benefit from a mild slope from inlet to outlet. When the flow path is long, consider level grade beams to maintain sheet flow. The intent is to fully use the filter area to avoid higher sediment deposition in lower areas of the basin.

5. **Underdrain System, Impermeable Liner, and Geotextile Separator Fabric:** See Section 4.0 *Filtration and Infiltration Systems* of this chapter for guidance and criteria based on the type of filtration and infiltration system selected. Underdrain systems in bioretention basins consist of a slotted PVC pipe placed within a layer of drain gravel beneath the bioretention media. A 6-inch layer of sand is also specified above the drain gravel in Section 4.0. Research (Herrera 2020) indicates that a sand layer below the media can serve as a polishing layer for the effluent.

6. **Bioretention Media:** Provide a minimum of 18 inches of bioretention media to enable establishment of the roots of the vegetation. If trees are planted, increase the media depth to 36 inches.

   MHFD's bioretention media is intended to balance high infiltration capacity with properties needed to support healthy vegetation. Table BR-1 outlines recommended parameters for bioretention media. MHFD's media recommendation begins with topsoil that can be amended as needed, typically with sand, until it meets the specifications in Table BR-1. See Availability of Bioretention Media in the MHFD Region (MHFD 2022) for more information. It is important that the media contain organic material with living soil organisms such as earthworms, bacteria, and fungi to enhance agronomic and infiltration properties and create a healthy, living media. Do not add compost to the bioretention media; instead, other forms of organic matter such as mulch, peat or woodchips should be used if needed because they have lower nitrogen and phosphorus content and are more resistant to microbial degradation (Davis, Hunt and Traver 2022).

   The media texture in Table BR-1 has a slightly higher proportion of silts and clays and a lower sand percentage compared to prior MHFD media specifications. The purpose of this change is to increase moisture and nutrient holding capacity to aid in the establishment of a dense vegetation cover, which ultimately helps to sustain infiltration capacity.

   A high level of quality control for the media is critical. Quality control measures include reviewing media particle size distribution data, media chemistry data, and results of nutrient analysis to ensure that the media meets specifications. The media can either be sampled after delivery and prior to placement, or sampled by the supplier just prior to site delivery. In any case, the samples should be collected within several days of placement of the media so that the results are representative of the media placed.

Table BR-1. Bioretention Media Properties

Parameter Classification	Parameter No.	Soil Parameter	Test Name	Bioretention Media Properties
Texture/Gradation				
	1	Texture/Gradation	Particle sizes based on the USDA soil classification system. Silt and clay percent by dry weight (ASTM D7928)	Particle Size Distribution: 70-80% Sand (0.05-2.0 mm diameter) 5-25% Silt (0.002-0.5 mm diameter) 5-15% Clay (<0.002 mm diameter) *(distribution is measured after gravel > 2 mm is removed from sample)*[2]
	2			
Organic Matter Content				
	3	Organic Matter	ASTM D2974	1-5% by dry weight
Salts/Sodium				
	4	Salinity/Salts (EC) dS/m or mmhos/cm	Saturated Paste	<3
	5	Sodium Adsorption Ratio (SAR)	USDA 60 6(20b)	<8
Soil pH				
	6	pH	ASA/AASHTO	6.0 - 8.5
Nutrients				
	7	Calcium Carbonate ($CaCO_3$)/Lime	Calcium Carbonate Equivalent (USDA 60 6(23c))	<2%
	8	Nitrate Nitrogen (ppm)	ASA2 33-3	<30
	9	Phosphorus (ppm)	Olson P when pH>6.2, otherwise Mehlich-3	<30
	10	Potassium (ppm)	Ammonium bicarbonate-DTPA test	>60
	11	Copper (ppm)		<1.0
	12	Zinc (ppm)		<3.0

7. **Vegetation:** The media must be vegetated. MHFD recommends drought-tolerant species that thrive in sandy soils. Approaches to vegetating bioretention areas can include planting sod-forming native grasses from seed, installing sand-grown sod, and/or planting container-grown plants or small trees. Consult with a vegetation specialist to understand which types of vegetation will be successful in a given location,

[2] Prior to particle size distribution analysis, gravel (> 2 mm diameter) is sieved from the sample. Bioretention media should have no more than 10% gravel.

considering shade, heat island effects, application of deicers in the watershed, and other site-specific factors. Recommendations for vegetation established from seed, planted in containers or plugs, and trees follow. While establishment from seed typically costs less than container-grown plants, container-grown plants establish more quickly and are less susceptible to being washed away during establishment. A mixture of container-grown plants and seed may help with initial vegetation cover and media stabilization.

Vegetation Establishment and Infiltration Rates

During vegetation establishment, water applied to bare media can mobilize and rearrange fine silt and clay particles on the surface to create a lower permeability layer. For this reason, vegetation is a critical component in maintaining infiltration in the bioretention system over time. When establishing vegetation from seed, install seed and blanket immediately after media is placed to reduce the mobilization of fines and facilitate germination of the seed.

Table BR-2 provides a suggested seed mix for sites that typically will not need to be irrigated after the grass has been established, except for periods of extended drought. Guidelines for establishing vegetation from seed include:

- Mix seed well and broadcast, followed by hand raking to cover seed and then apply mulch.
- Immediately after seeding, install a biodegradable 100-percent coconut erosion control blanket over the media to keep seed and media in place during runoff and irrigation events during establishment.
- Consider seasonality when planting to ensure establishment. Both frequent storms and extended hot, dry periods can affect seed establishment.
- Do not place seed when standing water or snow is present or if the ground is frozen.
- Weed control is critical in the first two to three years, especially when starting with seed.

When using sod, specify sand-grown sod which is available in Colorado, although not as common as conventional sod. Do not use conventional sod. Conventional sod is grown in clay soil that can seal the filter area, greatly reducing overall function of the SCM. Be aware that local jurisdictions may restrict use of turf varieties with high irrigation requirements (e.g., Kentucky bluegrass) and may require native grasses for water conservation reasons.

When selecting a container-grown plant palette, consider water needs, exposure (sun/shade), plant height and spread, recommended container sizes, plant spacing and future maintenance requirements. Common container-grown plants or plugs suitable for bioretention systems in urban areas are listed in Table BR-3 (City and County of Denver 2016). Other drought-tolerant plants may also be considered.

When using an impermeable liner, select plants with diffuse (or fibrous) root systems, not taproots. Taproots can damage the liner and/or underdrain pipe.

Table BR-2. Native Seed Mix for Bioretention

Common Name	Scientific Name	Variety	Pure Live Seed (PLS)	
			pounds/acre	ounces/acre
Sand bluestem	*Andropogon hallii*	Garden	3.5	
Sideoats grama	*Bouteloua curtipendula*	Butte	3	
Prairie sandreed	*Calamovilfa longifolia*	Goshen	3	
Indian ricegrass	*Oryzopsis hymenoides*	Paloma	3	
Switchgrass	*Panicum virgatum*	Blackwell	4	
Western wheatgrass	*Pascopyrum smithii*	Ariba	3	
Little bluestem	*Schizachyrium scoparium*	Patura	3	
Alkali sacaton	*Sporobolus airoides*		3	
Sand dropseed	*Sporobolus cryptandrus*		3	
Pasture sage[1]	*Artemisia frigida*			2
Blue aster[1]	*Aster laevis*			4
Blanket flower[1]	*Gaillardia aristata*			8
Prairie coneflower[1]	*Ratibida columnifera*			4
Purple Prairie Clover[1]	*Dalea (Petalostemum) purpurea*			4
Sub-Totals:			27.5	22
Total pounds per acre:			**28.9**	

[1] Wildflower seed (optional) for a more diverse and natural look.

Table BR-3. Container-grown Plants and Plugs for Bioretention
(Source: City and County of Denver 2016)

Common Name	Scientific Name
Grasses	
Dancing Wind Big Bluestem	*Andropogon gerardii* 'Dancing Wind'
Windwalker Big Bluestem	Winter *Andropogon gerardii* 'P003S'
Feather Reed Grass	Winter *Calamagrostis x acutiflora* 'Karl Forester'
Tufted Hair Grass	*Deschampsia caespitosa*
Blonde Ambition Grama Grass	*Bouteloua gracilis* 'Blonde Ambition'
Hot Rod Switchgrass	*Panicum virgatum* 'Hot Rod'
Northwind Switchgrass	*Panicum virgatum* 'Northwind'
Prairie Sky	*Panicum virgatum* 'Prairie Sky'
Prairie Blues Little Bluestem	*Schizachirium scoparium* 'Prairie Blues'
Undaunted Ruby Muhly	*Muhlenbergia reverchoni* 'Undaunted'
Prairie dropseed	*Sporobolus heterolepis*
Herbaceous Perennials	
Pearly Everlasting	*Anaphalis margaritacea*
Prairie Bluebell	*Mertensia lanceolata*
Dakota Sunshine Sunflower	*Helianthus maximiliani* 'Dakota Sunshine'
Western Blue Flag Iris	*Iris missouriensis*
Rocky Mountain Gayfeather	*Liatris ligulistylis*
Wild Bergamont	*Monarda fistulosa*
Eastern Bergamont	*Monarda bradburiana*
Evening Primrose	*Oenothera fruticose* 'Fireworks' / Fyrveckeri
Husker Red Penstamon	*Penstemon digitalis* 'Husker Red'
Garden Phlox	*Phlox paniculate* 'Blue Paradise'
Border Phlox	*Phlox paniculate* 'David'
Prairie coneflower	*Ratibida pinnata*
Bluebird smooth aster	*Symphiotrichum laeve* 'Bluebird' smooth aster
Bulbs	
Blue Danube Wild Hyacinth	*Camassia leichtlinii* 'Blue Danube'
Shrubs	
Leadplant	*Amorpha canescens*
Prairie Snow White Cinquefoil	*Dasiphora* (Potentilla) *fruticosa* var. *dahurica* 'Prairie Snow'
Apache Plume	*Fallugia paradoxa*
Pawnee Buttes Sand Cherry	*Prunus besseyi* 'Pawnee Buttes'
Autumn Amber Skunkbush Sumac	*Rhus trilobata* 'Autumn Amber'
Glow Girl Spirea	*Spirea betulufolia* 'Tor Gold'

Small trees may be considered in bioretention areas, provided that adequate media, irrigation, and space are available. Trees are generally better suited for larger bioretention areas. Recommendations for planting trees in bioretention areas include:

- Do not install trees in bioretention systems with an impermeable liner.
- Provide irrigation for trees.
- Consider planting trees on side slopes, above the more frequently inundated areas.
- Select trees that can withstand periods of inundation.
- Avoid conifers in areas exposed to deicing chemicals.
- Provide access for tree maintenance, which may include pruning, removal of bioretention media removal and replacement, tree removal and replacement, and incidental removal of other vegetation.
- Install trees at least 5 feet away from inlets, outlets, and underdrains because tree roots may obstruct inlets and outlets or damage the underdrain. Consider limiting the length of the underdrain to allow for placement of trees where desired.
- For deciduous trees, plan for additional seasonal maintenance to remove leaf litter and avoid media clogging.
- Avoid trees with fruit litter.
- Select shade-tolerant species for tree understory plants.
- When considering trees for bioretention systems located in easements, check local requirements regarding allowed vegetation types and replacement requirements.
- Be aware that some jurisdictions may not allow trees in bioretention.
- See Denver's Ultra-Urban Guidelines (Denver 2016) for tree pit/trench bioretention variations.

8. **Irrigation:** Irrigation is required for vegetation establishment, for supplemental water during extended dry periods, and may be needed on a routine basis depending on plant selection. During establishment, all plants should receive approximately 1 inch of moisture (combined rain and irrigation) per week for the first growing season to promote establishment. Some plants may require more than one growing season to become fully established. Providing a permanent irrigation system at the time of SCM installation provides greater flexibility in plant selection and aesthetics, even if regular irrigation is not routinely required after plant establishment.

   Install spray irrigation at or above the WQCV elevation when permanent irrigation is provided or place temporary irrigation on top of the bioretention media surface. Do not place sprinkler heads on the flat media surface. Remove temporary irrigation pipes that are laid on the surface once vegetation is established. If left in place, temporary irrigation will become buried over time and will be damaged during maintenance operations.

Adjust irrigation schedules during the growing season to provide the minimum amount of water necessary to maintain plant health, while maintaining free pore space for infiltration.

9. **Outlet:** Drain the underdrain to the outlet structure and use an orifice plate to drain the WQCV over approximately 12 hours. Section 6.0 *SCM Outflow Features* of this chapter includes conceptual details for the underdrain and orifice outlet to release the WQCV as well as conceptual details for outlets that incorporate detention of larger events via full spectrum detention. When designing for EURV and/or 100-year attenuation, flows greater than the WQCV are controlled and released at the outlet structure, rather than forced through the filter area of the bioretention basin. Provide a spillway for larger events that will convey overflows to the receiving drainage system without adversely affecting adjacent structures or infrastructure. The MHFD-Detention workbook performs calculations for outlet sizing, including the orifice control for the underdrain and outlet controls for larger runoff events.

Construction Considerations

Proper construction of bioretention areas involves careful attention to material specifications, final grades, and construction details. For a successful project, implement the following practices:

- Protect the bioretention area from excessive sediment loading during construction. This is the most common cause of clogging of bioretention systems. The portion of the site draining to the SCM must be stabilized before allowing flow into the bioretention area. This includes completion of paving operations.
- Avoid over-compaction of the bioretention area to preserve infiltration rates (for partial and full infiltration sections).
- Provide construction observation to ensure compliance with design specifications. It is important to avoid improper installation, particularly related to elevations of the inlet, underdrain and outlet. Observation/oversight is recommended for the following:
  - Conformance of subgrade with design assumptions.
  - Installation of impermeable liner (for no infiltration sections).
  - Construction of underdrain and installation of media layer.
  - Review of bioretention media test data to verify conformance with specifications prior to installation.
- Provide adequate construction staking to ensure that the site properly drains into the SCM, particularly with respect to surface drainage away from adjacent buildings.

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T-4 Sand Filters

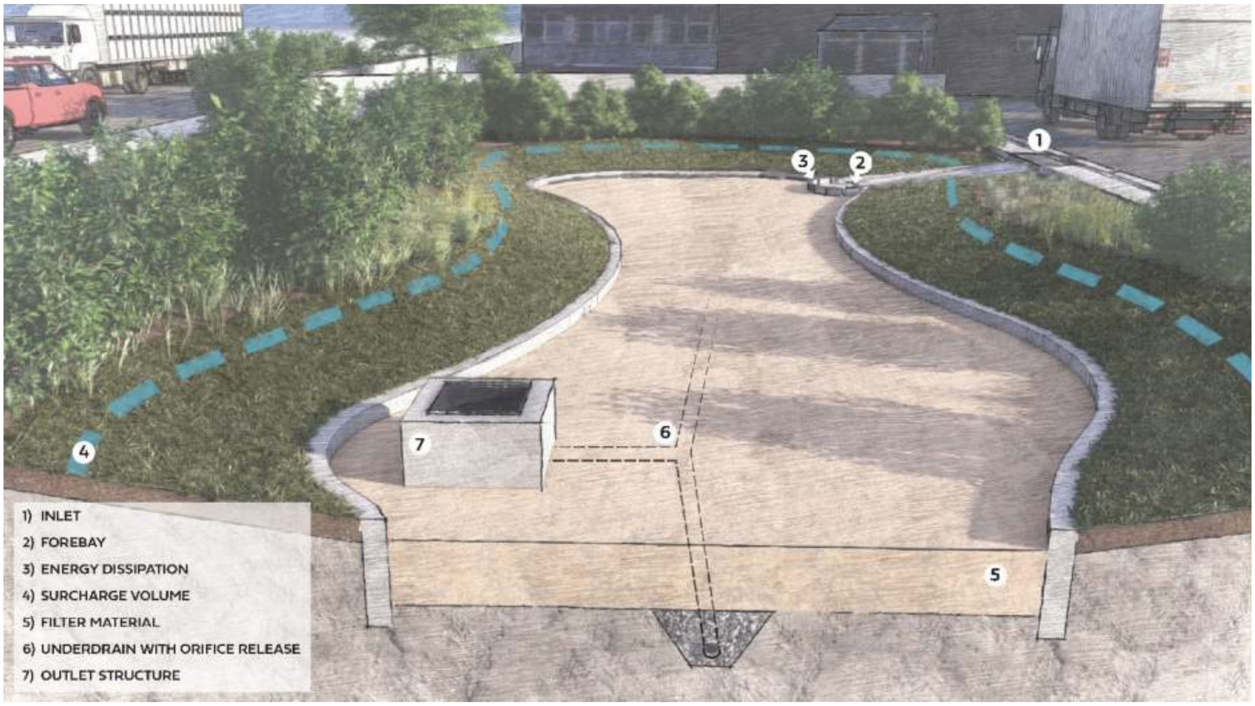

Figure SF-1. Sand Filter Components

Description

A sand filter treats runoff by filtration and also provides infiltration when unlined systems are used. A sand filter consists of a surcharge zone underlain by a sand bed, often with an underdrain system (Urbonas 1999). During a storm, runoff collects in the surcharge zone and gradually infiltrates into the underlying sand bed, filling the void spaces of the sand. The underdrain gradually releases the runoff that is filtered through the sand bed and discharges the runoff to a nearby channel, swale, or storm drain. When suitable based on site conditions, a partial or full infiltration section can be used to infiltrate some or all of the runoff from the water quality design event.

MS4 Permit Applicability (Dependent on design and level of treatment)	
Meets Runoff Reduction Standard	Potential
Meets WQCV Capture Standard	Yes
Meets Pollutant Removal Standard	Yes
Typical Effectiveness for Targeted Pollutants	
Sediment/Solids	High
Total Phosphorus	Medium
Total Nitrogen	Low
Total Metals	High
Bacteria	Medium
Common Applications	
Runoff Reduction (General)	No
Used for Pretreatment	No
Integrated with Flood Control	Yes
Cost	
Life-Cycle Costs	Medium

Photograph SF-1. This sand filter, constructed on two sides of a parking garage, is accessible for maintenance, yet screened from public view by a landscape buffer.

A sand filter is similar to bioretention in terms of filtration and infiltration treatment mechanisms but differs in that it is not specifically designed for vegetative growth. The absence of vegetation in a sand filter allows for active maintenance of the surface of the filter (i.e., raking to loosen the surface layer or to remove accumulated sediments). For this reason, sand filter criteria allow for a larger contributing area and greater depth of storage than bioretention but will also require more frequent maintenance at the surface of the filter to ensure adequate infiltration. A sand filter can be designed to include the Excess Urban Runoff Volume (EURV) and 100-year flood storage volume, released through a surface-release outlet structure. Sand filters can be placed in a vault for subsurface applications. However, these types of installations are more difficult to inspect and maintain and should only be used if surface treatment is infeasible.

SCM Components

The primary components of a sand filter include inlet(s), energy dissipation and forebay(s), the surcharge volume, filter material, an underdrain (for no- and partial-infiltration sections), and an outlet structure (Figure SF-1). The primary outlet for the Water Quality Capture Volume (WQCV) is typically an underdrain or infiltration into the underlying soil. Surface outlet structures are provided to convey flows that exceed the WQCV design volume and for facilities designed to manage the EURV and 100-year design events.

Component	Intent
Inlet	Allows stormwater to enter the SCM.
Forebay	Facilitates removal of trash and coarse sediments.
Energy Dissipation	Minimizes potential for erosion of sand filter surface. Often incorporated into forebay.
Surcharge Volume	Provides temporary storage volume needed for attenuation of design flows.
Filter Material	Removes pollutants in runoff by filtration through porous media (sand).
Underdrain with Orifice Release	Collects and slowly releases the WQCV over 12 hours to reduce erosion in the receiving stream and enhance treatment by increasing contact time with the media.
Outlet Structure	Conveys stormwater flows that exceed the design volume.

Site Considerations

When the tributary watershed includes ongoing phased construction, sparsely vegetated areas, or steep slopes in sandy soils, consider another stormwater control measure (SCM) or provide robust pretreatment before runoff from these areas reach the sand filter. Sand filters are susceptible to clogging and are better suited to stable watersheds without excessive sediment loading.

See Section 3.0 *Site Assessment* and Section 4.3 *Filtration and Infiltration Section Development* of this chapter to determine the section of the sand filter based on site-specific conditions.

Sand filters are often used in industrial settings, where pollutants may be present that warrant use of a lined system to prevent subsurface pollutant mobilization.

Community Values

Sand filters are highly functional SCMs that are well suited for industrial and large-scale commercial land uses that have generally lower aesthetic expectations. With an exposed sand bed and lack of vegetation, a sand filter is not the best SCM option for highly visible sites such as boutique commercial or mixed-use development, where aesthetics are important to business owners and property managers. Sand filters are also not generally ideal options for low-density residential or park and open space-type sites, where a more naturalistic aesthetic is generally expected. However, if properly screened with shrubs or other site elements (e.g., site walls, raised planters), a sand filter can be made inconspicuous and may be successfully integrated into almost any type of land use. When located in a visible area, frequent inspection and maintenance are critical to public acceptance because an unmaintained sand filter can become an unattractive weed patch with sediment and trash deposits.

While successfully integrating a sand filter into certain types of sites may be aesthetically challenging, their straightforward design and function provides some distinct advantages over other SCMs that require vegetation, including water conservation and a simplified maintenance regime. If creatively located and designed and well maintained, sand filters can be an appropriate and effective stormwater quality treatment solution for a wide variety of sites.

Maintenance

Periodic maintenance for sand filters includes removing sediment, scarifying the filter surface, and removal and/or replacement of the top layer of the media. More detailed maintenance recommendations for sand filters are provided in Chapter 6 of this manual. During design, the following should be considered to ensure ease of maintenance over the long-term:

- Provide forebays for inlets to remove coarse sediments and trash in a manner that can be easily accessed for maintenance.
- Provide energy dissipation to minimize erosion of the filter bed.
- Do not put a filter sock on the underdrain. This is not necessary and can cause the sand filter to clog, resulting in ponded water for extended periods.
- Install cleanouts to enable camera inspection immediately following construction to ensure the underdrain pipe was not crushed during construction. Cleanouts also facilitate maintenance over the life of the facility. Consider locating cleanouts in the side slopes of the basin and above the depth of ponding to prevent short circuiting of flow through the cleanouts to the underdrain.
- For facilities with side slopes, consider vegetated side slopes to pre-treat runoff by filtering (straining). This will reduce the frequency of maintenance. Use native vegetation to limit the need for irrigation of side slopes to the initial establishment period, with supplemental irrigation as needed during prolonged drought periods. Side slopes also may be stabilized with alternative permeable, non-erosive cover such as appropriately sized aggregate, provided that the material is designed to stay in place under design conditions up to and including the 100-year event.
- If a sand filter is located in an underground vault, design the vault in a way that allows for routine scarification of the filter surface and eventual media replacement. Multiple access manholes are typically required, and vaults must be designed with adequate clearance for access by equipment and maintenance personnel (an underground sand filter is a confined space). In some installations, grates can be used instead of solid covers, allowing for easier inspection and maintenance. Design of sand filter vaults is not addressed in detail in this fact sheet and requires additional design considerations to

Benefits

- Filtration processes effectively remove a range of pollutants, including phosphorus.
- Filter surface area does not require irrigation.
- Straightforward maintenance procedures.

Limitations

- Less attractive than vegetated bioretention systems unless additional aesthetic or vegetative screening is provided.
- Not suitable for installation while construction or major landscaping activities are taking place in the watershed.
- Susceptible to clogging if not properly equipped with a forebay and regularly maintained. If clogged, then stormwater flows are bypassed without treatment.
- Typical installations do not provide volume reduction.
- Ammonification and nitrification of organic nitrogen may occur in the media, resulting in nitrate export (Barrett 2003; Clary et al. 2020).

address issues such as biofouling, multi-chamber pretreatment considerations and other factors (DC DOEE 2020, Davis et al. 2022).

- When screening is provided for aesthetic reasons, maintenance access must still be provided.

Design Procedures and Criteria

The following steps outline the design procedure and criteria for a sand filter:

1. **Subsurface Exploration and Determination of a No-Infiltration, Partial Infiltration or Full Infiltration Section.** See Section 3.0 *Site Assessment* and Section 4.0 *Filtration and Infiltration Systems* of this chapter to determine the most appropriate section design for the sand filter based on site conditions. Given that sand filters are often used in industrial settings where subsurface pollutant mobilization should be avoided, lined systems (no-infiltration sections) should be considered based on site conditions.

Photograph SF-2. Underground sand filter at Denver Botanic Gardens has a grated top, which enables inspection and maintenance.

Photograph SF-3. Sand filter with incorporation of minor event flood attenuation provides water quality and detention for a substation.

2. **Inlets, Energy Dissipation, Forebays and Pretreatment**: Use inflow features that create sheet flow or shallow flow conditions to evenly distribute flow. Provide energy dissipation and a forebay at all locations where concentrated flows enter the sand filter. The only inflows that do not require energy dissipation and a forebay are sheet flow inflows to the sand filter. All piped or channelized inflows to sand filters require energy dissipation and forebays, ranging from concrete pads for smaller facilities to more formal structures for larger installations. See Section 5.0 *SCM Inflow Features* of this chapter for additional guidance. In addition to properly sized forebay(s), other types of pretreatment such as grass buffers, hydrodynamic separators, and trash collection devices may also be considered. Underground sand filters in vaults must have a separate pretreatment sedimentation chamber or pretreatment device.

3. **Design Storage Volume**: Calculate the storage volume provided above the sand bed of the basin equal to the WQCV based on a 12-hour drain time, after accounting for runoff-reduction SCMs in the contributing watershed. Determine the required WQCV or EURV (watershed inches of runoff) using Figure 3-2 of Chapter 3 of this manual (for WQCV) or equations provided in the *Storage* chapter of Volume 2 (for EURV).

4. **Sand Filter Geometry:** Sand filter geometry considerations include minimum surface area, side slope conditions and maximum ponding depth:

   - **Minimum Filter Surface Area**: Use equation SF-1 to calculate the minimum filter area for the WQCV, which is the flat surface of the sand filter. Sediment will deposit on the filter area of the sand filter. Therefore, if the filter area is too small, the filter may clog prematurely. If clogging of the filter is of particular concern, increasing the filter area will decrease the frequency of maintenance. Equation SF-1 provides the minimum filter area, allowing for some of the volume to be stored beyond the area of the filter. Note that the total volume must also equal or exceed the design volume.

$$A_F = 0.0125 \cdot A \cdot I \qquad \text{Equation SF-1}$$

Where:

A_F = minimum filter area (flat surface area) (ft^2)

A = area tributary to the sand filter (ft^2)

I = imperviousness of area tributary to the sand filter (percent expressed as a decimal)

   - **Side Slopes:** The side slopes of the basin should be stable and maintainable. For vegetated side slopes, a slope no steeper than 4:1 (horizontal: vertical) is recommended. Use vertical walls where side slopes are steeper than 3:1. Using milder side slopes is an effective way to manage the maximum ponding depth pf the WQCV in the SCM when space constraints allow.

     When side slopes use alternative permeable, non-erosive cover such as the aggregate shown in Photograph SF-3, the engineer must perform analysis to demonstrate the cover material placed on the slope will resist movement from tractive forces under design conditions. This analysis should consider the condition when the sand filter is filling and the side slopes may be exposed to overland runoff, as well as the condition when the facility is full and the spillway is operating.

   - **Maximum Ponding Depth:** The maximum recommended ponding depth is governed by the minimum filter area and basin geometry. For Full Spectrum Detention (FSD) facilities, limiting the WQCV depth to 18 inches will generally help to avoid excessive depths for the EURV and 100-year storage volume. Greater WQCV depths will require more frequent maintenance and may drive the depths of the EURV and 100-year storage volumes to undesirable levels for FSD facilities. Particularly in publicly accessible urban areas, consider surrounding land use and public safety when greater ponding depths are included in the design.

5. **Filter Material**: Provide, at a minimum, an 18-inch layer of AASHTO M43 fine aggregate (filter sand), as shown in Table 4-5 in Section 4.3.3 of this chapter. Maintain a flat surface on the top of the sand bed.

6. **Outlet:** Slope the underdrain into a larger outlet structure and use an orifice plate to drain the WQCV over approximately 12 hours. Section 6.0 *SCM Outflow Features* of this chapter includes conceptual details for the underdrain and orifice outlet to release the WQCV as well as conceptual details for outlets that incorporate detention of larger events via full spectrum detention. For facilities that are designed to treat the EURV and/or 100-year flood, flows greater than the WQCV are orifice-controlled and released to the surface, rather than forced through the sand filter. Provide a spillway for larger events that will convey overflows to the receiving drainage system without adversely affecting adjacent structures or infrastructure. The MHFD-Detention workbook performs calculations for outlet sizing, including the orifice control for the underdrain and outlet controls for larger runoff events.

Sand Filter Media Amendments

An area of evolving research for sand filter media includes various amendments that enhance performance for specific pollutants (e.g., bacteria, metals, nutrients). For example, iron-enhanced sand filter designs target phosphorus removal (MPCA 2022; Erickson and Gulliver 2010). Other examples include calcite/limestone, zeolite, aluminum-based media, manganese-based media, fly ash, olivine and various proprietary media (Davis et al. 2022). Research has also included layering of various media types to target specific pollutants (Prabhukumar et al. 2015).

Designers may consider use of novel amendments to improve water quality performance, provided that the functions and performance of media are maintained or improved. For example, novel amendments should not cause increases in nutrient or metals export or decrease the infiltration rate relative to MHFD's recommended media.

Construction Considerations

Proper construction of sand filters involves careful attention to material specifications and construction details. During construction, implement these practices:

- Protect area from excessive sediment loading during construction. The portion of the site draining to the sand filter must be stabilized before allowing flow into the sand filter.
- When using an impermeable liner, ensure enough slack in the liner to allow for backfill, compaction, and settling without tearing the liner as described in Section 4.0 *Filtration and Infiltration Systems* of this chapter. Concrete spray-on liners may also be used.

- Avoid application of herbicides for weed control within the sand filter and areas draining directly into the sand filter (e.g., embankments).

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T-5 Permeable Pavement Systems

PPS-1. Permeable Pavement System Components

Description

Permeable pavement systems include several types of pavements that allow stormwater to infiltrate through engineered surface layers below the pavement surface. Permeable interlocking concrete pavement (PICP), concrete grid pavement (CGP), and porous gravel pavement (PGP) are included in this fact sheet. Reinforced grass pavement (RGP) is also included, although this type of permeable pavement is most commonly used for fire lanes or to reduce impervious area and does not always provide treatment of the water quality capture volume (WQCV) from surrounding areas.

MS4 Permit Applicability (Dependent on design and level of treatment)	
Meets Runoff Reduction Standard	Potential
Meets WQCV Capture Standard	Yes
Meets Pollutant Removal Standard	Yes[1]
Typical Effectiveness for Targeted Pollutants	
Sediment/Solids	High
Total Phosphorus	Medium
Total Nitrogen	Medium
Total Metals	Medium
Bacteria	Medium
Common Applications	
Runoff Reduction (General)	Yes
Used as Pretreatment	No
Integrated with Flood Control	Yes
Cost	
Life-Cycle Costs	Medium[2]

[1] When designed in accordance with WQCV criteria.
[2] Relative to the life-cycle cost of conventional pavement.

Permeable pavement systems provide filtration of runoff through aggregate layers and store the WQCV in the aggregate reservoir with slow release via an orifice-controlled underdrain and/or infiltration into the subgrade. Permeable pavement systems provide runoff reduction via wetting and drying of the aggregate and infiltration in unlined systems. When designed to provide the WQCV, both lined and unlined permeable pavement systems are capable of providing effective water quality treatment. A permeable pavement system can be designed with an increased depth of aggregate to provide storage exceeding the WQCV, including the excess urban runoff volume (EURV) and the 100-year detention storage volume.

Benefits

- Permeable pavement systems provide water quality treatment while enabling use of the surface area for multiple purposes.
- Permeable pavement systems increase air and water conveyed into the ground to support healthier trees in urban areas.
- Permeable pavement systems are less likely to form ice on the surface than conventional pavements because as snow melts it infiltrates into the surface before it can freeze.
- Green and sustainable building certification credits may be available for permeable pavement systems.
- Permeable pavement systems can provide traffic calming benefits.
- Pavers are constructed of durable concrete mixes and can be removed and typically re-used after utility repairs or restorative maintenance.
- Permeable pavement systems can manage runoff when surrounding storm drain infrastructure is shallow or non-existent, potentially avoiding underground storage systems and pumps.

Limitations

- Permeable pavement systems <u>must</u> be protected from high sediment loads during construction and are not well-suited for areas expected to generate significant sediment loads (e.g., materials storage areas, areas of poor vegetative cover).
- Permeable pavement systems must be designed to allow for maintenance, repair, and replacement of underlying utilities.
- Installation in areas of frequent vehicle use may increase the load of particulate matter and frequency of maintenance.
- Permeable pavement maintenance requires specialized equipment.
- Lack of routine maintenance may result in costly repairs.

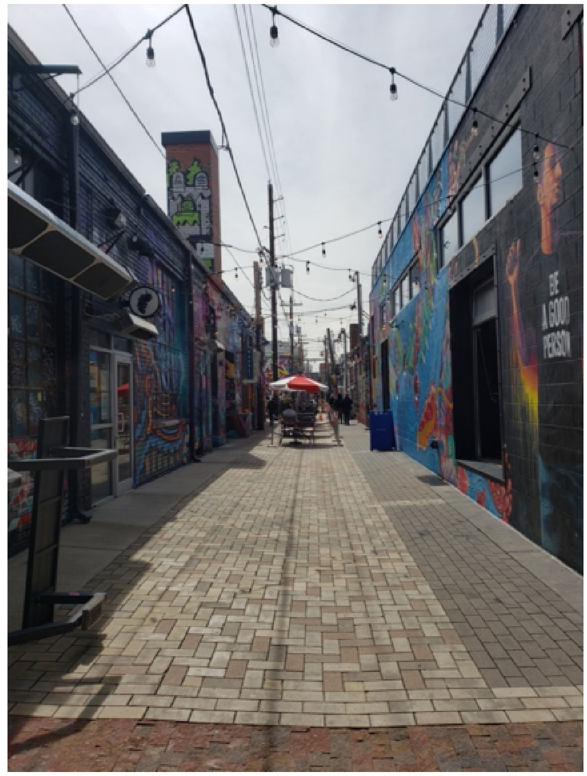
SCM Components

A permeable pavement system functions by filtering, storing, and infiltrating runoff. Filtration occurs as the water infiltrates through the pavement surface or between pavers through a leveling course into an aggregate reservoir. The aggregate reservoir stores the WQCV (or larger design volume such as the EURV or 100-year storage volume) and allows for infiltration into the subgrade for full and partial infiltration designs. The subsurface drainage system for a permeable pavement system, including use of underdrains, is site-specific, and guidance and criteria are provided in Section 4.0 *Filtration and Infiltration Systems* of this chapter.

Component	Intent
Pavement Surface (Wearing Course)	Provides the wearing course for the permeable pavement, allows infiltration into pavement section, and provides filtration.
Leveling Course	Provides bedding for the pavement surface (PICP and CGP) as well as filtration.
Aggregate Reservoir/ Subsurface Layers	Provides structural stability and storage for design storm events. Allows for quiescent settling of fine particulates not filtered by wearing or leveling courses.
Underdrain with orifice release (for partial and no infiltration sections)	Collects and slowly releases the WQCV over 12 hours to reduce erosion in the receiving waters and enhance water quality. Full infiltration designs infiltrate the WQCV into the subgrade.
Lateral Flow Barriers	Separate permeable pavement cells in stepped or sloped installations to prevent all runoff entering system from draining to lowest area. Also used to provide separation between permeable pavement section and adjacent structures or infrastructure.
Outlet Structure	Releases flows in accordance with required drain times and release rates for design events. For multi-cell systems, each cell must have an outlet to avoid flow between cells that overwhelms lower-elevation cells and can lead to washout and differential settlement.
Overflow Inlet	Provides route for runoff to reach the aggregate reservoir if pavement surface is clogged. Required for detention applications.
Overflow Path	Conveys runoff to street or storm drain system via surface flow if pavement surface or outlet is clogged or for events exceeding design flows.

Types of Permeable Pavement System Surfaces

There are several options for permeable pavement system surfaces including PICP, CGP, PGP, and RGP. Porous concrete and porous asphalt are not included in this fact sheet and MHFD does not recommend them due to past issues with durability and performance over time (MHFD 2013a&b). Permeable Interlocking Concrete Pavement (PICP)



Photograph PPS-1. PICP in alley provides stormwater treatment in a retrofit setting while also providing outdoor seating and an attractive pedestrian area.

PICP has a wearing course consisting of precast concrete blocks that, when placed together, create spaces between the blocks where runoff enters the pavement. The blocks contain ridges along the sides that both create these spaces and help ensure that the blocks are installed correctly. The joint spaces between the blocks must be filled with aggregate that allows runoff on the surface to migrate down into the aggregate reservoir. Depending on the manufacturer, these joints should provide an open surface between 5 and 15% of the pavement surface. Figure PPS-2 provides a typical full infiltration pavement section for PICP, and Figure PPS-3 shows a typical no infiltration section. The Interlocking Concrete Pavement Institute (ICPI) published a manual on PICP that includes detailed design, construction, and maintenance information (ICPI 2017) along with various technical specifications (e.g., ICPI 2015; ICPI 2020a,b&c).

Photograph PPS-2. PICP in alley treats runoff from roof drains and adjacent parking spaces. A surface overflow path to the street provides drainage if the system is clogged or overwhelmed by runoff.

PICP has many design options including various shapes, colors, and sizes that can be arranged in creative patterns and color schemes. Light-colored pavers can be used to mark pavements, thereby eliminating the need for painting.

Properly designed and maintained PICP systems sustain infiltration rates well over time and can be removed and replaced if utility work is needed below the surface. Most PICP systems can be constructed as an Americans with Disabilities Act (ADA)-compliant pavement.

Photograph PPS-3. PICP in downtown Ft. Morgan, CO. Note soldier course of light-colored pavers where PICP meets conventional pavement. Photo: SEH and the City of Ft. Morgan.

PICP may have a more expensive upfront cost than other types of permeable pavements, but it generally offers greater benefits. PICP's durable, high-strength concrete wearing surface offers more longevity than some other types of permeable pavements. PICP installation costs can also be offset by reductions in stormwater infrastructure requirements and increased land utilization. ICPI Tech Spec 18 provides additional information on the benefits of PICP (ICPI 2019).

Concrete Grid Pavement (CGP)

CGP consists of concrete block units with large openings (at least 20% of the total surface area) that are typically filled with free-draining aggregate. CGP has many of the same benefits of PICP in terms of flexibility with removal and replacement of blocks and maintaining good infiltration rates over time, but CGP is generally not ADA-compliant because of the extent of the open areas in the grid. Figure PPS-4 shows a typical section for CGP. CGP installation costs may be offset by reductions in stormwater infrastructure requirements. Detailed information on CGP is available in ICPI Tech Spec 8 (ICPI 2020c).

Photograph PPS-4. CGP installation allows for infiltration into subsurface via permeable infill material. Photo: True Grid.

Porous Gravel Pavement (PGP)

PGP is a lower-cost alternative to PICP or CGP that is most applicable to parking areas, materials storage areas (without potential to introduce pollutants), driveways, and maintenance access paths.[1] PGP is not ADA-compliant. Ruts typically will develop unless the surface is stabilized. Use a cellular grid confinement system to stabilize the PGP and prevent excessive rutting. Figure PPS-5 shows a typical section for PGP pavement.

Photograph PPS-5. PGP with grid for containment of surface material to minimize potential for rutting. Photo: True Grid.

Reinforced Grass Pavement (RGP)

RGP has the appearance of grass turf while providing the stability of pavement. Several types of reinforced grass products are available and provide various levels of turf protection and pavement stability. RGP is frequently used to provide emergency vehicle access, maintenance access to SCMs, parking in infrequently used areas, and stabilization of roadway shoulders. Irrigation will typically be needed to establish and maintain grass cover for RGP. Maintaining grass in more heavily used areas requires more irrigation. Figure PPS-6 shows a typical RGP section.

Photograph PPS-6. Reinforced grass pavement using concrete grid for maintenance access to a stormwater pond.

RGP should be treated similarly to other vegetated areas of a site. It reduces the site imperviousness and allows for reduction of runoff for impervious areas that drain to it, but it is not designed to capture and slowly release the WQCV like PICP, CGP, and PGP. It can be used as receiving pervious area; however, other SCMs will be likely be needed to meet water quality requirements.

[1] If PGP is used in a roadway subjected to vehicular traffic, refer to Gravel Roads – Maintenance and Design Manual, Appendix A: Gravel Road Thickness Design Methods (Skorseth and Selim 2000).

Selection Considerations for Reinforced Grass Pavement

- **Frequency of Use**: For more frequently used areas, it is important to select a system that protects the root system of the turf from compaction.
- **Appearance**: Concrete and plastic systems differ aesthetically.
- **Vehicle Loading**: Emergency vehicle access roads may need to be designed for high loads but will be used infrequently.
- **Irrigation Expectations**: Some pavements rely, in part, on the turf for stability.
- **Optimum Drainage Capability**: Where soils allow for infiltration, select a product that will bridge the subgrade, providing better protection from over-compaction.

Site Considerations

Permeable pavement systems provide unique opportunities for unseen stormwater storage and treatment beneath areas that often occupy highly visible and functional portions of a site. For a permeable pavement system to perform effectively, careful evaluation of underlying soils, and surrounding structures and infrastructure is critical. Section 4.0 *Filtration and Infiltration Systems* of this chapter describes site evaluations required for designing infiltration-based SCMs, including permeable pavement systems. Key considerations include:

- PICP and aggregate-filled CGP are well suited for situations where stormwater storage and treatment are required and the surrounding storm drainage infrastructure is shallow. PICP and aggregate-filled CGP installation costs may be offset by the costs of avoiding underground vaults, pumps, mechanical water quality treatment devices, and their associated long-term maintenance costs.
- Permeable pavement systems are generally not suitable in areas where heavy vehicles will be frequently loading/unloading or turning, areas with concentrated pollutant sources (e.g., trash or loose material storage areas, gas stations, fast food drive-throughs, near grease interceptors, and similar areas), sites with high sediment in runoff, and/or sites that use deicers or sanding for snow and ice management (ICPI 2019). See Section 4.0 *Filtration and Infiltration Systems* of this chapter for additional considerations that apply to all infiltration and filtration based SCMs.
- Permeable pavement systems are not appropriate near sediment source areas, including near loose material storage areas or areas with steep slopes and/or sparse vegetation. During construction, protect the permeable pavement system area from runoff with excessive sediment to preserve the infiltration capabilities of the area. Ideally, construct the permeable pavement system as a final step in construction after the contributing drainage area is stabilized. While this is not always feasible, installation of a permeable pavement system before the watershed is stabilized risks the facility failing to function as designed (ICPI 2019).

- When used in or adjacent to streets (e.g., in streetside parking spaces or bike lanes), consider underlying utilities that may require maintenance, repair, or replacement. Due to increased particulate loading in vehicular environments and increased potential for clogging, the ratio of unconnected to receiving pervious area may need to be lower than the maximum limits stated in this fact sheet for sustainable performance without excessive maintenance. Many local governments restrict the use of permeable pavement systems within the public right-of-way, especially when there are underlying utilities.

Photograph PPS-7. Perimeter barrier and trench with underdrain to protect street subgrade with adjacent PPS installation. Photo: Beck Group.

- Traffic loads must be considered for a permeable pavement system that will have vehicular traffic. Consult a geotechnical engineer for structural design of permeable pavements subject to vehicular traffic. Such applications may require a thicker and/or stabilized aggregate base/subbase. For PICP, review the structural design method in ASCE 68-18 Permeable Interlocking Concrete Pavement (ASCE 2018).
- Trees and plantings that seasonally drop leaves on permeable pavements will require regular maintenance to remove leaves to ensure that the systems remain functional.
- For sites with land uses or activities that can cause infiltrating stormwater to contaminate groundwater, special design requirements such as impermeable liners are required to ensure no exfiltration from the permeable pavement system into underlying soils and groundwater. In these cases, a permeable pavement system may not be the most appropriate SCM.
- Setbacks may be required between permeable pavement systems and nearby domestic wells, septic systems, or shallow groundwater tables. Check local requirements for required setbacks.
- When utilities are located beneath permeable pavement systems, provide access for the types of equipment that may be needed to repair or replace the utilities. Avoid utility installations below permeable pavement systems when practical, and sleeve utilities when they must be located within the pavement area. For utilities that are sleeved within a permeable pavement section, provide a cutoff wall against the soil/aggregate interface using an impermeable liner or concrete where the utility enters or exits the pavement section to prevent water exfiltration (piping) along the utility line bedding.

Community Values

Permeable pavement, particularly PICP, is a highly flexible and useful option for providing water quality, runoff reduction, and potentially Full Spectrum Detention (FSD) for very urban or constrained sites. Permeable pavement systems can be a particularly good option in urban areas where high levels of use, high land value, and visual sensitivity do not favor the use of other SCMs that require more dedicated space. The ability of permeable pavement systems to filter, capture, store, infiltrate, and convey stormwater below ground allows sites to be used to their maximum potential, which can justify higher installation costs compared to many other SCMs. PICP should be considered for areas such as urban plazas and courtyards, hotels, multi-family developments, conference venues, access drives and access roads, and high visibility parking lots that periodically function as event venues or gathering spaces. PICP can be aesthetically pleasing in areas of historic designation. It is also a good choice for visitor facilities and parking for sensitive natural and historic areas where minimizing disturbance from site development and associated infrastructure is a primary design objective.

Photograph PPS-8. PICP with striped ADA parking and tree planter. Photo: Creative Civil.

PICP is also an excellent way to manage surface drainage on highly constrained sites, and it can replace the need for curb and gutter, extensive inlets, and drainage piping to convey runoff through high use areas such as plazas and other high use/high visibility areas. PICP is useful for social gathering areas, where it can provide a hardscape environment that is truly barrier-free in terms of accessibility, visually pleasing, and designed to complement other site structures and improvements. Most PICP systems are ADA accessible. Verify ADA compliance with the manufacturer.

Other types of permeable pavement systems, such as CGP, PGP, and RGP, while less expensive than PICP, are less ideal for community uses, primarily due to their lack of ADA accessibility in many typical configurations, and in the case of RGP/CGP, their need for either irrigation (if soil and plant material are used to infill voids), or frequent weed control (if aggregate is used as infill). These types of permeable pavement systems may be suited for overflow parking areas or commercial/industrial areas where community value is a lower priority (i.e., areas not typically used by the public).

Maintenance

Recommended maintenance practices are specific to the type of permeable pavement system and are detailed in Chapter 6 of this manual. During design, consider the following to facilitate maintenance over the long-term:

- Develop an operations and maintenance plan (O&M Plan) that identifies the type(s) of equipment needed to maintain the permeable pavement system (e.g., the availability of a regenerative vacuum sweeper) and communicate expectations of this plan with the owner.
- Consider how the permeable pavement system will be accessed by maintenance equipment and allow space for maneuvering of equipment to access the full surface (ICPI 2019).
- Specify how snow will be removed from the permeable pavement system in the O&M Plan. Permeable pavement systems are not well suited in areas where deicers or sand are applied, so alternative means of managing snow and ice are necessary. In general, permeable pavement systems facilitate melting by infiltrating melting water instead of allowing it to refreeze (ICPI 2019). Plowing is the recommended snow removal process. Use plows with rubber tips on the blades to reduce the potential for damaging pavement.
- When utilities are located beneath the permeable pavement system, provide access and clearance for the types of equipment that may be needed to repair or replace the utilities.
- Include observation well(s) as needed to monitor the drain time of the permeable pavement system over time and assist with determining the required maintenance needs over time. See Figure PPS-7 for a typical observation well configuration. Include observation wells for detention applications and for WQCV applications that include an internal water storage zone below the underdrain. Observation wells are not needed for installations that are just intended to reduce impervious cover but that do not provide the WQCV (e.g., RGP for a maintenance access ramp).
- Periodic testing of the infiltration capabilities of the pavement surface is useful for assessing the need for maintenance. The simple infiltration test (SIT) is a method that can be used to assess the pavement infiltration rate in a relatively short period of time using a standardized method that has been correlated with the ASTM method for determining surface infiltration rates (Winston et al. 2016).

Design Procedures and Criteria

The following procedures are common to all types of permeable pavement systems in this fact sheet. Details specific to each pavement type are presented following the general procedure. MHFD recommends using ICPI standard details as a resource for developing a site-specific design. Conceptual design details are located at the end of this fact sheet.

1. **Subsurface Exploration and Determination of a Full Infiltration, Partial Infiltration or No-Infiltration Section:** Conduct subsurface investigations and determine infiltration section type. Follow the guidance and criteria in Section 4.0 *Filtration and Infiltration Systems* of this chapter to evaluate subsurface characteristics and select a full

infiltration, partial infiltration, or no infiltration section. Guidance and criteria are also provided for full, partial, and no infiltration sections including underdrain systems, filter sections, perimeter barriers, and impermeable liners.

Photograph PPS-9. The reservoir layer of a permeable pavement provides storage volume for the WQCV. Photo: Muller Engineering and Jefferson County Open Space.

2. **Inflows and Run-on Ratio:** Identify unconnected impervious area (UIA) that will drain to the permeable pavement system. The ratio of UIA to the permeable pavement area, which acts as receiving pervious area (RPA), is a critical design parameter that affects the sizing of the SCM, the treatment and runoff reduction effectiveness, and maintenance requirements. Limit the amount of impervious area run-on to the permeable pavement to keep hydraulic and pollutant loading at levels that will not require frequent maintenance over time. Permeable pavement systems are most effective when the ratio of UIA:RPA is low. For PICP, restrict the UIA:RPA ratio to 3:1 to minimize clogging. A maximum ratio of 5:1 is permitted where needed (ICPI 2019); however, at such a ratio, very frequent maintenance will be required. For other types of permeable pavements, the maximum recommended ratio of UIA:RPA is 2:1. If the permeable pavement will serve vehicular traffic, use lower ratios (e.g., 1:1) to account for the higher loading of particulate material.

   The ratio of UIA:RPA is directly proportional to the hydraulic and pollutant loading that the SCM will receive, with higher ratios requiring more frequent maintenance. With other parameters being similar, a permeable pavement designed with a 5:1 ratio would require maintenance more than twice as often as a permeable pavement designed with a 2:1 ratio, and a permeable pavement with a 2:1 ratio would require maintenance twice as often as one designed with a 1:1 ratio. Therefore, it is important to design permeable pavements with UIA:RPA ratios that will provide for sustainable infiltration given the resources and capabilities of the entity responsible for maintaining the pavement.

   For a permeable pavement system to be effective, run-on from adjacent areas must be distributed uniformly across the permeable pavement surface. Designs that direct run on to only a portion of the permeable pavement system effectively overload one part of the system and underutilize others. A level spreader, as discussed in Section 5.0 *SCM Inflow Features* of this chapter, may be needed to achieve uniform flow distribution for larger run-on areas.

   Because permeable pavement systems are often located near buildings, there are opportunities to treat and detain roof runoff in permeable pavement systems.

Downspouts from the roof may discharge onto the surface of the pavement as long as the vertical distance between the pavement surface and downspout outlet is less than 6 inches. This is necessary to avoid wash out of aggregate in joints. Roof downspouts also may discharge to a permeable pavement system via a sub-surface connection to the aggregate layer as showing in Figure PPS-8. When this approach is used, pretreatment is needed using a baffle box and screen to filter out particulates in runoff, as shown in Figure PPS-8.

3. **Design Storage Volume:** Determine the WQCV and other design volumes the system is intended to control. Account for all areas draining to the permeable pavement system and determine imperviousness calculated from the site plan. Use a 12-hour drain time for the WQCV. Calculate the required storage volume, accounting for runoff reduction SCMs in the contributing watershed. Determine the required WQCV or EURV (watershed inches of runoff) using guidance in Chapter 3 of this manual (for WQCV), or equations provided in the *Storage* chapter of Volume 2 for the EURV and 100-year storage volume. For permeable pavement systems, also add the precipitation that falls directly on the permeable pavement area to the total design volume for each event.

> **Designing for Flood Control**
>
> When designing for flood control volumes, provide an overflow inlet that will allow runoff to flow directly into the aggregate reservoir when the hydraulic loading rate exceeds the surface infiltration capacity or in the event the surface is clogged.

4. **Depth and Volume of the Aggregate Reservoir**: The aggregate reservoir consists of the layers of aggregate below the bedding course:

    a. For PICP and CGP, the aggregate layers beneath the bedding course consist of a minimum of 4 inches of AASHTO No. 57 or No. 67 coarse aggregate underlain by a minimum 6-inch-thick subbase of AASHTO No. 2 stone.

    b. For PGP, provide a minimum of 5 inches of AASHTO No. 57 or No. 67 coarse aggregate beneath the containment grid, given the typical 2-inch depth of the overlying 1/2” to 3/4” clean (< 2% passing No. 200 sieve), angular stone for the gravel surface. Provide a minimum 6-inch thick subbase of AASHTO No. 2 stone.

    c. For RGP, the subsurface layer consists of a mixture of aggregate and sandy soil. Consult with a geotechnical engineer on aggregate-soil mixture gradation in areas of vehicular loading.

Additional depth may be required to support anticipated loads or to provide additional storage (i.e., for flood control). This is usually achieved by deepening the subbase layer of AASHTO No. 2 stone. Size the void storage of the aggregate to accommodate the design volume. Assume a porosity of 40% for the aggregate reservoir. Specify fractured faces for reservoir aggregate.

When a permeable pavement system is installed on a slope, a stepped or sloped subgrade installation may be used to provide storage. Figures PPS-9 and PPS-10 depict stepped and sloped subgrade installations.

For preliminary sizing, calculate the storage volume using Equation PPS-3 for a flat or stepped subgrade installation. Use Equations PPS-4 and PPS-5 for a sloped subgrade installation. These equations allow for a minimum of 1 inch of freeboard. Flat installations are preferred because the design spreads infiltration more evenly over the subgrade.

Pavement Design for Vehicular Traffic

When used for vehicular traffic, a qualified engineer experienced in the design of permeable pavements and conventional asphalt and concrete pavements should design the pavement section. The permeable pavement must be adequately supported by a properly prepared subgrade, properly compacted filter material, and aggregate reservoir material designed for traffic loads.

For flat or stepped installations (0% slope at the reservoir/subgrade interface), calculate the volume using Equation PPS-1:

$$V = P\left[\frac{D-1}{12}\right]A_{Pavement}$$ Equation PPS-1

Where:

V = volume available in the reservoir (ft^3)

P = porosity, ≤0.4 for AASHTO No. 57 or No. 67 coarse aggregate and AASHTO No. 2 stone layers

D = depth of reservoir (in), 1 inch is subtracted from D in the numerator of Equation PPS-3 to provide a small amount of freeboard to reduce potential for washout of infill material

$A_{Pavement}$ = area of the permeable pavement (ft^2)

For sloped installations (slope of the reservoir/subgrade interface > 0%), use Equations PPS-2 and PPS-3:

$$V = P\left[\frac{D-6SL-1}{12}\right]A_{Pavement}$$ Equation PPS-2

$$L < \frac{2\ \mathrm{WQCV}}{SA_{Pavement}P}$$ Equation PPS-3

Where:

V = volume available in the reservoir (ft^3)

P = porosity, ≤0.4 for AASHTO No. 57 or No. 67 coarse aggregate and AASHTO No. 2 stone layers

S = slope of the reservoir/subgrade interface (ft/ft)

D = depth of the reservoir (in)

L = length between lateral flow barriers (see step 5) (ft)

$A_{Pavement}$ = area of the permeable pavement (ft^2)

$WQCV$ = water quality capture volume (ft^3)

Note that these are idealized equations for simple geometric situations and are not intended for final design. For sloped bottoms, it is not uncommon for the bottom to be sloped longitudinally along the underdrain and transversely toward the underdrain. For these cases, the volume provided by the permeable pavement system can be calculated based on the average cross-sectional area of the reservoir, adjusted for 1 inch of freeboard below the pavement surface. Multiply this average cross-sectional area by the porosity, P, and the pavement area, $A_{Pavement}$, to calculate volumes for irregular geometry. Where lateral flow barriers or irregular shapes exist, break the storage reservoir into several storage cells to be calculated separately and summed for total volume.

5. **Lateral Flow Barriers:** Lateral flow barriers help maximize storage volumes in stepped and steeply sloped systems. Lateral flow barriers also help use the full infiltration surface and ensure that water doesn't resurface in the lowest areas of the permeable pavement system. For installations with lateral flow barriers, each individual subsurface cell must be able to drain independently. For partial infiltration systems on steeper slopes, this may require lateral flow barriers that are several feet deep to prevent water that infiltrates in one cell from reemerging in another downgradient cell.

Lateral Flow

Consider subsurface areas adjacent to the permeable pavement system when evaluating the perimeter design. Lateral flow can negatively impact the adjacent conventional pavement section, structures, or other infrastructure (especially when the subgrade is sloped).

Construct lateral flow barriers using concrete walls or a 30 mil (minimum) PVC geomembrane. Figures PPS-9 and PPS-10 illustrate concrete lateral flow barriers in stepped and sloped systems, and Figure PPS-11 shows a typical plan view of a multi-celled system with lateral flow barriers. For lateral flow barriers constructed of PVC, see

Section 4.0 *Filtration and Infiltration Systems* of this chapter for geomembrane and geotextile fabric criteria. Place lateral flow barriers parallel to the contours of the subgrade (normal to flow). This maximizes the volume available for storage and avoids issues with stormwater resurfacing and washing out infill material. Lateral flow barriers are recommended for all permeable pavement system installations that have a sloped reservoir/subgrade interface. Space lateral flow barriers as needed to maintain at least 6 inches of AASHTO No. 57 or No. 67 coarse aggregate in the reservoir.

6. **Perimeter Barriers:** Perimeter barriers are required for all PICP and CGP systems to confine the permeable pavement system and prevent horizontal spreading and differential settlement under the weight of the layers of materials and loads on the permeable pavement system surface. Figure PPS-12 shows several typical configurations of perimeter barriers. Perimeter barriers may not be necessary for shallow PGP or RGP installations. Precast, cast-in-place concrete, or cut-stone barriers are required. Precast barriers must be interlocked or attached so that they do not separate. In urban areas, foundations and site walls can also be structurally designed as perimeter barriers.

Photograph PPS-10. Geomembrane attached to concrete perimeter barrier. Photo: Creative Civil.

When a permeable pavement system is adjacent to conventional pavements, a vertical impermeable liner or concrete perimeter barrier with an underdrain may be required to separate the two pavement systems and prevent saturation of the subgrade below the conventional pavement. Consult with the geotechnical engineer on protection required adjacent to conventional pavements. Municipalities may have additional regulations on subgrade protection adjacent to public streets. Section 4.0 *Filtration and Infiltration Systems* of this chapter provides additional guidance related to perimeter barriers.

7. **Features in Permeable Pavement Installations:** Light poles and trees are common features within many permeable pavement installations. Parking lot lighting or trees installed within a permeable pavement system typically are deeper than the permeable pavement system cross section. Design post bases with a horizontal breakaway footing (attach the liner to the footing when lined).

Photograph PPS-11. Geomembrane attachment to horizontal footing for light pole. Photo: Creative Civil.

There are a number of ways that trees can be incorporated within permeable pavement areas including soil planting vaults separated from the aggregate layer by an impermeable liner or aggregate-filled plastic crates to provide air and water with drainage to prevent prolonged saturation of roots. Regardless of the method, providing effective drainage is critical as prolonged saturation of roots will stunt or kill trees. Consult with an arborist or landscape architect knowledgeable of trees when planning trees within a permeable pavement area. See Figure PPS-13 for a tree planting concept with PICP over structural soil. It is important to avoid prolonged inundation of tree roots, so the base of the root ball is elevated above the bottom of the aggregate reservoir, and underdrains are provided to help drain the area around the tree's root ball.

Photograph PPS-12. Tree planter vault for PICP installation. Photo: Creative Civil.

8. **Outlets:** SCM outlets are customized around overall design constraints and design-storm events included in the reservoir layer. Sites can vary greatly in shape, size, elevations of reservoir cells and ultimately the depth of the connecting outfall system. In multi-cell installations, each cell must drain independently to avoid overflow between cells and washout. This requires the designer to know the depths of design events including the WQCV and larger design storage volumes within each cell to design an outlet for each cell that satisfies release criteria. A well-designed outlet will provide for ease of maintenance and cleaning. The entire system should be designed with consideration of the 100-year storm conveyance through the reservoir layers to the outlet to prevent backwashing paver joints, resulting in paver movement and settlement. The outlet

Photograph PPS-13. FSD outlet for PICP system. WQCV orifice is drilled in front of cap at bottom. EURV is controlled by the circular orifice midway up the riser. The 100-year event is released via rectangular orifices on the sides of the riser just below the band. The open top of the riser provides an emergency overflow. Photo: Creative Civil.

structure should be capable of conveying all storm events and maintaining the reservoir storage volumes per the design.

Outflows from permeable pavement systems are controlled using orifices and weirs designed as part of the outlet riser pipe. Figure PPS-14 shows a concept for an outlet structure designed to control the WQCV. In this application, a restrictor plate or cap with an orifice can be placed on the end of the underdrain where it enters the outlet structure. Larger events are conveyed into the outlet structure via a grated area inlet, bypassing the permeable pavement system. Figure PPS-15 provides an example of a conceptual permeable pavement outlet configuration for FSD design. In this case, the outlet structure consists of a riser with multi-level controls, and the WQCV, EURV, and 100-year design event are filtered through and stored in the aggregate reservoir levels before they are released by the multi-level control riser. All designs must implement properly sized overflow paths that do not result in paver displacement or settlement during events exceeding design storms for which the reservoir layers are sized.

Section 6.0 *SCM Outflow Features* of this chapter provides guidance on designing subsurface outlets to release the WQCV. The outlet sizing is based on the depth of the WQCV or other design storage volume in the aggregate reservoir. The aggregate reservoir can also be sized for the EURV and 100-year storage volume based on guidance in the *Storage* chapter of Volume 2. See Section 6.0 *SCM Outflow Features* of this chapter for conceptual outlet structures with single and multiple orifice-controlled release rates. It is important to know the depth of each volume stored to properly control release via the outlet structure.

For calculating depth of the WQCV using a flat/stepped installation (Figure PPS-9), use Equation PPS-4:

$$d = \frac{Design\ Storm\ Volume}{PA_{Pavement}}$$ Equation PPS-4

Where:

d = depth of storage in the reservoir (ft)

P = porosity, ≤0.4 for AASHTO No. 57 or No. 67 coarse aggregate and AASHTO No. 2 stone layers

$A_{Pavement}$ = area of permeable pavement system (ft^2)

Design Storm Volume = Storage volume for design storm (WQCV, EURV, 100-year) (ft^3)

For calculating depth of the WQCV using a sloped installation (Figure PPS-10), use Equation PPS-5:

$$d = 6\left[\frac{2\ \mathrm{WQCV}}{P\mathrm{A}_{Pavement}}\right] + \mathrm{sL}$$ Equation PPS-5

Where:

d = depth of WQCV storage in the reservoir (in)

$A_{Pavement}$ = area of permeable pavement system (ft^2)

s = slope of the reservoir/subgrade interface (ft/ft)

L = length between lateral flow barriers (ft)

WQCV = water quality capture volume (ft^3)

As with Equations PPS-1 through PPS-3, Equations PPS-4 and PPS-5 are applicable for permeable pavement designs with simple geometry. For irregularly shaped installations or those with laterally and transversely sloping subgrade, calculate the average cross-sectional area of the pavement section corresponding to the design volume (WQCV, EURV, and/or 100-year), and determine the depth for each design volume based on the porosity and area of overlying pavement and use this depth to calculate the head used in orifice and weir equations for outlet orifice and weir sizing.

MHFD-Detention (available at www.mhfd.org) can be used to size FSD for permeable pavement systems, including the WQCV, EURV, and 100-year detention storage volumes. Consult with a geotechnical engineer on restrictions on reservoir depth related to pavement stability, traffic loading, and other geotechnical constraints. Aggregate reservoir depths up to 6 feet have been implemented successfully along the Front Range of Colorado.

The following sections provide additional criteria that are specific to each permeable pavement type.

Permeable Interlocking Concrete Pavers (PICP)

Design of a PICP system follows the procedures outlined above in combination with guidance and criteria in Section 4.0 *Filtration and Infiltration Systems* of this chapter. The following additional criteria and considerations apply:

- Provide a 1.5- to 2-inch bedding course of AASHTO No. 8, 89, or 9 aggregate above a 4-inch thick open-graded base of AASHTO No. 57 or No. 67 aggregate to set the pavers. Provide a minimum 6-inch-thick subbase of ASSHTO No. 2 stone beneath the open-graded base. Increase the depth of the No. 2 stone layer as needed to achieve the design volume. See Figures PPS-2 and PPS-3 for illustrations of these aggregate layers.

- For vehicular applications, use herringbone patterns as demonstrated in Photograph PPS-15 and pavers with an overall length to thickness (aspect) ratio of 3:1.
- A continuous perimeter barrier is required for all PICP installations.
- Provide a line of uncut blocks adjacent to the concrete border. This will ensure that cut edges are not placed directly against the concrete border, which can cause damage to the paver at the interface with the concrete. This is often accomplished by specifying a sailor course or soldier course adjacent to the concrete edge.
- All cut pavers must be at least 50% of the full uncut paver size when subject to vehicular use.
- PICP pavers must not exceed a 101-square-inch surface area per ASTM C936 if subject to vehicular traffic. Specific paver thickness recommendations include:
    - Residential and pedestrian areas: 2-3/8" minimum thickness.
    - Vehicular areas: 3-1/8" minimum thickness with maximum aspect or overall length/thickness ratio of 3:1.

Photograph PPS-15. The very small cut paver shown in this photo could have been eliminated by rotating the paver above it 90 degrees.

Photograph PPS-15. Concrete collar helps avoid small-cut pavers around edges of inset features and can be colored to match surrounding pavers. Photo: Creative Civil.

- Where cutting pavers can be avoided, there is often a savings of time and cost. Additionally, the integrity of the paver is preserved.
- Avoid installation of circular inlets, valve boxes, bollards, light poles, and other similar features within PICP installations when practical. When used, install a square cast-in-place, reinforced concrete collar. It is helpful for the installer to provide framed box-outs where collars are needed within the PICP layout to avoid small paver cuts.

Concrete Grid Pavement (CGP)

The design of CGP follows the procedures outlined above in combination with guidance and criteria in Section 4.0 *Filtration and Infiltration Systems* of this chapter. The following additional criteria and considerations apply:

- For CGP, provide a 2-inch base course consisting of AASHTO No. 8 aggregate to set the concrete blocks and use the AASHTO No. 8 for infill material between the concrete block units. Provide the same layering described for PICP beneath the No. 8 base course.

- A concrete grid also may be filled with a sandy loam topsoil and seeded for reinforced grass pavement. In vegetated applications provide a ½ to 1-inch layer of bedding sand as a base for the grid. Plant the grid with grass plugs or seed with native grasses. Irrigation will be required for establishment of vegetation and may be required episodically in the future due to severe drought periods.
- A continuous perimeter barrier is required for all CGP installations.

Photograph PPS-16. Forms for concrete grid for reinforced grass pavement to access pond outlet structure.

Porous Gravel Pavement (PGP)

The design of PGP follows the procedures outlined above in combination with guidance and criteria in Section 4.0 *Filtration and Infiltration Systems* of this chapter. The following additional criteria and considerations apply:

Photograph PPS-17. PGP parking area with markers to delineate parking spaces. Photo: True Grid

- The gravel surface consists of 1/2” to 3/4” clean, angular stone (5/8” typical) with less than 2% passing the No. 200 sieve. This material is filled flush to the top of the containment grid. The containment grid, typically 2 inches deep but variable depending on the manufacturer, sits on a permeable subbase layer consisting of at least 8 inches of AASHTO No. 57 or No. 67 aggregate that is capable of storing the WQCV in the aggregate pore space beneath the containment grid. AASHTO No. 2 stone may be placed beneath the layer of No. 57 or No. 67 stone as needed for additional storage or structural stability.

- Use an interlocking plastic cellular paving product (or similar containment system) to stabilize the wearing course and avoid rutting in loose gravel. Without some type of containment system, rutting is likely to occur in driving or parking areas.
- If the PGP will experience vehicular traffic, refer to Gravel Roads – Maintenance and Design Manual, Appendix A: Gravel Road Thickness Design Methods (Skorseth and Selim 2000).

Reinforced Grass Pavement (RGP)

Figure PPS-5 shows a non-proprietary RGP section adapted from the Federal Aviation Administration (FAA) for aggregate turf pavement that can be used as a conceptual start for developing a site-specific design. In addition to this non-proprietary section, various products are available under the name of reinforced grass or turf pavement systems. The most common systems include:

- **Plastic Cellular Paving:** This category includes interlocking plastic pavers typically designed to be filled with turf. This system allows for a high percentage of grass surface within the pavement area. Plastic cellular paving is not recommended for areas that will have traffic loads due to potential for compaction and loss of infiltration capacity, unless a properly engineered permeable base layer is provided with adequate depth. Consult with a geotechnical engineer on how to meet structural needs (heavy loads), while retaining porosity to grow grass.

Photograph PPS-18. Concrete cellular paving grid for RGP provides maintenance access to the forebay. Photo: Creative Civil.

- **Concrete Cellular Paving:** This type of pavement consists either of interlocking pavers that have openings for the placement of grass or a similar cast-in-place system. Some systems include a reinforcement system that ties the pavers together, providing greater protection from over-compaction and greater resistance to differential movement. Although some systems confine the grass area to the openings in the concrete, others are designed to provide the appearance of a fully vegetated landscape.

Construction Considerations

Proper construction of permeable pavement systems requires measures to preserve natural infiltration rates (for full and partial infiltration sections) prior to placement of the pavement, as well as measures to protect the system from the time that pavement construction is complete to the end of site construction. The following recommendations apply to all permeable pavement systems and should be noted on plans as applicable:

1. On the plans, require a construction fence around pervious areas where infiltration rates need to be preserved and are vulnerable to compaction from construction traffic or storage of materials.
2. Hold a pre-construction meeting to ensure that the contactor understands how the permeable pavement system is intended to function.
3. When using an impermeable liner, ensure enough slack in the liner to allow for backfill, compaction, and settling without tearing the liner. Provide necessary quality assurance and quality control (QA/QC) overseen by a professional engineer when constructing an impermeable geomembrane liner system, including, but not limited to, fabrication testing, destructive and non-destructive testing of field seams, observation of geomembrane material for tears or other defects, and air lance testing for leaks in all field seams and penetrations. Consider requiring field reports or other documentation from the engineer. Avoid use of heavy equipment over the liners.

Photograph PPS-19. Underdrain penetration of geomembrane with boot. Photo: Creative Civil.

4. Follow subgrade and filter layer compaction criteria in Section 4.0 *Filtration and Infiltration Systems* of this chapter. Filter material placed above the prepared subgrade should be compacted to a relative density between 70% and 75% (ASTM D4253 and ASTM D4254) using a walk-behind vibratory roller, vibratory plate compactor, or other light compaction equipment. Do not over-compact because it will limit infiltration into the underlying subgrade. The reservoir layer may not be testable for compaction using a method based on specified density (e.g., nuclear density testing). The designer should consider a method specification (e.g., number of passes of a specified vibratory compactor) for those materials. The number of passes appropriate is dependent on the type of equipment and depth of the layer. For unlined systems, place the aggregate in 6-inch (maximum) lifts, compacting each lift by using a 10-ton or heavier, vibrating steel drum roller. Make at least four passes with the roller, with the initial passes made while vibrating the roller and the final one to two passes without vibration.
5. For lined installations, providing protection fabric on top of the liner is essential for protecting the liner from tears due to compaction of angular aggregates used in backfill. Install the lower 16 inches of aggregate in 4-inch maximum lifts using lightweight compaction equipment such as a walk-behind vibratory plate compactor or a walk-

behind vibratory roller. Heavier grade compaction equipment can be utilized for upper layers only.

6. To reduce sediment within the pavement section, specify all aggregate outside of the filter layer to be washed and have no more than 2% passing the No. 200 sieve per ASTM C136. Observe aggregate on-site prior to placement to ensure it is free of excess sediment.
7. Discuss the contractor's proposed sequence of construction and look for activities that may require protection of the permeable pavement system. Ensure that the permeable pavement system is protected from construction activities following pavement construction (e.g., landscaping operations). Protective measures may include covering areas of the pavement, providing alternative construction vehicle access, and providing education to all parties working on-site. Keep mud and sediment-laden runoff away from the pavement area. Temporarily divert runoff around the permeable pavement system or install sediment control measures as necessary to reduce the amount of sediment run-on to the pavement. Cover surfaces with a heavy impermeable membrane when construction activities threaten to deposit sediment onto the pavement area. Sequence construction of the permeable pavement system later in the construction process to avoid contamination of the permeable pavement system aggregates and joints with eroded sediments from construction disturbances. Aggregate contaminated with sediment should be removed and replaced with aggregate conforming to the recommdations herein.
8. It is important for the designer to observe construction of the permeable pavement system at key points during construction. At a minimum, the engineer should observe the construction for conformance to the design at the following milestones:
   i) Subgrade inspection – The engineer should review subgrade surveyed elevations to ensure design volumes can be obtained. Many local jurisdictions require record drawings (as-builts) to prove storage volumes were achieved. In these cases, a subgrade survey will be required by licensed surveyor.
   ii) Impermeable liner and underdrain installation and seams (if applicable).
   iii) Placement of underdrain and completion of filter layer.
   iv) Placement of aggregate reservoir material.

Photograph PPS-20. Mechanical placement in larger areas can reduce the unit cost of the pavement. Photo: Muller Engineering Company and Jefferson County Open Space.

v) Placement of leveling course and pavement surface.

vi) For PICP, verify that the specified types of pavers are used and that they meet the requirements in ASTM C936. Some pavers are designed to be used in permeable applications, and others are not. Do not allow design substitutions for pavers that do not comply with original design specifications.

9. Where cutting pavers can be avoided, there is often a savings of time and cost. Additionally, the integrity of the paver is preserved. The designer must provide clear examples for incorporating markings into the pavement without cutting paver blocks. Around inlets and curbs, a colored concrete band or specialty pattern should be considered to avoid small paver cuts that will be unstable. Consider using squared-off gutters for curb and gutter with radii smaller than 10 feet.

10. For landscaped areas adjacent to PICP and CGP, do not apply mulches that float or could potentially wash into and clog the paver joints.

Because proper installation of permeable pavement systems is critical for long-term function and structural stability, MHFD has developed example construction drawing notes for permeable pavement installations. The MHFD *Permeable Pavement Example Construction Drawing Notes* are available on the MHFD website and are intended as a starting point for designers to develop their own project-specific notes. Some of the *Permeable Pavement Example Construction Drawing Notes* may not be applicable in all situations, additional notes may be necessary, or notes may require alteration for site-specific installations. The MHFD *Permeable Pavement Construction Example Drawing Notes* are intended to convey to contractor, owner, and installers the basic functions, installation details, and cautions that must be followed for installation of a permeable pavement system that functions as intended. These notes <u>must not</u> be used without the design engineer editing the notes to reflect site-specific conditions.

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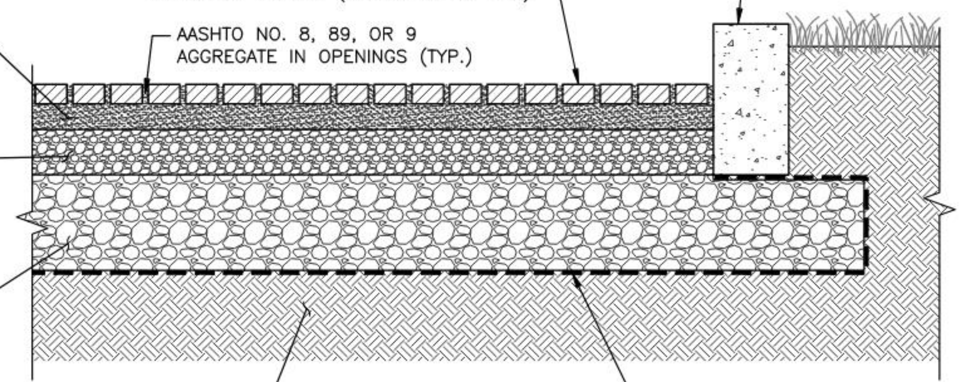
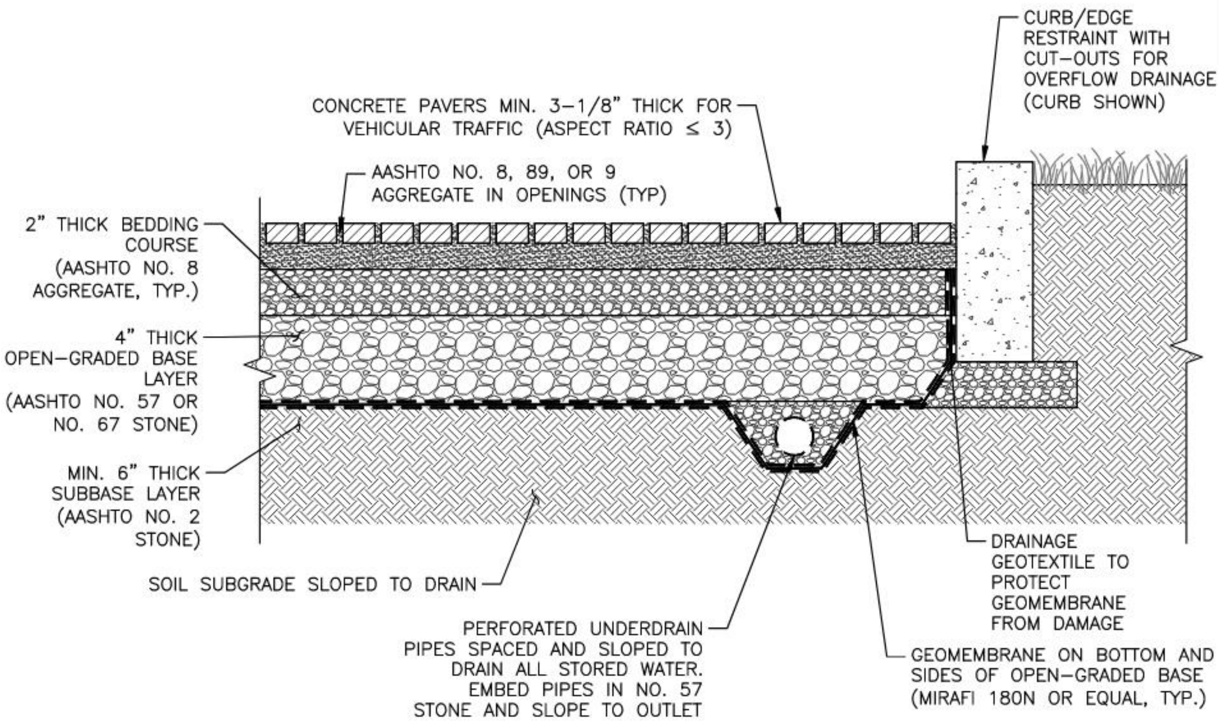


NOTES:

1. 2–3/8" THICK PAVERS MAY BE USED IN PEDESTRIAN AND RESIDENTIAL APPLICATIONS.
2. NO. 2 STONE SUBBASE THICKNESS VARIES WITH DESIGN. CONSULT INTERLOCKING CONCRETE PAVEMENT INSTITUTE (ICPI) PERMEABLE INTERLOCKING CONCRETE PAVEMENT MANUAL.
3. AASHTO NO. 2 STONE MAY BE SUBSTITUTED WITH AASHTO NO. 3 OR NO. 4 STONE.
4. SELECT GEOTEXTILE PER AASHTO M 288.
5. BASED ON ICPI DRAWING NO. ICPI–68. SEE OTHER ICPI DETAILS AVAILABLE ONLINE FOR VARIOUS CONFIGURATIONS AND EDGE TREATMENTS FOR PICP.
6. PAVEMENT DESIGN FOR TRAFFIC LOADING REQUIRED IN AREAS WITH VEHICULAR USE.

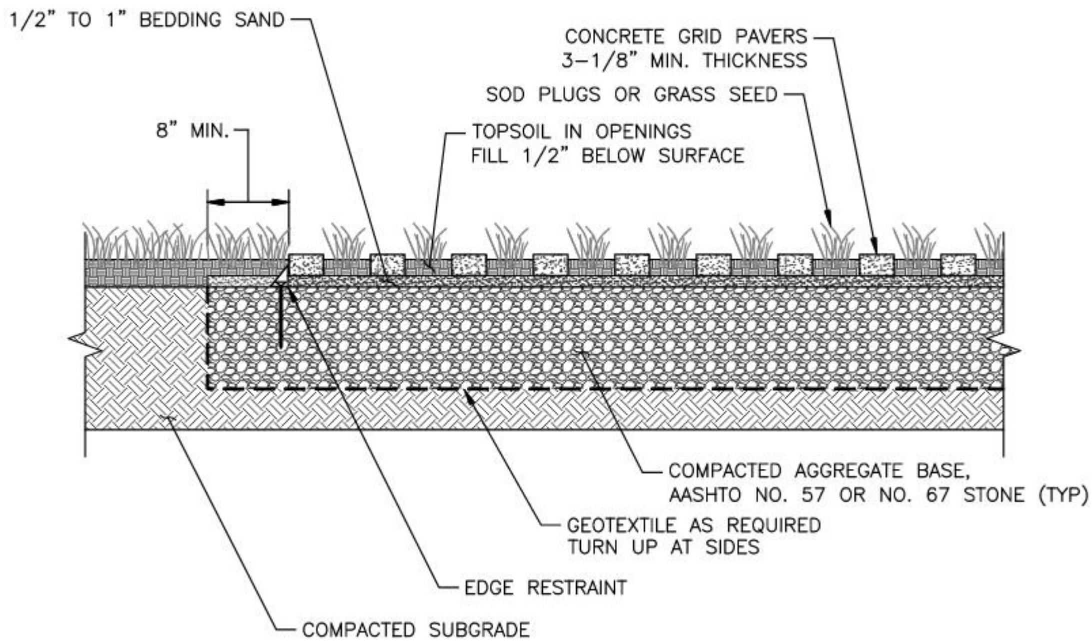
FIGURE PPS–2.
PERMEABLE INTERLOCKING CONCRETE PAVEMENT
WITH FULL INFILTRATION
SECTION VIEW (NOT TO SCALE)



NOTES:

1. 2-3/8" THICK PAVERS MAY BE USED IN PEDESTRIAN AND RESIDENTIAL APPLICATIONS.
2. AASHTO NO. 2 STONE SUBBASE THICKNESS VARIES WITH DESIGN. AASHTO NO. 3 OR NO. 4 IS ACCEPTABLE. CONSULT INTERLOCKING CONCRETE PAVEMENT INSTITUTE (ICPI) PERMEABLE INTERLOCKING CONCRETE PAVEMENT MANUAL.
3. PERFORATED PIPES MAY BE RAISED FOR WATER STORAGE FROM LARGE RAIN EVENTS WITH OUTLET(S) AT LINER BOTTOM TO DRAIN SMALL RAIN EVENTS.
4. SELECT GEOTEXTILE PER AASHTO M288.
5. BASED ON ICPI DRAWING NO. ICPI-70. SEE OTHER ICPI DETAILS AVAILABLE ONLINE FOR VARIOUS CONFIGURATIONS AND EDGE TREATMENTS FOR PICP.
6. PAVEMENT DESIGN FOR TRAFFIC LOADING REQUIRED IN AREAS WITH VEHICULAR USE.

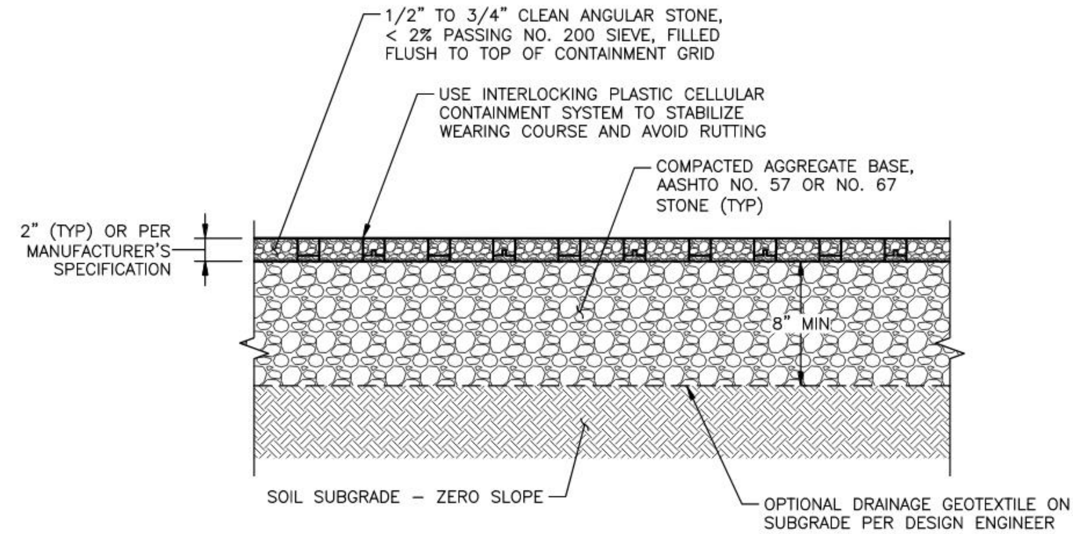
FIGURE PPS-3.
PERMEABLE INTERLOCKING CONCRETE PAVEMENT
WITH NO INFILTRATION
SECTION VIEW (NOT TO SCALE)



NOTES:

1. BASE THICKNESS VARIES WITH TRAFFIC, CLIMATE, AND SUBGRADE.
2. MINIMUM BASE THICKNESS: 6" RESIDENTIAL DRIVEWAYS, 8" FIRELANES AND PARKING LOTS.
3. FOR XERIC INSTALLATIONS, 1/2" TO 3/4" CLEAN ANGULAR STONE WITH <2% PASSING THE NO. 200 SIEVE MAY BE USED TO FILL OPENINGS AS ALTERNATIVE TO TOPSOIL AND SOD PLUGS OR SEED.
4. BASED ON INTERLOCKING CONCRETE PAVEMENT INSTITUTE (ICPI) DRAWING NO. ICPI-08. SEE OTHER ICPI DETAILS AVAILABLE ONLINE FOR TYPICAL CONFIGURATIONS OF CONCRETE GRID PAVEMENT.
5. PAVEMENT DESIGN FOR TRAFFIC LOADING REQUIRED IN AREAS WITH VEHICULAR USE.

FIGURE PPS-4.
CONCRETE GRID PAVEMENT
SECTION VIEW (NOT TO SCALE)



NOTES:

1. PAVEMENT SECTION SHOWN IS FOR FULL INFILTRATION SECTION, SEE FIGURE PPS–3 FOR TYPICAL UNDERDRAIN DETAIL IF A PARTIAL OR NO INFILTRATION SECTION IS USED.
2. PAVEMENT DESIGN FOR TRAFFIC LOADING REQUIRED IN AREAS WITH VEHICULAR USE.
3. INCREASE AGGREGATE RESERVOIR DEPTH FOR STORMWATER DETENTION.

FIGURE PPS–5.
POROUS GRAVEL PAVEMENT
SECTION VIEW (NOT TO SCALE)

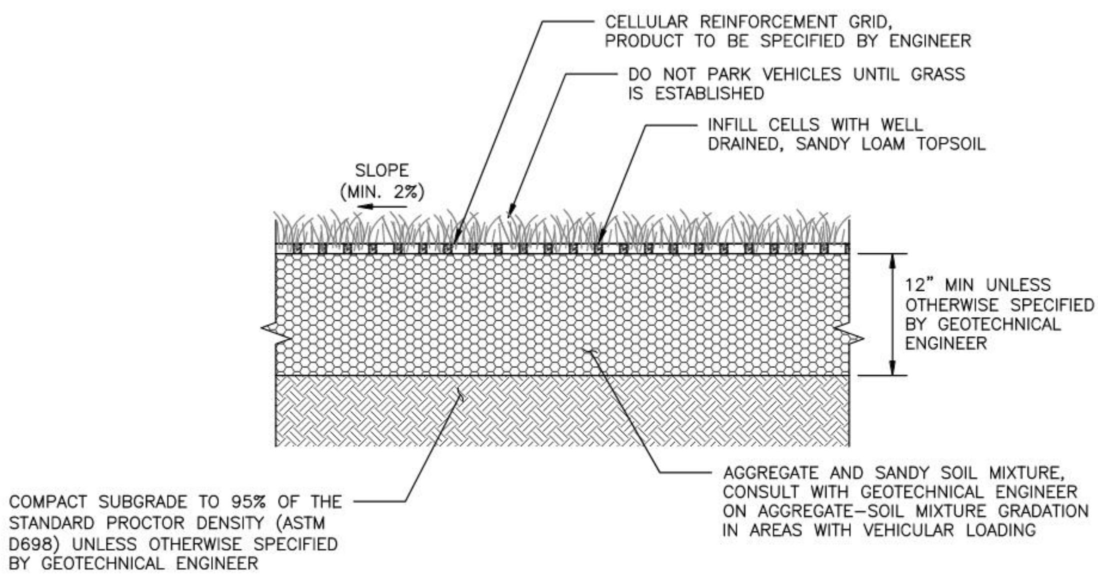
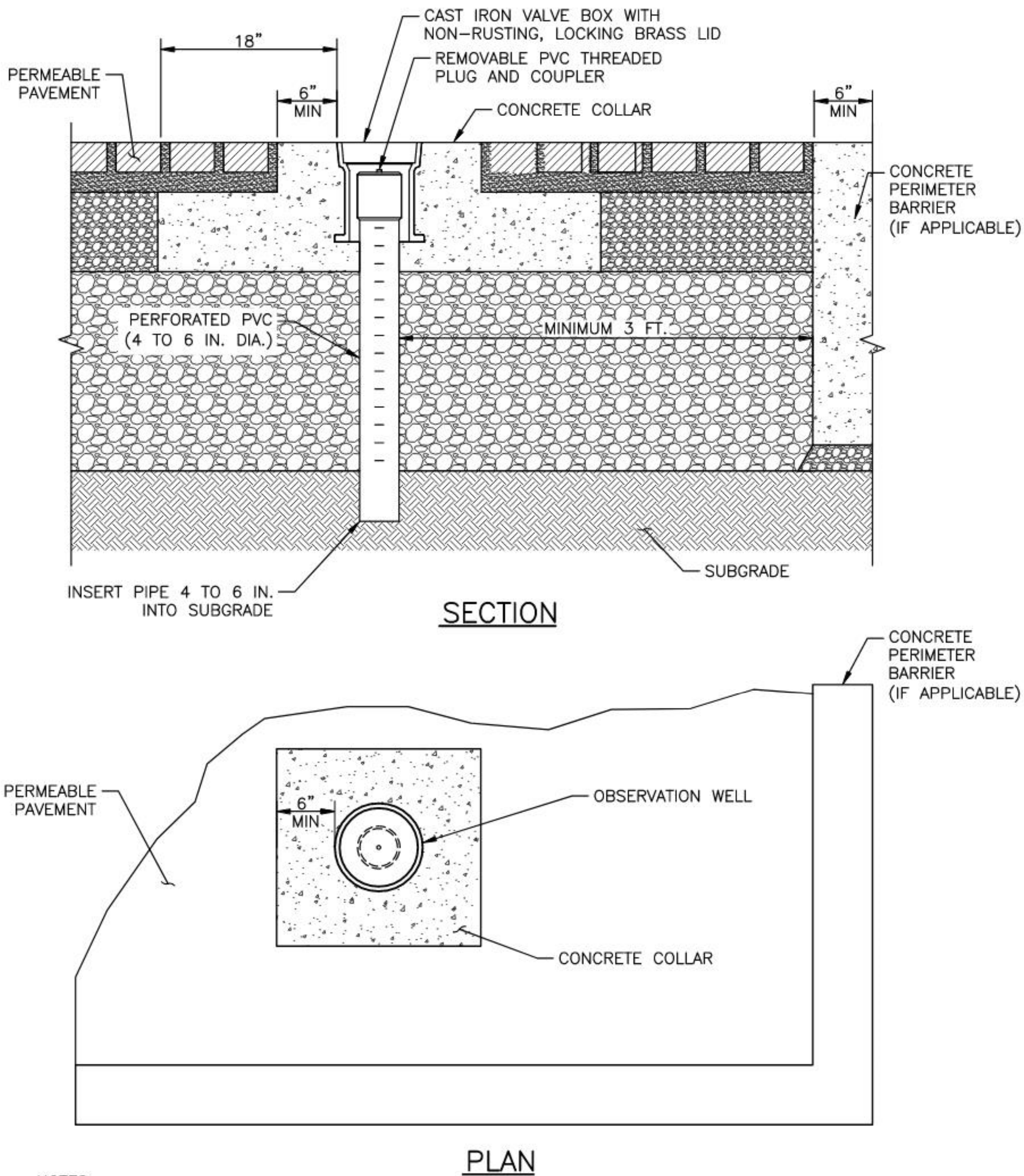


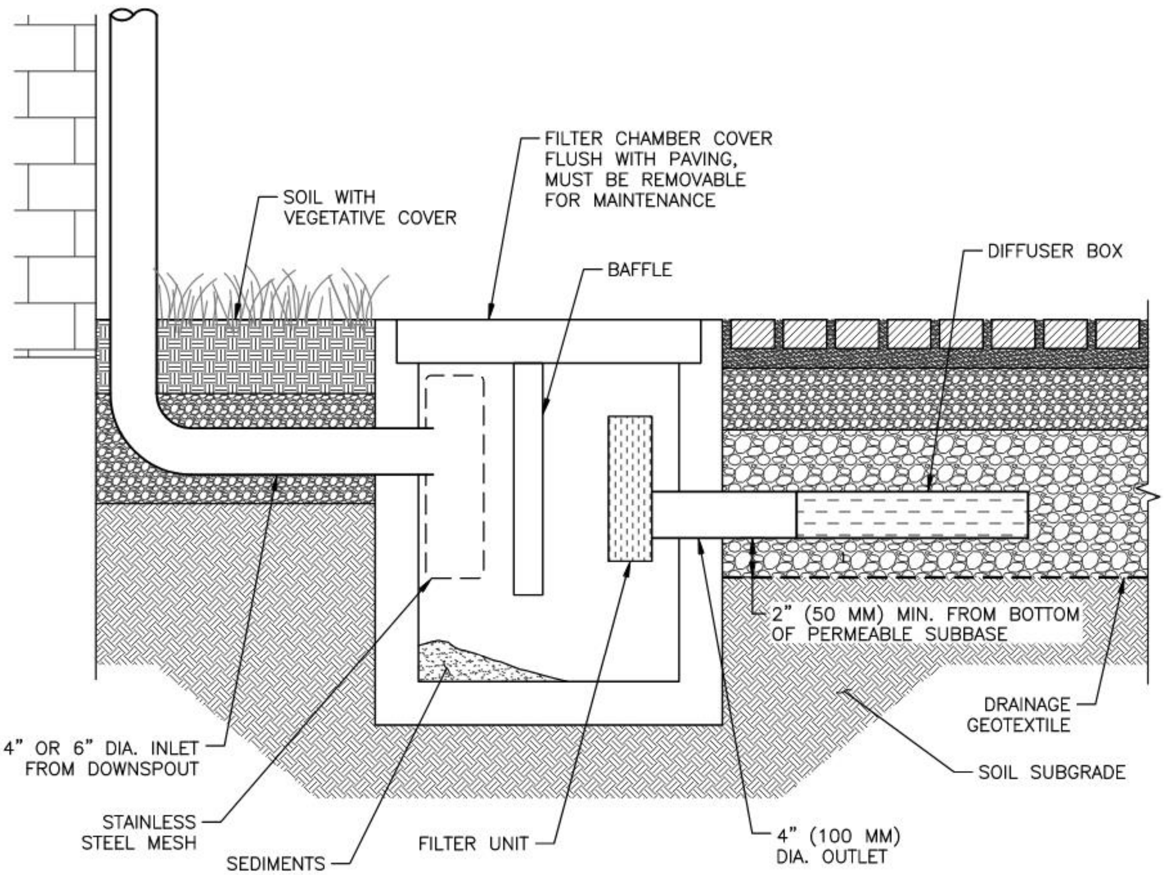
FIGURE PPS–6.
REINFORCED GRASS PAVEMENT
SECTION VIEW (NOT TO SCALE)



NOTES:

1. REFER TO INTERLOCKING CONCRETE PAVEMENT INSTITUTE (ICPI) DETAILS FOR ALTERNATIVE CONFIGURATIONS OF OBSERVATION WELLS LOCATED WITHIN AND OUTSIDE PERMEABLE INTERLOCKING CONCRETE PAVEMENT.

FIGURE PPS–7.
OBSERVATION WELL WITHIN PERMEABLE INTERLOCKING CONCRETE PAVEMENT
PLAN AND SECTION VIEW (NOT TO SCALE)



NOTES:

1. SELECT GEOTEXTILE PER AASHTO M 288.
2. DETAIL BASED ON INTERLOCKING CONCRETE PAVEMENT INSTITUTE (ICPI) DRAWING NO. ICPI–90.

FIGURE PPS–8.
ROOF DRAIN CONNECTION TO PERMEABLE INTERLOCKING CONCRETE PAVEMENT
SECTION VIEW (NOT TO SCALE)

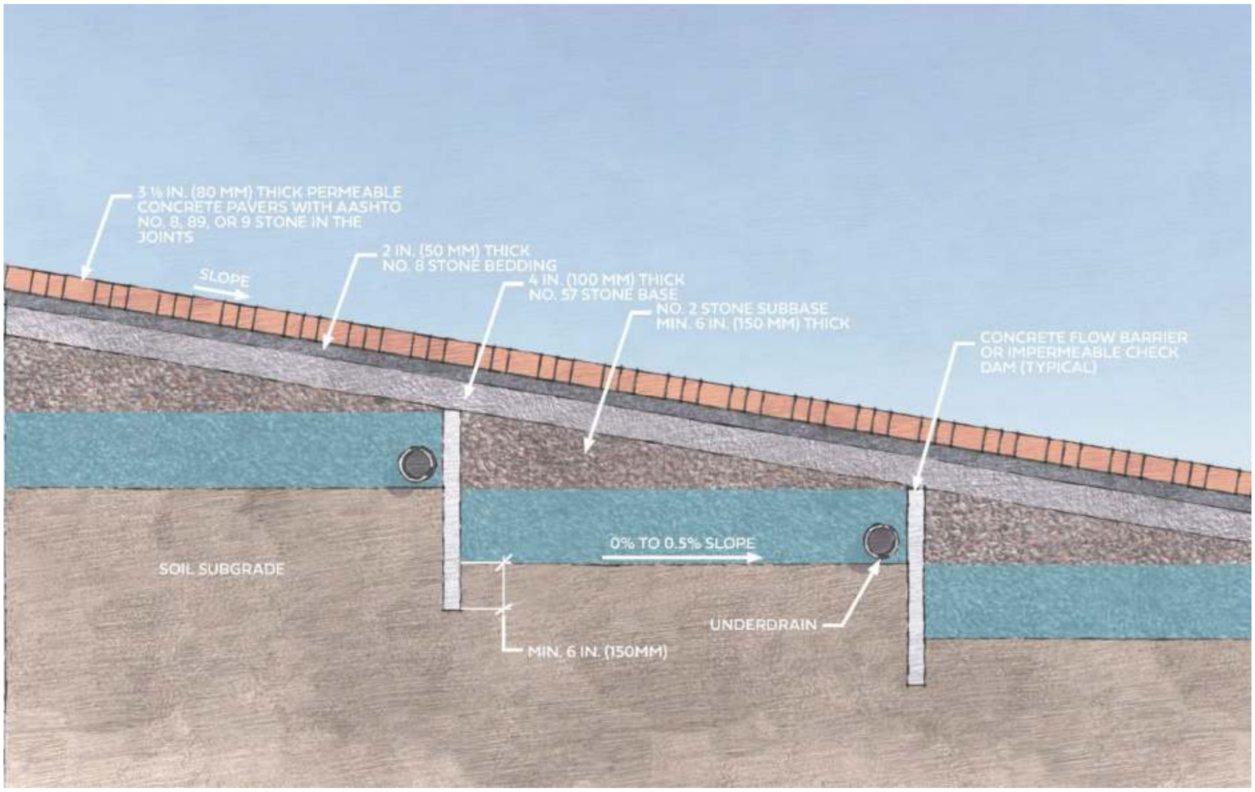


Figure PPS-9. Stepped Permeable Pavement System Installation

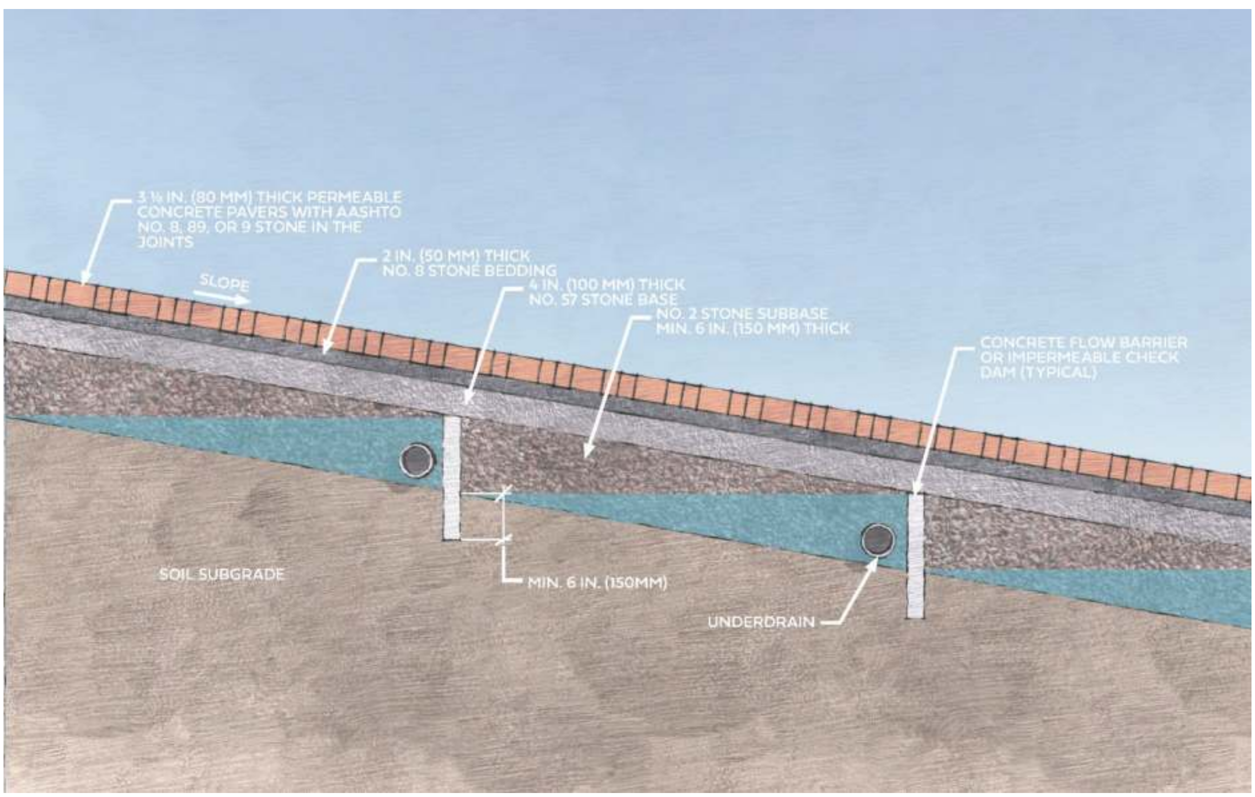
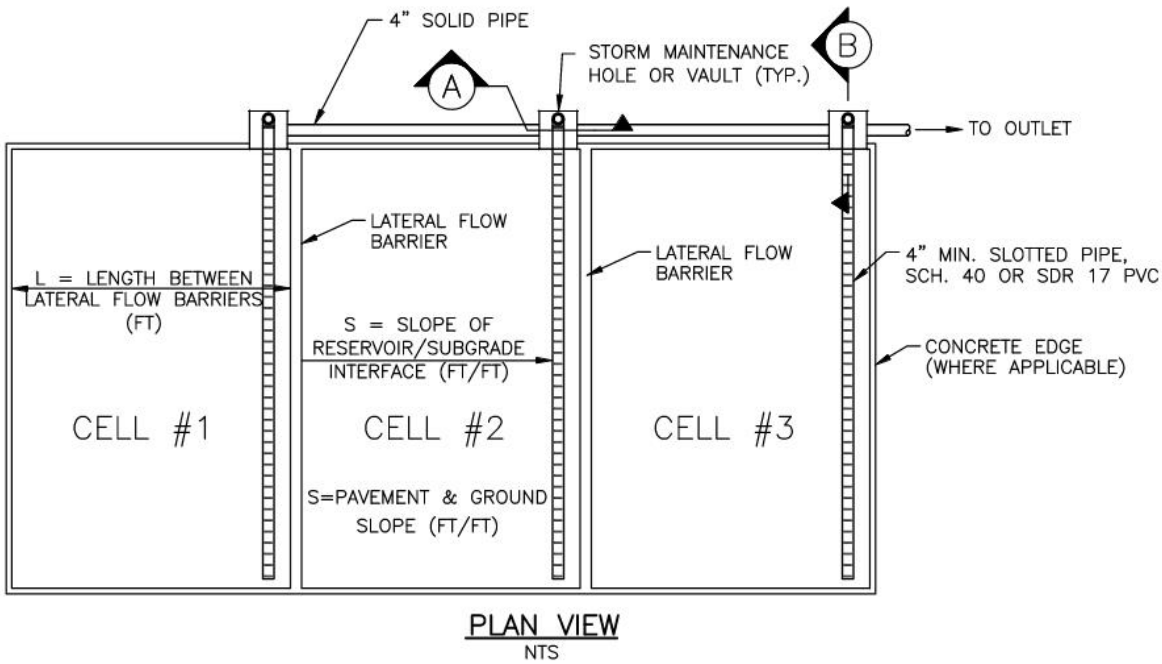
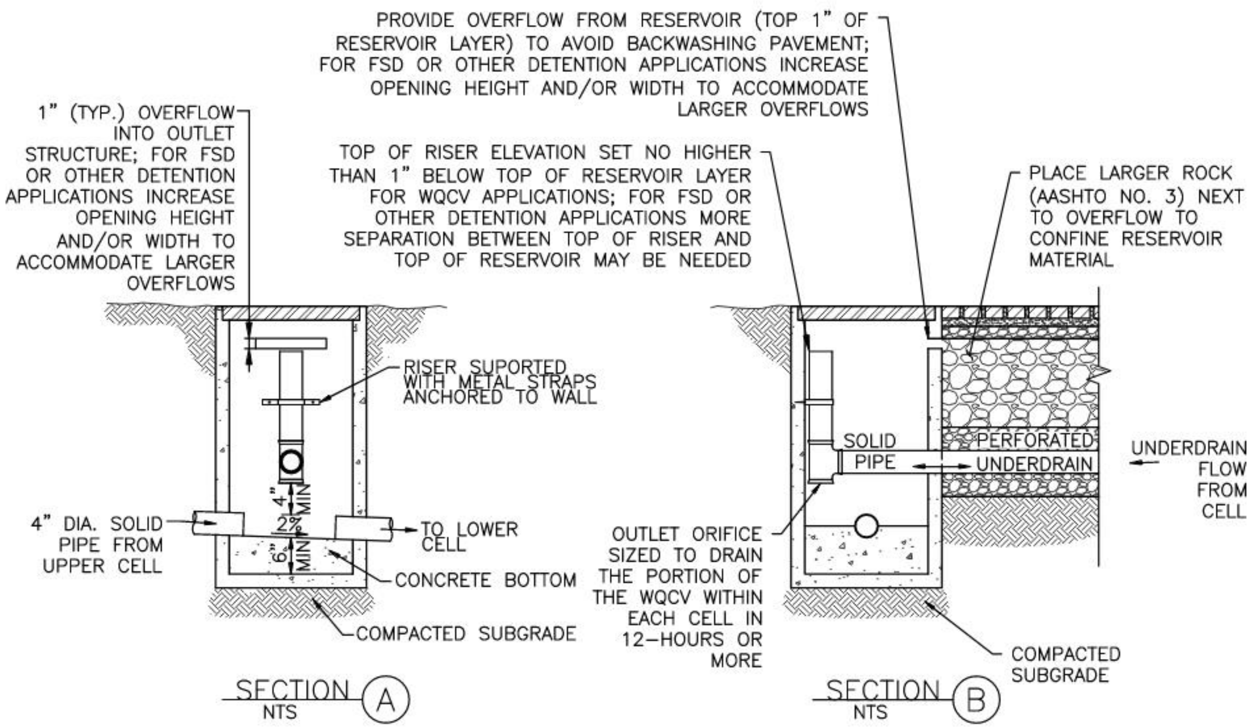


Figure PPS-10. Sloped Permeable Pavement System Installation





PPS-11.
MULTI-CELL PERMEABLE PAVEMENT INSTALLATION WITH LATERAL FLOW BARRIERS
PLAN AND SECTION VIEWS (NOT TO SCALE)

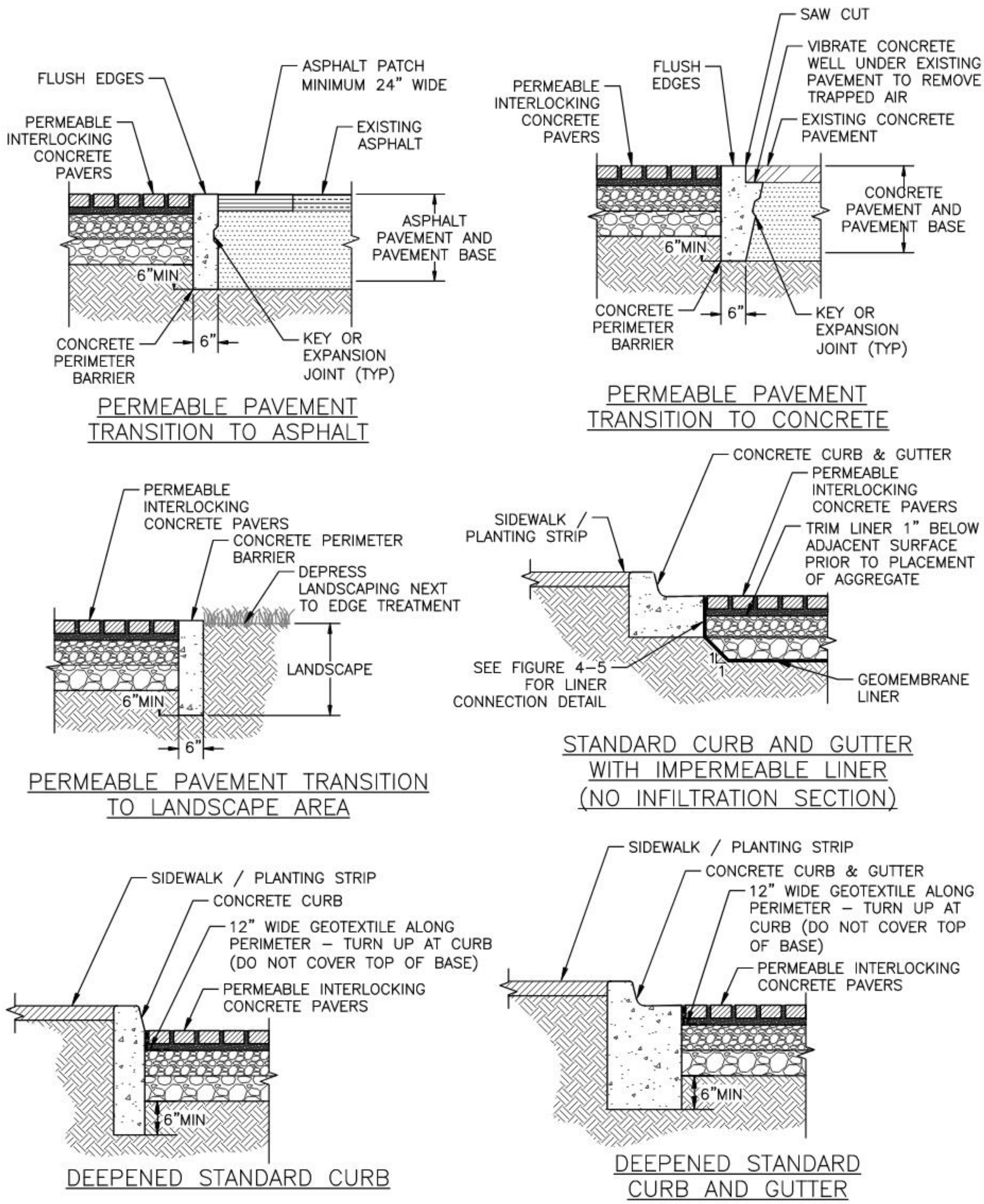
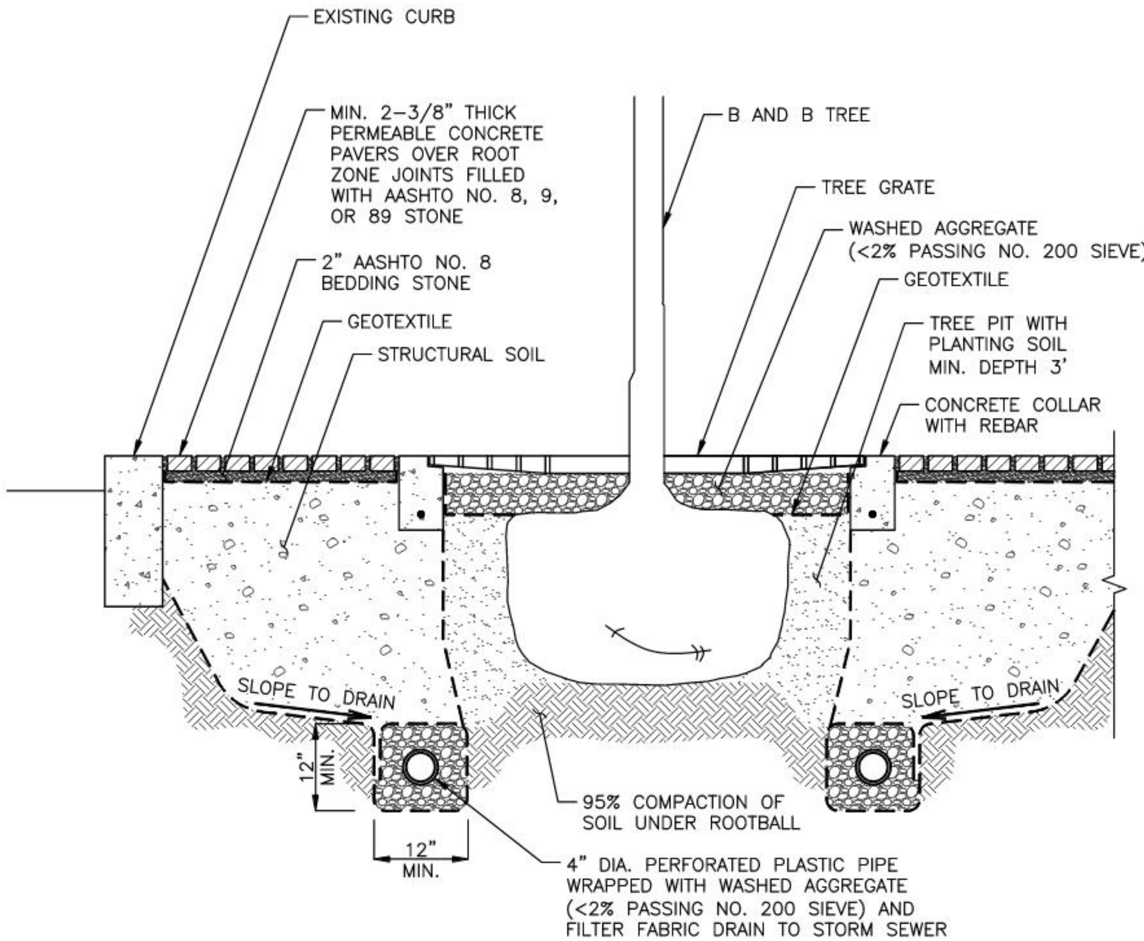


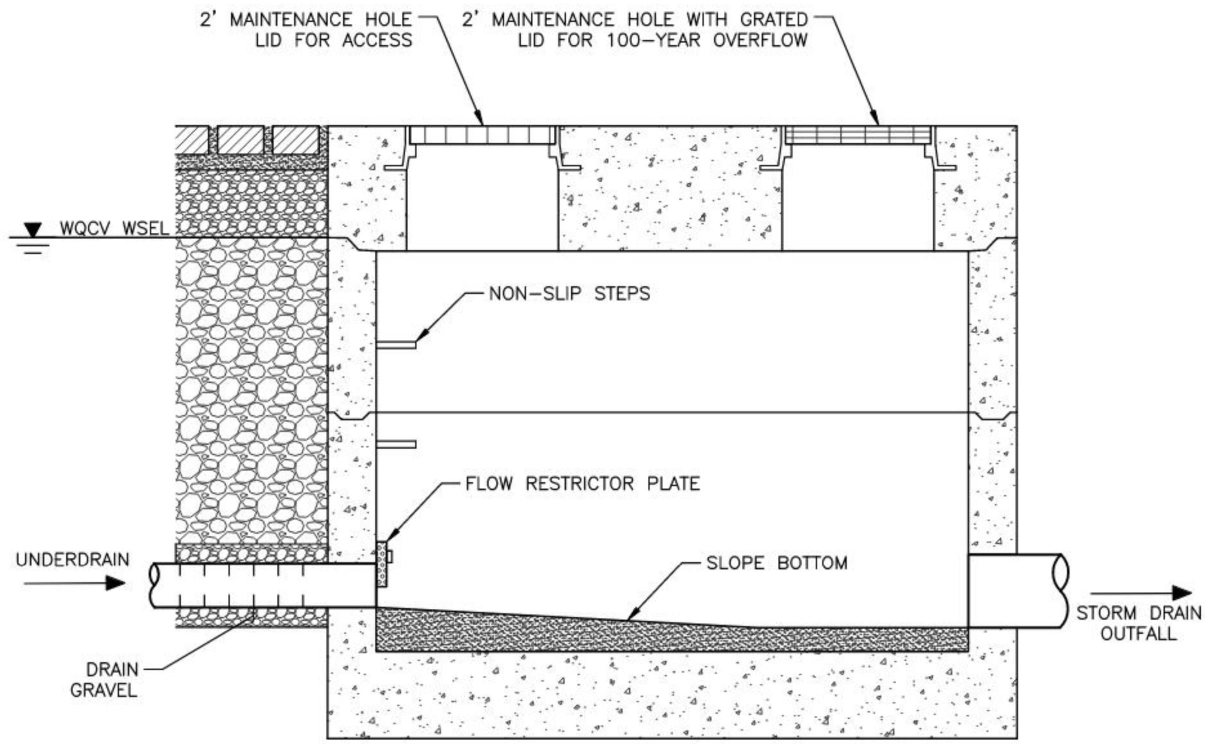
FIGURE PPS-12.
CONCEPTUAL DETAILS FOR PERIMETER BARRIER WALLS
SECTION VIEWS (NOT TO SCALE)



NOTES:

1. ROOT BARRIER MAY BE REQUIRED INSIDE OF CONCRETE COLLAR DEPENDING ON TREE SPECIES. CONSULT ARBORIST FOR THIS APPLICATION.
2. NON-VEHICULAR APPLICATIONS ONLY.
3. BASED ON INTERLOCKING CONCRETE PAVEMENT INSTITUTE (ICPI) DRAWING NO. ICPI-83.

FIGURE PPS-13.
CONCEPTUAL TREE PIT WITH PERMEABLE INTERLOCKING CONCRETE PAVEMENT OVER STRUCTURAL SOIL
SECTION VIEW (NOT TO SCALE)

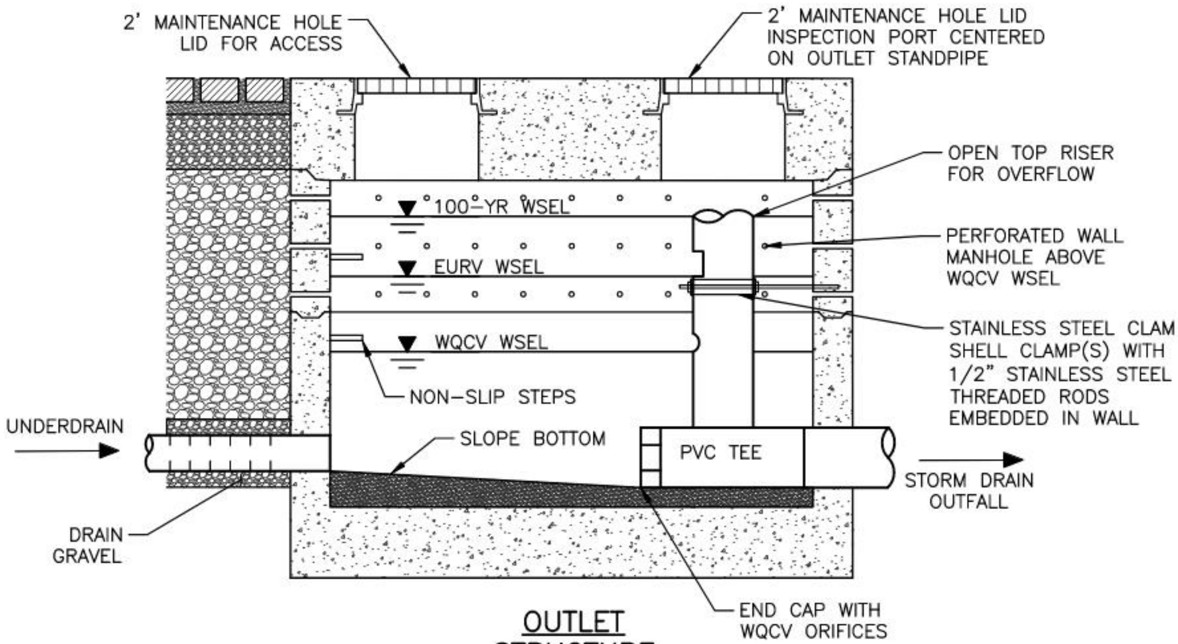


NOTES:

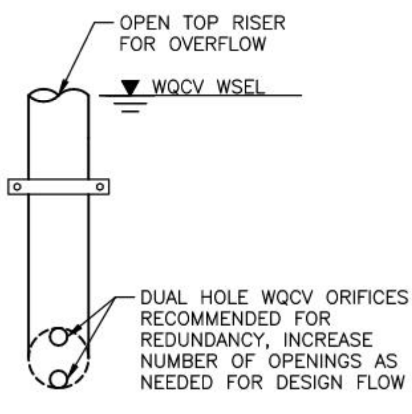
1. THE SECTION SHOWN REPRESENTS A CONCEPTUAL DESIGN OF A PERMEABLE PAVEMENT OUTLET STRUCTURE FOR BOTH WQCV ONLY USING A FLOW RESTRICTOR PLATE. SEE FIGURE PPS-15 FOR CONCEPTUAL DESIGNS OF A PERMEABLE PAVEMENT OUTLET STRUCTURE FOR BOTH WQCV ONLY AND A FULL-SPECTRUM DETENTION AND WQCV SCENARIO USING A STAND-PIPE.

2. REFER TO INTERLOCKING CONCRETE PAVEMENT INSTITUTE (ICPI) DETAIL ICPI-89 FOR ALTERNATIVE DETAIL FOR CONFIGURATION OF PERMEABLE PAVEMENT SYSTEM OUTLET STRUCTURE.

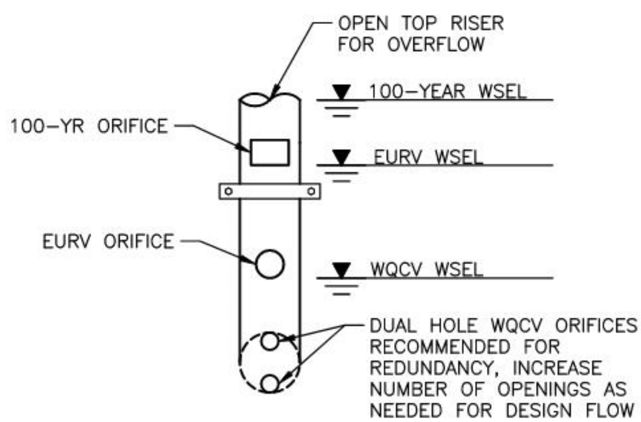
FIGURE PPS-14
CONCEPTUAL PERMEABLE PAVEMENT OUTLET STRUCTURE WITH WITH FLOW RESTRICTOR PLATE
SECTION VIEW (NOT TO SCALE)



OUTLET STRUCTURE



WQCV STANDPIPE ELEVATION



WQCV + FSD STANDPIPE ELEVATION

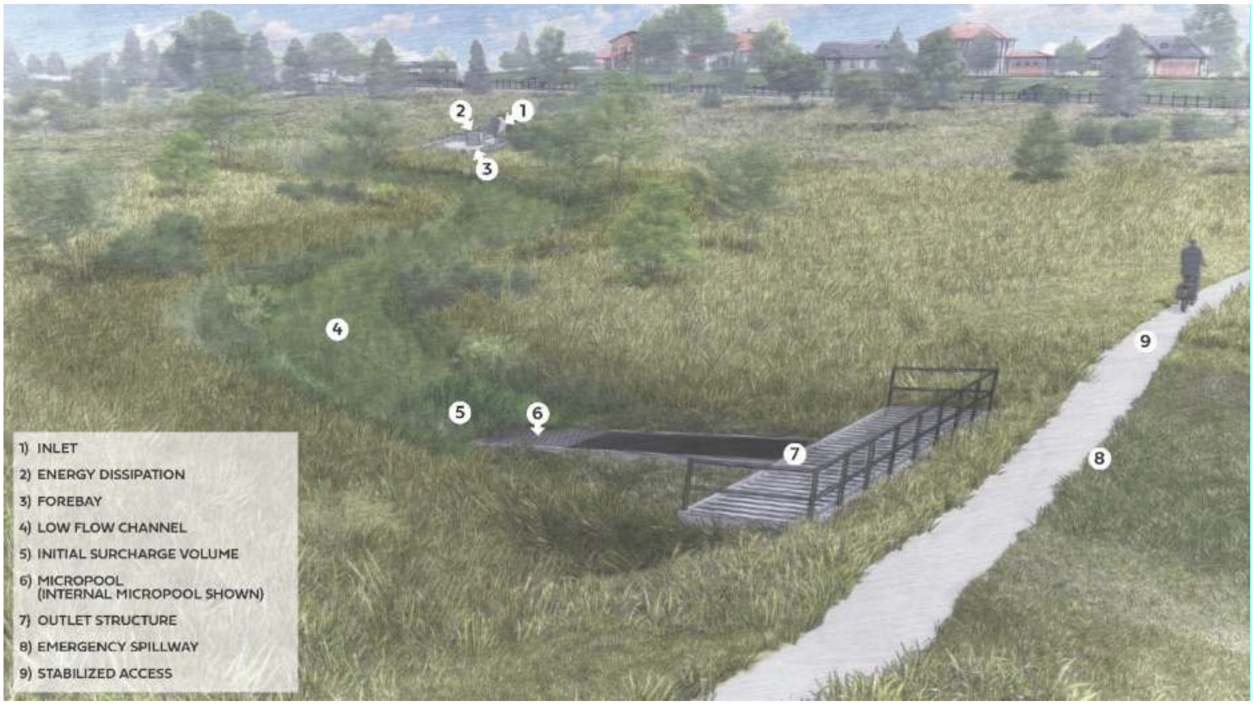
NOTES:

1. THE SECTION(S) SHOWN REPRESENT CONCEPTUAL DESIGN OF A PERMEABLE PAVEMENT OUTLET STRUCTURE FOR BOTH WQCV ONLY AND A FULL-SPECTRUM DETENTION AND WQCV SCENARIO USING A STAND-PIPE. SEE FIGURE PPS-14 FOR CONCEPTUAL DESIGN OF A PERMEABLE PAVEMENT SYSTEM OUTLET STRUCTURE WITH A FLOW RESTRICTOR PLATE.

2. REFER TO INTERLOCKING CONCRETE PAVEMENT INSTITUTE (ICPI) DETAIL ICPI-89 FOR ALTERNATIVE DETAIL FOR CONFIGURATION OF PERMEABLE PAVEMENT SYSTEM OUTLET STRUCTURE.

FIGURE PPS-15
CONCEPTUAL PERMEABLE PAVEMENT OUTLET STRUCTURE WITH FULL-SPECTRUM DETENTION
SECTION VIEW (NOT TO SCALE)

T-6 Extended Detention Basins



EDB-1. Extended Detention Basin Components

Description

An extended detention basin (EDB) detains and slowly releases stormwater runoff, providing time for sediments and particulate pollutants to settle to the bottom. EDBs are designed to release the water quality capture volume (WQCV) over a 40-hour drain time to allow time for sedimentation processes to occur. An EDB can be combined with full spectrum detention (FSD) to provide flood control as described in the *Storage* chapter.

EDBs are sometimes called "dry ponds" because they are designed not to have a significant permanent pool of water remaining between storm runoff events. EDBs can serve as a component in a treatment train downstream of distributed, infiltration-based stormwater control measures (SCMs) that provide runoff reduction and pre-treatment throughout the contributing watershed prior to treatment by the EDB.

MS4 Permit Applicability (Dependent on design and level of treatment)	
Meets Runoff Reduction Standard	No
Meets WQCV Capture Standard	Yes
Meets Pollutant Removal Standard	Yes
Typical Effectiveness for Targeted Pollutants	
Sediment/Solids	Medium-High
Total Phosphorus	Medium
Total Nitrogen	Low
Total Metals	Medium
Bacteria	Low
Common Applications	
Runoff Reduction (General)	No
Used for Pre-treatment	No
Integrated with Flood Control	Yes
Costs	
Life-Cycle Costs	Medium

SCM Components

Primary EDB components include inlet(s), energy dissipation measures and forebay(s) or other pretreatment practices, low flow channel(s), the initial surcharge volume, micropool, outlet structure, emergency spillway, and stabilized access as shown in Figure EDB-1. All of these components provide important functions in an EDB and omitting one or more of these components will put additional stress and importance on other components, requiring additional and sometimes more costly types of maintenance. Providing pretreatment with runoff reduction measures in the watershed can reduce the volume of runoff that must be managed by the EDB. Other pretreatment SCMs can also be used to capture and retain trash that may otherwise clog outlet structure orifices.

Component	Intent
Inlet	Allows stormwater to enter the SCM. Maximize distance between inlet(s) and outlet to minimize short-circuiting and increase hydraulic residence time.
Energy Dissipation	Reduces the velocity and energy of runoff entering the SCM through roughness and/or structural measures to promote sedimentation in the forebay.
Forebay	Facilitates removal of trash and coarse sediments in an accessible location to reduce the frequency of sediment removal in the main body of the EDB.
Low Flow Channel	Conveys low flows from the inlets to the outlet structure, limiting the inundation area of frequent flows to facilitate maintenance operations.
Initial Surcharge Volume	Stores runoff from frequently occurring events in an area with hydrophytic vegetation adapted to frequent and prolonged inundation.
Micropool	Reduces potential clogging at the outlet by providing a flow path below the permanent water surface elevation to the orifice plate even when the trash rack becomes clogged above the water surface.
Outlet Structure	Releases the WQCV through control orifices over a 40-hour drain time and conveys runoff from larger events to downstream conveyance system.
Emergency Spillway	Discharges flows exceeding design events to downstream conveyance system while protecting embankment stability.
Stabilized Access	Provides maintenance access to components of the EDB.

Site Considerations

EDBs can be located as regional, sub-regional, or onsite facilities as discussed in the *Storage* chapter in the context of FSD. One of the most important factors for assessing suitability of an EDB for a site is the contributing drainage area and imperviousness. EDBs are not appropriate for tributary areas with less than 2 acres of impervious area because the size of the orifice needed to release the WQCV over 40 hours becomes very small and cannot practically be protected from clogging. EDBs in large watersheds must account for additional factors such as baseflow and impact to stream stability. Table EDB-1 summarizes considerations for various contributing impervious areas.

Although there are many considerations and constraints that may dictate the location of EDBs, these SCMs function best when designed for contributing impervious areas of approximately 20 to 50 acres. This range provides the following benefits:

- At 20 acres of impervious tributary area, the orifices are typically large enough to use standard bar grating for the trash rack rather than a well screen. This will reduce required maintenance at the outlet structure.
- These EDBs are large enough to achieve meaningful flow attenuation and can be combined with FSD. In some cases, these facilities can be accepted for public maintenance, represented in watershed hydrologic models, and incorporated in floodplain evaluations, provided that they are properly designed and with adequate assurances for perpetual maintenance.
- EDBs of this size can be located to receive drainage from adjacent developed areas prior to entering the stream network, reducing impacts to streams.
- EDBs in this size range generally will not have baseflows large enough to complicate the design and function of outlet structures.

For watersheds with 2 to 20 impervious acres, consider filtration or infiltration SCMs instead of EDBs to avoid small orifices prone to clogging. To function properly, the orifices for EDBs in this size range require protection by a well screen, which requires frequent inspection and maintenance to ensure that the orifices and well screen do not become clogged.

Watersheds larger than 50 acres and watersheds with baseflows complicate EDB design, pose sedimentation issues, and may reduce the level of treatment provided. In these situations, the most effective water quality treatment can be achieved by subdividing the watershed into smaller areas where subregional EDBs or other practices can be used in an offline configuration.

The *Storage* chapter of Volume 2 provides guidance on locating EDBs and combining EDBs with FSD. The *Storage* chapter provides extensive discussion of siting considerations for onsite, subregional, and regional detention facilities that is applicable to planning and design of EDBs.

Table EDB-1. Contributing Impervious Area Considerations for EDBs

Contributing Impervious Area (acres)	EDB Considerations
0-2	• Not recommended - use filtration-based SCM.
2-20	• Consider sand filter, bioretention, or other filtration or infiltration SCM as alternative. • Limit EDB outlet to two WQCV orifices to maximize orifice size while still providing redundancy in case one orifice clogs. • Protect orifices less than 1.25 inches with well screen and consider additional measures such as standard bar grating upstream of well screen to reduce the frequency of maintenance of the well screen.
20-50	• Limit EDB outlet to two WQCV orifices to maximize orifice size while still providing redundancy in case one orifice clogs. • Protect orifices with standard bar grating unless orifice dimensions are less than 1.25 inches.
>50	• Evaluate baseflow under current and fully developed conditions considering irrigation return flows and design outlet to pass baseflows without affecting the storage provided by the WQCV. Baseflows may change seasonally and year to year, so if observed baseflows are used in design, be sure to consider recent climate. • Consider using multiple sub-regional EDBs throughout the watershed instead of designing the EDB for this size tributary. • Not suitable for drainage areas exceeding one square mile. • Must still provide WQCV for entire upgradient watershed.

Community Values

EDBs are important features in the urban landscape, and when designed thoughtfully, can provide significant value to the community above and beyond their water quality functions. There are generally two aesthetics for EDBs: 1) graded, landform-type basins with vegetated sides and bottoms and 2) architectural-type basins, using walls and other structures instead of earth for containment of the WQCV. Whether planning an architectural or a graded landform EDB, consider how the SCM contributes to or impacts its site, visitors, and the surrounding community, as well as how access is provided for maintenance operations. Since the graded landform type EDBs are most common, the following discussion focuses on this type of facility. Recommendations for architectural EDBs follow at the end of this section.

In addition to performing water quality treatment, EDBs should enhance the site's landscape, provide diverse vegetation for aesthetics and wildlife habitat, and incorporate visitor amenities such as walkways and seating. Key considerations for EDBs to integrate community values include:

- Create EDBs with interesting and attractive landforms. A simple but effective approach is to design landforms that appear to have been created by fluvial processes, with sinuous low flow channels, curving transitions between the EDB bottom and side slopes, and a more curvilinear, stream-like form versus a rectangular basin shape. Side slopes of the basin should be varied and may include intermediate terraces or benches to reinforce the idea of a water-sculpted landform. When shaping the basin, consider requirements for access and vegetation management.

Photograph EDB-1. This EDB illustrates the use of a soft, meandering low flow channel and varied bottom grading with vegetation selected for the associated hydrologic conditions.

- Consider designing EDBs with terraces of different elevations in the pond bottom (potentially stepping up from the lowest parts of the pond by 1 foot +/- elevation increments) to vary the inundation periods and depth of ponding for each terrace, and as a result, creating different water regimes and soil saturation levels for each. These different terraces can then be vegetated with specific vegetation types (emergent wetland, wetland fringe, riparian, upland, etc.) corresponding to their anticipated water regimes, resulting in a diverse and more resilient vegetative habitat within the EDB. Photograph EDB-1 illustrates an EDB with varied basin grading and vegetation. The variation in bottom surface elevation will also make it easier to maintain the vegetation of the pond, as the consistently wet areas will be limited and clearly defined so that the remainder of the pond will be less soggy and easier to maintain. Avoid flat-bottomed ponds with little or no variation in elevation in the bottom surface.

- Don't place active uses and/or substantial visitor amenities within the area that will be inundated by the WQCV. Any uses, amenities, or enhancements included as part of the EDB design should either be resilient to frequent inundation or placed out of prolonged inundation zones. Active uses within the facility, such as sports fields and walking trails, may either have very limited use due to flooding or soggy conditions or may require high levels of maintenance due to saturated soils and sediment deposition. MHFD discourages the use of irrigated bluegrass and other high maintenance turfgrasses in EDBs due to the wet conditions and accumulation of sediment expected in these facilities.

- Minimize negative impacts of required structural elements (i.e., outfalls, energy dissipation, and retaining walls) on the EDB's surroundings. Pay special attention to those elements visible from prominent viewing points. Techniques include positioning wall faces and culvert openings away from view areas, screening structures with vegetation, using natural materials such as boulders, using soil riprap in lieu of exposed riprap, using an upstream trash vault or hydrodynamic separator (HDS) for pretreatment (acting as a forebay), or custom-designing structural components to be attractive design elements that enhance the setting. Prominently placed standard drainage infrastructure elements such as precast flared end sections, "dragon's teeth" energy dissipators, and exposed riprap embankments communicate a message that a place is not intended for community use.

- Consider planting appropriate vegetation in addition to native grass. EDBs can sustain a wide variety of plant material, including trees, shrubs, and herbaceous plants. Plant diversity is beneficial for wildlife, pollinators, aesthetics, and people. Plant selection and placement should reflect the water regimes that will be created within the pond bottom (and any terraces, if employed) and should be appropriate for the anticipated level of maintenance that property managers are committed to providing for the long term. Avoid planting trees in locations where roots can damage structures and where sediment will accumulate. As with many other SCMs, an irrigation system is recommended, at a minimum for establishment of vegetation, but ideally for supplemental use during extended periods of drought.

Walls are generally discouraged due to concerns with safety, access, maintenance, and long-term replacement costs. Where walls are needed, install railing for safety and consider the following design approaches:

- Limit wall heights to a maximum of 3 to 4 feet for safety and to improve accessibility. If additional pond depth is necessary, use multiple walls with landscaped intermediate terraces. If internal landscaped terraces are not possible, consider screening the perimeter of the EDB with shrub plantings or hedges, prioritizing primary viewing areas to the facility.
- Use materials for structures and walls with aesthetic qualities that fit the context of the site, such as natural stone, colored and/or stamped concrete, or concrete textured by use of a form-liner. Provide thoughtful detailing to reduce apparent mass of walls and structures and add refinement. Potential techniques include visually breaking up large panels of concrete with reveals, chamfers or stone veneer, and by adding stone or pre-cast concrete capstones to walls.

Maintenance

Recommended maintenance practices for all SCMs are provided in Chapter 6 of Volume 3. Routine maintenance for EDBs includes cleaning sediment and debris from forebays, clearing debris from outlet structure orifices and trash racks as necessary, vegetation management, and cleaning accumulated sediment from low flow channels.

During design, consider the following to ensure ease of maintenance over the long-term:

- Route foundation drains and other groundwater drains to bypass the water quality plate, directing these drains to a conveyance element downstream of the EDB. This will reduce potential for excessively wet areas for prolonged periods of time within the EDB.
- A micropool, or alternative measures that provide equivalent function, is recommended

to reduce clogging of the orifices. If a micropool is not used, the low flow channel, initial surcharge volume, and outlet configuration become even more critical, and more frequent maintenance may be required.

- Provide an initial surcharge volume and follow criteria for the low flow channel. Whether the low flow channel is vegetated or concrete, follow design criteria for low flow section depth and width to limit the spreading of frequent inundation across the whole bottom of the EDB. Ensure that areas adjacent to the low flow channel have adequate slope to drain into the low flow channel.
- When available, use sandier-textured soils (loamy sand, sandy loam) in the bottom of an EDB to promote infiltration, quicker dewatering, and improved stability compared to clayey soils. For watersheds with low sediment loading, consider installing an underdrain and sand or bioretention media in the lowest portions of the EDB to help the basin bottom dry out after storm events.
- Provide a stable bottom for the forebay that can be scraped with maintenance equipment to remove sediment (e.g., concrete or a cast reinforced concrete system with open cells for vegetation).
- Identify what maintenance equipment will be used and provide stabilized access to the forebay and outlet for maintenance. Consider what flow management techniques such as temporary diversion or dewatering may be required in order to maintain the EDB.
- Limit walls to areas above the WQCV because failures are more likely in frequently inundated areas.
- Ensure walls do not impact access for maintenance equipment.
- During vegetation establishment, adjust irrigation systems (if present) on a monthly basis. Following establishment of vegetation, inspect plant material on a bi-monthly basis to determine if supplemental irrigation is needed for plant health.

Design Procedures and Criteria

The following steps outline the design procedure and criteria for an EDB, and Figure EDB-1 shows a typical EDB plan view. MHFD-BMP (MHFD 2018) is an Excel-based workbook that performs many of the design calculations below and checks for conformance to these criteria. Designers can use the MHFD-Detention workbook (MHFD 2021) to develop and route storm hydrographs through an EDB, either stand-alone or with FSD, and to design the outlet structure. Design details in Figures EDB-2 through EDB-13 are located at the end of this fact sheet.

1. **Design Storage Volume:** Determine the WQCV and other design volumes that the EDB is intended to control such as the EURV and/or the 100-year detention volume. Calculate the required storage volume, accounting for runoff reduction SCMs in the contributing watershed. Determine the required WQCV using guidance in Chapter 3 or use equations provided in the *Storage* chapter of Volume 2 for the EURV and larger design storms.

2. **EDB Shape:** Always maximize the distance between the inlet and the outlet. When feasible, shape the EDB so that the ratio of basin length (measured along the low flow channel from inlet to outlet) to average basin width is at least 1.5:1 (EPA 2021) and preferably greater than 2:1. A longer flow path from inlet to outlet reduces short circuiting and provides more residence time for sedimentation to occur. Meander the alignment of the low flow channel to increase the length while still maintaining a bench on one or both sides for equipment access. See the *Storage* chapter of Volume 2 for additional guidance on basin shape for multiuse facilities.

Designing to Attain the Required Storage Volume

It is good practice to design an EDB to provide slightly more volume than the minimum required. Most jurisdictions require a survey to confirm that the design volume is achieved. Given construction grading tolerances, providing slightly more volume reduces the chance that rework will be necessary to achieve the required volume. Designing with additional volume also allows for some accumulation of sediment while still maintaining the design volume. This may reduce the frequency of cleanout in some instances.

3. **Side Slopes:** EDB side slopes should be 4:1 or flatter for maintenance and aesthetics. In general, the use of walls is discouraged due to concerns with access, maintenance, and long-term replacement costs.

4. **Inlet and Forebay:** Design the inlet(s) and forebay(s) to satisfy criteria in Section 5.0 *SCM Inflow Features* of this chapter.

5. **Low Flow Channels and Basin Bottom Grading:** Design a low flow channel to convey concentrated runoff from inlets to the initial surcharge zone near the outlet. Low flow channels should be 18 inches deep to limit migration over time and reduce inundation of adjacent benches so that they remain stable to allow equipment access for maintenance. Side slopes for the low flow channel may be as

Photograph EDB-2. This EDB depicts a meandering low flow channel with adjacent benches that remain drier to allow equipment access for maintenance.

steep as 2:1 (horizontal:vertical) provided that the side slopes are designed with appropriate soils and groundcover to resist erosion from anticipated design flows.

EDB Grading and Shaping

EDBs can provide significant value to the community when thoughtfully designed. As discussed in the Community Values section, consider variation in basin shape, grading that provides terraces of mixed elevations and appropriate vegetation for varying hydrologic conditions.

Grade the bottom of the basin outside the limits of the low flow channel to slope at 2% or more to encourage drainage. Consider shaping the basin bottom to create zones of varied depths and hydrology. Provide at least 6 inches of suitable topsoil in the basin bottom and side slopes. See MHFD's *Topsoil Management Guidance* for information on texture and nutrients for suitable topsoil. Consider using sandier-textured soils (loamy sand, sandy loam) from onsite or imported sources in the low flow channel and bottom benches to promote higher infiltration capacity, quicker dewatering, and improved stability compared to clayey soils.

Low flow channel options include:

- **Vegetated Low Flow Channels:** Sedimentation is the primary pollutant removal mechanism for EDBs; however, when designed and maintained properly, vegetated low flow channels enhance treatment by slowing and filtering stormwater runoff and promoting infiltration and wetland treatment processes. Design vegetated low flow channels with sinuosity and varied grading to emulate a natural stream channel. Select riparian grasses, sedges, and rushes that thrive with frequent and prolonged inundation. Design vegetated low flow channels with a consistent longitudinal slope between 1 to 2% from the forebay to micropool with a minimum depth as shown in Figure EDB-2. Provide consistent longitudinal slope and depth and periodic concrete or boulder sills to demarcate the design grade and facilitate restorative maintenance when sediment removal in the low flow channel is necessary.

  Consider vegetated low flow channels for enhancement of stormwater quality via filtering and infiltration and to promote natural materials when compatible with the context of the site and the maintenance capabilities of the owner. MHFD recommends vegetated low flow channels on a case-by-case basis, with the approval of the local jurisdiction.

- **Low Flow Channels with Concrete Pan:** A low flow channel with a concrete pan establishes the bottom of the basin for routine maintenance. The concrete pan should have a 6-inch curb and additional depth created by side slopes adjacent to the concrete pan as shown in Figure EDB-2. The total depth of 18 inches will limit the area of the basin bottom inundated by frequent flows and reduce maintenance over time. See Figure EDB-2 for geometry. Design a concrete pan with a longitudinal slope between 0.4% and 1%; the flatter slopes reduce flow velocities, and the steeper slopes help avoid low points due to construction tolerances. Riprap and soil-riprap-lined low flow channels are not recommended due to past maintenance experiences where the riprap was inadvertently removed along with sediment during maintenance.

6. **Initial Surcharge Volume:** Provide a surcharge volume above the micropool to manage frequently occurring runoff and sedimentation. This helps to minimize prolonged standing water and sediment deposition in turf grass portions of the EDB, which is critical to turf maintenance and mosquito control. The initial surcharge volume has a minimum depth of 4 inches and extends from the water surface elevation of the micropool up to the lowest elevation of the low flow channel. When no micropool is provided, increase the depth of the initial surcharge volume to 12 inches to accommodate the additional clogging anticipated with this option. Plant hydrophytic vegetation in or hardscape the initial surcharge area. The initial surcharge volume is a part of the WQCV and does not need to be provided

Designing for Baseflows

Large tributary areas will generate baseflows that can be accommodated in a variety of ways. Consider the following:

- If water rights can be obtained, consider alternate SCMs such as a constructed wetland pond or retention pond.
- Anticipate and build in the ability to make future adjustments to the size of the lowest orifice. Following construction, monitor periodically. Intermittent flows can become perennial and perennial flows can increase over time. If baseflows increase over time, orifice adjustments may be necessary long after construction of the SCM is complete.
- When feasible, design foundation drains and other groundwater drains to bypass the water quality plate, directing these drains to a conveyance element downstream of the EDB. This will reduce baseflows and help preserve storage for the WQCV.
- When the watershed is fully developed and baseflow can be approximated prior to design, the water quality orifices should be increased to drain the WQCV in 40 hours while also conveying the baseflow. This requires reservoir routing using an inflow hydrograph that includes the baseflow, which can be accomplished using the *MHFD-Detention* workbook available at www.mhfd.org.
- Increase the initial surcharge volume of the pond to provide some flexibility when baseflows are known or anticipated. Baseflows are difficult to approximate and will continue to increase as the watershed develops. Increasing the initial surcharge volume will accommodate a broader range of flows.

in addition to the WQCV. Clearly show the initial surcharge area on the grading plan and in profile/section.

7. **Outlet Structure:** Locate the outlet structure in the downstream embankment at the low point of the EDB. As described in Section 6.0 *SCM Outflow Features* of this chapter and the *Storage* chapter, the outlet may be designed for release of the WQCV as well as other design volumes including the EURV and 100-year storage volume. Use the *MHFD-Detention* workbook to size the outlet geometry. Outlet structures can be designed in a variety of configurations including external or internal micropools, vertical or sloping trash grates, and different sized grating depending on the size of the orifices. Several example outlet configurations are summarized in Table EDB-2 and illustrated in Figures EDB-3 through EDB-7.

Table EDB-2 Example Outlet Structure Configurations

Figure	WQ or Full Spectrum	Micropool Type	Orifice Grating Configuration
EDB-3	WQ	External	Vertical
EDB-4	FSD	External	Vertical
EDB-5	FSD	External	Flush sloping
EDB-6	FSD	Internal	Flush sloping
EDB-7	FSD	None	Flush sloping

Wingwalls extending upstream of the orifices may be parallel or angled. Parallel wingwalls provide a consistent, reduced span length for flush-sloping grating configurations. In turn, flush-sloping grating provides increased trash grate area compared with vertical grating, facilitates trash removal, and may reduce the length of handrail required. Photograph EDB-3 shows an outlet structure with parallel wingwalls and flush-sloping grating similar to that depicted in Figure EDB-6.
Each of the example outlets shown in Figures EDB-3 through EDB-7 are based on water quality orifices large enough to be protected with standard bar grating, omitting the well screen. Figures EDB-8 through EDB-10 provide plan and section views for standard bar grating. For smaller orifices where a well screen is used, an example configuration of WQCV and EURV orifice plates (for full spectrum

Photograph EDB-3. Outlet structure with coarse safety grating covering the micropool in the foreground, standard bar grating flush with the top of parallel concrete wingwalls and extending down through the micropool, and coarse safety grating covering the 100-year drop box in the background.

detention) is shown in plan and section views in Figures EDB-11 through EDB-13.

Consider site context and public safety during design of outlet structure. Install handrails where needed to prevent the public from injury associated with vertical falls off of a structure or between the bars of a grate.

Protection to Minimize Clogging of Orifices

One of the key design considerations for EDBs is reducing the risk that the orifices clog with debris. A variety of techniques are used to reduce the likelihood of clogging, including:

- Protecting small orifices with well screen; however, well screen is so efficient at trapping debris that the screen itself is susceptible to clogging and requires frequent inspection and maintenance.
- Providing bar grating upstream of well screen to capture larger debris and reduce the amount of debris approaching the well screen.
- Eliminating well screen if orifices are large enough to be protected by standard bar grating. Standard bar grating has openings approximately 1 inch by 4 inches and is not as susceptible to clogging as the well screen. Orifice dimensions in the range of 1.25 to 2.5 inches are generally considered large enough to eliminate the well screen in favor of standard bar grating. If a well screen is not provided, the design of the micropool, initial surcharge zone, and low flow channel are particularly critical, as are frequent inspections and maintenance. Do not eliminate the well screen if the smallest orifice dimension is less than 1.25 inches.
- Reducing the number of orifices draining the WQCV to increase the size of the orifices. Using two orifices instead of three will increase orifice size while providing redundancy in case one orifice clogs.
- Locating EDBs to serve larger impervious areas with corresponding larger WQCV orifices.
- Designing trash deflectors to cover orifices that are not protected by well screen. Trash deflectors, shown Photograph EDB-4, consist of a vertical V-shaped plate projecting in front of the orifice to reduce the likelihood that debris can lay flat against the plate and block the orifice.

Key components of EDB outlets include:

- **Orifice Plate**: The water quality orifice plate releases the WQCV over 40 hours. As highlighted in Table EDB-1 and in order to maximize the orifice size and the allowable opening in the trash grates, MHFD recommends two orifices arranged vertically to drain the WQCV and a third orifice when designing for FSD. For most applications, an orifice plate consists of a 1/4-inch-thick steel plate with circular or rectangular openings spanning a concrete block-out. Figure EDB-12 provides a detail for a typical orifice plate for an EDB protected by a well screen. Orifices large enough to be protected with standard bar grating as opposed to a well screen may benefit from a trash deflector, shown in Photograph EDB-4, to reduce the likelihood that debris can lay flat against the plate and block the orifice.

Photograph EDB-4. Where orifices are large enough to omit well screen, trash deflectors can be used in combination with standard bar grating to reduce the likelihood that debris will plug one or more orifice.

- **Trash grates**: Well screens are necessary to protect orifices less than 1.25 inches. Depending on the characteristics of the contributing area, the designer may also want to consider well screens when an orifice dimension is in the range of 1.25 to 2.5 inches. Weigh the risk of clogging an orifice versus the risk of clogging the well screen when deciding to provide a well screen for orifices from 1.25 to 2.5 inches. As shown in Photograph EDB-5, the openings in the specified well screens are small and almost all trash and debris are filtered by the screen, making well screens susceptible to clogging and requiring frequent maintenance. When well screens are used, frequent inspection and maintenance is required. Design screens to be at least 2 feet wide to provide adequate net open area, regardless of orifice size. Consider designing the well screen to be removable and adding an upstream trash rack constructed of standard bar grating to reduce the amount of debris impacting the well screen and to facilitate maintenance. Table EDB-3 provides sizing information for well screen, standard bar grating, and safety grating. Refer to the *Culverts and Bridges* chapter of Volume 2 for additional guidance on the design of safety grates.

The grating over the drop box that receives 100-year flows should consist of standard bar grating or safety grating and may be flush or raised to provide a vertical opening for additional capacity with lower debris blockage. See the *Storage* chapter for various configurations for the grates over the 100-year drop box and recommendations for preventing debris blockage.

Photograph EDB-5. Well screen is intended to protect small orifices from clogging; however, the fine screen is itself subject to clogging and requires frequent inspection and maintenance to keep clear.

Design grating to satisfy two loading conditions with a deflection of ¼ inch or less: 1) a uniform load of 100 pounds per square foot and 2) a concentrated load of 200 pounds applied at the center of the span. Designing grates to support the full hydrostatic head is not recommended because this condition is unlikely and will increase the weight of steel members, making removal for maintenance difficult.

Table EDB-3. Properties of Trash Grates

Grate	Specification
Well Screen	Stainless steel screen with vertical No. 93 vee-wire and 0.139" openings between wires. Horizontal 0.074" x 0.75" support rods 1" on center spacing. (Johnson well screen or equivalent)
Standard Bar Grating	Aluminum or steel fabricated panels with bearing bars typically 1" or greater (based on span and load) x 3/16" at 1-3/16" on center and cross bars at 4" on center. Steel panels must be hot-dipped galvanized after fabrication.
Safety Grating	Panels fabricated of steel pipes or bars with maximum clear spacing of 5", hot-dipped galvanized after fabrication.

The outlet structure design must be completed by a licensed professional engineer and include details for the following components:

1. Steel reinforcement within concrete structure.
2. Orifice plate details, including connection to concrete structure.
3. Well screen details (if used), including connection details or guide channels for removable configuration.
4. Standard bar grating panel dimensions, orientation, connections, and hinges.

5. Coarse safety grating panel dimensions, orientation, and connections.
6. All other metal work and connections required for construction of the outlet structure.
7. Required corrosion protection; all steel members must be hot dip galvanized after fabrication.
8. Outlet pipe bedding and cutoff to reduce the possibility of water piping through the embankment.

Photograph EDB-6. In this outlet, runoff flows through safety grating (5-inch clear bars) to separate floating debris before continuing through standard bar grating that extends to the bottom of the micropool The grating extending down into the micropool can be raked through the gap in coarse safety grate to clear debris.

- **Micropool:** Design the micropool in conjunction with the orifice plate and trash rack to allow water to flow through a submerged portion of the trash rack, shown in Photograph EDB-6, and reach the openings in the orifice plate, even when floating vegetation and debris are matted against the portion of the trash rack that is above the water surface. MHFD recommends the use of micropools to avoid problems associated with clogging of trash grates and orifices and the resulting standing water and vegetation die-off.

8. **Emergency Spillway:** At a minimum, design the emergency spillway to convey the fully developed, undetained peak discharge for the 100-year design storm event. Design spillway structures in accordance with the *Storage* chapter, applicable Colorado dam safety regulations, and any local drainage criteria.

Photograph EDB-7. This EDB was originally constructed without a micropool and was retrofitted with a sand filter with underdrain to reduce the potential for clogging the outlet and water backing up in the basin.

9. **Vegetation:** A dense, healthy stand of vegetation reduces erosion, helps trap fine sediment, and enhances infiltration. Primary vegetative ground cover should be native grasses and other herbaceous vegetation and should be dominated by rhizomatous sod-forming grass species (rather than bunch grasses) to establish full cover. In addition to its functional role, vegetation adds aesthetic and habitat value. Designers may create a range of

planting zone types by creating terraces with varying elevations within the pond bottom, and thereby varying the water regimes of each. Higher terraces will have less depth of ponding and less time of inundation and will therefore support different plant species than lower terraces. Each terrace should be seeded/planted with appropriate multi-species seed mixes and plant materials that reflect the anticipated water regime for each location (e.g., wetland, wetland fringe, riparian, upland). Trees can be incorporated in EDB designs to provide shade, aesthetic values, and other benefits. Plant trees in areas that do not require frequent sediment removal (i.e., avoid the initial surcharge area) and consider the mature size of the tree as well as its root structure to avoid potential damage to structures and future maintenance access issues. Irrigation is recommended to aid in vegetation establishment. Where possible, place irrigation heads outside the basin bottom to prevent damage from pond sediment and damage during maintenance.

Alternatives to Micropools

Outlet structures without micropools will require more frequent maintenance to remove debris than outlets with properly designed micropools. If an outlet is designed without a micropool, it is essential to maximize orifice size, provide a deeper initial surcharge zone, and provide a low flow channel meeting MHFD's criteria. Figure EDB-7 shows an outlet structure alternative without a micropool.

To compensate in part for the increased maintenance issues associated with an outlet that does not have a micropool, consider incorporating these features:

1. **Deeper initial storage zone.** Because of the increased likelihood of debris blockage at the lowest portions of an outlet structure without a micropool, provide a deeper initial storage zone to contain water that may back up upstream of the outlet.
2. **Sand filter upstream of outlet**. As depicted in Photograph EDB-8, a sand filter section in the low flow channel upstream of the outlet structure can aid in dewatering the EDB. This requires an upstream watershed with low sediment loading to avoid rapid clogging of the filtration feature. When using a sand filter, size the surface area of the sand filter to be at least as large as the footprint of the forebays for the EDB. Provide a media depth of 1.5 feet and an underdrain. See the Sand Filter fact sheet for criteria for filter media and Section 4.3.3 *Underdrain Systems* of this chapter for criteria for underdrains.
3. **Increased sediment trapping efficiency**. Consider incorporating a larger forebay that exceeds minimum recommendations to increase sediment trapping efficiency. Consider ways to provide open-cell concrete in the bottom of the forebay to establish dense vegetation to slow flows and improve sediment trapping. Use a vegetated low flow channel for increased sediment trapping.
4. **Additional trash capture at inflow points**. Integrate trash collection features into the inflow conveyances entering the EDB. These may take the form of specially designed grating, debris "fences" at the downstream perimeter of the forebay, trash/debris nets, or manufactured treatment devices.

10. **Access:** Provide maintenance access into the forebay and the area next to the outlet structure. Consider the type of maintenance equipment that will be used and provide stabilized access for maintenance vehicles and excavation equipment where needed. The maintenance plan developed as a part of the design must provide details on required maintenance equipment and how sediment and trash will be removed from the outlet structure and micropool. Some review agencies may require vehicle access to the bottom of the EDB and into the low flow channel regardless of the size of the watershed. Use a minimum path width of 10 feet when designing for vehicle access. Do not exceed grades of 10% for haul road surfaces and 20% for skid-loader and backhoe access. Stabilized access includes concrete, articulated concrete block, concrete grid pavement, or reinforced turf pavement. Provide a cross-slope for the access path of 2%.

Construction Considerations

Successful construction of an EDB requires careful attention to proposed grades, construction details, and vegetation establishment. For project success, implement the following practices:

- If an area identified as an EDB is used as a sedimentation basin during construction, the area must be fully rehabilitated after construction by removing sediment and other materials accumulated during construction, placing topsoil, and establishing vegetation.
- Verify the subgrade elevations of the EDB prior to placement of topsoil. Adjusting pond grades after topsoil placement can be costly.
- Avoid over-compaction of the initial storage area and other areas that will be frequently inundated to promote improved infiltration within the EDB.
- Provide construction observation to help the contractor comply with design specifications and elevations. Improper construction of the forebay, outlet structure, and other features will result in a poorly functioning and difficult to maintain facility.

References

Mile High Flood District (MHFD). 2021. *MHFD Detention Version 4.04, February 2021*. MHFD: Denver, CO.

Mile High Flood District (MHFD). 2018. *UD-BMP Version 3.07, March 2018*. Urban Drainage and Flood Control District (now MHFD): Denver, CO.

United States Environmental Protection Agency (EPA). 2021. *Stormwater Best Management Practice, Dry Detention Ponds*. EPA-832-F-21-031A.

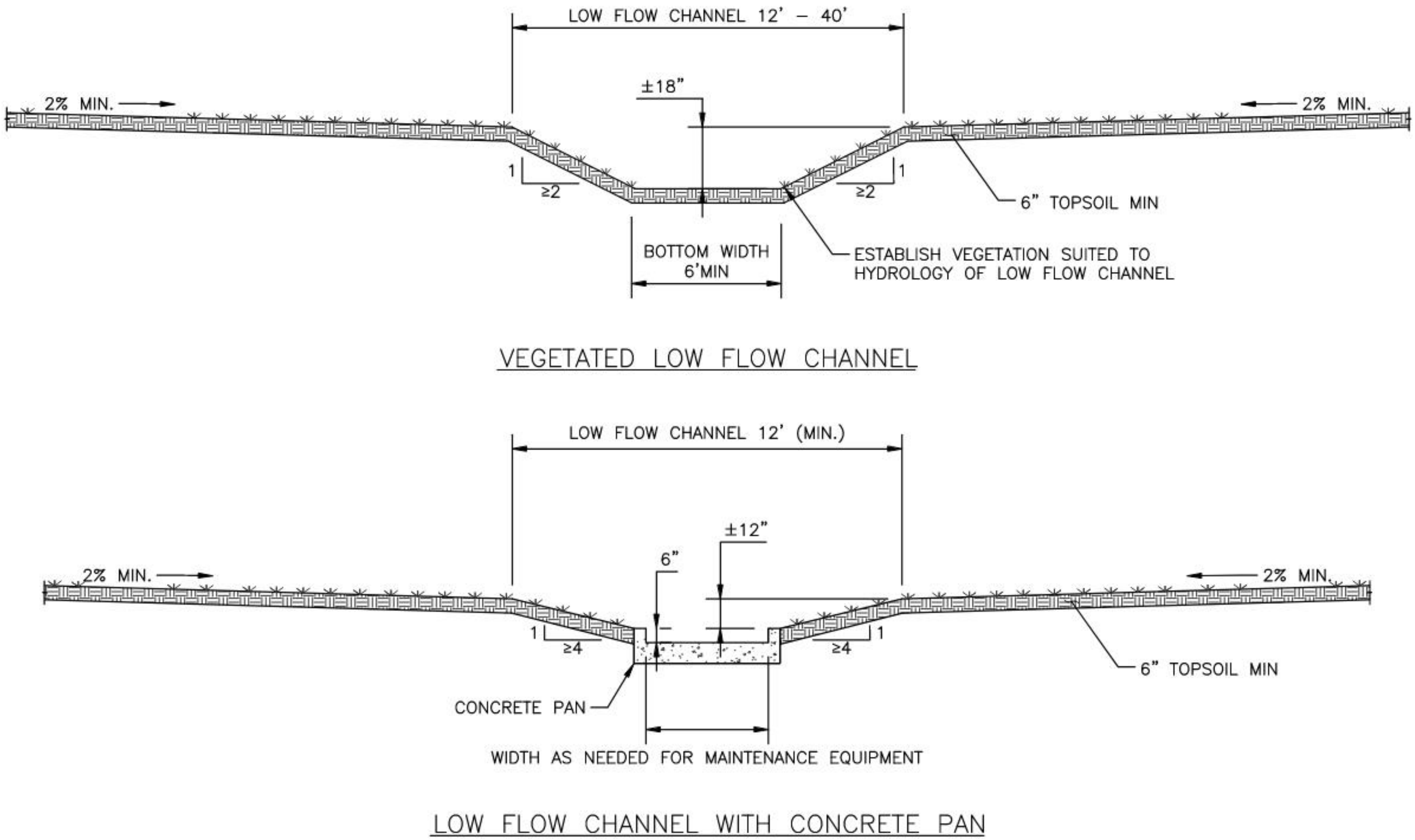
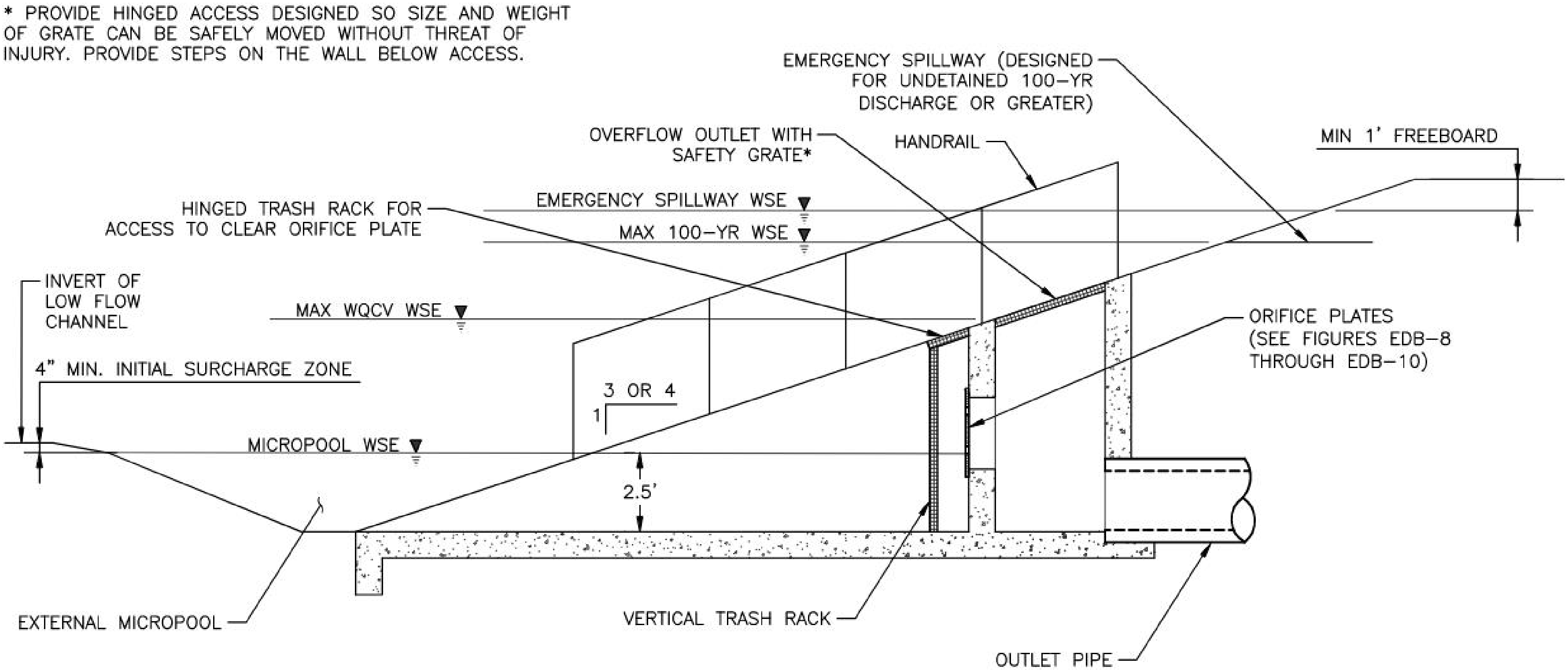
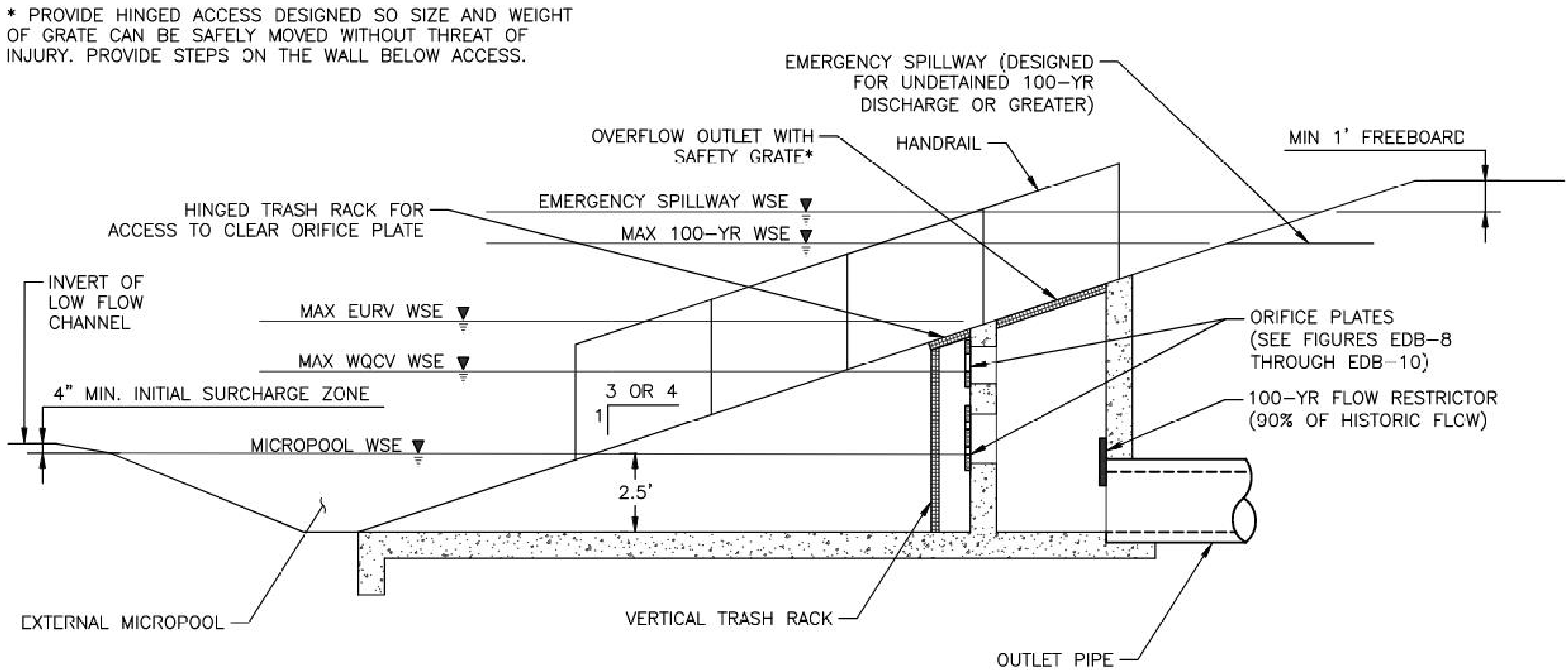


FIGURE EDB–2
CONCEPTUAL CROSS SECTIONS FOR LOW FLOW CHANNEL
WITH AND WITHOUT CONCRETE PAN



NOTE: CONFIGURATION ASSUMES ORIFICES ARE LARGE ENOUGH THAT A WELL SCREEN IS NOT REQUIRED. IF WELL SCREEN IS NEEDED, SEE FIGURES EDB-11 THROUGH EDB-13 FOR ADDITIONAL DETAILS.

FIGURE EDB-3
OUTLET STRUCTURE FOR WQCV TREATMENT WITH EXTERNAL MICROPOOL & VERTICAL TRASHRACK



NOTE: CONFIGURATION ASSUMES ORIFICES ARE LARGE ENOUGH THAT A WELL SCREEN IS NOT REQUIRED. IF WELL SCREEN IS NEEDED, SEE FIGURES EDB-11 THROUGH EDB-13 FOR ADDITIONAL DETAILS.

FIGURE EDB-4
OUTLET STRUCTURE FOR FULL SPECTRUM DETENTION WITH EXTERNAL MICROPOOL & VERTICAL TRASH RACK

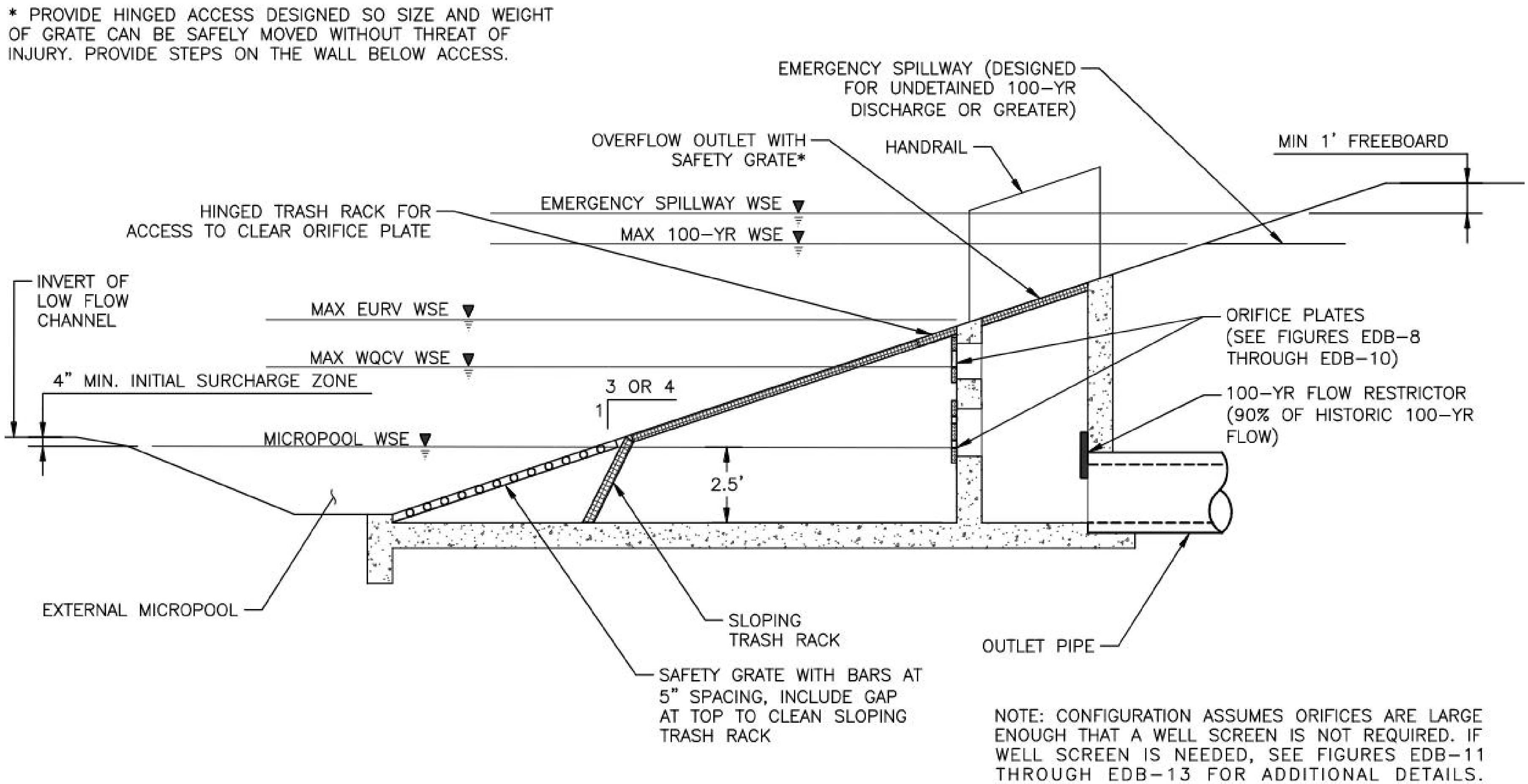
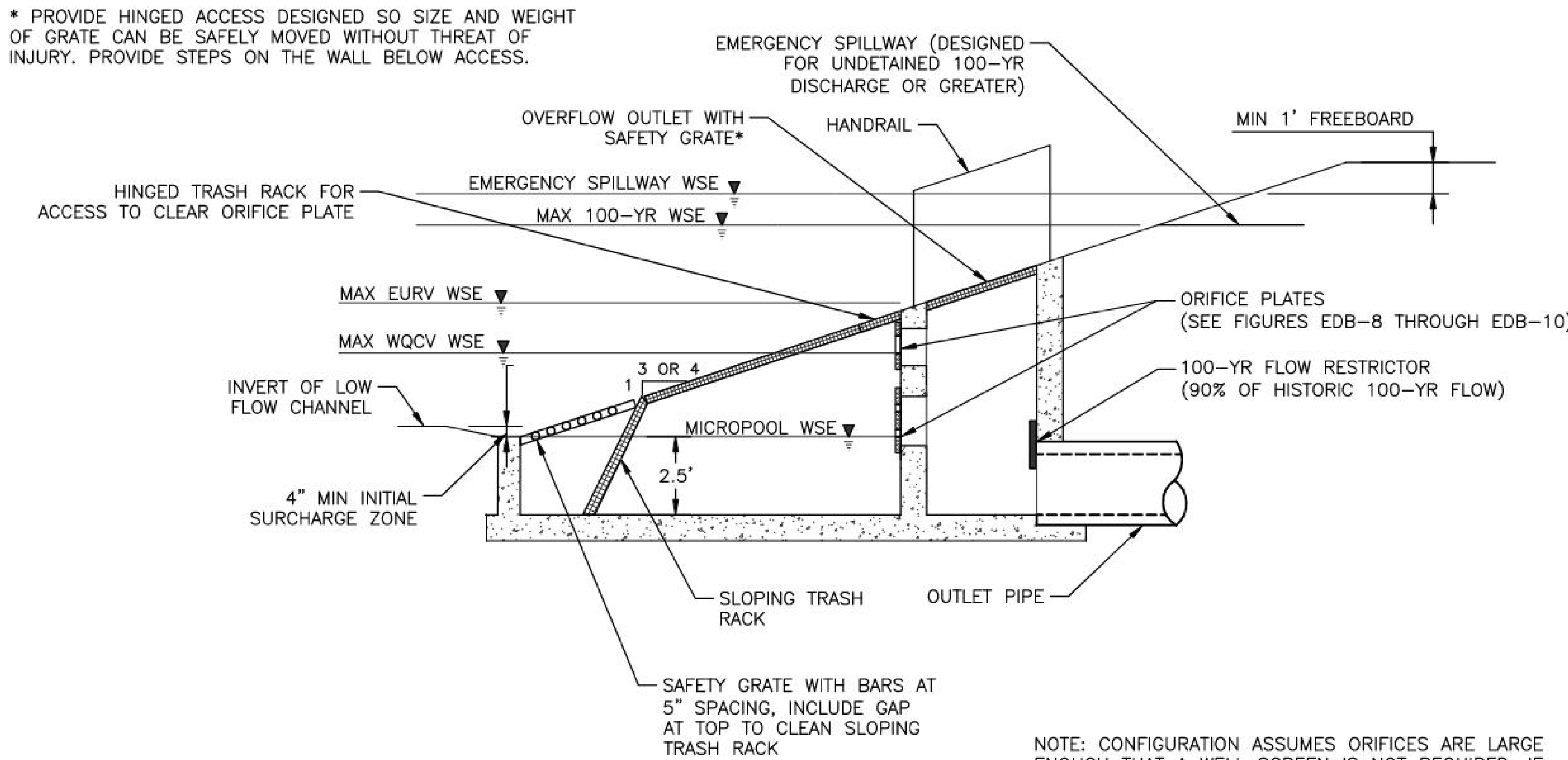
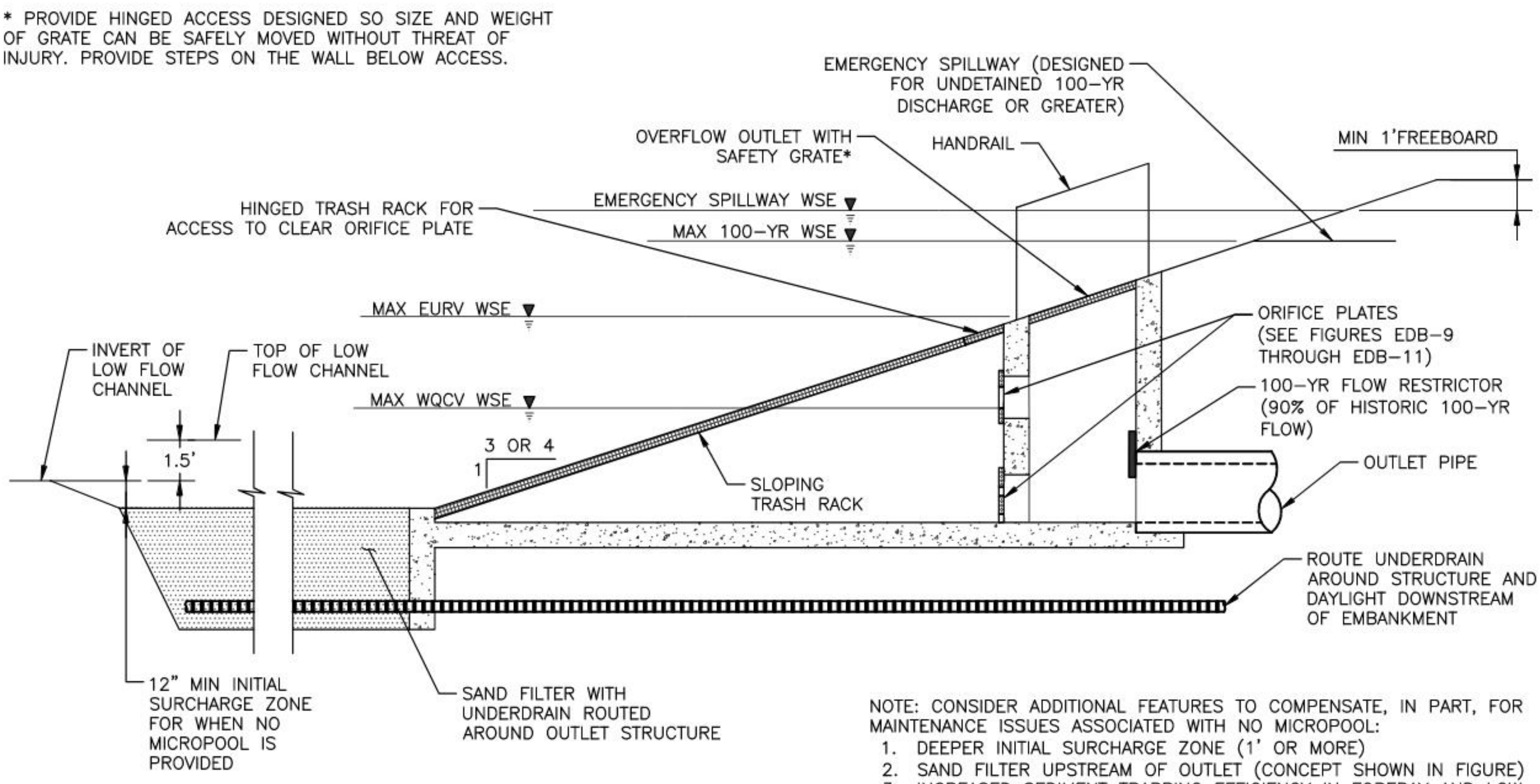


FIGURE EDB-5
OUTLET STRUCTURE FOR FULL SPECTRUM DETENTION WITH EXTERNAL MICROPOOL & SLOPING TRASH RACK



NOTE: CONFIGURATION ASSUMES ORIFICES ARE LARGE ENOUGH THAT A WELL SCREEN IS NOT REQUIRED. IF WELL SCREEN IS NEEDED, SEE FIGURES EDB-11 THROUGH EDB-13 FOR ADDITIONAL DETAILS.

FIGURE EDB-6
OUTLET STRUCTURE FOR FULL SPECTRUM DETENTION WITH INTERNAL MICROPOOL & SLOPING TRASH RACK



NOTE: CONSIDER ADDITIONAL FEATURES TO COMPENSATE, IN PART, FOR MAINTENANCE ISSUES ASSOCIATED WITH NO MICROPOOL:

1. DEEPER INITIAL SURCHARGE ZONE (1' OR MORE)
2. SAND FILTER UPSTREAM OF OUTLET (CONCEPT SHOWN IN FIGURE)
3. INCREASED SEDIMENT TRAPPING EFFICIENCY IN FOREBAY AND LOW FLOW CHANNEL
4. ADDITIONAL TRASH CAPTURE AT INFLOW POINTS
5. WATER QUALITY ORIFICES 2" OR GREATER
6. CONFIGURATION ASSUMES ORIFICES ARE LARGE ENOUGH THAT A WELL SCREEN IS NOT REQUIRED. IF WELL SCREEN IS NEEDED, SEE FIGURES EDB–12 THROUGH EDB–14 FOR ADDITIONAL DETAILS

FIGURE EDB–7
OUTLET STRUCTURE FOR FULL SPECTRUM DETENTION WITHOUT MICROPOOL & WITH SLOPING TRASH RACK

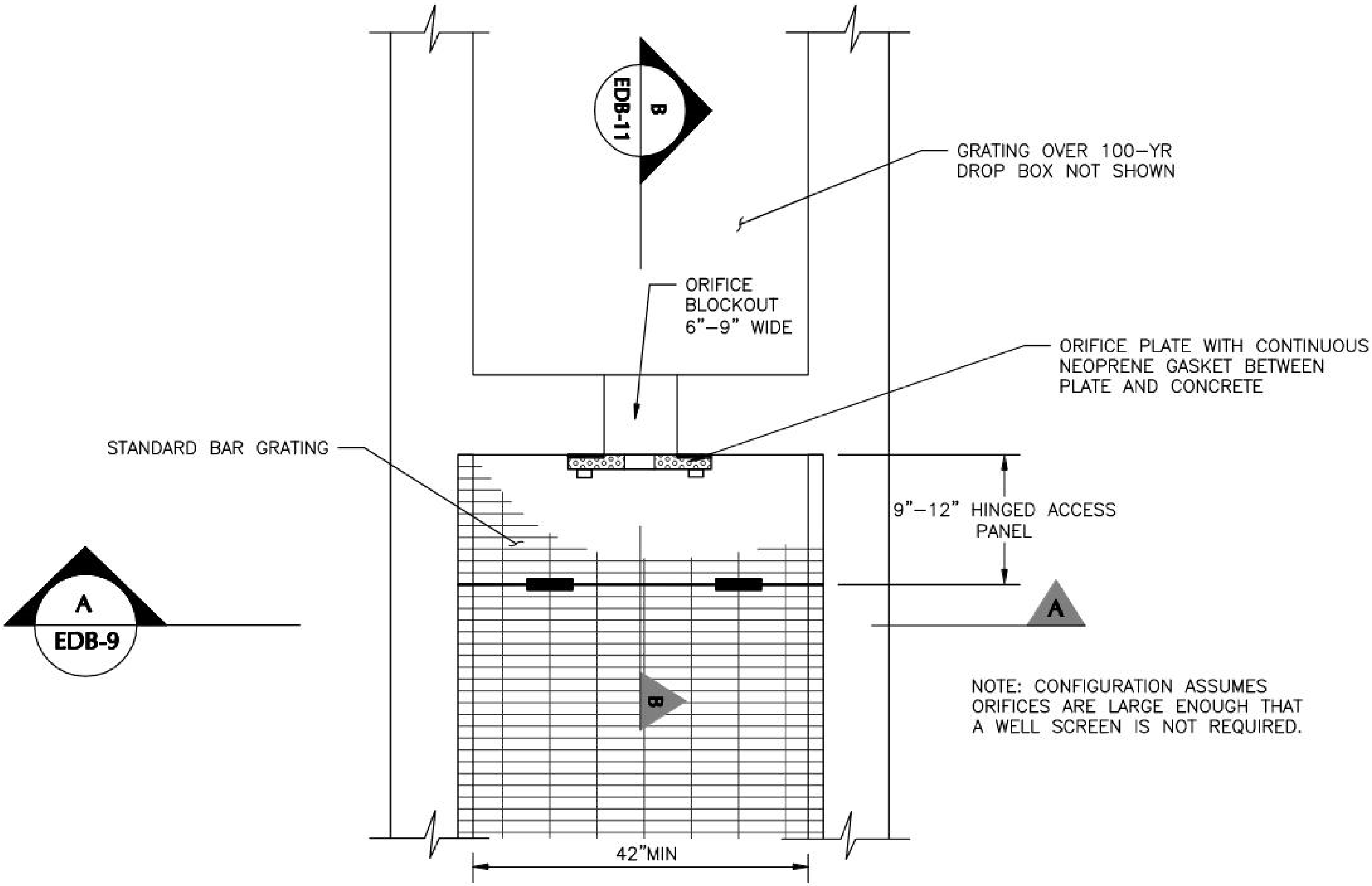


FIGURE EDB-8
CONCEPTUAL PLAN VIEW OF ORIFICE PLATES
WITH STANDARD BAR GRATING

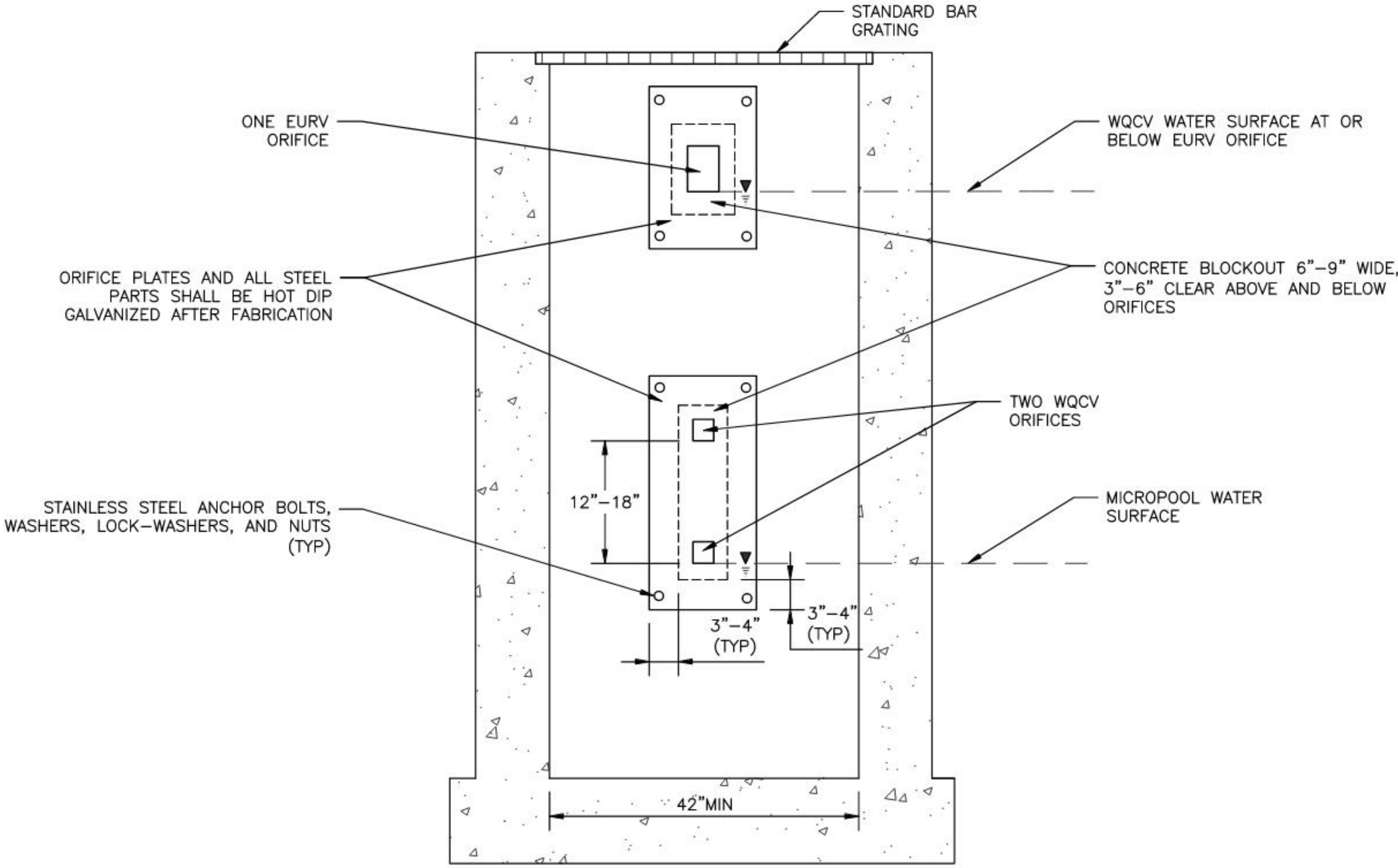


FIGURE EDB–9
CONCEPTUAL FRONT VIEW OF ORIFICE PLATES
WITH STANDARD BAR GRATING – SECTION A

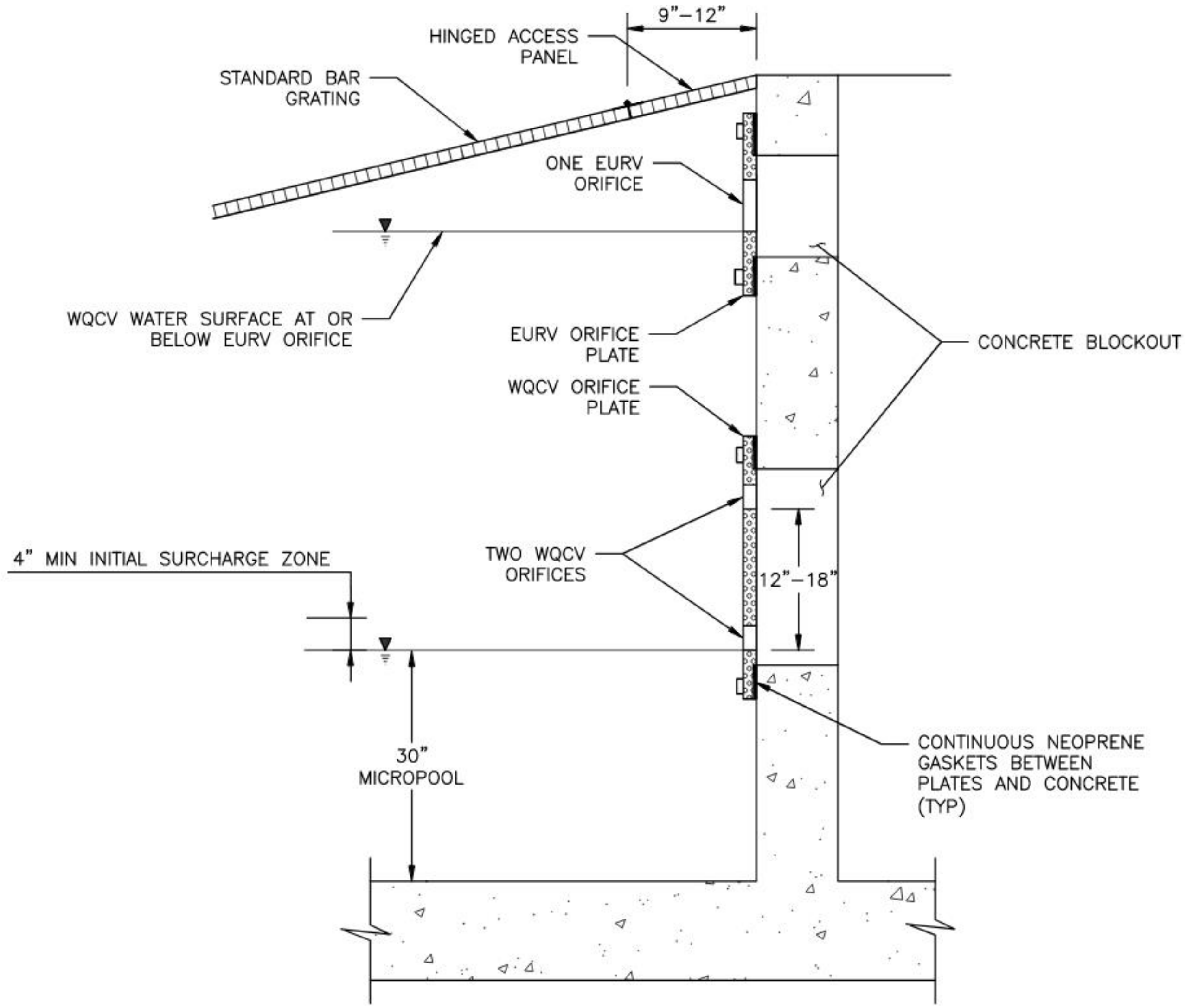


FIGURE EDB–10
CONCEPTUAL SIDE VIEW OF ORIFICE PLATES WITH STANDARD BAR GRATING – SECTION B

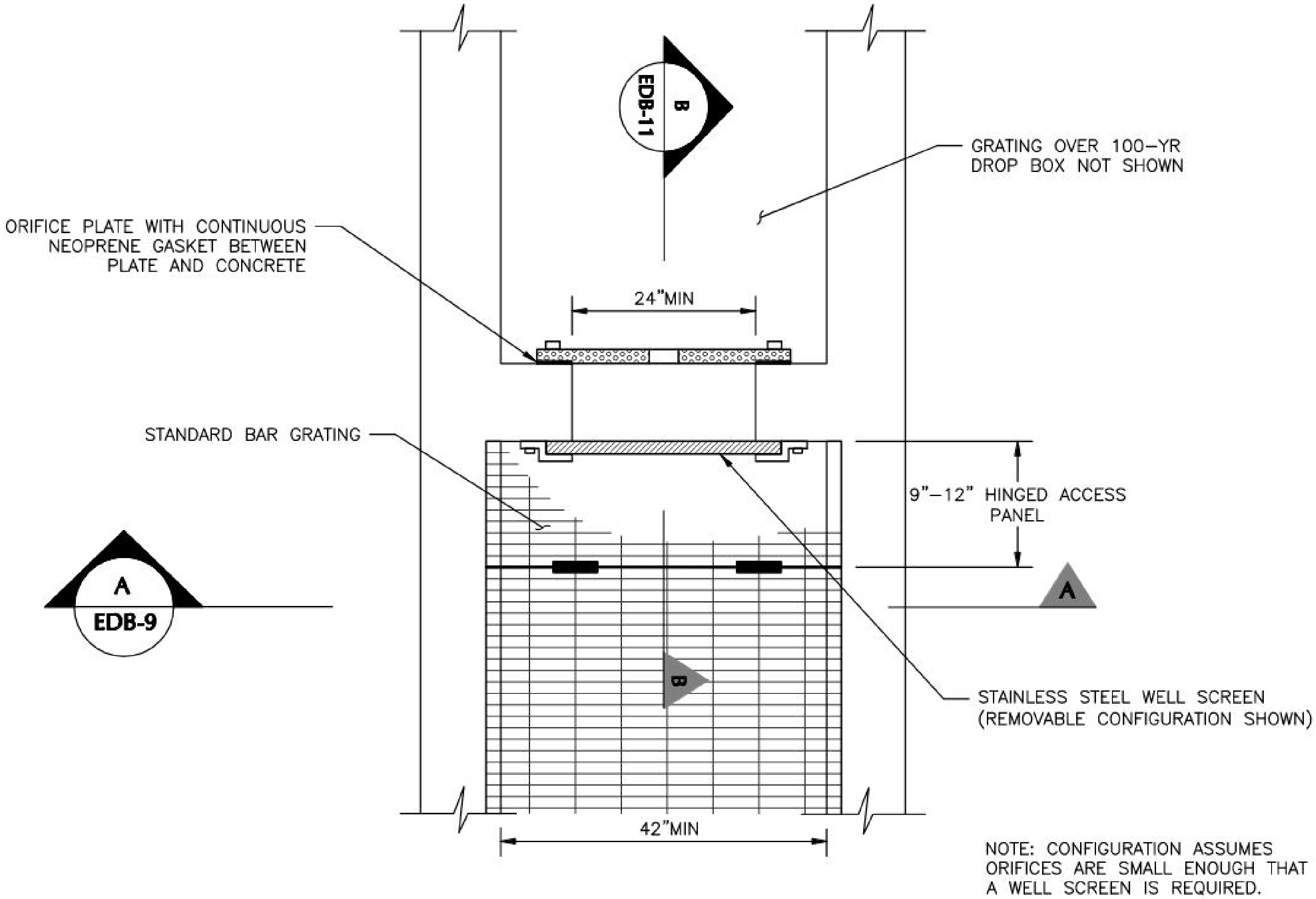


FIGURE EDB–11
CONCEPTUAL PLAN VIEW OF ORIFICE PLATES
WITH WELL SCREEN

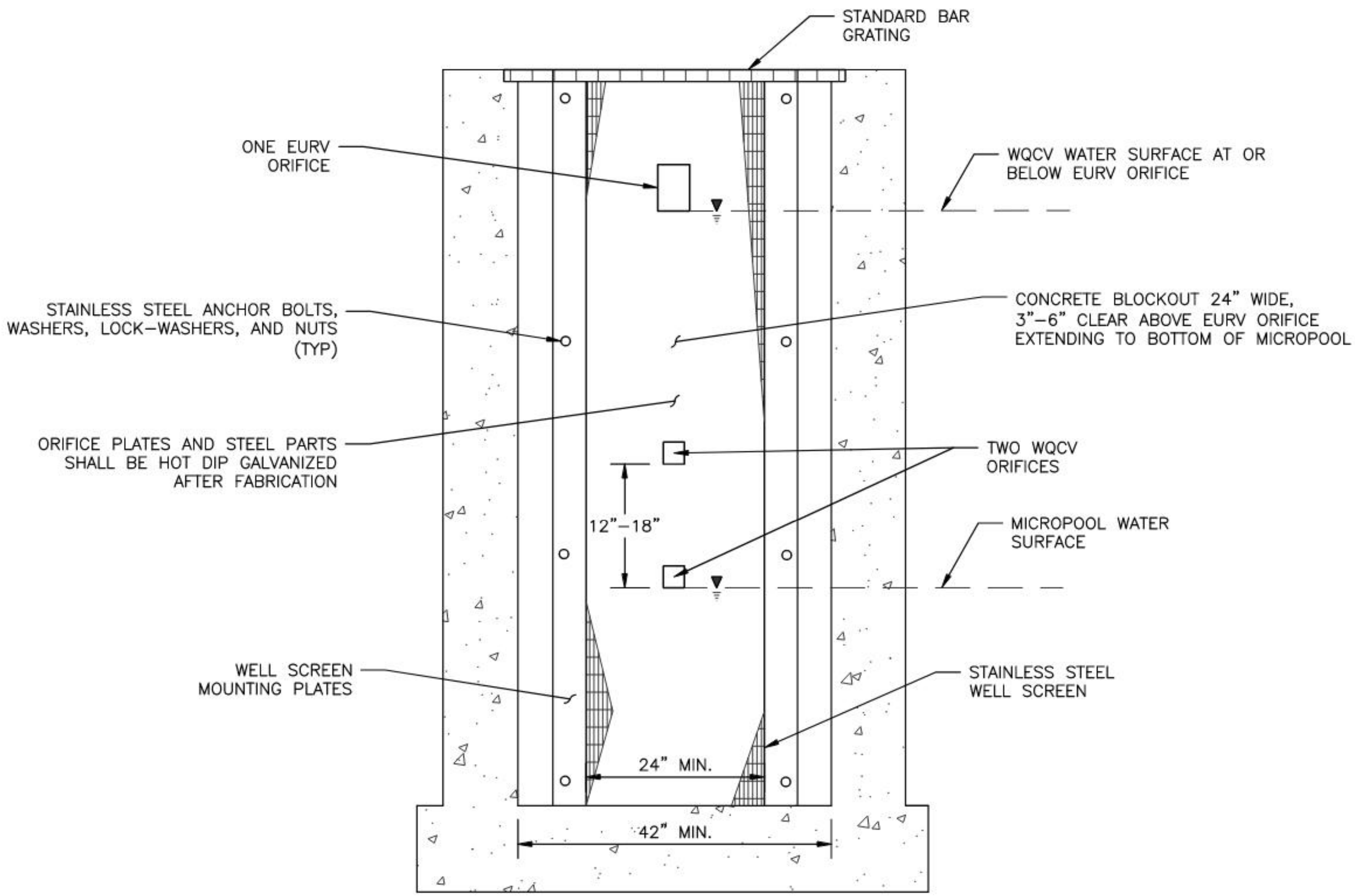


FIGURE EDB–12
CONCEPTUAL FRONT VIEW OF ORIFICE PLATES WITH WELL SCREEN – SECTION A

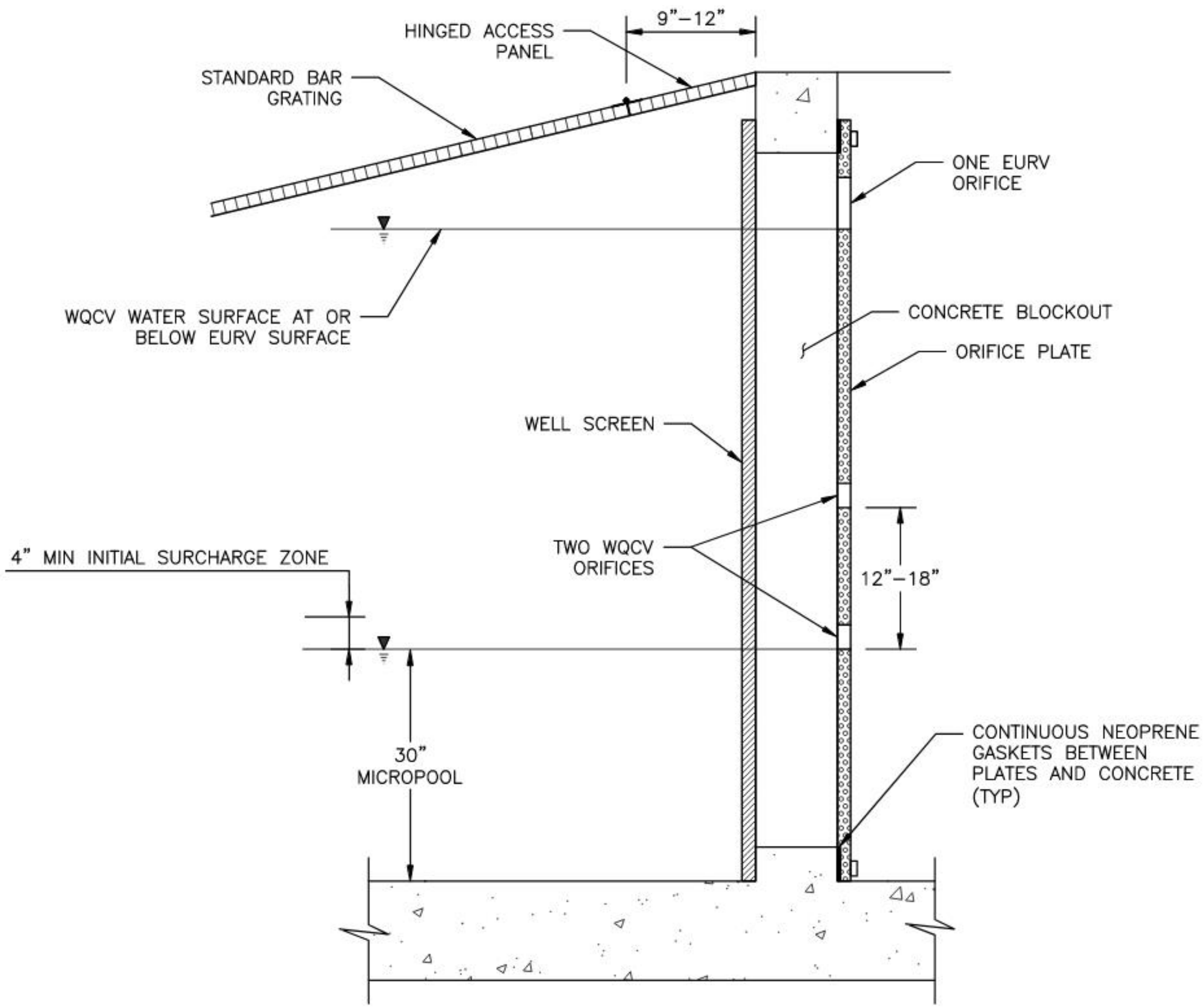


FIGURE EDB–13
CONCEPTUAL SIDE VIEW OF ORIFICE PLATES
WITH WELL SCREEN – SECTION B

T-7 Retention Ponds and Constructed Wetland Ponds

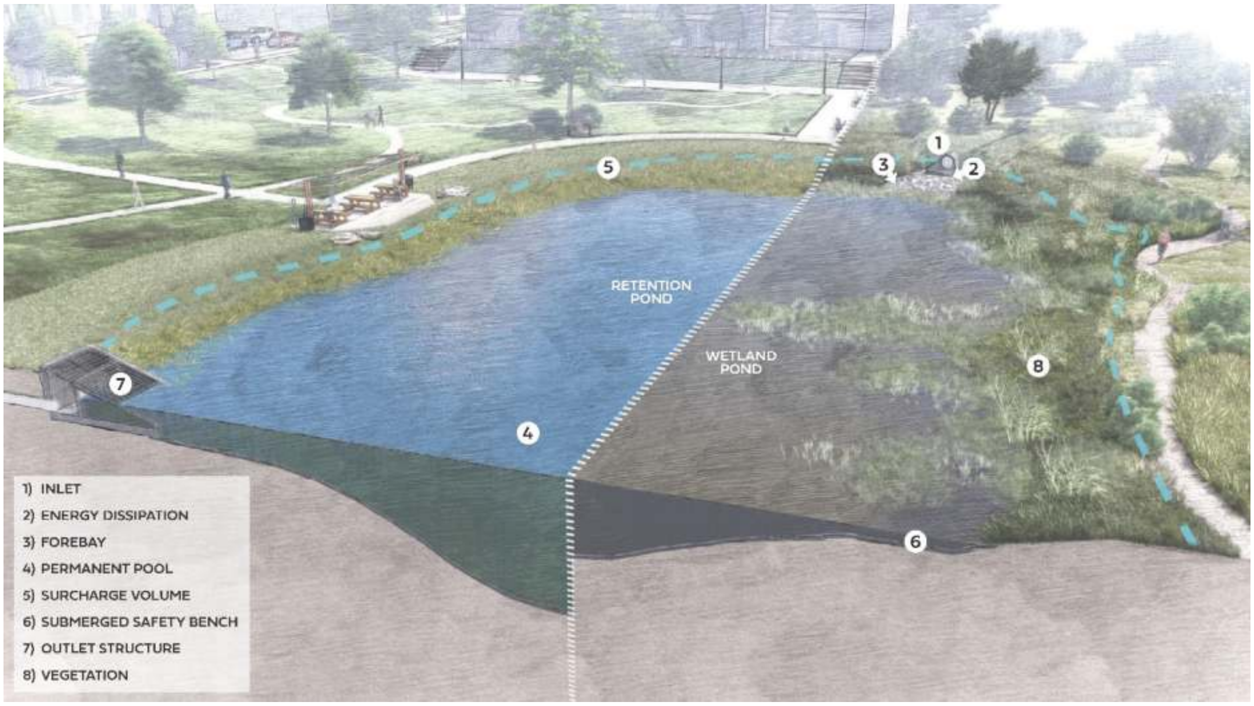


Figure RP/CWP-1. Retention Pond and Constructed Wetland Basin Components

Description

MS4 Permit Applicability (Dependent on design and level of treatment)	
Meets Runoff Reduction Standard	No
Meets WQCV Capture Standard	Yes
Meets Pollutant Removal Standard	Yes
Typical Effectiveness for Targeted Pollutants	
Sediment/Solids	High
Total Phosphorus	Medium-High
Total Nitrogen	Medium
Total Metals	Medium-High
Bacteria	Medium
Common Applications	
Runoff Reduction (General)	No
Use for Pre-treatment	No
Integrated with Flood Control	Yes
Cost	
Life-Cycle Costs	Medium

Retention ponds and constructed wetland ponds are SCMs that include a permanent pool of water with capacity above the permanent pool designed to capture and slowly release the water quality capture volume (WQCV) over an extended drain time of 12 hours for retention ponds and 24 hours for constructed wetland ponds.

The permanent pool is replaced, in part, with stormwater during each runoff event, mixing stormwater runoff with the permanent pool water. This allows for a reduced drain time compared to that of the extended detention basin (EDB). Slow release helps to replicate pre-development flows for frequent events and reduce the potential for short-circuiting treatment in smaller ponds. Retention ponds and constructed wetland ponds can be very effective in removing suspended solids, organic matter, and metals through sedimentation, as well as removing soluble pollutants like dissolved metals and nutrients through biological processes. However, these types of ponds require water rights due to the fact that evaporation from the permanent pool surface has the potential to cause depletions of water that would otherwise flow downstream (CDWR 2023; CDWR 2012).

Photograph RP/CWP-1. Retention ponds and constructed wetland ponds treat stormwater though sedimentation and biological processes including uptake.

SCM Components

The primary components of retention ponds and constructed wetland ponds (referred to as ponds, in general) include the pond inlet(s), the permanent pool, the temporary surcharge pool for the WQCV and flood events, the vegetation in and around the pond, and the pond outlet. An important feature of the permanent pool is a shallow safety bench around the edge of the pond that minimizes potential for people to inadvertently fall into deep water.

Component	Intent
Inlet	Allows stormwater to enter the SCM.
Energy Dissipation	Protects against erosion when inlet is elevated above the permanent pool.
Forebay	Facilitates removal of trash and coarse sediments. This is the primary location for sediment removal.
Permanent Pool	Provides for quiescent sedimentation and biochemical processes that remove or transform pollutants between runoff events.
Surcharge Volume	Provides the WQCV for slow release through the outlet.
Submerged Safety Bench	Minimizes safety hazard of people inadvertently stepping into deep water or onto steep, wet slope.
Outlet Structure	Ensures slow release of water to provide treatment and reduce erosion in the receiving stream.
Vegetation	Filters runoff, provides biological uptake of pollutants, creates habitat, and mediates biochemical reactions in the soil.

Site Considerations

Retention ponds and constructed wetland ponds require groundwater and/or dry-weather base flow if the permanent pool elevation is to be maintained year-round. Adequate physical supply and legal rights to store water are required for these types of ponds (CDWR 2023) along with "pond well" permits related to exposed groundwater (CDWR 2012). Water rights requirements are a primary reason that EDBs are used far more frequently in Colorado than "wet" ponds such as retention ponds or constructed wetland ponds. Consider the overall water budget for the pond to verify that the baseflow will exceed evaporation, evapotranspiration, and seepage losses (unless the pond is lined). Because high exfiltration rates can make it difficult to maintain a permanent pool in an unlined pond, line or otherwise seal the bottom and sides of the permanent pool for ponds on permeable soils and leave the areas above the permanent pool unsealed to promote infiltration of the stormwater detained in the surcharge storage volume. For ponds that have a permanent pool that is sustained by groundwater, lining is not necessary, but a pond well permit is required (CDWR 2012).

Studies show that ponds with permanent pools can cause an increase in outflow temperatures relative to inflows due to warming of water in the permanent pool between runoff events (EPA 2009). Retention ponds are discouraged upstream of receiving waters that are sensitive to increases in temperature (e.g., fish spawning or hatchery areas, streams identified as impaired for elevated temperature). Temperature effects should also be considered for constructed wetland ponds, given the warming that will occur in areas of the wetland with shallow permanent pools.

Benefits

- Provides recreation, aesthetic, and open space amenities to residents.
- Creates wildlife and aquatic habitat.
- Suited for larger tributary watersheds.

Limitations

- Open water creates safety issues that must be addressed in design.
- Physical supply of water and a legal availability (in Colorado) to impound water required.
- Sediment, floating litter, and algae blooms can be difficult to remove or control.
- May attract waterfowl that can add to the nutrients and bacteria leaving the pond.
- Ponds increase water temperature.
- Not suitable near airports due to Federal Aviation Administration (FAA) requirements related to bird-strike hazards as described in FAA Advisory Circulars 150/5320-5D and 150/5200-33B.

Photograph RP/CWP-2. Constructed wetland pond with diverse vegetation provides sedimentation, filtering and biological treatment.

Use caution when placing this SCM in a watershed where development will not be completed for an extended period, or where the potential for a chemical spill is higher than typical. When these conditions exist, it is critical to provide adequate containment and/or pretreatment of flows. In developing watersheds, frequent maintenance of the forebay may be necessary. Protect the pond from excessive sedimentation by providing effective erosion and sediment control measures in disturbed areas of the developing watershed.

Photograph RP/CWP-3. Variations in slope and texture around the pond, trails, and pavilions connect this retention pond to the community as a recreational and aesthetic amenity.

Community Values

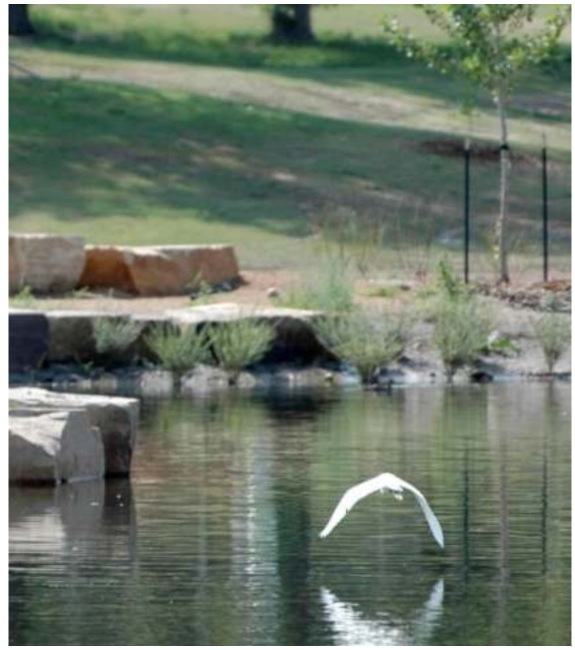
Ponds are often designed to provide aesthetic amenities and other benefits to the surrounding community and may be designed as feature attractions that provide open water and diverse vegetation, integrated with water quality treatment and detention for flood events. Ponds can support ecologically diverse vegetation and provide habitat for wildlife and also provide experiential opportunities for visitors. Because of the importance of these broader objectives, the aesthetic and experiential aspects of retention and constructed wetland ponds are essentials considerations in the design process.

Pond design objectives and aesthetics vary greatly depending on the surroundings, ranging from architectural design approaches featuring hard edges and manicured turf surcharge areas to naturalized designs with diverse vegetation in zones with varying hydroperiods to promote biological processes in the water and soil. Depending on project objectives, ponds may be very simple, or may be enhanced with public art, fountains, recirculating water features, bridges, boardwalks, and other elements to enhance experiential design objectives.

Ponds are successful as site amenities when they are integrated with their surroundings in ways that make them features of the landscape that do not stand out as heavily-engineered drainage structures. Minimizing the visual prominence of components such as energy dissipation structures, pre-cast flared end sections, outlet structures, and other concrete features helps to blend the SCM with the surroundings. These elements often can be hidden from view, or visually receded and blended with the overall landscape and minimize visual impacts.

Pay attention to the landforms that define the ponds. These should reinforce the chosen design aesthetic, whether formal or naturalistic. Focus on experiential aspects of the design, such as creating and framing special views of the ponds, creating destination areas and water access points for visitors, planning site pathways that provide interesting journeys, and possibly even highlighting the architecture of site buildings, depending on the overall objectives of the project.

Retention ponds are often more manicured than constructed wetland ponds, with more defined transitions between the permanent pool area and surcharge area and embankments and fewer wetland fringe areas. Many retention ponds have an aesthetic of park or golf course ponds, with a more ordered image of "nature" guiding the overall appearance. These ponds tend to be more adaptable to urban and suburban sites, where space limitations, maintenance requirements, and developer objectives tend to compress the overall area that can be dedicated to a pond. These types of ponds may have hard edges to create a more formal appearance or to aid in maintenance. These ponds provide fewer water quality and ecological benefits than naturalized ponds and generally require more frequent maintenance than more natural ponds in open space areas that incorporate soft, vegetated edges.



Photograph RP/CWP-4. Landscape elements such as vegetation and stone highlight the irregularly-shaped pond edge, making it appear more natural. Photograph courtesy of Design Concepts.

Constructed wetland ponds have more areas of shallow water within the permanent pool area that allow emergent wetland vegetation to develop and zones within and around the pond with varying hydroperiods supporting diverse vegetation that are well suited for a naturalized aesthetic. Vary side-slope grades and widths and shape the pond to create natural edges that appear to have been formed by flowing water. Use organic shapes and curves in place of straight lines and rectilinear forms for pond edges and elements. Compared to retention ponds, constructed wetland ponds should have more gradual transitions between open water and wetlands. Because of diverse wetland and riparian zones, constructed wetland ponds tend to attract more wildlife and have more ecological diversity than retention ponds and are more appropriate within a larger natural context. Once established, these types of ponds tend to evolve and change due to natural processes, developing seedbanks that allow different types of vegetation to thrive depending on hydrologic conditions

Photograph RP/CWP-5. Landscape elements including diverse vegetation and a wetland fringe, in combination with the irregularly-shaped pond edge, create a natural appearance. Sign states, "No Swimming" and warns "Ice Unsafe."

in different zones of the pond. Weed control is critical in the first few years of establishment. Specific recommendations to make sure that ponds are community amenities include:

- **Design for safety.** Ponds are attractive features that are inviting to people. The pond design must provide measures to dissuade visitors from entering the pond. Create a safe surface that allows anyone who inadvertently falls or enters the pond to recover and easily walk out to safety. Specific measures include the following:
    - Create natural barriers along pond edges using vegetation. Dense plantings of vigorous growing riparian shrubs such as coyote willow and other riparian/wetland shrub species can be excellent deterrents to pond access. In public areas, especially where children may be present, consider low visibility wire fencing. These fences can be located in areas of tall shrub and grass growth to minimize their visibility and impact to aesthetics.
    - If the pond will be accessible (e.g., not fenced off), design a mildly sloped, shallow safety bench in accordance with the side slope criteria in the Design Procedures and Criteria below.
- **Create vegetation plans based on the water regimes that are anticipated post-construction.** Plant wetland species around the edges of ponds, in areas of shallow ponding, and in areas where saturated soils are expected near the water table. See the Design Procedures and Criteria for more information.
- **Develop custom designs for structural elements such as outfalls, energy dissipaters, grade control structures, and spillway weirs to fit the specific attributes of the site.** Each site is unique, so using standard details for these elements without developing site-specific designs will fail to address the opportunities and constraints that each site presents. Choose materials based on the intent of each feature, either blending it with the site or purposefully creating a feature that stands out as “artful infrastructure,” where the design elements are intended to contrast the natural environment. Natural materials such as stone provide a more organic quality to structural elements, whereas concrete can be used to create bold counterpoints to the natural environment. Coloring and texturing concrete is another way to create desired effects with structural design elements and may help to blend the structures into the natural context.
- **Create unity in the design through repeated use of materials.** This is especially effective if the functional structures are made of the same materials as other landscape elements (such as seating areas, and terraces) throughout the site and contribute to creating a coherent and unified design.
- **Design for human experience by thinking about how people will use the site and providing elements that enhance their experiences.** Some examples of these types of elements include:
    - Trails – A trail network that creates walking loops around the site (preferably combined with maintenance access), with connections to nearby neighborhoods and other nearby trails. Consider where gateway elements should be located, as

well as demarcation of key viewpoints.

- Water access points – Consider creating informal “destination stone slabs” to accommodate visitors’ desires to be close to the water.
- Seating and shade – These can be informal or formal features, depending on the overall character of the pond and objectives of the site development and can range from boulders under cottonwood trees to benches under small shade shelters. Locate seating to take advantage of high points and good views.

Maintenance

Recommended ongoing maintenance practices for all SCMs are provided in Chapter 6 of this manual. During design, considered the following to facilitate maintenance over the long-term:

Photograph RP/CWP-6. Exceeding the minimum requirements for the permanent pool volume and depth can help to mitigate excessive growth of algae. Source control measures in the watershed that reduce nutrient loading may also be necessary.

- Provide energy dissipation and pretreatment for trash and coarse sediment upstream of the permanent pool using a forebay.
- Provide maintenance access to the forebay, permanent pool, and outlet structure.
- For retention ponds, greater depth deters algae growth by moderating temperature and providing deeper areas in the pond that receive less sunlight.
- Periodic removal of sediment from the pond bottom will be required to maintain depth and volume, reduce internal nutrient loading from sediment (Taguchi et al. 2020), and support beneficial habitat. Be aware that nutrient-rich inflows will produce algae blooms in ponds. Implementing source controls such as reduced fertilizer use, phosphorus-free fertilizer use, and irrigation management may help to reduce the potential for algae blooms and associated increased maintenance.
- Sediment removal typically requires dewatering of the pond. As part of the pond design and maintenance plan, provide and identify maintenance access for necessary equipment and identify an area nearby to spread out and drain wet sediments removed from the pond before hauling to a disposal location.

Design Procedures and Criteria

The following steps outline the design procedures and criteria for retention ponds and constructed wetland ponds. Figure RP/CWP-1 shows a conceptual configuration of a retention pond, and Figure RP/CWP-2 depicts a constructed wetland pond. MHFD-BMP, available at www.mhfd.org, is an Excel-based workbook that performs many of the design calculations based on the criteria in this fact sheet. MHFD-Detention, another workbook available on MHFD's website, can be used to develop and route storm hydrographs through a retention pond and design the outlet structure for the WQCV, the EURV and 100-year storage volume, as applicable.

1. **Site Assessment Considerations Related to Baseflow Availability**: Unless the permanent pool is established by groundwater, a perennial baseflow that exceeds water losses, including evaporation, evapotranspiration, and seepage, must be physically and legally available. Low inflows in relation to the pond volume can result in poor water quality due to stagnation. Perform net influx calculations to account for the range of annual and seasonal variations in hydrologic conditions. Estimate evaporation from existing local studies, pan evaporation data from nearby climate stations, or from the National Weather Service (NWS) Climate Prediction website. NOAA Technical Report NWS 33 is used by the State Engineer's Office and provides a spatial map of annual evaporation from free water surfaces for Colorado. Annual evaporation for Denver County ranges between 40 and 45 inches. Potential evapotranspiration (which occurs when water supply to both plant and soil surface is unlimited) can be approximated as the evaporation from a large, free-water surface such as a lake (Bedient and Huber 1992). When ponds are placed above the groundwater elevation, a pond liner is recommended, unless evaluation by a geotechnical engineer determines this to be unnecessary.

2. **Inlet**: Dissipate energy at the inlet to limit erosion and to diffuse the inflow plume. Design inlets and energy dissipation in accordance with Section 5.0 *SCM Inflow Features* of this chapter and the *Hydraulics Structures* chapter of Volume 2, which addresses design of impact basins and drop structures.

3. **Forebay**: Provide a forebay to trap trash and allow larger particles to settle out, which will reduce the required frequency of sediment removal in the permanent pool. See Section 5.0 *SCM Inflow Features* in this chapter for guidance and criteria for forebays. In some cases, an offline trash vault or a manufactured treatment device to collect trash and sediment prior to the stormwater outfall into the pond can provide a similar function to a forebay.

4. **Surcharge Volume:** Calculate the design volume for the surcharge volume above the permanent pool based on a 12-hour drain time for retention ponds and a 24-hour drain time for constructed wetland ponds. Determine the required WQCV or EURV (watershed inches of runoff) using Chapter 3 of Volume 3 (for WQCV) or equations provided in the *Storage* chapter of Volume 2 (for EURV).

5. **Permanent Pool Volume:** The permanent pool provides stormwater quality enhancement between storm runoff events through biochemical processes and quiescent sedimentation. Calculate the volume of the permanent pool:

$$V_p \geq C_V \left[\frac{\mathrm{WQCV}}{12}\right] A \qquad \text{Equation RP/CWP-1}$$

Where:

V_p = permanent pool volume (acre-ft)

C_V = volume sizing coefficient:

- 1.2 for retention ponds
- 0.75 for constructed wetland ponds

A = tributary catchment drainage area (acres)

6. **Pond Geometry and Features:**

- Always maximize the distance between the inlet and the outlet. A pond length to width ratio between 2:1 and 3:1 is recommended to avoid short-circuiting. Adjust the inlet and outlet locations as needed through the use of pipes, swales, or channels to accomplish this.
- Depth Zones:
  - Safety Wetland Bench: Provide a safety bench along the perimeter of the permanent pool(s) in retention and constructed wetland ponds, 6 to 12 inches deep and a minimum of 4 feet wide. The safety wetland bench provides a shallow area that allows people or animals who inadvertently enter the open water to gain footing to get out of the pond. Aquatic plant growth along the perimeter of the permanent pool can also help strain surface flow into the pond, protect the banks by stabilizing the soil at the edge of the pond, and provide biological uptake.
  - For a retention pond, the remaining pond area should be open water, providing a volume to promote sedimentation and nutrient uptake by phytoplankton. To avoid anoxic conditions, the maximum depth in the pool should not exceed 12 feet, unless an aeration system is provided. At greater depths, stratification has the potential to occur, which can deplete oxygen in the pond bottom and result in release of pollutants from accumulated sediments that can be flushed out in a subsequent runoff event. The best way to avoid the need for aeration is to ensure that there is

Diverse wetlands are healthy wetlands. Create zones with different depths and plant a variety of vegetation.

adequate baseflow of suitable quality (e.g., not nutrient-rich) and that the pond inlets and outlet are positioned to avoid short-circuiting and zones of stagnation as baseflows pass through the pond. Pumped recirculation of water in the pond can be designed to provide mixing in zones that are less-mixed by baseflows and also provides aesthetic benefits (e.g., fountains or small "waterfalls" of recirculating water at points around edges). Aeration systems are typically needed in remedial situations where a combination of long hydraulic residence times, nutrient rich inflows, warm temperatures, and zones of stagnation result in algae blooms that affect the appearance, water quality, odor, and overall function of the pond. In these cases, a variety of alternatives exist for aeration from bubbler systems placed on the bottom of ponds to floating solar pumps that move around the surface of the pond recirculating water.

- For a constructed wetland pond, distribute wetland habitat within and surrounding the permanent pool using vegetation suited for variations in the pool depths and the runoff hydroperiod at varying elevations to establish diverse ecology. Distribute pond area in accordance with Table RP/CWP-1.

Table RP/CWP-1. Recommended Open Water Surface Area and Design Depth Ranges for Constructed Wetland Pond Zones

Pond Zones	Percent of Pond Surface Area	Design Water Depth
Forebay, outlet, and open water surface areas	30% to 50%	2 to 4 feet
Wetland zones with emergent vegetation	50% to 70%	6 to 12 inches[1]

[1] One-third to one-half of this zone should be 6 inches deep.

7. **Side Slopes**: Side slopes must be stable and sufficiently mild to limit rill erosion and facilitate maintenance. Side slopes above the safety wetland bench should be no steeper than 4:1, preferably flatter. The safety wetland bench should be relatively flat with the depth between 6 to 12 inches and should extend at least 10 feet into the pond from the edge of water. The side slope below this bench should be 3:1 (or flatter when access is required or when the surface could be slippery). The steeper 3:1 slope below the safety wetland bench can be beneficial to deterring algae growth as it will reduce the shallow area of the pond, thereby reducing the amount of sunlight that penetrates the pond bottom.

   Vegetation: Vegetation is a key component of ponds and wetland basins, providing multiple functions related to nutrient uptake, erosion control around the perimeter, and overall site stability. Plant berms and side-slopes with native grasses and vegetate the safety wetland bench with native aquatic species.

For retention ponds, transition from wetland to riparian vegetation over a depth of approximately 30 inches above the permanent pool, and transition from riparian to upland vegetation from 30 inches to 5 feet. Pay special attention to specification of vegetation in pond surcharge areas because vegetation in these areas must be able to tolerate moderate periods of inundation, as well as prolonged dry conditions between large rain events.

For constructed wetland ponds, plant wetland vegetation based on tolerance for permanent inundation at depths of 6 to 12 inches and riparian vegetation on banks that are inundated by the WQCV.

Retention and constructed wetland ponds present great opportunities for designers to use a wide variety of plant species to create biodiversity and provide flowering plants for pollinators. Dense vegetation around the perimeter of an open water body can discourage frequent use of the pond by geese and filter (strain) pollutants entering the pond.

8. **Outlet:** Design the outlet to release the WQCV over a 12-hour period for retention ponds and over a 24-hour period for constructed wetland ponds. The MHFD-Detention tool, available at www.mhfd.org, performs these calculations, as well as sizing calculations for the EURV and 100-year storage volume for retention ponds that also are designed for flood control. See Section 6.0 *SCM Outflow Features* of this chapter for additional information on designing outlet structures pertaining to structure geometry, grates, trash racks, the orifice plate, and all other necessary components.

Photograph RP/CWP-7. This pond outlet structure is accessible and functional while not interfering with the overall pond aesthetic.

9. **Trash Rack**: Provide a trash rack of sufficient size to prevent clogging of the primary water quality outlet. Extend the trash rack protecting the orifice plate into the permanent pool a minimum of 28 inches. See Section 6.0 *SCM Outflow Features* of this chapter for additional information on designing trash racks for excluding debris and for safety.

10. **Overflow Embankment**: Design the embankment to be stable during the 100-year storm. If the embankment falls under the jurisdiction of the State Engineer's Office (SEO), it must be designed to meet SEO requirements for dam safety. Design embankment slopes to be no steeper than 4:1, preferably flatter, and planted with turf grasses. Excavate and replace poorly compacted native soils. Compact embankment

soils to 95% of maximum dry density for ASTM D698 (Standard Proctor) or 90% for ASTM D1557 (Modified Proctor). Design spillway structures and overflows in accordance with local drainage criteria and consider the use of stabilizing materials such as buried soil riprap or turf reinforcement mats installed per manufacturer's recommendations.

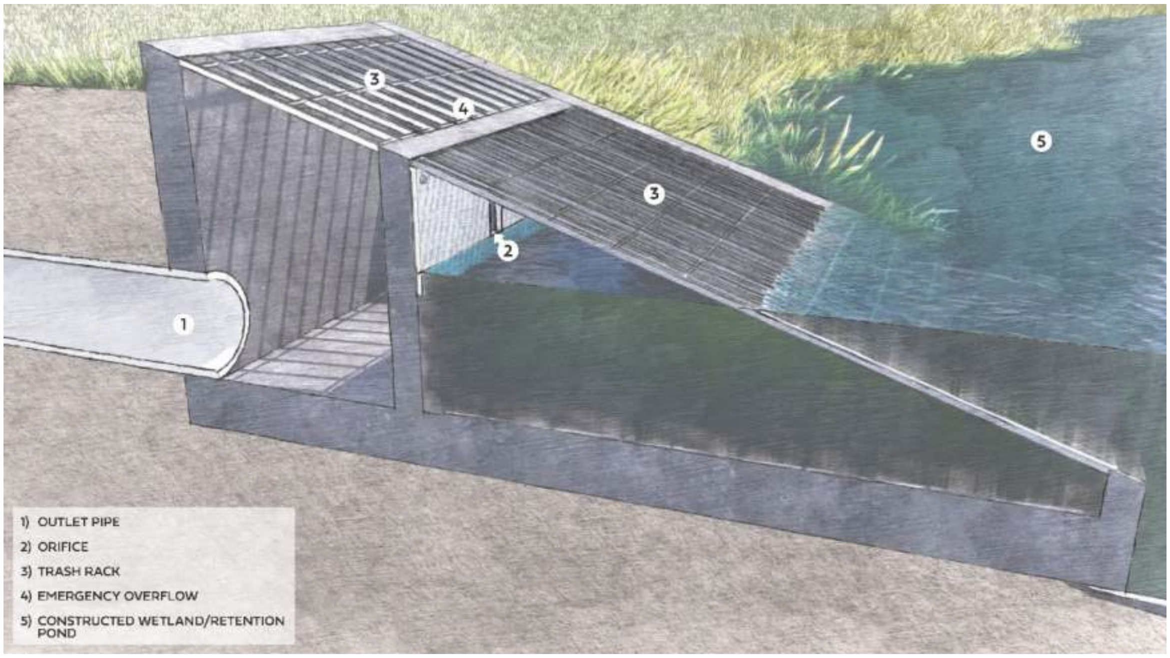


Figure RP/CWP-2. Retention Pond/Constructed Wetland Basin Outlet Structure

11. **Pond Drain for Maintenance:** Provide a means to drain the pond to allow the pond to dry out when it must be "mucked out" to restore volume lost due to sedimentation. Provide drainage via gravity when feasible. An underdrain around the perimeter of the pond with a valved connection to the outlet structure may achieve this objective. Other alternatives include providing a drywell with a piped connection to the outlet structure or to a downstream conveyance element or connecting a valved pipe directly to the outlet structure. The pipe should include a valve that will only be opened for maintenance.

12. **Maintenance Access:** Provide all-weather stable access to the pond bottom, forebay, and outlet for maintenance vehicles. Design grades that do not exceed 10% for haul road surfaces or 20% for skid-loader and backhoe access.

Photograph RP/CWP-8. Barnum Park constructed wetland park shows transition from hydrophytic rushes to upland grasses.

Provide a solid driving surface such as gravel, concrete, articulated concrete block, concrete grid pavement, or reinforced grass pavement. The recommended cross slope for the access road is 2%.

Construction Considerations for Retention and Constructed Wetland Ponds

Successful construction of a retention or constructed wetland pond requires attention to management of water, installation of a liner (if used), and installation and establishment of the vegetation. Key construction considerations include:

- When using the pond area as a sedimentation basin during construction, fully rehabilitate the area to remove sediment and other materials accumulated during construction prior to filling and revegetating the pond.
- If the pond is located on a perennial or ephemeral drainageway, a temporary diversion may be required for construction of the SCM. See the Temporary Diversion fact sheet (SM-08) in Chapter 7 for additional information.
- If construction dewatering is required, a construction dewatering discharge permit from the Colorado Department of Public Health and Environment and/or local governments may be required.
- Plant health is critical to establishing a constructed wetland or retention pond. Inspect plants prior to installation to ensure they are healthy.
- After planting wetland species in a constructed wetland pond or on a wetland safety bench in a retention pond, the permanent pool should be kept at 3 to 4 inches deep in the newly-planted emergent plant zones to allow growth and to help establish the plants. Once vegetation is established, raise the pool to its final operating level.
- Plan for selective weed control during the vegetation establishment period. Use of herbicides is not recommended within the pond area since it is a water quality facility.
- When ponds are lined to reduce or eliminate seepage from the permanent pool, quality assurance/quality control is critical for liner installation to avoid puncturing the liner, leaky seams, improper anchoring, or other problems that can damage or reduce the lifespan of the liner.
- Temporary irrigation may be needed to establish wetland, transitional, and upland vegetation, especially if drier than normal conditions occur during the establishment period.

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T-8 Manufactured Treatment Devices

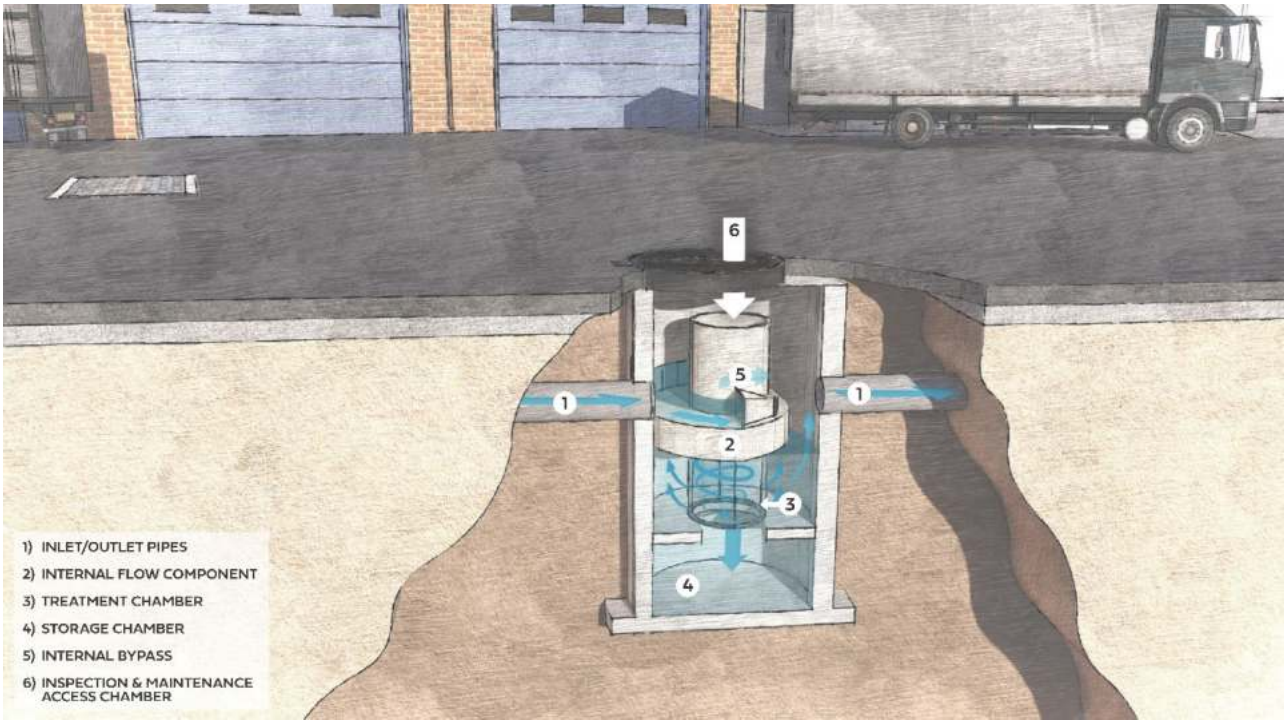

Figure MTD-1 Sedimentation MTD: Hydrodynamic Separator

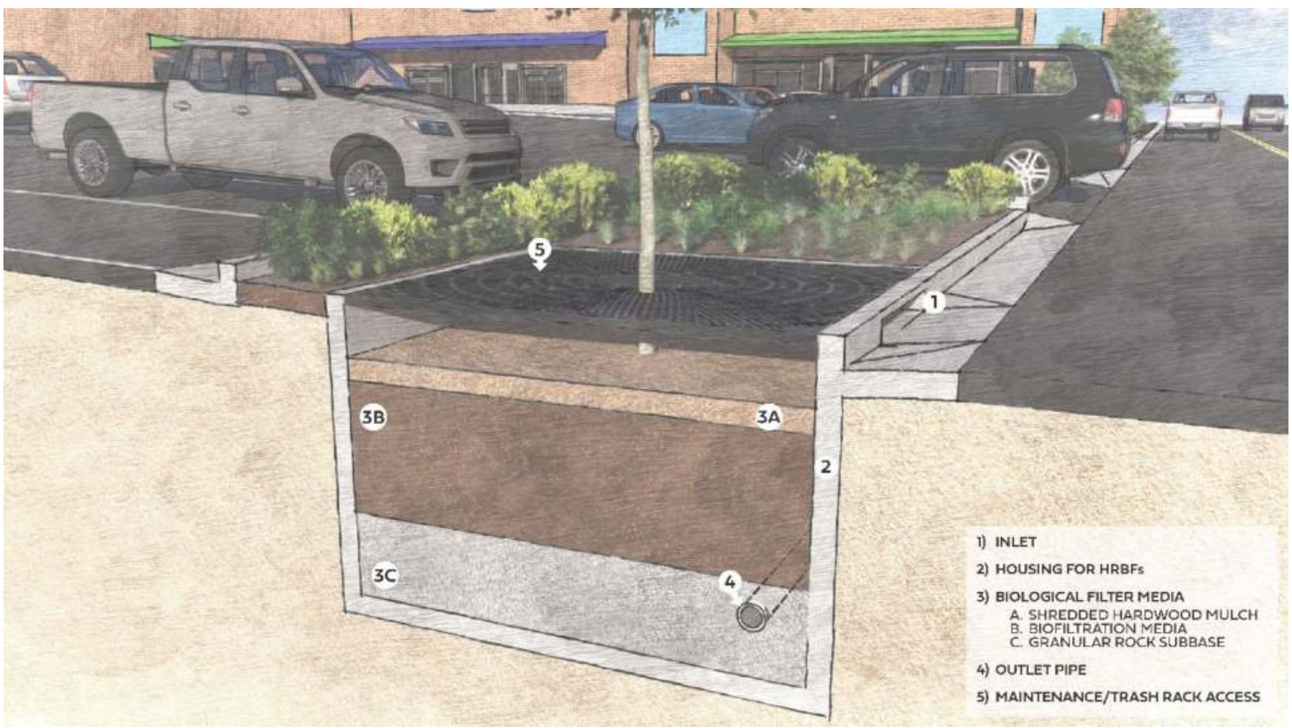

Figure MTD-2. Filtration MTD: High Rate Biofilter

General Description

Manufactured Treatment Devices (MTDs) include many different types of proprietary devices that use various treatment processes and designs to remove targeted pollutants. For example, some MTDs are suitable for pretreatment and gross solids removal, whereas others incorporate advanced designs targeting specific metals, nutrients, and other pollutants in stormwater runoff. Standardized testing protocols and third-party performance verification can be used to support selection of MTDs that meet treatment objectives for a site.

This fact sheet discusses two general categories of MTDs: sedimentation MTDs and filtration MTDs. Sedimentation MTDs use sedimentation processes to remove pollutants. The most common sedimentation MTDs are hydrodynamic separators (HDSs). Filtration MTDs utilize various filtration processes to remove pollutants and are subcategorized in this fact sheet as high-rate media filtration (HRMF) and high-rate biofiltration (HRBF) devices. Other types of MTDs are also available on the market but are not discussed in this fact sheet.

MS4 Permit Applicability (Design-Dependent)	**HDS**	**HRMF**	**HRBF**
Meets Runoff Reduction Standard	No	No	No[3]
Meets WQCV Capture Standard	No	No	No
Meets Pollutant Removal Standard	No[1]	Yes	Yes
Typical Effectiveness for Targeted Pollutants[1,2]	**HDS**	**HRMF**	**HRBF**
Sediment/Solids	Medium	High	High
Total Phosphorus	Low	High[4]	High[4]
Total Nitrogen	Low	Medium	Medium
Total Metals	Low	High	High
Bacteria	Low	Low-Medium	Low-Medium
Common Applications	**HDS**	**HRMF**	**HRBF**
Runoff Reduction (General)	No	No	No[3]
Pretreatment (in Treatment Train)	Yes	No	No
Primary Treatment	No	Yes	Yes
Integration with Flood Control	No	No	No
Cost	**HDS**	**HRMF**	**HRBF**
Life-Cycle Costs	Medium	Medium-High	Medium

[1] Typical effectiveness for HDSs is based on New Jersey Department of Environmental Protection laboratory testing protocol for HDSs (NJDEP 2021), with testing requirements for specific composition and gradation, average particle size, influent concentration, required inflow rates, and other parameters.

[2] Filtration MTD performance varies based on proprietary media/filter designs and targeted pollutants. "Typical" effectiveness descriptions are based on a combination of Washington Ecology's approved treatment technologies based on the Technology Assessment Protocol–Ecology (TAPE) use designation and the International Stormwater BMP Database 2020 Summary Statistics.

[3] The Runoff Reduction Standard is not typically met with HRBF devices sold as-is. HRBFs can be designed/retrofitted with additional appurtenances, such as extra underdrain pipe(s) or a chamber on the downstream side of the device, which will detain and regulate the release of treated stormwater and allow for infiltration. Open-bottomed HRBFs may meet the runoff standard, depending on site-specific conditions.

[4] Total phosphorus removal is typically high when it is specifically targeted for removal with proprietary media.

Sedimentation MTD Description

Sedimentation MTDs include hydrodynamic separators (HDSs) and other MTDs utilizing sedimentation processes. These devices typically use gravity and/or centripetal force coupled with strategically placed components to separate, settle, trap, and retain coarse particulates. The primary target pollutant of sedimentation MTDs is suspended sediment.[1] Some systems target sediment exclusively, while others also provide trash and debris removal and/or oil and grease separation. Collected pollutants are typically directed to and stored in a collection chamber within the device, and treated stormwater is discharged back into the storm drain system.

Most sedimentation MTDs are constructed as concrete vaults with maintenance access. Concrete vaults typically use swirl concentration, a series of baffles or weir plates, or a combination of these sediment removal methods. Sedimentation MTDs are generally housed in precast concrete or plastic pipe (HDPE, PVC, PP) structures, depending on the specific device and manufacturer. These structures serve as housing for the internal components of the MTD. The inner components and configurations differ among products and manufacturers.

Sedimentation MTD Terminology

There are several commonly used terms that are used to define how a sedimentation MTD functions, such as swirl concentration, cyclonic separation, vortex separation, and screening. These terms are synonymous, each referencing the process of using centripetal force and/or gravity, coupled with a target velocity, to provide the hydraulics required to remove a specified amount of sediment of a specified particle size gradation from stormwater. This process has become most widely referred to as hydrodynamic separation, and the MTDs that perform this process are called HDSs.

HDSs are the most commonly installed sedimentation MTD in the Front Range of Colorado. Unlike SCMs that detain and release, filter, or infiltrate the WQCV, HDSs treat stormwater over a short residence time, typically providing a lower level of treatment than storage-, filtration-, or infiltration-based SCMs. As stand-alone practices, sedimentation MTDs do not meet the Runoff Reduction, WQCV, or Pollutant Removal Standards[2] in Colorado MS4 Permits. Therefore, these MTDs are most appropriate for a stormwater treatment train system as a pretreatment component. For example, many HDSs can remove coarse particulates and buoyant materials like trash and debris; therefore, they can play an important role in providing pretreatment to reduce maintenance requirements and costs for downgradient SCMs in a treatment train.

When evaluating sedimentation MTDs, it is important to evaluate the maintenance frequency needed to maintain performance. For most MTDs, the volume of sediment is the primary indicator for when maintenance is needed. In this case, frequency of maintenance is ultimately a function of available storage capacity. Storage capacities vary widely among the many available sedimentation MTDs on the market today. If unavailable from the manufacturer,

[1] Suspended solids are often measured as suspended sediment concentration (SSC), which is similar to total suspended solids (TSS), but typically is a slightly higher concentration due to the inclusion of larger particles as a result of the SSC sampling method. See Gray (2000) for additional information.

[2] As of 2022, HDSs have not met the 30 mg/L effluent Pollutant Reduction Standard when following standard TAPE or NJDEP (2021) laboratory testing protocols.

consider referencing the NJDEP certification letter for the MTD, which lists verified storage capacities.

Sedimentation MTD Components

Sedimentation MTDs include a variety of designs to promote sedimentation. For HDSs, the primary components typically include: 1) an inflow pipe that conveys runoff into the device, 2) a "swirl" and/or treatment chamber that removes pollutants, 3) a storage chamber for removed pollutants, 4) various internal plates and/or weirs that promote sedimentation, 5) an outlet pipe that conveys treated runoff to the downstream storm drain system, and 6) a maintenance hole that provides access to the chambers to allow sediment removal. These components often are housed in a precast concrete vault or maintenance hole. The internal components of the MTD create unique hydraulics that remove and retain sediment and other pollutants while allowing runoff that is treated to pass through the MTD.

HDS Components	Intent
Inlet Pipe(s)	Convey runoff into the MTD.
Internal Flow Components	Create hydraulic conditions to remove sediment, trash, debris, and other pollutants (components vary by device).
Treatment Chamber	Provides an environment where hydrodynamic separation and/or gravitational settling occurs. The treatment chamber often has a cylindrical shape to create a vortex as runoff flows through the device. Sediment is removed by gravitational settling, centripetal forces, and/or screens and weirs.
Storage Chamber	Stores pollutants removed from the treatment chamber.
Internal Bypass	Provides integrated internal bypass mechanism to convey flows that exceed the peak design flow of the system.
Outlet Pipe	Conveys runoff from the BMP into the storm drain.
Maintenance Access	Allows access for inspection and maintenance of chambers via a maintenance hole or access hatch at grade.

Filtration MTD Description

Filtration MTDs, including high-rate media filters (HRMFs) and high-rate biofilters (HRBFs), treat stormwater by filtering it through engineered media at high hydraulic loading rates. As a result, HRMFs and HRBFs require a smaller footprint than traditional bioretention and sand filter SCMs to treat a given runoff volume.

HRMFs use one or more media types to remove pollutants from stormwater. Commonly used materials include sand, peat, crushed rock, volcanic rock, granular activated carbon, compost, minerals, granular organic materials, and fabrics. Consult with the manufacturer for information on media types targeted to treat specific pollutants. The filter media, configuration of internal parts, and hydraulics of HRMFs are proprietary and differ among HRMFs.

HRBFs treat stormwater with engineered media that supports vegetation. Physical, biological, and chemical processes occur between the media and the vegetation of an HRBF. Treatment processes include filtration, transpiration, evaporation, settling, biological uptake, microbiological uptake, and pollutant transformation.

Both HRMFs and HRBFs are well suited to provide treatment in densely developed urban settings, new developments with limited available space, urban retrofits, and large-scale projects where traditional bioretention is cost-prohibitive due to the surface area required to meet large-volume treatment goals.

Filtration MTD Components

The primary components of HRMFs and HRBFs include: 1) an inflow pipe that conveys runoff into the MTD, 2) a chamber that contains the various layers of biological filter media (HRBF) or non-biological filter media (HRMF) to remove pollutants, 3) one or more storage chambers for removed pollutants (HRMFs and some HRBFs), 4) an outlet pipe to convey treated runoff to the downstream storm system or other outfalls, and 5) maintenance access points to the filter media and storage chambers. For HRBFs, the filter media layers typically include shredded hardwood mulch as the top layer, a proprietary biological media mixture, and a well-draining, compactible gravel subbase layer with an underdrain to facilitate drainage to the outlet. Some types of HRBFs are installed similarly to conventional bioretention and may not require a housing chamber.

HRMF/HRBF Components		**Intent**
Inlet Pipe		Conveys stormwater into the MTD.
Housing Chamber		Houses internal components in concrete vaults, maintenance holes, steel containers, plastic containers, or steel mesh baskets.
Filter Media (for HRMFs)		Removes targeted pollutants via filtration through proprietary media and a specific type of filtration process. Media filter and hydraulic configurations vary substantially among devices (e.g., cartridges or other filter units, upflow or downflow).
Biological Filter Media (for HRBFs)	Shredded Hardwood Mulch	Removes coarse particulates and other buoyant materials from runoff, helps media retain water for later vegetative use, provides pretreatment for other filter media layers.
	Bio-filtration Media	Filters and treats stormwater through physical, biological, and chemical processes and biological interaction with vegetation. Decomposes organics, reduces heavy metals through adsorption and removes fine particulates and hydrocarbons. Enables biological growth.
	Subbase & Underdrain	Provides gravel layer with underdrain to facilitate drainage to the outlet pipe.
Pollutant Storage Chamber(s)		Provides internal storage for collected pollutants.
Outlet Pipe		Conveys stormwater out of the filtration MTD.
Maintenance Access		Provides access to pollutant storage chambers and media chambers to facilitate inspection and maintenance activities. Enables repairs and part replacements (e.g., replace filter cartridges, wash filters).

HRMFs and HRBFs are considered “high-rate” when stormwater can infiltrate through the media at a faster rate than the infiltration rate of typical saturated Type A and B soils. Some products have been third-party verified as having infiltration rates up to 175 inches per hour while also meeting target treatment performance standards (Washington Ecology 2020). Although stand-alone HRBFs typically do not meet the Runoff Reduction Permit Standard, they can be configured as a treatment train with a pipe or downstream storage chamber that enables infiltration of treated stormwater.

Typical Benefits and Limitations of Selected MTD Types			
Characteristic	**HDS**	**HRMF**	**HRBF**
Removes trash, debris, and other buoyant materials and stores material below ground (out of sight).	Yes[1]	Yes	No[2]
Depending on the product, it may include processes to remove oil and grease.	Yes	Yes	Yes
Effective pretreatment for primary treatment SCMs and detention facilities.	Yes	No[3]	No[3]
Effective treatment at high surface loading rates with a small footprint. Suitable for constrained sites in highly urbanized areas (space-efficient).	Yes	Yes	Yes
Delivered as one package for assembly and/or installation.	Yes	Yes	Yes
Provides vegetated features in urban areas.	No	No	Yes
Allows other uses of surface area due to underground installations and/or small surface footprint.	Yes	Yes	Yes
Meets one or more MS4 Permit design standards. (Effective for stand-alone treatment of stormwater.)	No	Yes	Yes
Depending on the product and its media design, it may remove fine particles, targeted metals, or phosphorus.	No	Yes	Yes
Potential for resuspension of captured pollutants.	Yes[4]	No	No
Maintenance needs are visible at surface.	No	No	Yes

[1] Most HDS systems remove trash, but not all have appropriate configurations to retain captured trash and still provide the same level of performance for retaining sediment. If add-ons are proposed to provide trash capture, it is important to verify treatment performance is not adversely affected. This can be done by contacting the manufacturer or verifying whether the specific MTD reviewed by NJDEP included the proposed add-ons. If the device verified by NJDEP did not include add-ons, reported performance levels may be affected. If trash capture is a specific objective, California State Water Control Boards (2021) provides recommendations for MTDs suitable for trash removal.

[2] Can remove trash and other materials, but the captured material is typically stored aboveground.

[3] Considered primary treatment SCMs.

[4] Most modern HDS systems have been tested for scour through the NJDEP protocol at 200% of the maximum treatment flow rate. Additionally, ASTM has developed a standard for testing for scour. Check test results to confirm that scour rates are acceptable.

Site Considerations for MTDs

MTDs are most applicable in highly developed, space-limited urban areas because they require a nominal area of land at grade. Underground MTDs generally are located beneath parking lots, sidewalks, and low-traffic streets. HRBFs are often situated along sidewalks, curbs, parking islands, or landscaped areas.

Consider the following factors when determining if an MTD is suitable for a site:

- **Tributary Area:** As the first step in MTD selection and sizing, characterize the tributary drainage area of the site, land use and imperviousness, pollutant types and sources, and soil erosion characteristics. Use this information to evaluate whether various MTDs can effectively control pollutants at the site. For example, a sedimentation MTD is unlikely to provide meaningful treatment for areas where targeted pollutants are fine sediment, nutrients, or dissolved pollutants. Conversely, if a site has coarse sediment, trash, and debris, an appropriately sized and maintained sedimentation MTD can serve as effective pretreatment practice to reduce long-term O&M costs for downstream control measures.
- **Assess the Need for Pretreatment:** For filtration-based MTDs, assess conditions in the tributary area to determine whether pretreatment may be needed to prevent overloading of filter media.
- **Third-Party Verification for Treatment Objectives:** Review information provided in third-party verification programs to verify whether performance expectations for the MTD meet the treatment needs at the site and/or MS4 permit design standards. For example, treatment objectives could include pretreatment for a stormwater facility, treatment for targeted pollutants, or specific pollutant removal objectives in critical areas. Treatment capabilities among MTDs vary; therefore, review of third-party performance verification is a required step in MTD selection.
- **Geotechnical Considerations:** Consult with a geotechnical engineer to determine if soils on a site will provide the necessary bearing capacity for the MTD without settlement over time and to identify any soil preparation or backfill requirements needed for a stable foundation and appropriate backfill around the device. Additionally, in areas of shallow bedrock, ensure that there is enough depth available to accommodate the specified MTD. If soils are contaminated and the MTD does not require imported fill to be used as backfill, consider specifying a soil-tight MTD.
- **High Water Table:** Exercise caution when using underground MTDs in areas with a shallow water table due to potential issues with the exfiltration of stormwater to groundwater or infiltration of groundwater into the device. Surface-based MTDs are more appropriate in areas with high water tables because they require less depth to install than underground MTDs. MTDs should also be used with caution in areas with contaminated soils. Additional waterproofing may be necessary to prevent the exfiltration of stormwater from the MTD into the contaminated soils or infiltration of contaminated water into the MTD system. In some cases, high groundwater is not anticipated or evaluated during design and prior to construction. In such cases, waterproofing methods similar to those used for sanitary maintenance holes are recommended. When systems are expected to be partially submerged in groundwater for periods of time, buoyancy must be evaluated. Consult with the manufacturer and review buoyancy calculations.

- **Location and Access:** Evaluate land uses that will occur above the MTD to ensure clear and unobstructed access for routine and emergency inspection and maintenance activities. Areas directly above the MTD should be clear of structures, vehicles, and other items that could obstruct access or visual inspection at any time. When feasible, avoid locating maintenance holes or vaults beneath traffic lanes so that traffic control is not required for routine maintenance activities. When possible, provide signage related to the facility to ensure others do not block maintenance access or use the location as a staging area (for materials or snow storage). Additionally, if the device is located under a street or parking lot, the MTD will need to be rated for traffic loads.
- **Parking Structures and Other Structures Built Above MTDs:** Avoid installing MTDs beneath parking structures or other types of buildings. In cases where no alternatives are feasible, local governments should consider additional requirements to ensure adequate maintenance access and operation throughout the MTD's life cycle. Coordination with geotechnical and structural engineers is required to ensure that the device will not interfere with the building foundation, structural support, dewatering systems, or other utility lines. MTDs installed beneath parking garages or other structures must be accessible at all times (e.g., maintenance access holes cannot be located beneath parking spots, frequent access routes, or storage areas). Parking garages often limit height clearances and do not provide enough vertical clearance for maintenance vehicles to enter and access subsurface MTDs during maintenance operations.
- **Elevation Constraints:** Evaluate elevation constraints. The depth of the MTD and the invert elevations of the inlet and outlet pipes often depend on the elevation of the local storm drain outfall when a site discharges treated stormwater into a public storm drain system. When discharging to a stream or river, consider the normal high-water elevation. Verify that the MTD will work with the operational head provided from the inlet pipe to outlet pipe and is consistent with the system tested for pollutant removal through TAPE or NJDEP. The operational head is a critical variable; if there is not enough head, the system may not achieve the desired flow rates and pollutant removal demonstrated in the verification testing. Verify that the MTD will work with pipes installed at elevations that give enough fall to the public storm drain system or receiving water and that the depth of the device is adequate to provide the necessary treatment and storage volumes. Assess the potential effects of tailwater from the downstream conveyance system. Tailwater effects can impede MTD performance by affecting the hydraulics of the device. Many MTDs can be designed with customized internal flow controls to accommodate tailwater conditions.
- **Existing Underground Utilities**: For retrofits or projects proposed in developed areas, identify existing underground utilities that may constrain the footprint and depth at which the MTD can be placed.

Organizations with Testing Protocols for MTDs

TAPE – Technology Assessment Protocol–Ecology (TAPE) is the stormwater quality treatment certification program implemented by the Washington State Department of Ecology for evaluating the performance of emerging technologies to treat polluted stormwater (WSDOE 2018a&b). The TAPE protocol is recognized in dozens of states and municipalities across the country to assist with approving MTDs and innovative stormwater treatment technologies.

TARP – Technology Acceptance Reciprocity Partnership was the stormwater treatment certification protocol used by New Jersey Department of Environmental Protection prior to 2015 to certify the level of treatment performance of MTDs. This program was disbanded in 2015.

NJDEP HDS Protocol – New Jersey Department of Environmental Protection published the Laboratory Protocol to Assess Total Suspended Solids Removal by a Hydrodynamic Sedimentation Manufactured Treatment Devices in 2021 (NJDEP 2021). (This protocol essentially supplants the TARP program.) Additionally, NJDEP certifies performance using the HDS or filter protocol, as opposed to "verifying" manufacturer claims.

NJCAT – New Jersey Corporation for Advanced Technology has a Technology Verification Program that specifically encourages collaboration between vendors and users of technology. This program evaluates vendor-specific performance claims. Be aware that NJCAT verification is not synonymous with NJDEP certification.

STEPP –The National Municipal Stormwater Alliance (NMSA) established the National Center for Stormwater Testing and Evaluation for Products and Practices (STEPP) to promote development of a national testing and verification program for MTDs and public domain stormwater practices. STEPP will provide a program for third-party testing and verification of pretreatment MTDs, primary treatment MTDs, and traditional surface-based SCMs that will be a useful reference for designers and reviewers once the program is launched.

ASTM – American Society for Testing and Materials is currently developing a national standard for the performance of MTDs under ASTM Committee E64 on Stormwater Control Measures. The standard is consistent with the NJDEP laboratory testing protocol and, once published, can be used to evaluate the performance of MTDs. Additionally, a field-testing protocol is under development similar to the TAPE protocol.

Community Values

The primary benefit of underground MTDs to the surrounding community is maximizing the amount of surface space dedicated to other uses in dense urban environments, including plazas, parking areas, and other services that benefit the community. MTDs can create space available for recreation, benches, parks, and landscaping, street trees, and other public amenities.

For MTDs with dead storage and standing water, care must be taken to avoid creating nuisance conditions. Performing regular maintenance can prevent nuisances such as mosquitos and odor in the summer months. Additionally, if vector control is a specific issue for the site, some manufacturers can provide solutions to address and control the issue.

In the case of HRBFs, the vegetated surface area, which may include native plants and/or trees, can serve as an aesthetic amenity in urban areas while still having a relatively small surface footprint. Many HRBF vendors can provide a regional plant list to help select appropriate plants for the Front Range climate. Provide irrigation for establishment of vegetation and use drought-tolerant species.

Maintenance

Maintenance requirements are a fundamental consideration when specifying an MTD. Proper routine maintenance is critical for the adequate function of the MTD. Before MTD selection, obtain and review manufacturer's maintenance guidance, including inspection methods, maintenance frequency, types of maintenance activities, equipment, maintenance methods, and cost. The guidance should clearly describe how to inspect and maintain the device, triggers for maintenance, and methods for measuring sediment to determine when maintenance is needed. Pollutant loading and characteristics can vary based on site characteristics; therefore, adjust maintenance frequency and costs accordingly. Also, consider confined space entry requirements, availability of maintenance contractors, materials replacement cost/frequency, and sediment disposal requirements. Maintenance requirements can vary significantly depending on the specific MTD. An operations and maintenance plan is needed for each installation. As part of the MTD selection process, request estimates of life-cycle costs from the manufacturers.

Most sedimentation MTDs require a vacuum truck with a hose that will extend to the storage chamber. This can remove most trash and debris in addition to sediment. In some MTDs, trash, litter, and debris are stored in a separate compartment from accumulated sediment, and access may be through a different maintenance hole or hatch. Confined space entry access may be necessary.

For sedimentation MTDs that act as traps for trash, debris, and sediment, the need for maintenance is indicated by sediment accumulation, with triggers for maintenance typically specified by the manufacturer. Frequency of maintenance is ultimately a function of available storage capacity, pollutant loading rates for the tributary watershed, and the removal efficiency of the treatment devices.

HRMF maintenance focuses on its filter media and filter configuration; therefore, each HRMF has a unique set of maintenance requirements based on media type and the unit's hydraulics. Typical maintenance involves either cleaning the filter media or replacing it with new media. The former usually involves thoroughly rinsing the filter media with clean water and removing any collected pollutants. When maintenance requires the replacement of filters or a component of the filter, the manufacturer's instructions should provide clear information on methods, costs, expected frequencies, and proper disposal of materials.

Maintaining HRBFs typically requires routine replacement of the shredded mulch on the top layer of the MTD and removal of trash and debris that has accumulated on top of the mulch or against the inlet trash rack or grate. Over time, sediment will clog the mulch layer and inhibit stormwater from flowing through the underlying media layer as intended. The shredded hardwood mulch specified by the manufacturer should be used exclusively when replacing the mulch layer. When properly maintained on a regular basis, biofilter media below the mulch layer and the plants of some HRBFs has been reported to have a low media replacement frequency (e.g., some manufacturers report 8-10 years).

Similar to other vegetated SCMs, irrigation of HRBFs may be necessary; therefore, water availability for irrigation can be an essential consideration for HRBF selection. Some HRBFs can customize internal components to provide additional water availability for vegetation in arid conditions. Drought-tolerant species may also alleviate or reduce the volume of water needed for irrigation. If a limited water supply is available for irrigation, the smaller footprint of HRBFs may require less irrigation compared to other SCMs.

Maintenance Considerations During MTD Selection

To avoid selection of MTDs with onerous maintenance requirements, consider the following:

- Review manufacturer's maintenance guide to determine the frequency and types of maintenance activities required. The guidance should clearly describe how to inspect and maintain the device, triggers for maintenance, and methods for measuring accumulated pollutants to determine when maintenance is needed.
- MTD collection chambers must be accessible by maintenance equipment and unimpeded by internal weirs and baffles. MTDs that allow visual observation of collected pollutants are easier to inspect and maintain than devices that do not provide visual indicators.
- Assess how much time it will take to inspect and maintain the MTD and whether the time requirement is a reasonable expectation for the entity responsible for maintenance.
- Avoid MTDs that require confined space entry for routine maintenance activities. Be aware of confined space entry requirements for clearing out clogged orifices, pipes, and weirs that will likely be required under certain conditions for underground MTDs.
- Identify and review documents, forms, and tools needed for inspection and maintenance. These may include an inspection and maintenance plan, inspection forms, required personal protective equipment, and equipment necessary for maintaining the MTD.
- For HDSs, identify how a vacuum truck will access the different chambers of the MTD and ensure that standard suction hose lengths can reach the bottom of the vault of the maintenance hole. MTD designs should allow easy access with the suction hose to maneuver the vacuum suction hose to extend to the bottom and the full extent of each device's chamber.
- Salts from deicing contribute to the deterioration of concrete and other materials in sedimentation MTDs. Therefore, for installations where deicing activities regularly occur during the winter, plan on a few additional inspection and maintenance visits during winter to rinse accumulated salts out of the device with a hose. Salt may also affect plant growth in HRBFs.

Design Procedure

Design procedures and criteria are specific to the type of MTD selected and must follow the manufacturer's design and specification procedure, as well as local jurisdiction requirements. Most sedimentation- and filtration-MTDs are sized based on flow rate; however, some can be sized based on volume and/or flow rate. The general steps for sizing and specification based on flow rate are described below as general guidance, recognizing that some variation in the procedure may be required or help to optimize application of various MTDs for different site requirements. The generalized procedure below is typically applicable to sedimentation MTDs; where this design procedure conflicts with the manufacturer's design procedure, follow the manufacturer's design procedure, provided that the water quality event defined in Volume 1 is treated. Some steps below may apply only to certain types of MTDs.

Simplified Design Procedure Overview

A simplified overview of key steps in the design procedure for MTDs includes:

1) Calculate the water quality event design flow for the site.
2) Calculate peak bypass flow for the site.
3) Select an approved MTD based on project requirements. Use the NJDEP list of approved MTDs for projects that only require sedimentation (pre-treatment). Use the Washington State Department of Ecology list of MTDs with a General Use Level Designation (GULD) for Basic, Enhanced, or Phosphorus for projects that require filtration to meet the Colorado MS4 performance standard of 30 mg/L.
4) Follow manufacturer's design recommendations to design each MTD specified.

1. **Calculate the water quality event peak flow rate, Q_{WQ}:** Sedimentation and filtration MTDs are typically sized based on a design peak flow rate. The water quality event peak flow rate (Q_{WQ}) is the peak discharge associated with the 80th percentile runoff event, corresponding to a storm depth of 0.6 inches. See the *Runoff* chapter in Volume 1 for guidance on calculating the discharge associated with the water quality event.

2. **Determine the maximum treatment flow rate, Q_{MAX}:** The maximum treatment flow rate is the greatest flow rate than can be discharged through an MTD while still achieving specific treatment efficiency goals such as percent TSS removal and/or maximum effluent concentrations of TSS. Third-party verification of maximum treatment flow rates is important to ensure that the MTD does not surcharge or experience excessive scouring of accumulated sediment at the maximum treatment flow rate.

   For HDSs, the manufacturer specifies the maximum treatment flow rate for a given HDS type and size. To ensure that the selected HDS provides adequate performance at the maximum treatment flow rate, verify that that the HDS is included on the "Laboratory Verified and NJDEP Certified" list.[3]

   For HRMFs and HRBFs, the manufacturer specifies the maximum treatment flow rate for a given HRMF/HRBF type and size. To ensure that the selected HRMF/HRBF provides

[3] For a list of NJDEP-certified devices, see https://www.nj.gov/dep/stormwater/treatment.html.

adequate performance at the maximum treatment flow rate, verify the HRMF/HRBF infiltration or hydraulic loading rates specified in the TAPE GULD approval letter.[4]

Verifying Performance When Selecting an MTD

MHFD does not have a technology verification program or maintain a list of "approved" MTDs. Instead, designers should utilize information available through other state and national verification programs to support MTD selection. National verification programs such as STEPP, supported by new ASTM standards, are under development as of publication of this fact sheet and may be appropriate for use in the future. Two existing well-established programs that can be used to support MTD selection are described below. Ultimately, it is the responsibility of the design engineer, not the manufacturer, to ensure that the specified MTD will meet the water quality requirements for a given project.

NJDEP for Sedimentation MTDs

Sedimentation MTDs on the "Stormwater Technologies: Laboratory Verified and NJDEP Certified" list on the NJDEP's website (https://www.nj.gov/dep/stormwater/) are verified to provide levels of treatment that are suitable for pretreatment of runoff (i.e., 50% TSS removal). If a product claims to be "NJCAT-verified" but is not on the list referenced above, it is not an acceptable pretreatment device. This is because NJCAT "verification" is not synonymous with meeting the NJDEP protocol. A product can receive verification from NJCAT for any performance criterion it can demonstrate it meets; however, the performance criterion for which it receives verification may not meet the performance standards in the NJDEP (2021) Laboratory Protocol to Assess Total Suspended Solids Removal by a Hydrodynamic Sedimentation MTD (and likely does not meet them). See NJDEP (2022) and NJDEP (2021) for additional information.

More than a dozen sedimentation MTDs on the NJDEP list are verified and certified to meet the performance standards outlined in the NJDEP HDS protocol; however, not all offer internal bypass capability. Most devices target TSS, but not trash, and many, but not all, can remove oil and grease using absorbent pads. Storage capacities vary widely between the different devices, as do maximum treatment flow rates necessary to meet the pollutant removal standard for a given device size.

TAPE for Filtration MTDs

The Technology Assessment Protocol – Ecology (TAPE) is the program implemented by Washington State Department of Ecology for reviewing and certifying proprietary MTDs. The agency's website https://ecology.wa.gov/ (use search terms "TAPE" or "Stormwater Treatment Technologies"), categorizes proprietary products approved for use in Washington State based the level of use each product has been approved for, and the type of treatment each product provides, in accordance with the TAPE program.

Filtration MTDs expected to meet Colorado's MS4 performance standard for 30 mg/L TSS include those with a General Use Level Designation (GULD) for Basic, Enhanced, or Phosphorus treatment categories under the TAPE program.

[4] For a list of TAPE-approved technologies, see https://ecology.wa.gov/ and use search terms "TAPE" or "Stormwater Treatment Technologies".

3. **Identify potentially appropriate MTDs:** To select an appropriately sized MTD, compare the calculated water quality event peak flow (Q_{WQ}) with the maximum treatment flow rate (Q_{MAX}). The MTD is acceptable for further consideration if Q_{MAX} is greater than or equal to Q_{WQ}. Because various MTDs will meet the water quality event peak flow rate requirements for a given site, consider which devices are best suited to site characteristics, the pollutants targeted at the site, and the ability to meet MS4 permit design standards. Verify performance claims based on data obtained through established testing protocols, including established third-party verification programs (see text box).
4. **Evaluate inflow and outflow pipes configurations:** Allowable pipe configurations vary widely between products, and designers must understand vertical and horizontal pipe placement constraints. The angle between the inlet and outlet pipe, often dictated by the proposed storm drain system layout, is crucial for sedimentation MTDs to function as intended. The design engineer must understand the manufacturer's allowable pipe layouts and entrance/exit locations, any pipe orientation or angle constraints, and horizontal and vertical placement requirements for the MTD. Some sedimentation MTDs accommodate multiple inlet pipes, while others only allow one inlet and one outlet pipe. Some devices require a 180-degree angle between the inlet and outlet pipes, while others allow for variable angles and multiple inlet pipes. During design, check that inflow and outflow elevations are appropriate for the MTD being specified and within the design flow recommendations from the manufacturer. Some MTDs are very sensitive to inlet and outlet elevations. For example, filtration MTDs often require specific operational head (drop from inlet to outlet). Elevations that differ from the tested and verified configuration can influence whether the MTD functions as intended. If atypical elevations or operational head are present, consult with the manufacturer to build in redundancy and conservatism in order to meet treatment objectives.
5. **Evaluate internal flow components:** Internal flow components in a sedimentation MTD facilitate sedimentation and retain captured pollutants despite the short hydraulic residence times of runoff in these devices. Internal flow components may include baffles, weirs, deflection plates, screens, and other features and are typically standard features designed by the manufacturer rather than the design engineer. Therefore, the designer should evaluate the ability of internal flow components to control targeted pollutants, ease of maintenance, and durability when comparing MTD alternatives.
6. **Assess storage chamber size and access:** Most sedimentation MTDs have a separate chamber or sump area that stores collected pollutants. The storage chamber is designed to retain sediment, litter, and debris removed in the treatment chamber and minimize the potential for resuspension. Consider the sediment, trash, and debris loads from the contributing drainage area, and select a device with sufficient storage to limit routine maintenance to once or twice per year. An undersized storage chamber leads to nuisance conditions and frequent maintenance. Provide direct access from the street level to the storage chamber for inspection and maintenance.
7. **Specify selected MTD.** Once the MTD has been selected (based on the process and considerations above), the remaining design steps for the specified MTD can be completed.

8. **Size the internal bypass:** An internal bypass is built into some sedimentation MTDs to divert flow that exceeds the water quality event peak flow rate and convey flow around the treatment and storage chambers to prevent resuspension of pollutants. This mechanism is called an "internal bypass" because the pipe or weir that bypasses the larger flows are typically incorporated as a component within the MTD. Internal bypasses generally tend to be less expensive than an external bypass, which requires additional maintenance holes and more length of pipe. Internal bypass configurations may vary widely across devices; however, the layout of the bypass must be hydraulically compatible with the storm drain system's upstream and downstream elevations. Size the internal bypass peak flow rate for the maximum design flows expected in the upstream and downstream storm drains. If a sedimentation MTD does not have an internal bypass, an external bypass is required.
9. **Compute the Hydraulic Grade Line (HGL) and Energy Grade Line (EGL):** Compute the HGL and EGL for the MTD and the upstream and downstream storm drain system following procedures and criteria in the *Streets, Inlets, and Storm Drains* chapter of Volume 1. The bypass should be designed to avoid pressurized flow and prevent resuspension of accumulated pollutants. When backwater conditions are present, account for high tailwater when evaluating the hydraulics of the MTD and bypass, and verify that the device will operate as intended (some MTDs require a specific range of velocities within the treatment chamber to create unique hydraulic effects to remove sediment). For purposes of evaluating emergency overflows, calculate the HGL and EGL for design flow rates assuming that the filter is completely plugged and passes no flow.
10. **Plan access to all chambers:** Maintenance access configurations vary between products. Direct, unobstructed access to all chambers of a sedimentation MTD is required for maintenance operations and repair.

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