DEPARTMENT OF TRANSPORTATION

Stormwater BMP Inspection and Maintenance Resource Guide

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University of Minnesota

June 2024

Research Project
Final Report 2024-09

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16. Abstract (Limit: 250 words)

Stormwater treatment practices, often referred to as stormwater best management practices (BMPs), require a substantial commitment to maintenance, including regular inspections and assessments. Existing regulations require governmental units to develop a systematic approach for ongoing inspection and maintenance to ensure that they are achieving their desired treatment goals. A lack of maintenance will lead to a decrease in BMP performance and will often result in expensive rehabilitation or rebuild. In 2009, SRF Consulting produced a maintenance guide for the Local Road Research Board (LRRB) (Marti, et al. 2009). In 2023, the LRRB commissioned the University of Minnesota St. Anthony Falls Laboratory to update this guide to reflect new best practices. The Stormwater BMP Inspection and Maintenance Resource Guide (the Guide) is a supplement to the Minnesota Stormwater Manual (MPCA 2023) and will help the reader plan for recommended long-term maintenance activities through guidance on visual inspection, testing, and monitoring methods for identifying what maintenance is needed, and when it is needed. The Guide describes inspection and maintenance for constructed stormwater ponds (both dry and wet) and wetlands, underground sedimentation practices, infiltration practices, filtration practices, bioretention practices, permeable pavements, and stormwater harvesting. In addition, the Guide includes a section on Meeting Stormwater Management Objectives, which provides information on achieving reductions for sediment, phosphorus, nitrogen, metals, chloride, pathogens, and organic chemicals. The Guide also includes Field Inspections Resources, which contains inspection checklists and maintenance activity recommendations for all of the practices listed above.

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Stormwater BMP Inspection and Maintenance Resource Guide

Final Report

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Table of Contents

List of Figures

List of Tables

List of Acronyms

ACPA = American Concrete Paving Association
ACI = American Concrete Institute
ACSE = American Society of Civil Engineers
ASTM = American Society of Testing and Materials
BOD = Biochemical oxygen demand
BMP = Best management practice
CEC = Chemicals of emerging concern
CCWMO = Carver County Watershed Management Organization
COD = Chemical oxygen demand
CWA = Clean Water Act
EPA = Environmental Protection Agency
FHWA = Federal Highway Administration
FTW = Floating treatment wetlands
ISBD = International Stormwater BMP Database
LRRB = Local Road Research Board
MnDOT = Minnesota Department of Transportation
MPCA = Minnesota Pollution Control Agency
NAPA = National Asphalt Pavement Association
NPDES = National Pollutant Discharge Elimination System
OSHA = Occupational Safety and Health Administration
PACB =Permeable articulated concrete blocks
PAH = Polycyclic aromatic hydrocarbon
PCB = Polychlorinated biphenyl
PDEP = Pennsylvania Department of Environmental Protection
PICP = Permeable Interlocking Concrete Pavements
TCE = Trichlorethylene
TP = Total Phosphorus
TSS = Total Suspended Solids
UDFCD = Urban Drainage and Flood Control District
WCA = Wetland Conservation Act
WTR = Water Treatment Residuals

Chapter 1: Introduction

The federal Clean Water Act of 1972 (CWA) mandated that states begin to address both point source and nonpoint source discharges of pollutants into the nation's surface waters. "*The Clean Water Act establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters," states the CWA.* (Link Here) In the early years, implementation of the CWA focused on controlling point source pollution (wastewater treatment plans, etc.) with the issuance of National Pollution Discharge Elimination System (NPDES) permits. Starting in the late 1980s, efforts to regulate stormwater runoff, or nonpoint source pollution, increased significantly through the issuance of NPDES general permits. In Minnesota, the Minnesota Pollution Control Agency (MPCA) administers the various regulatory programs of the CWA.

Minnesota, through the 1982 Metropolitan Water Management Program (Minnesota Statutes, Section 103B.201, et seq.), the 1990 Comprehensive Local Water Management Program (M.S., Section 103B.311 et seq.), and Watershed Law (M.S. Chapter 103D) requires planning and implementation strategies for the control of water quantity and quality. On a regional level, and specifically in the metropolitan area, watershed management organizations have incorporated planning and regulations through watershed plans and implemented specific projects to protect waters in their respective jurisdictions. Cities and counties are charged with implementing strategies to meet the various federal and state regulatory requirements to control nonpoint source pollution.

Stormwater treatment practices, often referred to as stormwater best management practices (BMPs), require a substantial commitment to maintenance, including regular inspections and assessments. Existing regulations require governmental units to develop a systematic approach for ongoing inspection and maintenance to ensure that they are achieving their desired treatment goals. A lack of maintenance will lead to a decrease in BMP performance and will often result in expensive rehabilitation or rebuild.

A lack of maintenance will lead to a decrease in BMP performance and will often result in expensive rehabilitation or rebuild.

In 2009, SRF Consulting produced a maintenance guide for the Local Road Research Board (LRRB) (Marti, et al. 2009). It addressed local Minnesota government inspection and maintenance activities for various categories of BMPs. In 2023, the LRRB commissioned the University of Minnesota St. Anthony Falls Laboratory to update this guide to reflect new best practices. The updated guide is a supplement to the *Minnesota Stormwater Manual* (MPCA 2023) and will help the reader plan for recommended long-term maintenance activities.

1.1 Inspection and Maintenance Considerations

Stormwater BMPs operate at their greatest efficiency when properly maintained. In most fully functioning applications, stormwater BMPs are designed to provide specific pollutant removal efficiency. Most are designed to capture and treat the first inch of runoff for water quality, to settle and retain particles of sediment, and retain or remove dissolved substances for a specific contributing sub-watershed. As it fills with debris and sediment, the BMP's efficiency decreases to the point of being non-functioning unless it is properly maintained. The goal is to provide proper maintenance at a proper frequency to maintain the most cost-effective balance between total lifecycle cost and BMP performance.

Stormwater BMPs operate at their greatest efficiency when properly maintained.

Pollutant retention refers to the capture of pollutants within a BMP, such as phosphorus via particle attachment. Retained pollutants remain in the BMP but can be released under certain conditions. Pollutant removal refers to pollutants that are removed or eliminated from the BMP, such as nitrogen being converted to nitrogen gas, which is released to the atmosphere. Pollutants may be removed from the practice via volatilization, biological decomposition, and the harvesting of vegetation within the practice. Both pollutant retention and removal will reduce the concentration of pollutants from stormwater, but retained pollutants remain in the practice and should not be considered removed.

As shown in Figure 1-1, Kang et al. (2008) breaks maintenance activities into three categories: routine, non-routine, and major. ***Routine maintenance*** occurs frequently (e.g., once per year or more) and regularly (e.g., every quarter, twice per year) and is typically less time and/or labor intensive per site visit than the other categories. Examples of routine maintenance are visual inspection, mowing grass, raking the surface of a sand filter, litter and trash removal, and weeding.

Non-routine maintenance is less frequent than routine maintenance, irregular (i.e., only as needed, not scheduled) and is more time and labor intensive per site visit than routine maintenance. Examples of non-routine maintenance include structural repairs, sediment removal, and partial rehabilitation of the practice.

Major maintenance actions are rare, very time and labor intensive, and include actions such as replacing an entire media bed in a filtration practice, full rehabilitation of the practice, or total reconstruction.

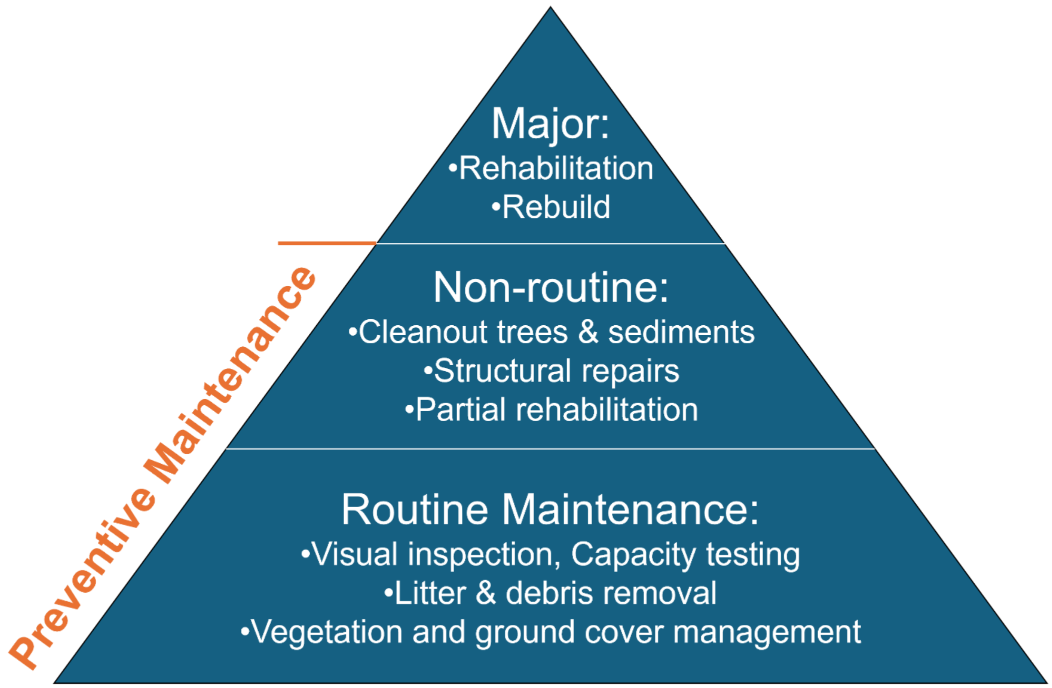

Figure 1-1: Stormwater treatment practice maintenance pyramid (Kang et al. 2008).

The frequency of any maintenance activity, regardless of its level on the maintenance pyramid, depends on a vast array of variables including type and characteristics of the particular practice, watershed size, land use and soil characteristics, type and number of trees nearby, amount of construction in the watershed, and rainfall patterns and amounts. While maintenance schedules should be determined for each individual practice, typically, routine maintenance occurs from 2-4 times per year with more frequent maintenance sometimes being necessary.

A stormwater best management practice (BMP) must be assessed to determine if it needs maintenance. ***Assessment is the evaluation of the practice to determine if it is functioning as desired.*** Thus, all maintenance plans and budgets should include the regular assessment and corresponding resources for the assessment of BMPs. A holistic view of the watershed and the most beneficial and efficient locations to locate the BMPs should also be taken. There are various levels of assessment that span a wide range of difficulty and cost. Erickson et al. (2013) list four levels of assessment, in increasing levels of time and cost, as 1) visual inspection, 2) capacity testing, 3) synthetic runoff testing, and 4) monitoring.

Visual Inspection: quick, simple, visual assessment to determine function.

Capacity Testing: Point measurements to pinpoint failure and inform maintenance.

Synthetic Runoff Testing: Filling a practice with synthetic runoff to measure performance.

Monitoring: Measuring natural rainfall events to determine performance.

1.1.1 Visual Inspection

Visual inspection is simply a visual evaluation of a stormwater treatment practice. It should include photographs and/or video of the practice and detailed field notes related to site conditions and weather conditions at the time of inspection and on previous days. To comply with the MPCA's requirements for Municipal Separate Storm Sewer Systems (MS4) permits, all BMPs must be inspected at least once every 5 years with a goal of 20% of an agency's BMPs being inspected annually. However, city and county engineers and maintenance crews understand that certain stormwater treatment facilities in their system may require more frequent inspections and/or maintenance than others. To effectively maintain stormwater facilities, cities and counties may want to specify a storm event that triggers inspection activities for these select locations (e.g., one inch rainfall over a 30-minute, two-year event).

Visual Inspection includes:

Field Notes:
☑ Site Conditions
☑ Weather Conditions

Photographs and/or

Video

Visual inspections can usually be completed in less than half an hour and can sometimes be used to identify obvious problems with a practice. For example, if it has not rained in the previous 2 days, visual inspection of a rain garden may reveal that it contains standing water and dead or dying vegetation. This would lead one to conclude that the rain garden is not infiltrating water as designed and needs maintenance. Visual inspection, however, is limited in the information it can provide. If upon visual inspection a rain garden does not have standing water and the vegetation looks healthy and normal with no invasive species, it does not guarantee that the rain garden is functioning properly. Stormwater entering the rain garden could be short-circuiting through the rain garden or its media or, if it has been several days since it rained, it may not be infiltrating water quickly enough.

1.1.2 Capacity Testing

The second level of assessment, capacity testing, is performed by making a series of point measurements throughout the treatment practice. For example, the overall infiltration capacity of a treatment practice can be assessed with an infiltrometer to measure the infiltration capacity at a series of spatially distributed points throughout the practice (Figure 1-2). Regarding sediment storage, staff can probe to determine retained sediment elevations within a practice to assess the remaining storage capacity.

Figure 1-2: Multiple infiltration capacity tests at a roadside swale (left) using the MPD Infiltrometer (right). Photos: John Gulliver.

Advantages of capacity testing include low time commitment, cost, and difficulty level. It can also identify specific areas within a practice that need maintenance and areas that do not. Thus, maintenance activities can be focused only on those areas needing attention, thereby saving time and resources. See Erickson et al. (2013) for more information on applying capacity testing and Ahmed et al. (2015) and Weiss and Gulliver (2015) for more information on infiltration testing.

1.1.3 Synthetic Runoff Testing

The next level of assessment, synthetic runoff testing, is accomplished by adding synthetic stormwater to a treatment practice to evaluate the hydraulic characteristics of the practice and/or the effectiveness of pollutant retention or removal. Typically, the water source is either an approved fire hydrant or a water truck. The required volume of water cannot exceed the available water supply. The water may be unaltered (e.g., straight from a hydrant) if only assessing the hydraulic characteristics of the practice. If pollutant retention or removal effectiveness is to be assessed, an appropriate dose of pollutant(s) can be added to the water to achieve desired influent pollutant concentration(s).

In Figure 1-3 (red circle), unaltered water is added to a bioretention facility from a fire hydrant. The topography and soil moisture content were measured prior to adding the water, and the speed of infiltration was recorded, enabling the resultant saturated hydraulic conductivity for the bioretention facility to be determined.

Figure 1-3: Synthetic runoff test using a metered fire hydrant (red circle) at a bioretention practice. After water fills the bioretention practice, the recession of the water surface is measured over time. Photo: John Gulliver.

A predetermined mass of pollutant is typically added to and mixed in a water truck to give the desired pollutant concentration. If using a fire hydrant, pollutants are fed to the influent stream upstream of the practice at a predetermined pollutant mass flow rate to give the desired pollutant concentration in the water entering the practice. Figure 1-4 shows a synthetic runoff test of an underground pre-treatment practice that is using a fire hydrant as the water source. A sediment feeder, located downstream of the fire hydrant and before the treatment practice, is used to dose the influent stream with well-characterized sediment. The mass discharge rate of the sediment feeder has been set to correspond with the volumetric flow rate from the fire hydrant to give the desired sediment concentration in the synthetic stormwater entering the practice.

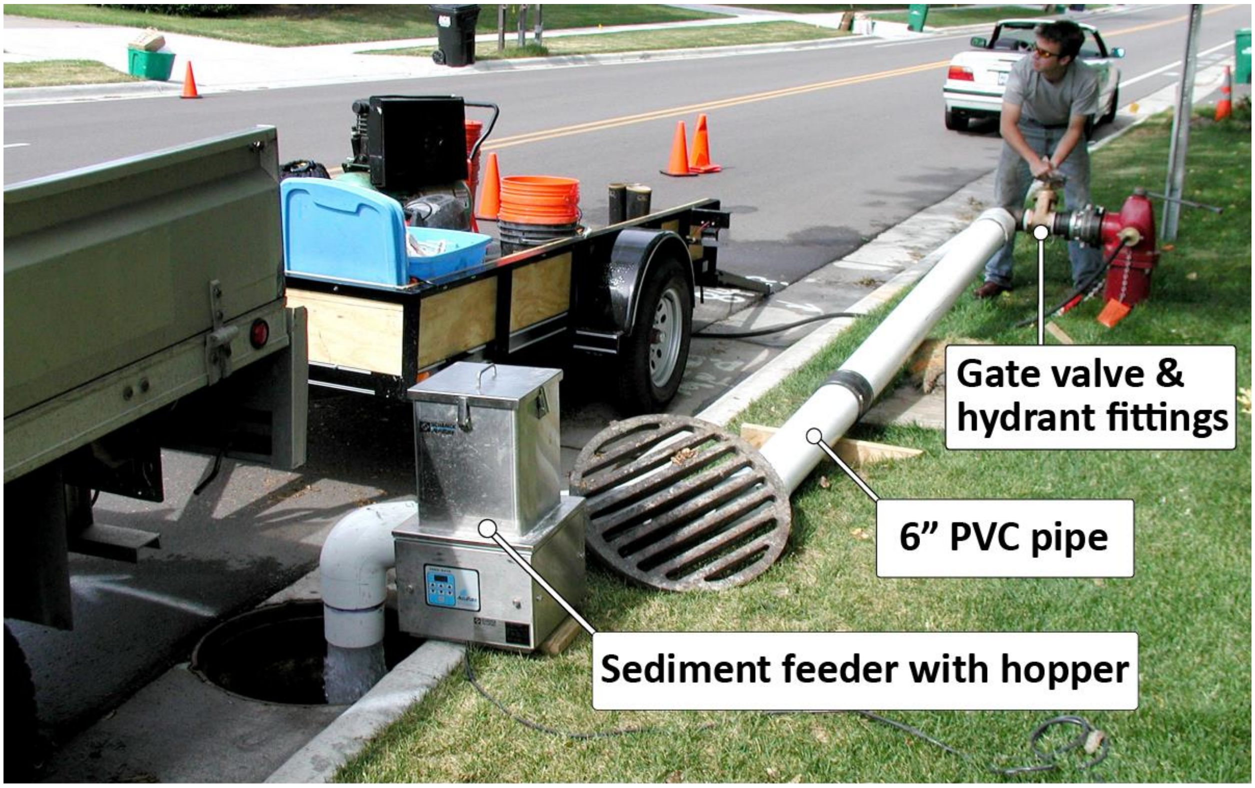

Figure 1-4: Synthetic runoff testing of sediment capture by an underground pre-treatment chamber. Photo: John Gulliver.

Synthetic runoff testing can be used to assess the overall performance of a practice. Because it does not rely on point measurements to represent the entire practice, it is more accurate in this regard than capacity testing. Unlike capacity testing, however, synthetic runoff testing cannot identify specific areas within a practice that need maintenance. It can only assess how the overall practice is performing. Thus, it is possible that some areas of a practice that are underperforming will go undetected.

Synthetic Runoff Testing is easier than **monitoring** and should be considered before monitoring to save time, resources, and cost.

1.1.4 Monitoring

The fourth and last level of assessment, monitoring, is the most time consuming and expensive. It also involves more uncertainty than synthetic runoff testing. Monitoring can be used to assess runoff volume reduction, peak flow reduction, and pollutant removal efficiency. It can also be used to assess the performance of the stormwater BMP in the watershed. ***Monitoring is performed by measuring all influent and effluent volumetric flow rates entering and exiting a practice during natural rainfall or snowmelt events. If pollutant removal efficiency is to be assessed, pollutant concentrations of all volumetric flow rates must also be sampled and determined throughout the runoff period.***

Unlike synthetic runoff testing that can be controlled to maintain constant volumetric flow rates and constant pollutant concentrations for relatively short testing periods, natural runoff events have large variability in flow rate and pollutant concentration within events, and separate events can have vastly different durations. As a result, flow and pollutant concentration must be measured throughout a runoff event. The duration and volume of a runoff event are unknown prior to the event, so there can be problems with automatic samplers, which are typically pre-programmed to collect samples at a particular time or flow volume increment. As a result, automatic samplers can fill before the end of a runoff event, thus missing key samples that pass the sampling point after the sampler is full. Also, if all sample bottles are not filled by the end of a runoff event, sampling opportunities are similarly lost.

The high variability encountered monitoring real-world storm events means a corresponding higher uncertainty in results compared with synthetic runoff testing. Due to unpredictable weather conditions, monitoring involves a variable time commitment. For example, equipment must be maintained and ready for use even during long periods between rain events. However, monitoring may be more representative than synthetic runoff testing because it relies on natural runoff events with the full range of pollutants that occur in the watershed. Synthetic runoff testing is typically dosed with only the pollutant(s) of interest; this can impact pollutant removal effectiveness when processes such as adsorption and ion exchange are involved.

1.2 Summary

All stormwater treatment practices require maintenance. Too much maintenance is a waste of time, money, and resources, but too little maintenance leads to the degradation and failure of the practice. Assessment can be used to determine when maintenance is necessary and can help optimize limited resources and budgets. Assessment must occur at least once every five years for MS4-permitted jurisdictions, but more frequent assessments may be warranted depending on watershed characteristics, the treatment practice, and other variables.

Different levels of assessment that vary in cost and time commitment are available. They range from simple visual inspection and documentation, which may take 30 minutes, to monitoring natural runoff events that may last for months or years. Thus, the construction of any stormwater treatment practice must be accompanied by an assessment and maintenance plan with a corresponding budget to support the plan for as long as the practice is to remain in service. More details about conducting any of the four levels of assessment and about recommended maintenance activities for specific stormwater treatment practices are provided by Erickson et al. (2013).

All stormwater treatment practices require maintenance. Too much maintenance is a waste of time, money, and resources, but too little maintenance leads to the degradation and failure of the practice.

Chapter 2: Constructed Stormwater Ponds and Wetlands that Treat Stormwater

2.1 Description

Stormwater ponds are typically installed as an end-of-pipe BMP at the downstream end of a sub-watershed. ***The primary water quality function of a stormwater pond is to remove a significant portion of sediment and associated pollutants from stormwater runoff prior to it being released to downstream water bodies.*** The retained solids must be periodically removed from the stormwater pond to maintain effective performance. Stormwater ponds also can be used to reduce peak discharges from a site and are often used to meet such regulations.

Virtually all stormwater ponds have one or more outlet control structures. These can take various forms and can be constructed of a variety of materials depending on the specific requirements for the pond and the surrounding topography (Figure 2-1). A typical outlet control structure will provide skimming so that floatables are retained in the pond. It will typically also control the rate of discharge from the pond. A second outlet control structure will provide an emergency overflow for large storm events.

There are several distinct sub-categories of stormwater ponds presented in the Minnesota Stormwater Manual (MPCA 2023) which are discussed below.

2.2 Sub-categories of Stormwater Ponds

Several pond design variants are typically described in stormwater management literature. While it is possible that any one of these pond types could be beneficially implemented somewhere in Minnesota, both the climatic conditions and the applicable regulations prevalent throughout the State strongly favor the use of one of them in particular, namely the wet extended detention pond. The wet extended detention pond (*Link Here*) is the only design variant fitting the description of a Wet Sedimentation Basin as described in the MPCA Construction General Permit (*Link Here*. For this reason, while other design variants are presented, much of this discussion focuses on wet extended detention ponds (MPCA 2023).

2.2.1 Constructed Stormwater Pond

A constructed stormwater pond is defined as an upland (not wetland) constructed water body of less than 10 acres in surface area which has infrastructure to deliver and release stormwater runoff. An example of a constructed stormwater pond is provided in Figure 2-1. Such ponds typically contain standing water the majority of the time. Sub-classifications of constructed stormwater ponds make up three main design variants of stormwater ponds (MPCA 2023):

Wet extended detention pond. The wet extended detention pond (Figure 2-2) is a combination of permanent pool storage and extended detention storage above the permanent pool to provide additional water quality or rate control.

Micropool extended detention pond. This variation of the wet extended detention pond has a smaller permanent pool at the pond outlet to prevent resuspension of settled material leaving the pond.

Flow-through pond (no extended detention) design. The flow-through pond design has an essentially unrestricted spillway as its primary outlet, with its crest at the elevation of the permanent pool. It provides water quality treatment by holding a volume of stormwater equal to the permanent pool volume, permitting settling to occur. The water stored in the pond is later displaced by new runoff. Note that the flow-through pond contains a storage volume allocated for treatment that is entirely below the permanent pool, making it inaccessible to new runoff in frozen conditions.

Figure 2-1: Typical constructed stormwater ponds that are upland from wetlands. Photos: Noah Czech, City of St. Cloud; Link Here

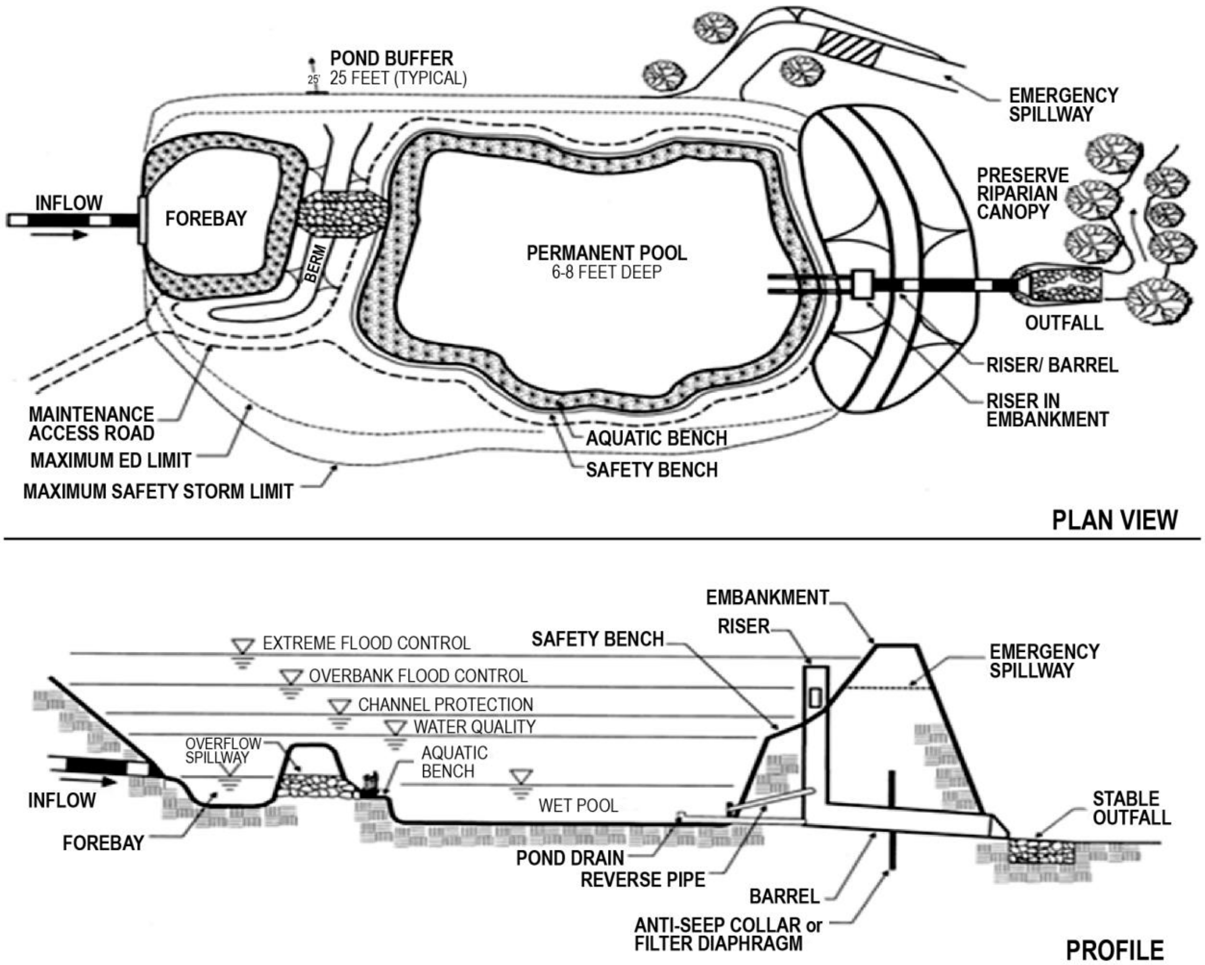

Figure 2-2: Plan view and profile of a wet extended detention pond (MPCA 2023).

2.2.2 Wetlands that Treat Stormwater

Prior to the Wetland Conservation Act (WCA) of 1991, wetlands were often plumbed to be utilized as stormwater treatment wetlands. An example is provided in Figure 2-3. Existing wetlands are no longer adapted to treat stormwater. Because wetlands are regulated waterbodies, corrective maintenance activities typically require permits, and removal of sediment can only be done to a specific elevation.

Figure 2-3: Example of a converted wetland (before 1991) that treats stormwater. Photo: Poornima Natarajan.

2.2.3 Dry Detention Pond

A dry detention pond has no permanent pool, as shown in Figure 2-4; it is designed to temporarily detain stormwater runoff and allow large sediment particles and associated pollutants to settle to the bottom of the pond. Water is gradually released through an outlet into the storm drain system. Dry ponds are susceptible to sediment resuspension but are useful for rate control.

Figure 2-4: Example of a dry detention pond (MPCA 2023).

2.3 Benefits and Limitations of Stormwater Ponds

2.3.1 Benefits

Reduce Pollutant Load. Stormwater ponds can reduce substantial pollutant load through sedimentation.

- The International BMP Database (ISBD 2022) documents the following median retention rates in detention ponds (constructed stormwater ponds and wetlands that treat stormwater): total suspended solids 76%; phosphorus 51%; nitrogen 26%; cadmium 50%; chromium 50%; copper 49%; lead 67%; and zinc 57%.
- The International BMP Database (ISBD 2022) documents the following median retention rates in dry detention ponds: total suspended solids 66%; phosphorus 26%; nitrogen 2%; cadmium 26%; chromium 25%; copper 48%; lead 67%; and zinc 67%. While dry detention ponds do not have the retention characteristics of wet detention ponds, they do provide some retention of total suspended solids and other relevant compounds.

Peak Flow Reduction. Stormwater ponds can reduce runoff peak flow rates for annual storms. A typical wet extended detention pond or dry detention pond design will reduce peak runoff rates for a two-year storm frequency.

Wildlife Habitat. Stormwater ponds can provide wildlife habitat and aesthetic enhancement when properly maintained. Ponds are attractive for wildlife and the area immediately around ponds can have vegetation that serves as a habitat.

Construction Phasing. Ponds may also be used as a temporary sedimentation basin during construction in the watershed.

Predictability. These types of ponds have been used as a BMP for 50 years or more, so the design procedure is well established.

2.3.2 Limitations

Designated space requirement. Stormwater ponds are one of the larger stormwater BMPs. They are an efficient use of space due to their large drainage area to pond ratio (~40:1, Claytor and Schueler, 1996), but cannot be dispersed into multiple locations next to roads and parking lots or placed close to buildings.

Thermal Impacts. The large surface area to volume ratio of stormwater ponds tends to increase water temperature and may cause downstream thermal impact to trout streams.

Potential for nuisance insects or odor. The primary nuisance insects in Minnesota are mosquitoes, which require five days of calm water to hatch. This has not been observed for open-water ponds, even with floating plants present, but may occur in ponds with a large population of emergent plants. Unpleasant odors can occur when water with a low dissolved oxygen concentration (less than 1 mg/L) reaches the surface. There are stormwater ponds in Minnesota that have odor problems.

Wildlife Habitat. The wildlife that often inhabit ponds can be seen as a nuisance (e.g., geese).

Potential High Phosphorus Export. It has been documented (Taguchi, et al. 2020) that many stormwater ponds are stratified at depths of 1 ft or less. With the high organic loading of stormwater ponds resulting in a large sediment oxygen demand, dissolved oxygen concentration in ponds may decrease towards zero as stratification prevents oxygen-rich water near the surface from mixing throughout the water column. This may result in an anaerobic environment near the sediments. In an anaerobic environment, iron-related precipitated phosphorus can dissolve and become mobile. The sediments can thus release phosphate (internal loading), which will increase algal and floating plant growth and may increase the export of phosphorus to receiving water bodies.

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2.4 Assessment Activities – Stormwater Ponds

There are two types of assessment (Erickson et al. 2013) that are relevant to scheduling maintenance for stormwater ponds, depending upon the goal of the assessment: Visual inspection and capacity testing. These are described below.

2.4.1 Visual inspection

Visual inspection of constructed stormwater ponds and of wetlands that treat stormwater require inspection and documentation of the amount and distribution of retained solids. For example:

- A large deposit of solids at the inflow location of a dry pond may alter the inflow conditions or increase re-suspension of solids. See Tables A-1 through A-3b in the Field Inspection Resources, for detailed instructions about visual inspection of sedimentation practices.
- Inspect all inlet and outlet structures for clogging and/or structural damage. Schedule removal of debris and repair/replace outlet structure, if necessary.
- The outflow location(s) should also be inspected to make sure a tailwater condition is not impeding discharge from the pond.
- See the section on Maintenance Actions in this chapter and Table A-1 for actions relevant to sediment deposition and clogged structures of a stormwater pond.

Visual inspection can also be used to assess the presence of high phosphorus concentrations in wet ponds. A study by Natarajan, et al. (2022) found that a good indicator of high phosphorus concentration in Minnesota is floating plant cover such as duckweed (*lemna*) and watermeal (*wolffia*). Photographs of the pond are valuable for this assessment. This correlation is illustrated in Figure 2-5.

A good indicator of high phosphorus concentration in Minnesota is floating plant cover such as duckweed (lemna) and watermeal (wolffia).

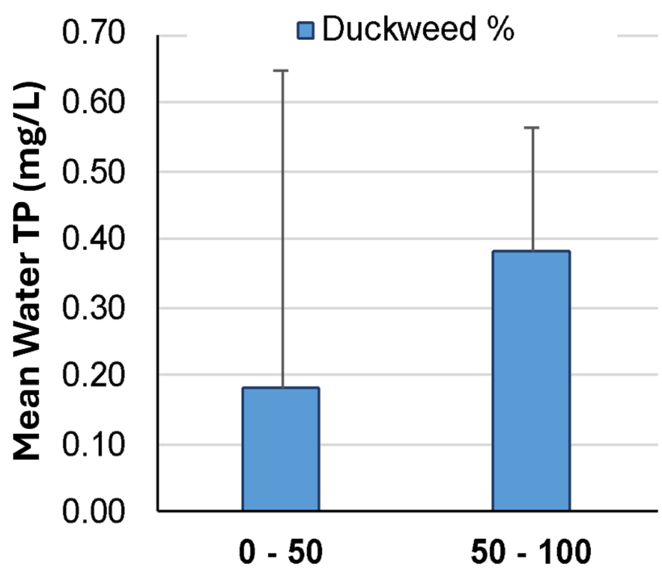

Figure 2-5: Floating plant cover in mid-summer, defined as the fraction of pond surface area covered by small, free-floating plants (Lemna and Wolffia), tended to be strongly associated with higher total phosphorus (TP) concentrations in ponds (Natarajan, et al. 2022).

2.4.2 Capacity testing

Capacity testing can be applied to sedimentation practices to estimate sediment storage capacity. All sedimentation practices can be assessed with sediment retention tests if adequate access is available. The infiltration capacity of dry ponds can also be assessed with hydraulic conductivity (i.e., infiltration) measurements.

Constructed Stormwater Ponds and Wetlands that Treat Stormwater. Sediment retention tests can be performed on a wet pond to estimate the depth and volume of sediment retained:

- Bottom elevations in a wet pond can be measured with a sonar depth measurement device or a mushroom anchor.
- The water surface can be used as a local elevation standard if a staff gauge has been installed in the pond to measure water surface elevation.
- Sonar depth measurements can be made in the winter when the wet pond is covered with sufficient ice to traverse or in the summer from a boat or while using waders.
- Corresponding longitude and latitude are recorded either with GPS or with a total station (i.e., surveying equipment).
- Using the measured basin topography and the original topography (from as-built plans or design drawings), the amount of sediment retained in the pond can be estimated.
- The volume of retained sediment can be compared to the design capacity to determine the remaining available sediment retention capacity and to estimate when the pond will require maintenance (i.e., sediment cleanout).
- It is recommended that these tests be performed soon after construction is complete to develop as-built plans as a benchmark for future assessment. If repeat measurements are made over time, the sediment accumulation rate can be estimated, which can be used to estimate when future maintenance will be necessary.

Dry Detention Ponds. Sediment retention tests are used to estimate the depth and, subsequently, volume of sediment retained in a dry pond.

- Surface elevations are measured either with a level and level rod or a total station, and the corresponding longitude and latitude are recorded either with GPS or with a total station.
- Using the basin topography and the original topography (from as-built plans or design drawings), the amount of sediment retained in the dry pond can be estimated.
- The amount of retained sediment can be compared to the design capacity to determine the available sediment retention capacity and to estimate when the pond will require maintenance (i.e., sediment cleanout).
- One to three days are typically required to perform a sediment retention assessment of a dry pond.

Hydraulic conductivity measurements of dry ponds are used to estimate the rate that stored water infiltrates into the soil, which can be used to estimate the runoff volume reduction by infiltration (Erickson et al. 2013). Point measurements with a falling head infiltrometer (Tecca et al. 2022) can each take between five minutes and several hours, depending on the soil characteristics of the dry pond. Hydraulic conductivity measurements for a single dry pond typically require four to eight hours to complete. These hydraulic conductivity tests should be performed shortly after construction to establish a baseline for future tests and to investigate or identify construction impacts on infiltration capacity. Repeat measurements over several years can be used to estimate the change in infiltration rate as the dry pond ages.

Repeat measurements over several years can be used to estimate the change in infiltration rate as the dry pond ages.

2.5 Maintenance Activities – Stormwater Ponds

Whenever work is performed on a stormwater pond, it is essential for maintenance crews to know:

- If a permit from another regulatory agency is required to perform work on the pond.
- The extent of excavation that is allowed by city, county, or other regulatory agencies.
- If the Minnesota Pollution Control Agency will require a dredged materials permit or notification.
- If dredged, materials may require testing to determine acceptable disposal methods. Metals and polycyclic aromatic hydrocarbons (PAHs) tend to collect in the sediments.

2.5.1 Maintenance Actions

<u>*Constructed Stormwater Ponds and Wetlands that Treat Stormwater (Wet ponds)*</u>. Solids captured in the pond will need to be removed (dredged), as shown in Figure 2-6. Before dredging, sediments must be tested to determine the PAH (polycyclic aromatic hydrocarbons) and metals concentration in order to assign a management level based on sediment characterization (analyzing the type and level of pollutants). This dictates the appropriate disposition level: Level 1 (Suitable for use or reuse on properties with a residential or recreational use category), Level 2 (Suitable for use or reuse on properties with an industrial use category), or Level 3 (Contact with MPCA staff is requested for information on disposal requirements).

Before dredging, sediments must be tested to determine the PAH (polycyclic aromatic hydrocarbons) and metals concentration to assign a management level that is based on sediment characterization (analyzing the type and level of pollutants).

Wet ponds must be inspected regularly to determine their condition, but the required frequency of inspection and maintenance is dependent on the watershed land use (e.g., urban, rural, farm, etc.), construction activities in the watershed, and rainfall amounts and intensity. Recommended maintenance frequencies are provided in Table 2-1. Although the current MS4 permit requires inspection once every permit cycle (5 years), it is recommended that inspection of inlet and outlet structures and bank erosion be performed at least once per year along with any associated needed maintenance; inspections are essential to pond function. Recommendations applicable to wet ponds are reproduced in Table 2-1. A maintenance activity worksheet is provided in Table A-1 of the Field Inspection Resources.

Figure 2-6: Water levels in a wet pond are drawn down to facilitate dredging with a backhoe. Photo: Noah Czech, City of St. Cloud, MN.

Table 2-1 Maintenance Recommendations and Frequencies for Wet Ponds (revised from Hunt and Lord 2006).

Task	Frequency	Notes
Measure sediment depth in forebay and deep pools	Once every 3 years	Can be performed with capacity testing
Remove all sediment from forebay and deep pool (dredging)	Variable (Once every 10 to 15 years is typical in stable watersheds)	In unstable watersheds (i.e., those with active construction), the frequency can be as low as once per year.
Maintain outlet structures, if required	Once per year and after every storm over 2 inches	Follow visual inspection guidelines
Remove floating trash and debris	Once per season as needed	Increase frequency, if needed
Remove vegetation from dam top and faces, if applicable	Once per year	Increase frequency, if needed
Mow wet pond perimeter	From every other week to once per year	--
Remove muskrats and beavers, if relevant	Inspect annually	Destroy muskrat holes whenever present. Contact a professional trapper to remove beavers

Capacity testing or monitoring is required to determine if a wet pond is retaining pollutants as expected. Wet ponds are most effective in retaining suspended solids and pollutants that tend to adsorb to solids. Wet ponds are usually not implemented to reduce temperature impacts or to retain dissolved pollutants. An exception is when algae or floating plants take up dissolved nutrients and turn them into particulate nutrients: this results in a reduction in dissolved nutrients. If a wet pond is not retaining suspended solids or pollutants adsorbed to suspended solids at expected levels, the following steps should be taken:

1. Check that the desired levels of pollutant retention are realistic. For example, if the target pollutant is total phosphorus and the runoff entering the pond contains a large fraction of dissolved phosphorus, large retention rates of total phosphorus may not be possible for a device that retains pollutants mostly by sedimentation. Or, if the inflowing sediment size distribution contains an uncharacteristically large fraction of fines of a size less than 0.02 mm, the hydraulic retention time may not be adequate to achieve the desired retention rate.
2. Perform a sediment capacity assessment to determine the remaining sediment storage capacity of the pond. If there is no remaining capacity or if the capacity is nearly exhausted, the sediment must be removed to allow for additional storage.
3. If there is adequate storage capacity remaining in the pond and pollutant removal is still below expected values, a tracer study should be performed to determine if the system is short

circuiting. If short-circuiting is occurring, consider adding one or more baffles or retrofitting the pond to redirect the flow of water in a manner that eliminates or minimizes short-circuiting.

Wet ponds can stratify from chloride concentration and temperature at 1 ft depth or less (Taguchi, et al. 2020). This stratification cuts off the bottom of the pond from oxygen that enters the water column at the water surface; the high organic content of the sediments causes the dissolved oxygen concentration to approach zero. These low oxygen concentrations create anoxic conditions, causing the release of phosphate from the sediments (internal loading of phosphorus) which will reduce the phosphorus retention of wet ponds. Taguchi et at. (2022) have studied maintenance techniques to reduce internal phosphorus loading and found 1) sealing the sediments with aluminum sulfate (alum) or iron filings and 2) mixing through coarse bubble aeration to be the most cost-effective techniques. More research is needed, however, on other maintenance techniques.

Low oxygen concentrations create anoxic conditions, causing the release of phosphate from the sediments (internal loading of phosphorus) which will reduce the phosphorus retention of wet ponds.

Dry Detention Ponds (Dry Ponds). Dry detention ponds can be effective at retaining suspended solids and pollutants that typically adsorb to solids. Captured solids will eventually need to be removed. The dry pond must be regularly inspected to determine its condition. The required frequency of inspection and maintenance is dependent on the watershed land use (e.g., urban, rural, farm, etc.), construction activities in the watershed, and rainfall amounts and intensities. It is recommended, however, that visual inspection and any associated maintenance be performed once per year.

If an assessment reveals that a dry pond is not draining a runoff event that has a volume less than or equal to the design storm volume within the specified designed time, the following measures should be taken.

1. Inspect all outlet structures for clogging and/or structural damage. Remove debris and repair/replace outlet structure(s), if necessary.
2. Inspect the outflow location(s) to make sure a tailwater condition is not impeding discharge from the pond. If this is the case, the tailwater should be eliminated or the outlet modified in such a way that drainage occurs within the desired time.
3. If the pond still does not drain within the specified design time, the hydraulics of the pond should be reevaluated, and the pond geometry and outlet structure redesigned.

Hunt and Lord (2006) discuss the maintenance requirements of wetlands and wet ponds. Even though Hunt and Lord do not specifically discuss dry ponds, their recommendations that do apply to dry ponds have been included in Table 2-2.

Table 2-2: Maintenance Recommendations and Frequencies for Dry Ponds (revised from Hunt and Lord 2006).

Task	Frequency	Notes
Measure sediment depth	Once per every 3 years	Can be performed with capacity testing
Remove retained sediment	Variable (Once every 10 to 15 years is typical in stable watersheds)	In unstable watersheds (i.e., those with active construction), the frequency can be once per year.
Maintain outlet structures	Once per year and after every storm over 2 inches	Follow visual inspection guidelines
Remove floating trash and debris	Once per season as needed	Increase frequency, if needed
Remove vegetation from dam top and faces, if applicable	Once per year	Increase frequency, if needed

Dry detention ponds are most effective in retaining suspended solids and pollutants that tend to adsorb to solids and are usually not implemented to reduce temperature impacts or achieve retention of dissolved pollutants. Thus, the following discussion only considers solids and pollutants which typically adsorb to solids. If a dry detention pond is not retaining suspended solids (or other adsorbed pollutants) at expected levels, the following steps should be taken.

Dry detention ponds are most effective in retaining suspended solids and pollutants that tend to adsorb to solids and are usually not implemented to reduce temperature impacts or achieve retention of dissolved pollutants.

1. Check that the desired levels of pollutant retention are realistic. For example, if the target pollutant is total phosphorus and the runoff entering the pond contains a large fraction of dissolved phosphorus, large retention rates of total phosphorus may not be possible for a device that retains pollutants mostly by sedimentation. Or, if the sediment size distribution contains an uncharacteristically large fraction of fines of a size less than 0.02 mm, the hydraulic retention time may not be adequate to achieve the required retention rate. If retention of the desired pollutant is not realistic, consider implementing another stormwater BMP to achieve desired results.
2. Perform a sediment capacity test to determine the remaining sediment storage capacity of the pond. If there is no remaining capacity or if the capacity is nearly exhausted, the deposited sediment should be removed to allow for additional storage.
3. If there is adequate storage capacity remaining in the pond and pollutant removal is still below expected values, a tracer study should be performed to determine if short-circuiting is

occurring. If short-circuiting is occurring, consider adding one or more baffles or retrofitting the pond to redirect the flow of runoff to eliminate or minimize the problem.

2.6 Factors Affecting Pond Performance

Typical maintenance of stormwater ponds includes sediment and trash removal, fixing clogged pipes, and addressing invasive vegetation. Table 2-3 lists the most frequent causes of deterioration of BMP performance as ranked by responding municipalities. The less frequent causes of BMP performance deterioration, such as bank erosion and structural problems, are nonetheless serious when present. Recent studies have noted that many constructed stormwater ponds and wetlands that treat stormwater are stratified and will then release phosphorus from the sediments into the water column. Current recommendations are treatment of the sediments with aluminum sulfate or iron filings or mixing of the water column by mechanical mixing or aeration (Taguchi et al. 2022).

Many constructed stormwater ponds and wetlands that treat stormwater are stratified and will release phosphorus from the sediments into the water column.

Table 2-3: Percent of Respondents who indicated the listed factor frequently caused deterioration of Sedimentation Practice performance. Taken from Kang, et al. (2008).

Factor	Dry Ponds	Wet Ponds
Sediment Buildup	24%	26%
Litter/Debris	31%	19%
Pipe Clogging	18%	21%
Invasive Vegetation	16%	10%
Bank Erosion	8%	11%
Groundwater Level	2%	7%
Structural Problems	0	7%

2.7 Maintenance Costs of Stormwater Ponds

The International Stormwater BMP Database (ISBD 2023) reports annual operating and maintenance costs for routine maintenance of stormwater management practices in 2018 dollars. The dollar amounts are based on actual costs entered into the database by users and are considered to be “ballpark” values. Extended dry detention basins had a median operation/ maintenance cost of $2744/year (range from $1176/year to $6174/year) and wet basins had a median operation/ maintenance cost of $2616/year ($275/year to $16,972/year). No other maintenance costs information was reported.

2.8 Floating Treatment Wetlands

2.8.1 Description

Floating Treatment Wetlands (FTWs) are essentially constructed islands designed to float in wet ponds (i.e., stormwater ponds that have a permanent pool of water). FTWs have been used for tertiary treatment of wastewater since 1986 (USEPA 1993, Sharma et al. 2021) but are relatively new for stormwater management (Figure 2-7). FTWs are planted with vegetation so the roots dangle in the water underneath the island but do not reach the bottom of the pond. Like docks, these islands are typically anchored to the bottom of the pond to prevent lateral movement but are free to move up and down as the water surface elevation in the pond fluctuates. FTWs can increase contaminant retention and/or removal in stormwater ponds and should therefore be considered to improve solids retention in undersized ponds.

Figure 2-7: Floating treatment wetland (recently constructed) at the Tamarack Nature Center in White Bear Lake, MN. Photo: https://midwestfloatingisland.com/

FTWs reduce water column turbulence and mixing caused by currents and wind; as a result, particle settling is enhanced (Kalin and Smith 1992, Smith and Kalin 2000). The establishment of an extensive root system is critical to FTW performance with respect to retention and removal of pollutants (Pavlineri et al. 2017). This is because the roots can physically filter solids (Chen et al. 2016) and they promote settling. Furthermore, root biofilms provide a surface that can capture solids, degrade organic pollutants, and uptake nutrients and metals (Weragoda et al. 2012, Merkhali et al. 2015). Even fine particles not typically removed by settling can adhere to the roots, accumulate, slough off, and settle (Karnchanawong and Sanjitt 1995, Headley and Tanner 2012). The root system and biofilms on the vegetation are main factors in retaining/removing both particulate and dissolved pollutants. In addition to aiding the settling process, they are also involved in microbial uptake and degradation of pollutants (Pavlineri et al. 2017), all of which reduce pollutant stormwater concentrations and mass loads. Microbes in the biofilm also aid in plant uptake of organics by converting complex organics into forms that can more easily be taken up by the plants (Billore and Prashant 2009). By degrading organics, microbes reduce biochemical oxygen demand (BOD) and chemical oxygen demand (COD) (Ma et al. 2019). Finally, the roots themselves release substances that balance pH and increase humic levels in the water, promoting adsorption and/or precipitation of solids (Sharma et al. 2021).

Variables affecting the performance of FTWs include plant species and planting density (Garcia Chance and White 2018, Tallec et al. 2008). The area of the FTW, the FTW bypass regions in the pond, the percent coverage of the pond water surface area by the FTW, the location of the FTW in the pond also impact performance (Khan et al 2013) as does its orientation (Jenkins and Greenway 2005). The water column depth in the pond also impacts FTW performance (Headley and Tanner 2012, Pavlineri et al. 2017, Chang et al. 2012) as does the aeration of the pond water (Garcia-Chance and White 2018).

2.8.2 Benefits and Limitations of Floating Treatment Wetlands

2.8.2.1 Benefits

Increased Pollutant Retention/Removal. FTWs can improve wet pond retention and/or removal of solids, phosphorus, nitrogen, metals, BOD, and COD, among other pollutants.

Ability to withstand substantial changes in water depth. Because the vegetation floats on the surface of the pond, the vegetation rises and falls with the water surface whereas traditional planted vegetation would become inundated, potentially killing the vegetation.

Suitable for Retrofits. Existing ponds can be retrofitted with FTWs with no additional land acquisition or construction.

Enhanced habitat and aesthetics. FTWs can potentially enhance habitat and improve aesthetics in urban and suburban areas.

2.8.2.2 Limitations

Design and Maintenance Recommendations. There is a lack of clear and consistent design and maintenance recommendations available.

Root Length. Selecting vegetation with proper root length can be challenging. The roots of vegetation should not be allowed to reach the bottom of the pond. If they do, they could become anchored to the bottom and, with an increase in pond depth, the vegetation could be inundated and perish. If the roots of the vegetation are too short, however, flow can bypass the system, reducing efficacy.

Plant Harvesting. To improve nutrient removal, plants typically need to be harvested. Harvesting of the entire plant (roots and shoots) is more effective but more difficult than harvesting only the shoots. The optimal time and frequency of harvests is unknown.

2.8.3 Assessment and Maintenance Activities – Floating Treatment Wetlands

Visual inspection of a wet pond with FTWs will follow the same protocol as a conventional wet pond inspection but with some additional considerations:

- Look for dead or dying vegetation, overgrown vegetation, and invasive vegetation species and remove it.
- If the density of the remaining healthy vegetation is low, additional plants may be added.
- If vegetation is consistently less than expected, the cause should be investigated.
- Ensure plant roots are not touching or attaching to the pond bottom.

Capacity testing can also be performed on a wet pond with FTWs as previously described. The capacity of the FTW itself, however, cannot be assessed. Borne et al. (2015) recommended annual harvesting of plant shoots in early summer to promote plant growth and prevent buildup of detritus on the FTW surface. It was also suggested that, due to increased sedimentation caused by the FTW, more frequent maintenance for sediment removal (as compared to conventional ponds) is needed. Additional maintenance recommendations from Borne et al. (2015) are as follows:

- For the first six months, install netting or protective grids over the vegetation to provide protection from animals feeding on the plants.
- Dredge to maintain sufficient water storage volume, including proper disposal of dredged sediment.
- Inspect and maintain the site at least every four months, especially until the vegetation becomes established. Routine maintenance includes verifying the health and development of the vegetation (and remediation, if necessary), weeding, checking the anchoring system and the location of the FTWs, removal of detritus and other debris.

2.9 Recommendations for Constructed Stormwater Ponds and Wetlands that Treat Stormwater

2.9.1 Assessment

Visual aerial (or satellite) inspection is recommended for assessment of all ponds at regular intervals (Table A-1), typically during July or August. If there is floating plant coverage, consider reducing internal phosphorus loading. Capacity testing is recommended for assessment of infiltration in dry ponds or for the assessment of sediment accumulation in wet ponds.

2.9.2 Maintenance

Wet and dry ponds are designed to retain suspended solids and pollutants that typically attach to solids. Captured solids need to be removed periodically. The ponds must be regularly inspected to determine if sediment removal is necessary. The required frequency of inspection and maintenance is dependent on the watershed land use (e.g., urban, rural, farm, etc.), construction activities in the watershed and rainfall amounts and intensities. The MS4 permit requires inspection once during the permit cycle, or once every 5 years. We recommended that visual inspection and any associated maintenance be performed (Table A-1) at least once per year.

Chapter 3: Underground Sedimentation Practices

3.1 Description

Underground sedimentation practices are designed and engineered to allow suspended solids to settle out and be retained. They may also decrease the flow velocity, provide temporary storage of stormwater runoff, or both.

Underground sedimentation practices take a variety of forms and use a variety of technologies or methods to improve stormwater quality. There are many types and names applied to these devices: oil/grit separator, grit chamber, ***sump*** manhole/catch basin, wet vault, water quality inlet, and proprietary settling device, among others. Those typically used in Minnesota are presented and discussed in the Minnesota Stormwater Manual (MPCA 2023). The discussion includes stormwater credits, supporting information, guidance and recommendations, and links to additional information.

Many underground sedimentation practices use the physical principles of sedimentation to separate grit. Submerged outlets are used to retain floatables such as trash, oil, grease, etc. Baffles are frequently included to trap floatables. Sedimentation will retain a fraction of the influent phosphorus and metal loads that typically attach to solid particles. Underground settling practices retain little to no dissolved pollutant load (MPCA 2023).

Because pollutants are not actually removed by the devices, resuspension of the trapped sediments can occur in some practices without regular and proper maintenance, flow restrictions with a bypass of the device, or ***scour*** prevention. Removing retained solids may be possible with a vacuum truck through maintenance ports located at the ground surface (Figure 3-1). For many practices there is minimal attenuation of flow since the practices are designed without a significant storage volume and hydraulic residence time.

A **sump** is the lowest chamber in a sewer system, designed to retain sediment. **Scour** is the erosion of captured sediment.

Some underground practices, however, are designed primarily for volume storage and peak flow rate reduction but may also retain some sediment. These systems may be constructed from vaults, arches, or large diameter, rigid pipes with capped ends and can be made of concrete, plastic, steel, or aluminum. Several prefabricated, modular systems are also commercially available. Storage structures, inlet and outlet pipes, and maintenance access manholes are fitted and attached in a predetermined excavated area, and then the entire area either has a support structure placed in it or is backfilled to the desired height and subsequently surfaced. Integrated into the downstream end of the system, control structures or smaller pipes regulate the rate at which runoff is discharged from the system.

Figure 3-1: Example of a vactor truck in operation. Photo: www.jolinpavingandexcavating.com

Many of the available proprietary practices are intended to be installed below the frost-line and, therefore, operate as designed under all weather conditions. They are also typically designed to provide optimal removal efficiency for smaller, more frequent storms and minimal removal and/or flow bypass systems for larger, less common storms. Thus, they are typically used as pretreatment in combination with other stormwater management practices, but they can operate as a stand-alone practice on small sites where space is limited or where lower levels of water quality improvement are acceptable.

Some underground devices are designed to retain dissolved fractions of pollutants such as phosphorus, nitrogen, and metals. To do this, the practice typically has a filter with special material that can retain the targeted dissolved pollutants. Filters also tend to retain smaller particles than sedimentation practices and are not covered in this chapter. For information on these devices, please see Chapter 5 on filtration.

Underground sedimentation practices can be divided into the sub-categories discussed below.

3.1.1 Sump Catch Basins

Catch basins are chambers installed in a storm sewer network, which allow surface runoff to enter the network. ***Some catch basins are designed with the basin bottom two feet or more below the lowest pipe invert elevation (Figure 3-2). This low area is called a "sump" and is intended to retain sediment.*** By trapping coarse sediment, the sump catch basin prevents solids from clogging the storm sewer or being washed into receiving waters. The sumps, however, must be cleaned frequently to maintain their sediment-trapping ability; during high flow events they are susceptible to ***scour (i.e., erosion of captured sediment)*** and release of previously retained sediment (Yang et al. 2022).

There are proprietary porous baffles (Figure 3-3) that can be inserted into a conventional catch basin to minimize scour of retained solids (Howard et al. 2011; Marr 2019). The main impact of the baffle is that it quells turbulence of incoming flows and helps minimize the resuspension and scour of solids previously retained in the sump.

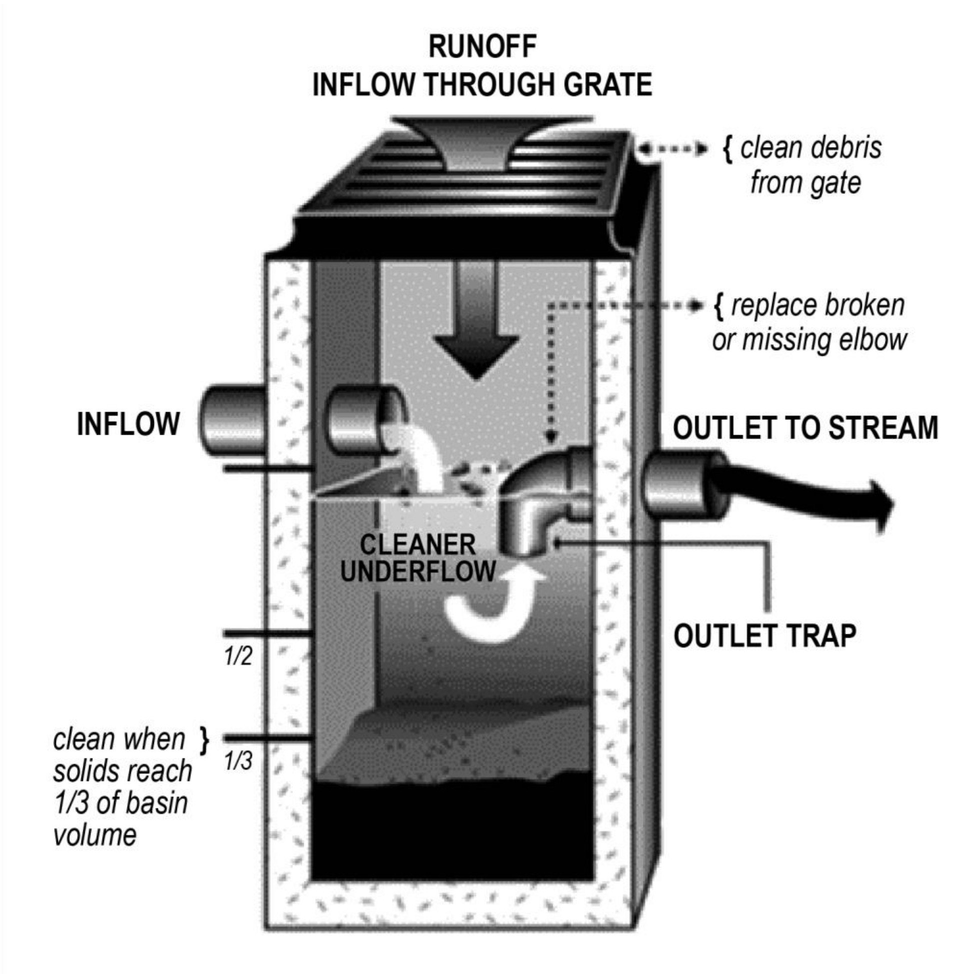

Figure 3-2: Cross-section of a sump catch basin. Image: Dejana Industries.

Figure 3-3: SAFL baffle inserted into an existing sump catch basin. Photo: Upstream Technologies.

3.1.2 Wet Vaults

A wet vault is an underground structure designed to provide temporary storage for stormwater runoff from a storm event. They are typically built with walls and a support structure to support surface infrastructure or have a large pipe configuration (Figure 3-4). Wet vaults have a permanent pool of water, which dissipates energy and improves the settling of particulate stormwater pollutants. Wet vaults are typically on-line, end-of-pipe practices with treatment mechanisms similar to surface ponds, except that biological pollutant removal mechanisms do not occur because wet vaults are not exposed to sunlight (MPCA 2023). A wet vault may have a valve at or near the bottom of the structure that can provide a gravity outlet to drain the structure for maintenance.


Figure 3-4: Installation of a wet vault in Litchfield Park, AZ. Photo: Contech Engineered Solutions.

Wet vaults may require more frequent inspection to minimize noxious gases and subsequent odor complaints from adjacent property owners. Although vacuum trucks may be used to perform maintenance, maintenance may be more labor-intensive than other BMPs and may require underground chamber, confined space authorized personnel. Additionally, many maintenance activities require that Occupational Safety and Health Administration (OSHA) confined-space safety procedures be used, because accumulated sediment and stagnant conditions may cause noxious gases to form in the vault, especially if regular maintenance is neglected (MPCA 2023).

3.1.3 Aggregate Pits

Aggregate pits are relatively deep storage pits filled with gravel, tire derived aggregate, or other aggregate material that has a high porosity and can act as a replacement for a wet vault or a pond (Figure 3-5). They require more space than a wet vault for the same storage capacity but are typically less expensive. Access is limited, so there are maintenance activities that cannot be performed without removing the material.

Figure 3-5: Installation of tire derived aggregate as an underground storage and sedimentation chamber. Photo: TDA Manufacturing

3.1.4 Proprietary Settling Devices

Many companies have proprietary designs for improving the effectiveness of underground treatment devices. These proprietary settling devices are similar to a sump catch basin with additional features that also capture oil, grease, and other floatables, most often through the use of baffles or screens. They also reduce wash out of deposited sediment during large storms. Figure 3-6 shows a typical proprietary settling device. Similar to sump catch basins, these devices typically provide retention of larger particles for smaller, more frequent storms with minimal retention for smaller particles or larger storms. To maintain retention effectiveness, the devices require regular removal of accumulated sediment and floatables. As previously discussed, the Minnesota Stormwater Manual (MPCA 2023) provides additional details on many proprietary products used in Minnesota.

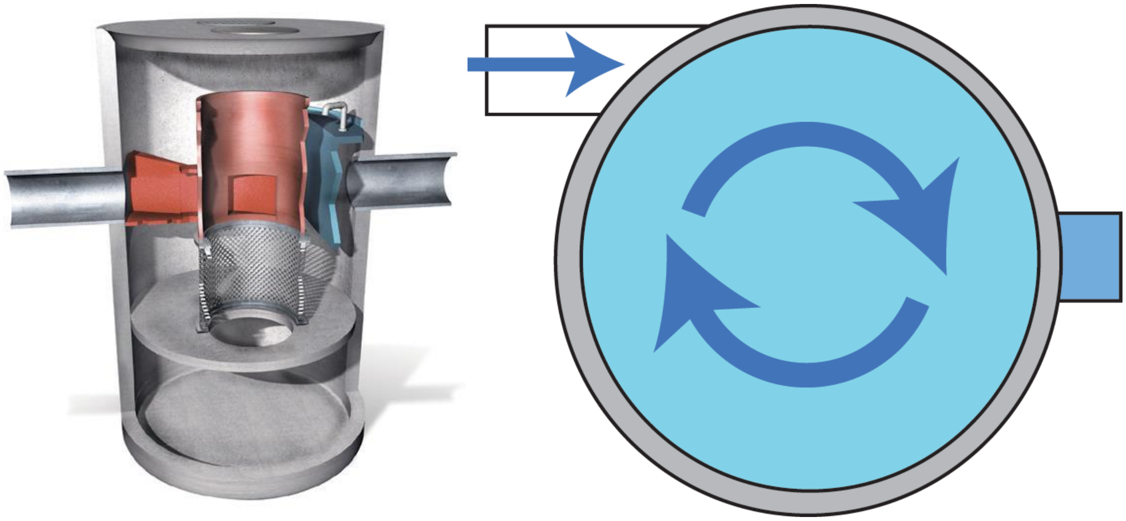

Figure 3-6: Typical proprietary settling device. Image: Contech and New Hampshire Stormwater Center.

3.2 Benefits and Limitations of Underground Treatment Devices

3.2.1 Benefits

Space Savings. The footprint of underground treatment devices can be used for additional purposes. For example, they can be placed in a road right-of-way, under a road, under a parking lot, or other spaces, which allows the land to be used for other purposes in addition to stormwater management. Because of this unique ability, they may also be installed in fully developed sites and can be implemented when retrofitting existing sites and stormwater management systems.

Reduce Pollutant Load. Underground sedimentation practices are designed to retain solids (~100 microns and larger in sump catch basins and proprietary settling devices and ~2 microns and larger in wet vaults and aggregate pits). By retaining solid particles, pollutants that have a fraction of their load attached to solids, such as phosphorus and metals, will also be partially retained. Devices that retain larger particles can provide effective pretreatment for other stormwater management practices.

Underground sedimentation practices are designed to retain solids (~100 microns and larger in sump catch basins and proprietary settling devices and ~2 microns and larger in wet vaults and aggregate pits).

Peak Flow Reduction. Larger underground practices (wet vaults and aggregate pits) designed for detention can reduce peak flow rates leaving the site. The extent of peak flow reduction depends on the design volume and outflow mechanism, but they can be designed to meet specific objectives for known design storms.

Cold Climate Operation. If installed below the frostline, underground sedimentation practices are suitable for cold climates and can remain effective during winter months. These practices, however, will likely have reduced effectiveness in the winter because the higher viscosity of cold water will reduce particle settling velocities.

Convenience. Whether a wet vault or a more complex proprietary device, many underground treatment devices are purchased in installation- ready (or near ready) condition. The size and/or quantity of the devices are often designed by or with the help of the manufacturer. These factors make design and installation relatively easy (Met Council 2001). Furthermore, proprietary devices are usually designed with maintenance access in mind. Thus, both installation and continual maintenance are more convenient than many other stormwater management practices.

Durability. Because many proprietary underground devices are made of concrete or durable, inert plastic, they have design lives of 50 years or more.

3.2.2 Limitations

Maintenance Frequency. Because of their smaller size and smaller sediment storage capacity, sump catch basins and proprietary settling devices require more frequent maintenance than other, larger practices such as ponds and wet vaults.

Hydraulic Impact. Underground treatment devices may reduce the hydraulic capacity of the conveyance system. The hydraulic properties of any device should be known and should be incorporated into the design process to ensure satisfactory water levels throughout the conveyance system. Devices should have a bypass mechanism to limit inflow water surface elevation increases, which could cause localized flooding and damage.

Limited treatment. Again, because of their smaller size and lower hydraulic residence time compared to ponds, basins, and other practices, sump catch basins and proprietary settling devices will retain a smaller fraction of sediment. They are also only effective for sediment near approximately 100 microns in size or larger. Thus, they may not meet stormwater management objectives when used alone and are typically used as a pretreatment practice only. Also, devices that rely only on sedimentation for water quality improvement do little to retain dissolved pollutants.

Limited Access. Aggregate pits have limited access, and maintenance may require excavation of the media, a non-routine maintenance procedure. Devices and riser manholes/structures should be assessed carefully to verify that the owners' equipment can access and clean the devices.

Confined Space. Many underground treatment devices fall under the jurisdiction of OSHA confined space requirements. As such, entry into the practice must follow all OSHA procedures. Entrances to confined space areas must be clearly marked. This may be accomplished by hanging a removable sign in the access riser just under the access lid (Met Council 2001).

Many underground treatment devices are considered OSHA confined spaces.

3.3 Assessment Activities – Underground Sedimentation Practices

Proprietary devices should have assessment and/or maintenance guidelines provided by the manufacturer. It is recommended that users follow these guidelines. Many underground sedimentation practices, both proprietary and non-proprietary, often fall under OSHA confined space regulations, and those must always be followed. Finally, material removed from underground sedimentation practices may be regulated by the Minnesota Pollution Control Agency; all corresponding disposal regulations must be followed.

To maintain effectiveness and reduce scour and export of solids previously retained, maintenance must include periodically removing accumulated sediment. To prevent sediment from being transported to downstream water bodies during removal, sediment should be removed by mechanical means rather than flushing. If flushing is the only cleaning option, special care should be taken to trap and remove sediment before it moves downstream (Met Council 2001, USEPA 2001).

To maintain effectiveness and reduce scour and export of solids previously retained, maintenance must include periodically removing accumulated sediment.

Assessment of sedimentation-based underground treatment devices is similar to other such practices (such as ponds), but on a smaller scale. Assessment of underground devices is described below.

3.3.1 Visual inspection

Visual inspection of underground sedimentation practices includes a site visit and photographic and written documentation, and looking for indicators that the practice is not functioning properly. Time since the last runoff event should be recorded. Note any trash or debris and how (or if) it is affecting (or could affect) the flow through the practice. It's possible that a leaking influent or effluent pipe could be causing erosion of adjacent soil. Thus, the area in the proximity of the practice, including the inlet and outlet, should be inspected for signs of erosion. Correspondingly, inspect each practice for structural instabilities in the inlet, outlet, and overall.

The discharge location should be inspected for any obstructions (including tailwater) that may impact discharge from the practice. Finally, the presence of standing water in the practice or accumulation of sediment, floatables, or other material in the practice should be documented in writing and with photographs.

Visual inspection checklists and maintenance guidance for underground sedimentation practices are available in Tables A-3a and A-3b.

3.3.2 Capacity Testing

If the sediment collection area can be accessed, sediment retention assessment can be performed by utilizing staff gauges or visual benchmarks and as-built plans to determine the volume of sediment retained. These measurements can be used with estimates or measurements of sediment inflow rates to develop a maintenance or cleanout schedule. When the collected solids volume meets or exceeds the solids storage capacity of the practice, solids will no longer be removed at desired levels. Furthermore, resuspension of retained solids can result in export of solids and pollutants that are attached to the solids, such as phosphorus and metals.

3.3.3 Synthetic Runoff Testing

Synthetic runoff testing can be used to estimate the retention of solids in an underground sedimentation practice. Influent synthetic runoff can be dosed with sediment to assess solids removal performance (Wilson et al, 2008). The solids removal performance can be determined either by collecting and measuring sediment concentrations in effluent samples or by extracting and measuring the sediment retained by an initially clean device. The latter method is likely to be more accurate because all retained solids are collected and weighed, whereas the former analyzes only the sediment in samples of water exiting the device. Follow the American Society for Testing and Materials (ASTM)'s sediment retention performance testing standard ASTM C 1745 (ASTM 2018) for underground sedimentation practices.

The hydraulic behavior of an underground sedimentation practice can be investigated by dosing influent synthetic stormwater with a conservative tracer and measuring concentrations of the tracer in effluent samples. The process is identical to determining retention performance with respect to a dissolved pollutant except that, in this case, concentrations of the tracer in effluent samples are determined.

Some underground sedimentation practices also infiltrate stormwater. For more information on these practices, including their assessment and maintenance, see the corresponding section in Chapter 4 – Infiltration Practices.

3.4 Maintenance Activities

Underground sedimentation practices generally target the same pollutants as dry and wet ponds but they are typically smaller and have a lower design flow and total solid capture capacity because they are smaller. Underground sedimentation practices may also capture fewer small particles compared to dry ponds and wet ponds because of their small size and shorter hydraulic retention time. Maintenance is required more frequently for underground treatment devices.

If an underground sedimentation practice is underperforming, the following steps should be taken (see also Tables A-3a and A-3b).

1. If the device is proprietary, follow the manufacturer's maintenance procedures and/or contact the manufacturer.
2. If visual inspection or capacity testing reveal that the sediment storage capacity is more than 75% full, remove sediment.
3. Inspect all outlet structures for clogging and/or structural damage. Remove debris and repair/replace outlet structure, if necessary.
4. Inspect outflow location(s) to make sure a tailwater condition is not impeding discharge from the device. If impeding discharge, the tailwater level must be lowered.
5. If the device is perforated, check to make sure the perforations are not clogged with sediment or debris. Remove sediment and debris, if present.

If assessment reveals that an underground sedimentation practice is not draining as expected, the following steps should be taken (see also Tables A-3a and A-3b).

1. Inspect all outlet structures for clogging and/or structural damage. Remove debris and repair/replace outlet structure, if necessary.
2. Inspect outflow location to make sure a tailwater condition is not impeding discharge from the pond. If this is the case, the tailwater must be eliminated.
3. If the device is proprietary, contact the manufacturer.
4. If maintenance actions do not sufficiently resolve the issue, the device may need to be replaced.

3.5 Factors Affecting Performance

Maintenance efforts for underground sedimentation practices typically include removing sediment and trash and fixing clogged pipes. Table 3-1 lists the most frequent causes of deterioration by percent according to responses of surveyed municipalities (Kang et al. 2008). The most frequent factors causing deterioration of performance were sediment buildup, litter and debris, pipe clogging and invasive vegetation. Bank erosion, groundwater level and structural problems, however, can cause serious and rapid deterioration of performance when present.

The most frequent factors causing deterioration of performance were sediment buildup, litter and debris, pipe clogging and invasive vegetation.

Table 3-1: Percent of respondents who indicated the listed factor caused deterioration of underground sedimentation practices (from Kang et al. 2008).

Issue	Percent of Respondents
Sediment Buildup	58%
Trash	21%
Pipe clogging	11%
Bank Erosion	0%
Groundwater level	5%
Structural problems	5%

3.6 Maintenance Costs of Underground Sedimentation Practices

The International Stormwater BMP Database (ISBD 2023) reports annual operating and maintenance costs for routine maintenance of stormwater management practices in 2018 dollars. The dollar amounts are based on actual costs entered into the database by users and are considered to be "ballpark" values. Proprietary settling devices had a median value of $4347/year (range from $1320 to $6074/year). Oil and grit separators, which are essentially a wet vault designed to retain sediment and oil, had a median value of $1800/year ($1174 to $2544/year).

3.7 Recommendations for Underground Sedimentation Practices

3.7.1 Assessment

Visual inspection is recommended for assessment of all underground sedimentation practices at least once per year. Tables A-3a and A-3b provide guidelines for visual inspection. Capacity testing is recommended for assessment of sediment accumulation. If an adequate water supply is available, synthetic runoff testing can be used for the assessment of solid retention performance. A tracer study can be used to assess the hydraulic performance of an underground treatment device.

3.7.2 Maintenance

Underground sedimentation practices are designed to retain suspended solids and pollutants that typically attach to solids but are not effective at retaining dissolved pollutants. After continued operation, the retained solids must be removed for the device to remain effective. The sedimentation practice must therefore be regularly inspected to determine its condition. The required frequency of maintenance is dependent on the watershed land use (e.g., urban, rural, farm, etc.), construction activities in the watershed, and rainfall amounts and intensity. Removed sediment must be discarded in accordance with all governing regulations. Tables A-3a and A-3b provide guidelines for maintenance given visual inspection results.

Chapter 4: Infiltration Practices

4.1 Description

Stormwater infiltration practices capture and temporarily store stormwater before allowing it to infiltrate into the existing soil. Infiltration occurs when water moves vertically downward from the stormwater management practice and into the existing soil where it enters the groundwater. If drain tiles collect the water and convey it downstream in the stormwater management system then, by definition, this is filtration. For more information on filtration practices, refer to Chapter 5. Design variants of infiltration practices include infiltration trenches, infiltration basins, rain gardens, dry wells, tree trenches (or tree boxes), and underground infiltration systems. As stormwater penetrates the underlying soil, chemical, biological, and physical processes remove pollutants and delay or reduce peak stormwater flows (MPCA 2023).

This chapter discusses structural practices whose main stormwater treatment process is infiltration. Although vegetation may exist in some practices discussed in this chapter, the vegetation does not contribute to the main treatment process. For example, in tree trenches, the trees mostly serve an aesthetic purpose and, as a result, tree trenches are discussed in this chapter. Bioretention practices often infiltrate a significant runoff volume, but they are discussed in Chapter 6 because a portion of the treatment process is performed by vegetation, microbes, and other biological processes. Although bioretention basins, some underground devices, and permeable pavement have a significant infiltration component, those practices are discussed in more detail in other chapters that are specifically focused on that specific kind of practice.

In general terms, infiltration systems can be described as natural or constructed depressions located in or on permeable soils and these depressions capture, store, and infiltrate stormwater runoff. The depressions can be located on the surface of the ground (e.g., infiltration basin) or they can be designed as underground practices (e.g., underground infiltration vault). Infiltration practices, like most BMPs, must include at least one pretreatment practice upstream of the main infiltration practice as required by the Minnesota Stormwater Construction General Permit (MPCA 2023). Pretreatment will reduce maintenance frequency and effort geared towards the infiltration practice and extend its life.

Pretreatment will reduce maintenance frequency and effort on the infiltration practice and extend its life.

As part of a stormwater management system, an infiltration-based practice may be used to achieve one or more of the following objectives (MPCA 2023):

- Reduce pollutant load in stormwater runoff,
- Increase groundwater recharge,

- Decrease peak flow rates and stormwater runoff volumes,
- Preserve base flow in streams,
- Reduce thermal impacts of runoff.

Infiltration practices are applicable to sites with naturally permeable soils, a sufficient vertical distance to the seasonally high groundwater table, bedrock, or other type of impermeable layer, and a sufficient horizontal distance from buildings, utilities, and other items. If a particular site has ongoing drainage problems, karst soils, shallow bedrock, or is located above a wellhead protection area, infiltration practices may be inappropriate and/or prohibited.

4.2 Sub-categories of Infiltration Practices

4.2.1 Infiltration Basins and Rain Gardens

Infiltration basins are constructed impoundments that capture, temporarily store, and infiltrate runoff, typically within 48 hours. Infiltration basins contain a flat, densely vegetated floor situated over naturally permeable soils. Rain gardens are smaller than infiltration basins and store water at a shallower depth but also have vegetation as a key component. Because both of these practices contain vegetation as an integral part of their design and function, they are covered in Chapter 6: Bioretention Practices.

4.2.2 Infiltration Trench

An infiltration trench is a narrow, excavated trench, typically three to six feet deep, that is backfilled with coarse stone aggregate that allows for the temporary storage of runoff in the void space of the material (Figure 4-1). Discharge of this stored runoff occurs through infiltration into the surrounding naturally permeable soil. Infiltration trenches may be modified to become stormwater tree trenches and boxes (as discussed below) where applicable with the addition of a growing medium. All water captured by the practice must leave within 48 hours through infiltration and/or a drain. Trenches are commonly used for drainage areas less than five acres (MPCA 2023).

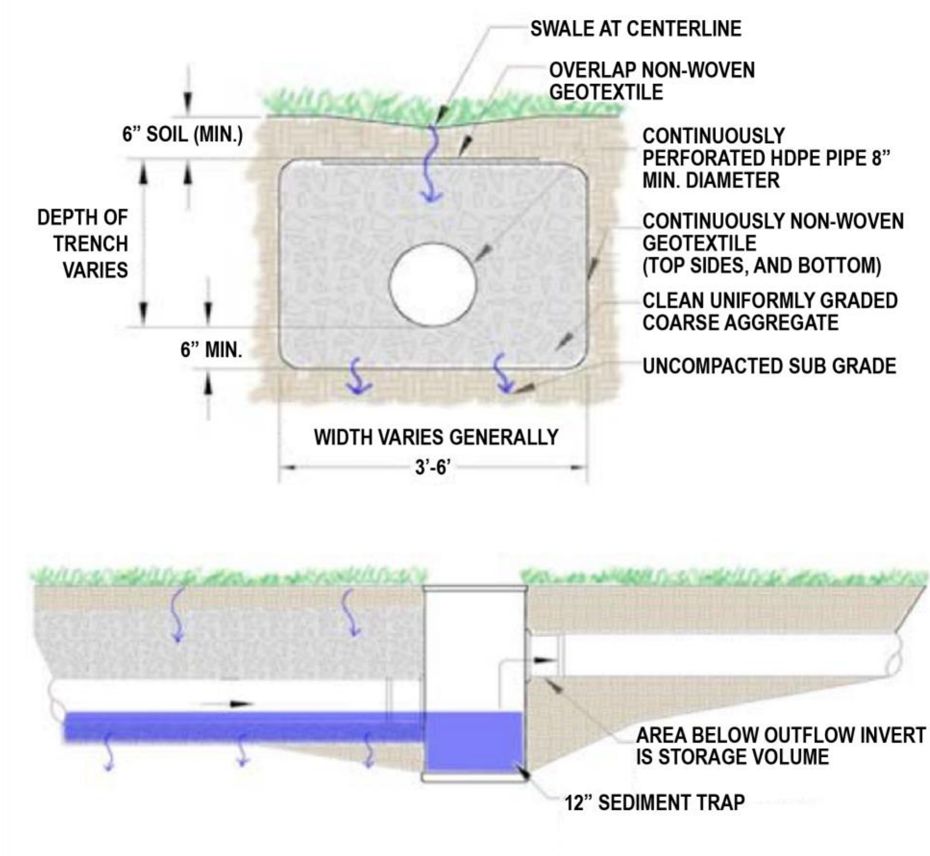

Figure 4-1: Sketch of a typical infiltration trench (Penn EPA 2006).

4.2.3 Dry Wells

A dry well or soak away pit is a smaller variation of an infiltration trench (Figure 4-2). It is a subsurface storage practice (a structural chamber or an excavated pit backfilled with a coarse stone aggregate) that receives and temporarily stores stormwater runoff. Discharge of the stored runoff occurs through infiltration into the surrounding naturally permeable soil. Due to their smaller size, dry wells are typically designed to handle stormwater runoff from drainage areas that are less than one acre, such as roof tops (MPCA 2023).

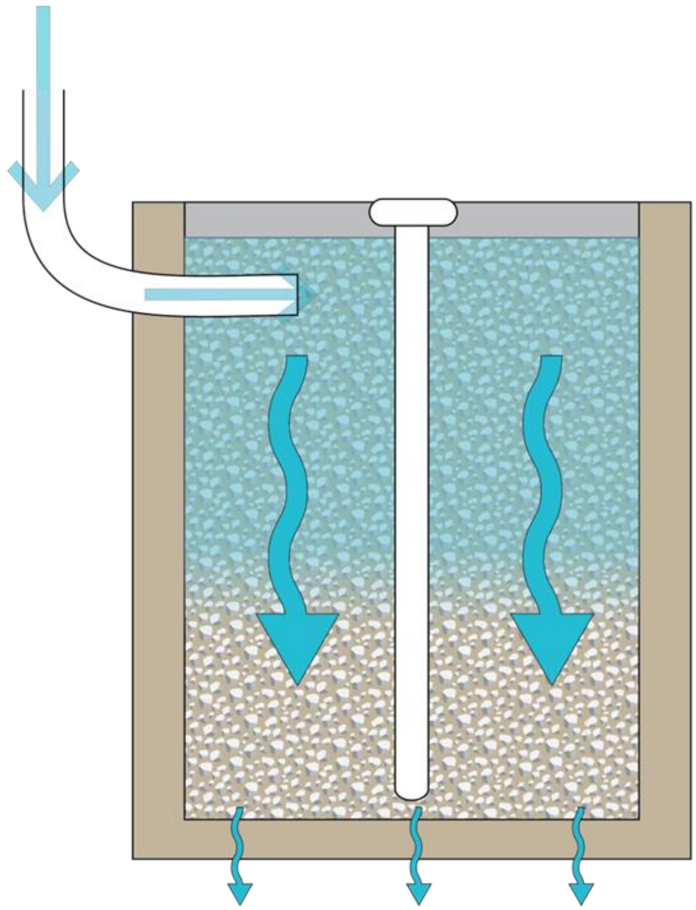

Figure 4-2: Sketch of a typical dry well (MPCA 2023).

4.2.4 Underground Infiltration Systems

Several underground infiltration systems, including pre-manufactured pipes, vaults, and modular structures, have been developed as alternatives to infiltration basins and trenches for space-limited sites and stormwater retrofit applications (Figure 4-3). Underground infiltration systems are occasionally the only stormwater management options on fully developed sites or highly urban environments because they can be located under other land uses such as parking lots or play areas. They are like infiltration basins and trenches in that they are designed to capture, temporarily store, and infiltrate a design volume of water. Underground infiltration systems are typically used for development sites less than 10 acres and should be installed in areas that are easily accessible for routine and non-routine maintenance. These systems should only be installed in areas or below structures that can be excavated if the system needs to be replaced or invasive maintenance is required.

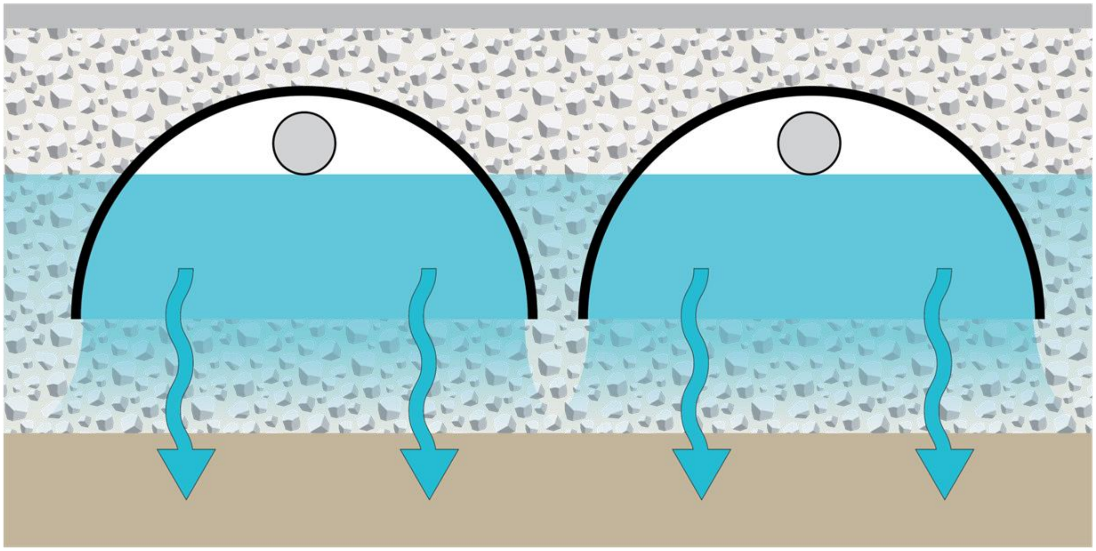

Figure 4-3: Sketch of a typical underground infiltration system (MPCA 2023).

A concern with dry wells and underground infiltration systems is that they may meet the U.S. Environmental Protection Agency (EPA) definition of a Class V injection well, which includes any dug hole that is deeper than its widest surface dimension. If it does, a Class V injection well permit is required. There are also concerns related to pollutant retention and contamination of underlying groundwater. MPCA (2009) lists some concerns as:

A concern with dry wells and underground infiltration systems is that they may meet the U.S. Environmental Protection Agency (EPA) definition of a Class V injection well, which includes any dug hole that is deeper than its widest surface dimension. If it does, a Class V injection well permit is required.

- Roadways and parking lots with high volumes of traffic have higher concentrations of certain pollutants, including metals and gasoline related pollution,
- Underground systems do not allow for the pollutant removal that is accomplished through biological activity and vegetation uptake,
- The minimum separation requirement of three feet between the bottom of the infiltration system and the seasonally high groundwater elevation may be insufficient for adequate pollutant removal,
- Maintenance of underground systems is critical for effective pollutant removal. Access for maintenance, however, is often prohibitively difficult.

The Minnesota Stormwater Manual (MPCA 2023) has more information on this topic.

4.2.5 Tree Box/Tree Trench

Tree boxes/trenches are a system of trees that are connected by an underground or near-surface infiltration structure (Figure 4-4). The system consists of a stormwater tree trench or box with structural stone, gravel, or soil boxes in which the trees are placed. Tree systems consist of an engineered soil or rock layer designed to treat stormwater runoff via filtration through plant and soil/rock media, and through evapotranspiration from trees. Discharge of this stored runoff occurs through infiltration into the surrounding naturally permeable soil. Tree species should be carefully selected to survive both inundation and drought conditions. They also may need to be tolerant of sodium, chloride, and other pollutants. Tree trenches and boxes drainage areas should be less than five acres depending on the size of each trench. Irrigation is strongly encouraged during the tree's establishment period (MPCA 2023).

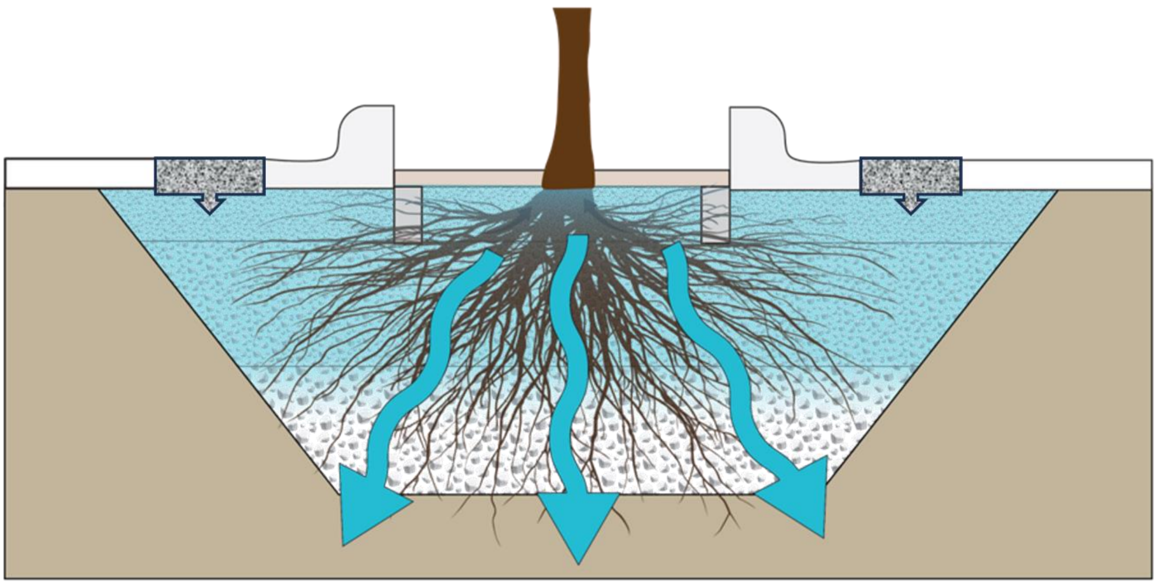

Figure 4-4: Sketch of a typical tree trench. Adapted from MPCA (2023).

For more information on infiltration systems and sub-categories of these systems, see the Minnesota Stormwater Manual (MPCA 2023).

4.3 Benefits and Limitations of Infiltration Practices

4.3.1 Benefits

<u>*Reduce Pollutant Load.*</u> Infiltration practices can reduce pollutant loads to surface waters through reducing volume of runoff. They can also reduce overall pollutant load (including infiltrating water) through physical straining of solid particles by the soil. Biological activity in the soil can degrade pollutants, including dissolved pollutants. Additionally, infiltration into the existing soil lowers the temperature of the runoff and thereby reduces thermal impacts to surface water bodies even if the water flows as shallow groundwater and discharges into lakes or streams.

Peak Flow Reduction. Infiltration practices can reduce peak flow rates in relation to the size of the practice. Practices that store large water volumes can reduce peak flow rates on a regional scale whereas smaller practices, such as trenches or tree boxes, can reduce peak flow rates on a smaller, site scale, such as a parking lot. For less intense storms, runoff will fully infiltrate during the storm, resulting in an elimination of the peak flow.

Volume Reduction. Infiltration practices will reduce the volume of stormwater runoff by diverting runoff into the existing soil and out of the conveyance system. The extent that the runoff volume will be reduced is related to the amount of infiltration provided by the practice and, on a regional scale, the number of practices implemented in the watershed.

Groundwater Recharge. Infiltrated water can either flow as shallow groundwater, which may reemerge as baseflow in streams or feed a lake, or it can infiltrate to greater depths and recharge groundwater aquifers.

4.3.2 Limitations

Limited Applications. Infiltration practices are not recommended for areas with steep slopes, karst topography, wellhead protection areas or those that are stormwater "hotspots," which are defined as areas that generate high levels of pollutants. For more information on such limitations, consult the Minnesota Stormwater Manual (MPCA 2023). They also should not be placed near buildings, utilities, or other underground structures that could be negatively impacted by the infiltrated water. To determine the extent and/or range of underground impact, a groundwater mounding analysis may be required (MPCA 2023).

Maintenance. Infiltration systems are susceptible to clogging. To remain effective, regular maintenance must be performed and maintenance for underground systems may require special access and equipment.

Construction. Effectiveness is sensitive to construction. For example, care must be taken not to compact the soil with heavy equipment as this will limit the infiltration ability of the soil. Also, any vegetation in the practice must be able to handle periods of inundation and drought, which limits selection. Finally, to increase longevity and decrease maintenance frequency, pretreatment devices must be included just upstream of the infiltration practice to reduce sediment load (especially coarse sediment), before it reaches the practice.

To increase longevity and decrease maintenance frequency, pretreatment devices must be included just upstream of the infiltration practice to reduce sediment load (especially coarse sediment), before it reaches the practice.

Confined Space. Underground infiltration practices may fall under the authority of OSHA confined space requirements. As such, entry into the practice must follow all OSHA procedures. Entrances to confined space areas must be clearly marked. This may be accomplished by hanging a removable sign in the access riser just under the access lid (Met Council 2001).

Karst regions may provide direct pathways for infiltrated stormwater to reach groundwater with little to no treatment. If karst soils are known to exist or even may exist in an area, consult the Minnesota Stormwater Manual (MPCA 2023) for more information.

Groundwater Protection. Infiltration may be limited or prohibited in areas over sensitive groundwater aquifers such as those protected by wellhead protection plans. All governing regulations must be followed. Contact the Minnesota Department of Health for more information.

Karst Aquifers. Although infiltration practices can be used to meet many stormwater management objectives, care must be taken when considering infiltration. Karst regions may provide direct pathways for infiltrated stormwater to reach groundwater with little to no treatment. Also, infiltration into karst soils may create sinkholes. If karst soils are known to exist or even may exist in an area, consult the Minnesota Stormwater Manual (MPCA 2023) for more information. Also, infiltration options may be limited or prohibited in wellhead protection areas or other areas above sensitive groundwater aquifers. All governing regulations must be followed.

4.4 Assessment Activities – Infiltration Practices

Without proper construction and regular maintenance, infiltration practices will fail quickly.

Without proper construction and regular maintenance, infiltration practices will fail quickly. Because improper construction can limit the effectiveness of infiltration practices, efforts should be made throughout the construction process and as soon as possible after construction to assess the practice and ensure that it will (or that it is) operating effectively. If the practice operates effectively immediately after construction, common reasons for future failure include lack of proper maintenance and clogging due to solids such as sediment and organic debris. Other causes may include soil compaction, poor site selection, and lack of effective pretreatment (Gulliver et al. 2010).

Some level of assessment should occur at least once per year. All assessment activities need to be undertaken in a manner that does not lead to soil compaction, because such compaction will reduce infiltration. Assessment methods are described below.

4.4.1 Visual Inspection

Visual inspection of infiltration practices should be conducted at least every year. See Tables A-4a, A-4b, and A-4c for examples of inspection forms. Visual inspection of an infiltration practice involves investigation of the practice for signs of inadequate infiltration capacity and clogging. There may be other aspects to visual inspections depending on the objective and the particular type of infiltration practice.

Infiltration trenches typically do not promote the growth of vegetation on the trench itself because the media is primarily coarse granular rock. One of the main indications of poor infiltration capacity of a trench is a crust or layer of fine sediment on the surface of the trench, indicating that there was standing water for an extended duration. If a crust is present, even if it shows signs of desiccation cracking, the crust could easily become a barrier to infiltration upon rewetting.

While it might not be obvious during visual inspection, the pores of the trench material and/or the pores in the existing soil that make up the walls or bottom of the trench could be clogged below the surface, even if the surface is clear of sediments. Closer examination by poking just beneath the surface of the trench with a trowel or shovel might reveal this clogging. If the clogging is deeper into the trench, much greater efforts are needed to reveal the clogging.

Although no vegetation may grow in the trench material, an indication of poor infiltration in the trench could be poor vegetative growth in the area surrounding the trench. If infiltration rates are low through the trench, water will pond around the trench for extended time periods, increasing the chances that the resident vegetation in these areas will suffer.

Tree boxes may promote vegetation growth on the surface of the practice, otherwise, visual inspection for dry wells and tree boxes is very similar to infiltration trenches. Thus, for these infiltration practices, please see the section on visual inspection for infiltration trenches.

4.4.2 Capacity testing for Infiltration Practices

Capacity testing can be applied to some infiltration trenches and tree boxes (if the surface is accessible), to measure saturated hydraulic conductivities at various locations within the practice and estimate an overall average saturated hydraulic conductivity of the practice. It is not feasible, however, to use capacity testing to assess dry wells or other underground infiltration practices.

Testing the infiltration capacity of infiltration practices involves a series of hydraulic conductivity point measurements. Even in infiltration practices with engineered soil that one might expect to be uniform, hydraulic conductivity often has a large variability (i.e., up to 1000x). Thus, numerous measurements are necessary to accurately represent the practice (Figure 1-2). There are many techniques available for measuring the infiltration capacity (Tecca, et al. 2021, 2022). See Gulliver et al. (2010) and Erickson et al. (2013) for additional information. Also, it may be convenient to represent the practice with an estimated single overall effective value of saturated hydraulic conductivity based on the numerous point measurements taken. This can be done using a method developed by Weiss and Gulliver (2015).

Even in infiltration practices with engineered soil that one might expect to be uniform, hydraulic conductivity often has a large variability (i.e., up to 1000x).

4.4.3 Synthetic Runoff Testing of Infiltration Practices

For synthetic runoff testing of an infiltration practice, the practice is filled with water as a simulation of a natural runoff event (Figure 1-3). This approach requires careful planning because the volume of water required to fill the stormwater treatment practice can be significant and might far exceed the capacity of the nearby fire hydrant or available water trucks. To conduct a synthetic runoff test, the practice is filled with water and the rate that the water infiltrates is estimated based on the rate of drop of the water surface. It may be desirable to place a pressure sensor in the practice to provide measurements that will result in water level over time, especially if the presence of gravel or soil media restricts a visual assessment of water drop. See Gulliver et al. (2010) or Erickson et al. (2013) for more information. Periodic tests results can be compared to determine when maintenance will need to be performed in the future.

The most reported reason for failure of infiltration practices is clogging due to sediment and organic debris.

4.5 Maintenance Activities

Every stormwater BMP must be maintained to remain effective. This is particularly true, however, for infiltration practices because they are prone to clogging. Some early studies on infiltration practices revealed how susceptible they are to failing. For example, in a Maryland study that inspected infiltration trenches (Lindsey et al. 1991), 53% were not operating as designed, 36% were clogged, and 22% showed reduced infiltration. In a study of twelve infiltration basins (Galli 1992), none of which had pretreatment systems installed upstream, all had failed within the first two years of operation. Finally, a U.S. EPA (1999) study found that over 50% of infiltration systems either partially or completely failed within the first five years of operation. With proper and regular maintenance, however, infiltration practices can last years and provide significant contributions towards meeting stormwater management objectives.

Every stormwater BMP must be maintained to remain effective. This is particularly true, however, for infiltration practices because they are prone to clogging.

Sediment removal from an infiltration practice should not be performed by flushing. This can wash sediment downstream where it can pollute surface water bodies. If flushing is the only cleaning option, sediment may need to be trapped before or just after exiting the practice (Met Council 2001).

The most reported reason for failure of infiltration practices is clogging due to sediment and organic debris (Erickson et al. 2010). Due to susceptibility of clogging, pretreatment of stormwater upstream of an infiltration practice is required under the Minnesota Construction Stormwater General Permit (MPCA 2023). To maintain proper function and maximum pollutant removal, infiltration practices require regular maintenance and inspection. Maintenance activity checklist and guidance are given in the Field

Inspection Resources, Tables A-4a, A-4b, and A-4c. Table 4-1 provides guidance on typical maintenance tasks and time frames. Note that maintenance activities must not cause soil compaction. Compaction will reduce infiltration rates.

Table 4-1: Typical maintenance tasks and frequencies associated with infiltration practices (adapted from the Watershed Management Institute 1997).

<table>
<tr><th>Task</th><th>Frequency</th></tr>
<tr><td>Remove sediment and oil/grease from pretreatment practices and overflow structures</td><td rowspan="2">Standard maintenance, as needed.</td></tr>
<tr><td>Stabilize locations that are eroding, repair undercut and eroded areas (often near inlet and outlets)</td></tr>
<tr><td>Inspect pretreatment practices and diversion structures (if present) for signs of sediment buildup and structural damage</td><td>Two times per year</td></tr>
<tr><td>Disc or otherwise aerate the bottom</td><td>One time per year</td></tr>
<tr><td>If flow bypass is possible, maintain a dry practice for an extended period of time (this may increase infiltration capacity in the short term)</td><td>Every 5 years</td></tr>
<tr><td>Total rehabilitation of the trench to maintain storage capacity within 67% of the design storage volume (i.e., WQV) and a 48 hour drain time</td><td rowspan="2">Upon failure</td></tr>
<tr><td>Excavate trench or tree box walls to expose clean soil</td></tr>
</table>

If any method of assessment indicates unacceptable levels of infiltration, sediment layers or crust on the surface should be removed. If this does not sufficiently restore the practice, the filter fabric, if present, should be inspected and, if warranted, replaced or removed. If infiltration rates do not increase to acceptable levels, the entire practice should be renovated and/or replaced.

4.6 Factors Affecting Performance

Maintenance efforts for infiltration practices are typically focused on removal of accumulated sediment and litter/debris. For a list of all factors that were deemed frequent causes of deterioration of stormwater treatment practice performance see Table 4-2. The percent of responding municipalities indicating a particular practice as “most frequent” is listed in the table as well. Landphair et al. (2000) noted that the performance of an infiltration trench is expected to decrease with time as the void spaces in the surrounding native soil fill with fines from the runoff which has infiltrated.

Table 4-2: Percent of respondents who indicated that the listed factor frequently impacted the performance of an infiltration practice (Erickson et al. 2010)

	Infiltration Trench
Sediment Buildup	36%
Litter/Debris	21%
Pipe clogging	10%
Invasive Vegetation	5%
Bank Erosion	5%
Groundwater level	13%
Structural problems	5%
Oil spill	3%
Mechanical problems	3%

4.7 Recommendations for Infiltration Practices

4.7.1 Assessment

During proper operation of an infiltration practice, solid particles will be filtered at the soil surface as well as within the soil matrix. Over time, accumulation of solids will result in lower infiltration rates, thus the practice must be regularly inspected to insure it is functioning properly and the appropriate maintenance actions taken. The required frequency of inspection is dependent on the watershed land use (e.g., urban, rural, farm) and rainfall amounts and intensity. However, it is recommended that visual inspection be performed a minimum of once per year. Guidance for visual inspection is provided in Tables A-4a, A-4b, and A-4c.

If an adequate water supply is available, synthetic runoff testing is recommended for assessment of drainage time in small infiltration practices. For assessment of drainage time on practices too large for synthetic runoff testing, capacity testing is recommended, or tests may be performed immediately after a rainfall event large enough to fill the practice.

4.7.2 Maintenance

To remain effective, all infiltration practices must have regular and appropriate maintenance. The required frequency of inspection and maintenance is dependent on the watershed land use (e.g., urban, rural, farm), construction practices in the watershed, and rainfall amounts and intensity. Pretreatment practices are required upstream of all infiltration practices (MPCA 2023) and should be designed to retain large solids before they

An effective pretreatment practice will extend the life of an infiltration practice and reduce the required frequency of non-routine maintenance.

can enter the infiltration practice. An effective pretreatment practice will extend the life of an infiltration practice and reduce the required frequency of non-routine maintenance. As such, all pretreatment practices should also be regularly inspected and maintained. As with all other stormwater management practices, inspection of pretreatment practices should occur at least once per year. Guidance for maintenance activities given the results of inspection are provided in Tables A-4a, A-4b, and A-4c.

Chapter 5: Filtration Practices

5.1 Description

Filtration is the process of removing suspended solids from stormwater by passing the water through a bed of porous media consisting of sand and/or soil. In filtration, the solids removed from the water are retained on top of or within the filter media. The primary retention mechanism is sieving, where solids that are larger than the pore spaces in the sand or soil structure are captured and retained as the stormwater passes through the filter media. Filtration differs from infiltration in that the water in a filtration system is collected by an underdrain system after it passes through a designed depth of media while in infiltration systems, the water infiltrates into the existing soil because there is no underdrain system.

Filtration practices have widespread applicability and are suitable for all land uses, as long as the contributing drainage areas are limited (e.g., typically less than 5 acres). Filters are not as aesthetically appealing as bioretention practices, which makes them more appropriate for commercial or light industrial land uses or in locations that will not receive significant public exposure. Filters are particularly well suited for sites with high percentages of impervious cover (e.g., greater than 50%). Also, because filtered runoff is collected by drain tiles and, if an impermeable barrier is used, does not enter the existing soil, they are also well suited for sites with high pollutant loads (i.e., stormwater hotspots). Additionally, filters may be installed underground to prevent the consumption of valuable land space.

With all else constant, the filtration rate is greater for filter media with large pore spaces (i.e., large grain size such as gravel) than for filter media with small pore spaces (i.e., small grain size such as sand or silt). Filter media with large pores, however, allow larger solids, and subsequently more solids, to pass through the filter, which reduces solids retention efficiency. Therefore, designing a filtration practice is a balance between filtration rate and solid retention efficiency. While there are currently no effluent or performance regulations other than TMDLs (Total Maximum Daily Loads), the Minnesota Stormwater Manual (MPCA 2023) states that the design storm runoff volume should be able to pass through a filtration practice within 48 hours of a storm event. Additional guidance on filtration practice design and installation can be found in the Minnesota Stormwater Manual (MPCA 2023).

Designing a filtration practice is a balance between filtration rate and solid retention efficiency.

5.2 Types of Filtration Practices

5.2.1 Surface Sand Filters

A typical surface sand filter is shown in Figure 5-1. As described in the Minnesota Stormwater Manual (MPCA 2023), surface sand filters have a flow splitter to divert runoff into an off-line sedimentation chamber. The chamber may be either wet or dry and provides pretreatment for the sand filter. Runoff is then distributed into the second chamber, which contains the surface sand filter, which consists of a sand filter bed (typically about 18 inches thick). Runoff is stored temporarily on the filter bed as it infiltrates vertically down and through the sand media. Pollutants are trapped or strained out at the surface of the filter and within the media. A series of drain tiles located in a gravel bed underneath the sand layer collect the runoff after it has passed through the sand. The runoff then leaves the sand filter and is transported downstream in the conveyance system. If underlying soils are permeable, and groundwater contamination unlikely, the bottom of the filter bed may have no lining, which allows a portion of the filtered runoff to infiltrate.

Figure 5-1: Typical surface sand filter in Austin, Texas. Photo: Andy Erickson.

Retention of dissolved pollutants such as phosphorus is typically minimal via sand filters. To retain dissolved pollutants, amending agents (discussed below) must be added to the media. If the filter bed surface has a vegetative cover, it is a bioretention filter. For more information on bioretention filters, see Chapter 6 on bioretention.

5.2.2 Underground Sand Filters

As discussed in the Minnesota Stormwater Manual (MPCA 2023), the underground sand filter was adapted for sites where surface land space is at a premium (Figure 5-2). In this design, the sand filter is placed in a three-chamber underground vault accessible by manholes or grate openings. The vault can be either on-line or off-line in the storm drain system. The first chamber, which relies on a wet pool, is used for pretreatment and temporary runoff storage. It is connected to the second sand filter chamber by an inverted elbow, which keeps the filter surface free from floating trash and oil. The filter bed is typically 18 inches thick and may have a protective screen of gravel or permeable geotextile to limit clogging. During a runoff event, up to the water quality volume is temporarily stored in both the first and second chambers. Flows that exceed the filter's capacity are diverted through an overflow weir. Filtered runoff is collected using perforated underdrains that extend into the third "overflow" chamber. The runoff is eventually transported downstream in the conveyance system.

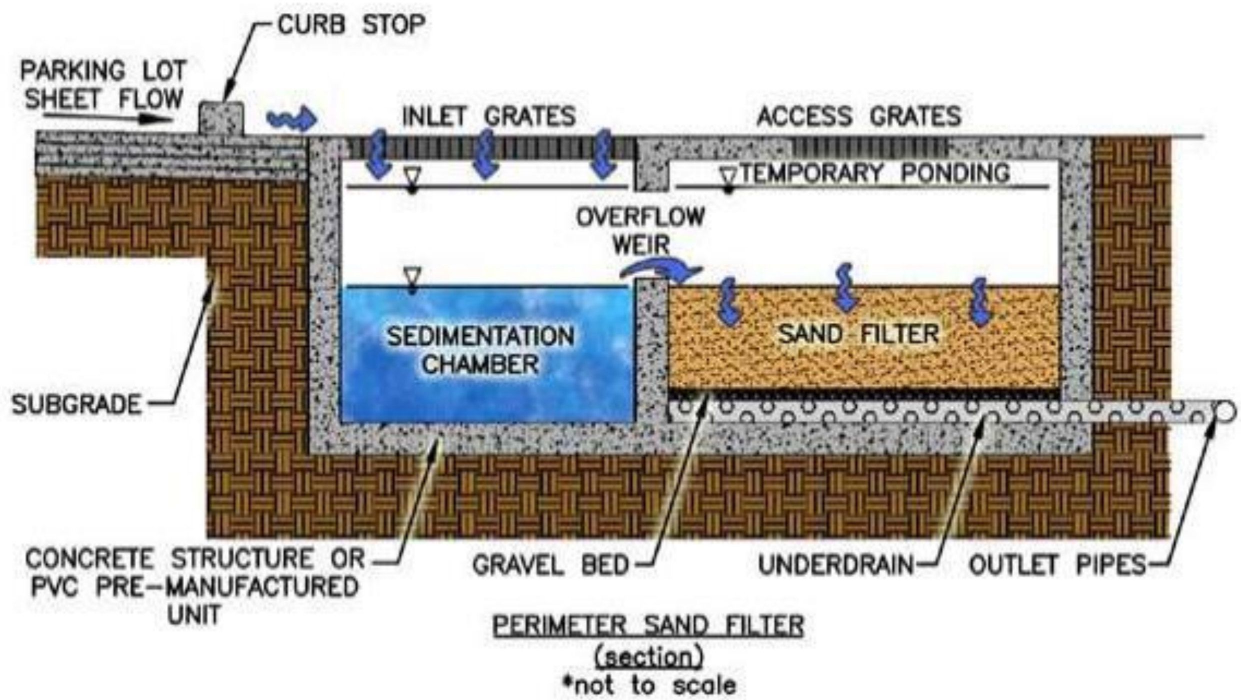

Figure 5-2: Sketch of a typical underground sand filter. (Photo: Link Here)

5.2.3 Perimeter Sand Filters

According to the Minnesota Stormwater Manual (MPCA 2023), the perimeter sand filter consists of two parallel trench-like chambers that are typically installed along the perimeter of a parking lot (Figure 5-3). Parking lot runoff enters the first trench, which has a shallow permanent pool of water. The first trench provides pretreatment before the runoff spills into the second trench, which consists of a sand layer that is typically 12 inches to 18 inches thick. During a runoff event, runoff is temporarily ponded above the normal pool and sand layer in the first and second trenches, respectively. When both chambers fill up to capacity, excess parking lot runoff is routed to a bypass drop inlet. The remaining runoff is filtered through the sand, collected by underdrains, and delivered to a protected outflow point.

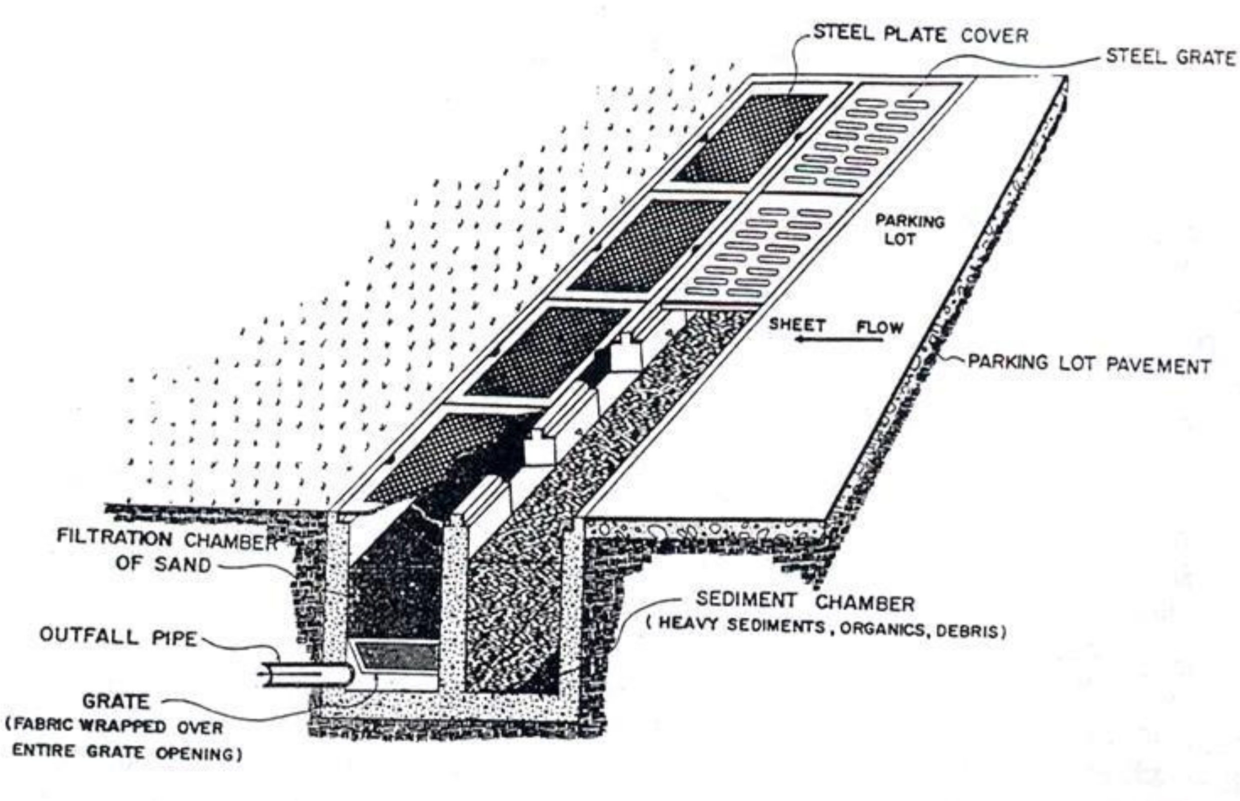

Figure 5-3: A typical perimeter sand filter placed at the perimeter of a parking lot (MPCA 2023).

5.2.4 Biofiltration Practices

A biofiltration practice is a bioretention practice that has a drain tile collection system. The drain tile collects runoff that has passed through a designed media depth and conveys it downstream in the stormwater management system. For more information on these practices, please see Chapter 6 on Bioretention Practices.

5.3 Sand Filter Amendments

5.3.1 Description

Conventional sand filters retain solid particles by physical straining but do little to retain dissolved pollutants. Amending agents, however, can be added to the sand media to retain dissolved pollutants. These amending agents may be used to retain dissolved phosphorus or other pollutants such as nitrogen, dissolved metals (e.g., cadmium, copper, lead, zinc, etc.), or bacteria, among others. This section briefly describes some amending agents that can improve the retention performance of conventional sand filters for specific, targeted pollutants., All have been used successfully in Minnesota or elsewhere and/or have shown potential in research studies.

5.3.2 Amending Agents

Iron Enhanced Sand Filter (IESF). The addition of iron shavings to retain phosphate is common in Minnesota and described in detail in the Minnesota Stormwater Manual (MPCA 2023). Elemental iron particles shaved from select recycled iron are mixed with sand to produce an iron enhanced sand filter (Erickson et al. 2007, 2012). The elemental iron oxidizes, and the oxidized portion adsorbs phosphate in the filtered stormwater. If the iron is of a form that does not oxidize (i.e., "rust"), it will not be effective in retaining phosphate. Typically, 5 – 8% elemental iron by weight is used, because higher concentrations will merge when the iron oxidizes and form a lower permeability mass that can be bypassed by water flowing through the filter (Erickson and Gulliver 2010). Installed IESFs include filter basins (Figure 5-4), pond-perimeter trenches (Figure 5-5), and pumped filter basins, which operate more consistently without waiting for rainstorms. Research has considered designs to capture phosphate released by the compost via mesocosms of compost and sand on top of an IESF (Weiss et al. 2017, Erickson et al. 2022).

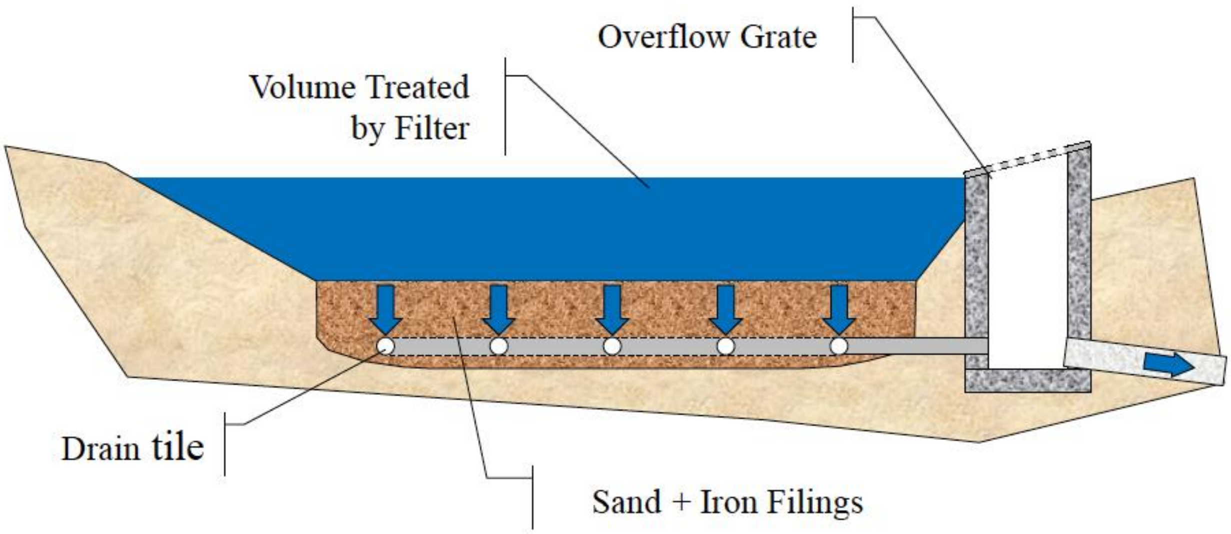

Figure 5-4: Sketch of an Iron enhanced sand filter basin. Image: Andy Erickson.

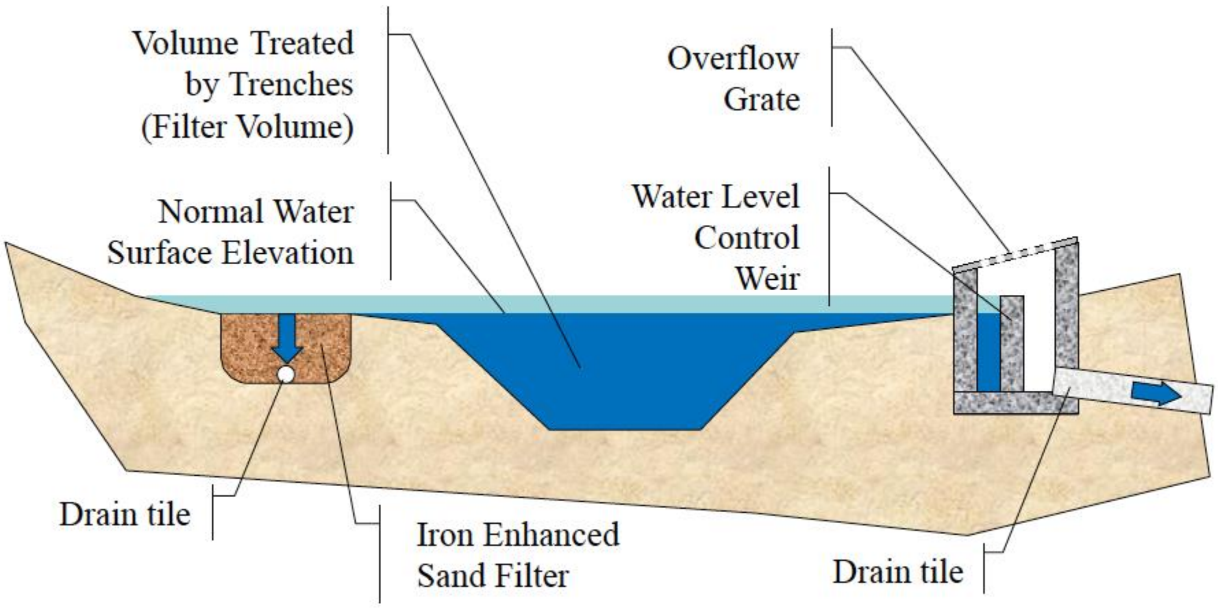

Figure 5-5: Sketch of an iron enhanced sand filter bench. Image: Andy Erickson.

Water Treatment Residuals. Water treatment residuals (WTRs) are the sludge-like by-products of water treatment for drinking water. Drinking water treatment residuals are primarily sediment, metal (aluminum, iron, or calcium) oxide/hydroxides, activated carbon, and lime removed from raw water during the water purification process (Agyin-Birikorang et al., 2009). Aluminum sulphate (commonly known as alum), ferric chloride, and lime are added as flocculants in the water treatment process. This process results in the generation of large quantities (generally between 10 and 30 mL of WTRs for every liter of water clarified) of WTRs. Different sources of WTR have different properties, including retention effectiveness, depending on the amount of iron or aluminum in the source material and many other variables such as source water characteristics, water treatment methods, and length of storage time prior to use. Major components of WTRs are soil separates, organic materials, and Al and Fe hydrous metal (hydr)oxides, depending on the metal salt used for coagulation. WTRs require an outlet for their disposal or end use (Dassanayake et al. 2015). A common disposal method is landfilling. Due to the iron or aluminum in WTRs, however, they can retain dissolved phosphorus from stormwater runoff.

When used as a sand filter amendment, WTRs are dried then mixed with the filter sand media. Wet WTR is not recommended for stormwater treatment (MPCA 2023). Each water treatment facility uses a unique source of water and different treatment chemicals and processes, producing WTRs with different physical and chemical compositions and phosphorus retention capability.

WTRs may have the ability to increase the retention rate of other pollutants such as nitrogen, metals, organics, bacteria, and viruses. There are also concerns related to using WTRs, such as the reduction of available phosphorus in unintended water bodies, and the input of aluminum and other chemicals often found in WTRs (e.g., arsenic, selenium, manganese) into the environment. For more information, see the Minnesota Stormwater Manual (MPCA 2023).

Amendment Coated Sand. Iron coated sand is a byproduct of the production of drinking water from anoxic groundwater. In the production process, anoxic groundwater is passed through a sand filter and aerated to remove dissolved iron in the water. It is often assumed that this process is due solely to oxidation-floc formation but, as this practice continues over weeks and months, sand particles become coated with iron. (Sharma et al. 2002). The iron coated sand can retain dissolved phosphorus from stormwater runoff when used in a stormwater filter (Groenenberg et al. 2013, Chardon et al. 2022).

Iron coatings can be added to sand or other media intentionally by soaking the sand in an iron solution and drying (Mostafa et al. 2011). Similar processes can be used to make aluminum coated sand (Johannsen et al. 2016) for dissolved phosphorus retention. Sand coated with other amendments that have potential to retain dissolved phosphorus or other pollutants in stormwater are also possible. For example, manganese-oxide coated sands have been used to break down bisphenol, a trace organic chemical (Charbonnet et al. 2018). There has been minimal research on the application of iron-coated sand to stormwater treatment practices.

Biochar and Granular Activated Carbon. Biochar is made by heating biomass at high temperatures under low oxygen conditions. Activated carbon is a biochar activated chemically or physically to have a highly charged surface. Both have large surface areas that promote retention of pollutants, and they can be regenerated and disposed of easily (Geca et al. 2022).

Depending on the source material and how it is made, biochar and activated carbon can retain or enhance retainment of a variety of pollutants such as nitrogen (Erickson et al. 2016, Sang et al. 2019), phosphorus (Sang et al. 2019), trace organic pollutants (e.g., pesticides and flame retardants, Ulrich et al. 2017), metals (Liu et al. 2019, Hasan et al. 2020, Sun et al. 2020), microbes (Mohanty and Boehm 2014, Afrooz and Boehm 2017), polychlorinated biphenyls (PCBs, Shinneman 2019), and benzene, ethylbenzene, toluene, and xylene (Wang et al. 2020). In some cases, the surface of the biochar or activated carbon may be impregnated with other material such as iron or aluminum to increase pollutant retention (Hasan et al. 2020, Sun et al. 2020). In general, biochar and activated carbon are used to capture metals and some organic compounds and to deactivate microbes.

Other Amendments. Other amendments may be used to increase phosphorus retention or target other pollutants for retention or removal. Native iron rich soils such as those in the Piedmont of the Mid and Southern Atlantic USA (Hunt et al 2012) and Krasnozem soil in Australia (Lucas and Greenway, 2011) are effective. Additionally, commercially available materials marketed for stormwater management applications could be used in, or as, stormwater filter media.

5.4 Benefits and Limitations of Stormwater Filters

5.4.1 Benefits

Reduce Pollutant Concentrations and Loads. Stormwater filters physically strain solid particles and retain them on the surface and within the media. They can retain more bacteria and smaller particles than are typically retained in ponds or other stormwater management practices reliant on settling for solids retention. By retaining solids, filters also retain a portion of the pollutants that attach to solids such as phosphorus and metals. Standard sand filters do little to retain dissolved pollutants but amending agents, such as iron, water treatment residuals, or biochar, can be added to the filter media to target dissolved pollutants for retention.

Peak Flow Reduction. Large, surface filtration practices can reduce peak flow rates in relation to the size of the practice. The extent of peak flow reduction is directly correlated with the storage volume of the practice and the outlet hydraulics.

Space Savings. In areas where space is limited, small filters can be placed underground allowing land area to be allocated for other purposes. Underground filters can also be used in retrofit projects that are in fully developed areas with little to no space available for surface stormwater management practices.

Winter Operation. Filters located underground and below the frostline can remain effective throughout winter.

Groundwater Protection. Filters lined with impermeable barriers prevent water from infiltrating into the existing soil, reducing the potential for groundwater contamination.

5.4.2 Benefits of Sand Filter Amendments

Targeting of Specific Pollutants. Sand filter amendments can be used to target specific pollutants for retention. For example, if it is desired to retain a specific metal, an amendment can be selected that has a high retention rate for the metal.

5.4.3 Limitations

Clogging. Filters are susceptible to clogging. To maintain sufficient infiltration rates, regular maintenance is required.

Maintenance. Due to their susceptibility to clogging, filters typically require more frequent maintenance than other stormwater practices such as ponds.

Volume Reduction. Because filters do not typically infiltrate runoff, they do not reduce runoff volumes.

Due to their susceptibility to clogging, filters typically require more frequent maintenance than other stormwater practices such as ponds.

Winter Operation. Filters located on the surface or above the frostline are susceptible to freezing. If the practice and the media are not drained before temperatures drop to below freezing, ice can form on top of and within the filter media. This will reduce or eliminate efficacy.

Aesthetics. Filters may be considered less aesthetically pleasing than other stormwater management practices such as rain gardens or other vegetated practices.

Confined Space. Underground filtration practices may fall under the authority of OSHA confined space requirements. As such, entry into the practice must follow all OSHA procedures. Entrances to confined space areas must be clearly marked. This may be accomplished by hanging a removable sign in the access riser just under the access lid (Met Council 2001).

5.4.4 Limitations of Sand Filter Amendments

Capacity. Retention sites for pollutants are not infinite and the amending agent will, at some point, exhaust its capacity for retention. The effective life of the amending agent depends on the agent, the source of its raw materials, how it was produced, retention rates, pollutant concentration in stormwater, depth of runoff treated (total volume treated divided by the surface area of the filter), other pollutants in the water that compete for adsorption sites, and many other variables.

5.5 Maintenance Costs of Filtration Practices

The International Stormwater BMP Database (ISBD 2023) reports annual operating and maintenance costs for routine maintenance of stormwater management practices in 2018 dollars. The dollar amounts are based on actual costs entered into the database by users and are considered to be “ballpark” values. Sand filters had a median value of $2107 (range from $1764 to $4704) based on fourteen reported inputs, though size/ area of practices were not indicated. No other maintenance cost information related to filtration practices was reported.

5.6 Assessment Activities – Filtration Practices

Along with discerning the structural integrity of a filtration practice, an assessment typically investigates the infiltration rate into the media (i.e., hydraulic capacity) and the pollutant retention performance of the filter. Although visual inspection can provide information on the structural integrity of the practice and the extent of sediment buildup on the media surface, it cannot provide information on infiltration rate and pollutant retention. To assess the latter two variables, capacity or synthetic runoff testing must be performed. Capacity testing can provide information on the infiltration rate at specific locations on the filter surface, but it cannot provide information on pollutant retention. Synthetic runoff testing must be conducted to assess pollution retention. Visual inspection and synthetic runoff testing are discussed below.

5.6.1 Visual inspection of Filtration Practices

Visual inspection is useful for identifying obvious problems with filtration practices. Visual indicators that the filter media may be clogged include standing water more than 48 hours after a runoff event or the presence of a visible layer of fine material (i.e., mud) on the surface of the filter. If standing water is observed in a filtration practice 48 or more hours after a runoff event, the practice is not functioning as designed. A layer of fine material on the surface of the sand filter indicates that stormwater was present for an extended period such that fine material was allowed to settle out of the stormwater and onto the filter surface. The lack of dense, healthy vegetation on the surface of a biofiltration practice may also mean the filter is clogged. See section 6.2.4 for more information on biofiltration practices.

Visual inspection of a filtration practice involves inspecting the practice approximately 48 hours after a large runoff event to look for standing water. A properly functioning filtration practice should filter the design volume in 48 hours or less (Claytor and Schueler 1996, MPCA 2023). Thus, the presence of standing water after 48 hours suggests that the filtration system is clogged. The practice should be designed so that storms larger than the design storm will overflow (e.g., through an emergency spillway) or bypass the practice so that the runoff captured by the filtration practice still drains within 48 hours. Visual inspection of filtration practices should be conducted at least annually.

5.6.2 Capacity testing for Filtration Practices

Capacity testing for filtration practices involves a series of hydraulic conductivity point measurements. These conductivity tests are used to estimate the filtration rate, which can subsequently be used to estimate the drain time of the practice. After the overall average filtration rate is estimated from the point filtration rate measurements, the design storm water volume can be divided by the filtration rate (volume/time) to determine the time required to drain the design storm. See Gulliver et al. (2010) and Erickson et al. (2013) for more information.

Hydraulic conductivity tests can also be used to detect the presence of macropores within a filtration practice. Sand filter design recommends a saturated hydraulic conductivity value of 3.5 ft/day (Claytor and Schueler 1996, MPCA 2023). If the results from the hydraulic conductivity tests indicate that the median hydraulic conductivity for the entire practice is larger than 280 ft/day, macropores may be reducing solids retention. Additionally, if an area of the filtration practice has a hydraulic conductivity greater than 280 ft/day, macropores may be significantly reducing solids retention in that specific area on the filter surface. Filtration rates less than 280 ft/day do not preclude the presence of macropores but indicate that macropores, if present, are not significant. Hydraulic conductivity tests are applicable to all filtration practices and all filter media.

5.6.3 Synthetic Runoff Testing of Filtration Practices

Synthetic runoff testing can be used to measure the filtration rate (i.e., hydraulic capacity) of filtration practices if an available water supply can provide a sufficient water volume and discharge rate: fire hydrants can typically produce between two and four ft^3/s for up to approximately 30 minutes and a water truck can produce up to approximately one ft^3/s. Most commercial water trucks have a storage volume of approximately 500 ft^3, though a large water truck can hold up to 1000 ft^3, which allows the maximum discharge to be provided for approximately 15 to 20 minutes.

Given accurate contours of the filter basin, drafting software such as AutoCAD can be used to calculate the surface storage volume of a stormwater filter. If the practice is initially empty, the volume of water required for synthetic runoff testing is the storage volume of the stormwater filter plus the estimated volume of water that will pass through the filter while the practice is being filled. Also, the water supply must provide a discharge that can fill the practice in an acceptable amount of time (i.e., 1-2 hours). For additional information, including information on estimating storage volume without drafting software and on determining if a water supply is adequate, please see Gulliver et al. (2010) and Erickson et al. (2013).

Synthetic runoff tests can be used to detect the presence of macropores in filter media. Sand filtration design recommends a saturated hydraulic conductivity of 3.5 ft/day (Claytor and Schueler 1996, MPCA 2023). If the results from the synthetic runoff tests indicate that the hydraulic conductivity for the filtration practice is larger than 280 ft/day, macropores may be reducing solids retention. Filtration rates less than 280 ft/day do not preclude the presence of macropores but indicate that macropores, if present, are not necessarily significant.

For filtration practices, synthetic runoff testing may require the same or less effort than capacity testing. In other words, if a sufficient water supply is available, it may be easier and require less time to fill a filtration practice and measure the change in water level (i.e., ponded depth) than to perform multiple point infiltration measurements. This is especially true of underground filtration practices, which are typically small systems with limited access.

The results of capacity testing for a filtration practice will produce more specific information than synthetic runoff testing and can be used to guide localized maintenance. For example, synthetic runoff testing of a filtration practice may indicate that the practice is able to drain the design storm within 48 hours and is therefore functioning as designed. Capacity testing, however, may indicate that 25% of the filtration practice is not filtering water at all and the remaining 75% is responsible for the filtration of the entire design volume. Maintenance efforts could then be focused on the 25% that is not filtering water.

The pollutant retention efficiency of a filtration practice can be estimated by adding a pollutant (e.g., sediment, phosphorus, etc.) at a known concentration to the water supply, collecting effluent samples over time, and measuring the concentration of pollutant in the effluent samples.

5.7 Maintenance Activities

Maintenance of filtration practices can range from trash removal to the much more expensive and time-consuming tasks such as complete removal and replacement of the filter media and underlying drain tile system. Much of the information in this section is drawn from Erickson et al. (2010). As presented in the Minnesota Stormwater Manual (MPCA 2023), typical maintenance tasks and guidelines for frequency are given in Table 5-1.

Table 5-1 Typical maintenance tasks and frequencies associated with filtration practices (WMI 1997, Pitt 1997).

Task	Frequency
Manual manipulation of the surface layer of sand may be required. Remove the top few inches of media, roto-till or otherwise cultivate the surface, and replace media with like material meeting the design specifications	Standard maintenance, as needed.
Replace any filter fabric that has become clogged	
Ensure that contributing area, facility, inlets and outlets are clear of debris	Monthly
Ensure that the contributing area is stabilized and mowed, with clippings removed	
Remove trash and debris	
Check to ensure that the filter surface is not clogging (also check after storms greater than about 1”)	
Ensure that activities in the drainage area minimize oil/grease and sediment entry to the system	
If permanent water level is present in pre-treatment chamber (e.g., perimeter sand filter), ensure that the chamber does not leak, and normal pool level is retained	
Check to see that the filter bed is clean of sediment and the sediment chamber is not more than 6 inches of sediment. Remove sediment as necessary	Annually
Make sure that there is no evidence of deterioration, spalling or cracking of concrete	
Inspect grates (perimeter sand filter)	
Inspect inlets, outlets and overflow spillway to ensure good condition and no evidence of erosion	
Repair or replace any damaged structural parts	
Stabilize any eroded areas	
Ensure that flow is not bypassing the facility	
Ensure that no noticeable odors are detected outside the facility	
Remove and replace the top 2-5 inches of media every 3 to 5 years for low sediment applications, more often for areas of high sediment yield or high oil and grease	At least every three to five years

Two primary reasons filtration practices fail are clogging and the presence of macropores. The same maintenance actions are required for all filters to reduce clogging and maximize filtration rates, regardless of whether they are under or above ground or whether they contain an amending agent (such as iron) or not. The assessment and maintenance of sand filters with an amending agent to increase pollutant retention is discussed later in this section.

Two primary reasons filtration practices fail are clogging and short-circuiting due to macropores.

Filtration practices are typically implemented, at least in part, to reduce suspended solids in stormwater runoff. Pretreatment with a separate stormwater treatment practice just upstream of the filtration practice is required (MPCA 2023) and must be maintained, as well.

If any level of assessment indicates that the filter is not draining or will not drain the design runoff volume within 48 hours, the following steps can be taken:

1. Inspection of outlet structures and the drain tile system followed by the corresponding removal of material, if any, that is obstructing flow and/or the replacement of structural components, if necessary.
2. Performing capacity testing and/or synthetic runoff testing to determine filtration rates of the filter media. If filtration rates are low, the following steps may correct the problem.
3. Rototilling of the top six inches of filter media.
4. Removal and replacement of any sediment layer and the top six to eight inches of filter media.
5. Removal and replacement of the entire media bed.

If, at any time, it is determined that filtration rates are too large or the total suspended solids retention rate is too low, it is likely that there is a short-circuit in the filter media. The following steps can be taken to confirm and address the problem.

1. Visually inspect the filter media to ensure there are no large holes, ruts, or other openings in the media that would allow runoff to pass without being sufficiently filtered. If any such areas are present, the media in the suspect area should be replaced only after any underlying causes (e.g., insufficient gravel subbase, tear in geosynthetic fabric separating filter media and gravel subbase) are found and corrected.
2. Perform capacity testing to determine filtration rates at various locations on the filter surface. Any locations where the hydraulic conductivity is determined to be larger than 280 ft/day should be corrected by removing and replacing the filter media in that area.
3. Perform synthetic runoff testing to determine an overall average hydraulic conductivity value for the filter by methods discussed in Gulliver et al. (2010) and Erickson et al. (2013). A disadvantage of synthetic runoff testing is that it will not identify specific locations in the media where short-circuiting is occurring. As a result, if synthetic runoff tests identify short-circuiting and no additional testing is performed (i.e., capacity tests), the entire media bed must be replaced.

While frequency of filter media replacement will vary depending on the watershed, watershed land use, filter size, rainfall amounts and intensities, etc., Wossink and Hunt (2003) reported that removal of the top layer of filter media typically is required from once per year to once every three years. Landphair et al. (2000) reported that surface sand filter media typically needs to be replaced every three to five years.

Removal of the top layer of filter media is typically required from once per year to once every three years.

If an iron or otherwise enhanced sand filter is achieving less than satisfactory dissolved pollutant retention, the media mix of sand and amending agent may need to be replaced. If the amending agent is in a separate layer on the filter surface or within the media, the layer of amending agent alone may be replaced.

For iron-enhanced sand filters, total phosphorus at the outlet consistently exceeding 60 to 70 micrograms per liter indicates that the phosphorus binding capacity of the sand-iron media has been consumed (MPCA 2023). If this condition is true, samples should be taken from the iron-sand bed and analyzed for total phosphorus and total iron. Total phosphorus to total iron ratios exceeding 5 milligrams of phosphorus per gram of elemental iron (Erickson et al., 2007, 2012) indicate the phosphorus binding capacity of the iron-sand bed is exhausted and should be replaced.

5.7.1 Assessment and Maintenance Activities – Sand Filter Amendments

If an amended filter is achieving less than acceptable dissolved pollutant retention, the media mix of sand and amending agent may need to be replaced in order to retain the dissolved pollutant of interest. If the amending agent is in a separate layer on the filter surface or within the media, the layer of amending agent alone may be replaced.

For iron-enhanced sand filters, soluble reactive phosphorus concentrations at the outlet consistently exceeding 60 to 70 micrograms per liter may be used as an indicator that the phosphorus binding capacity of the sand-iron media has been substantially reduced. If this condition is true, samples should be taken from the iron-sand bed and analyzed for total phosphorus and total iron. Soluble reactive phosphorus to total iron ratios exceeding 5 milligrams of phosphorus per gram of elemental iron (Erickson et al., 2007, 2012) indicate the phosphorus binding capacity of the iron-sand bed is substantially reduced and should be replaced.

5.8 Factors Affecting Performance

Maintenance efforts for filtration practices are typically focused on the removal of filtered sediment buildup and litter/debris. Survey results (Erickson et al. 2010) indicate that maintenance efforts were also needed to address the issues of groundwater and oil spills. Table 5-2 lists the percentage of respondents that indicated a factor most frequently causing deterioration of their stormwater treatment practice performance. Other factors not listed in Table 5-2, such as invasive vegetation and bank erosion, were listed as possible survey choices but received zero responses and are, therefore, not listed.

Table 5-2: Percent of respondents who indicated the listed factor frequently caused deterioration of stormwater treatment practice performance (Erickson et al. 2010).

Factor	Surface Filters	Underground Filters
Sediment Buildup	50%	50%
Litter/Debris	30%	25%
Pipe clogging	10%	13%
Groundwater level	0%	13%
Oil spill	10%	0%

5.9 Recommendations for Filtration Practices

5.9.1 Assessment

The required frequency of inspection and maintenance is dependent on the watershed land use (e.g., urban, rural, farm) and rainfall amounts and intensities. It is recommended, however, that a visual inspection be performed at least twice per year.

If an adequate water supply is available, synthetic runoff testing is recommended for assessment of filtration rates of small surface filters or underground filters. For assessment of sites too large for synthetic runoff testing, capacity testing is recommended. Pollutant retention performance of surface and underground filtration practices is well established and therefore visual inspection, capacity testing, or synthetic runoff testing is recommended for assessment of pollutant removal performance.

5.9.2 Maintenance

A pretreatment system such as a sediment forebay can significantly reduce the frequency and extent of maintenance by removing settleable solids before they reach the filtration practice. Maintenance of sediment forebays is easier than maintenance of a filtration practice. For guidance on maintenance and sediment forebay design, see the Minnesota Stormwater Manual (MPCA 2023).

A pretreatment system such as a sediment forebay can significantly reduce the frequency and extent of maintenance by removing settleable solids before they reach the filtration practice.

Even with a pretreatment system, retained solids will eventually need to be removed from the filter. If the retained solids are at or near the surface of the filter media, the practice can often be repaired by removing the top 2 to 5 inches of filter media, rototilling the surface, and replacing the removed media with similar or approved alternative media (MPCA 2023). If this procedure does not resolve the problem, the entire filter bed may need to be replaced to restore functionality.

If an iron enhanced sand filter has been found to inadequately retain dissolved phosphorus, the filter media (iron-sand mix) may need to be replaced. Similarly, if other amending agents are used with or in place of iron, the agent may need to be replaced when retention ability is exhausted.

Macropores such as wormholes can cause short-circuiting of the filtration practice and can diminish solid retention efficiency and peak flow reduction. Macropore problems can be resolved by mixing the media bed or replacing it entirely.

5.10 Minnesota Case Studies of Iron Enhanced Sand Filters

There are over 150 iron enhanced sand filters in the State of Minnesota, and some are well-documented. These fall into three types of IESFs:

5.10.1 Iron Enhanced Sand Filter Basin (Ramsey Washington Metro Watershed District)

A traditional amended sand filter basin where water enters the filter, filters through the amended sand and flows into either the stormwater system or the receiving water body. An example of these is the Beam Avenue IESF, in the Ramsey Washington Metro Watershed District (Figure 5-6) which takes water from a parking lot and surrounding roads, filters it to retain suspended solids and phosphate, and flows into the stormwater system headed towards Kohlman Lake.

Figure 5-6: Beam Avenue iron enhanced sand filter (Ramsey Washington Metro Watershed District). Flow enters the basin, filters through pea gravel on the surface, and iron enhanced sand below the pea gravel, and finally into pea gravel that allows the flow to be exported by drain tiles. Photo: Andy Erickson.

5.10.2 Pond Perimeter Trench (Capitol Region Watershed District)

A pond-perimeter IESF finishes water leaving a pond. The pond has treated stormwater by removing solids and phosphate before the stormwater travels to the receiving water body. An example of this type of IESF is the Como Golf Course Pond IESF in St Paul, in the Capitol Region Watershed District (Figure 5-7). Runoff fills the Como Golf Course Pond and begins to enter the IESF at the edge of the pond, which treats the water before it goes to Como Lake.

Figure 5-7: Como Golf Course Pond IESF in St Paul (Capitol Region Watershed District). Pond, filter covered with vegetation, and grate covered overflow structure are shown. The IESF has two drain tiles, both discharging to the same structure. Photo: Peter Weiss.

5.10.3 Pumped IESF Basins (Rice Creek Watershed District)

A pumped IESF, where water is pumped from a pond or stream into an IESF, typically at a higher elevation, which then flows into a receiving water body or the stormwater system. An example of a pumped IESF is located at Hanson Park, in the Rice Creek Watershed District (Figure 5-8). The water collected in the Hanson Pond is pumped into a four-filter system which can alternately drain and fill when there is a high discharge. Water then enters a channel and is conveyed to Long Lake.

Figure 5-8: One of four Hanson Park IESFs (Rice Creek Watershed District), where four filters alternate during high discharges to allow drain and drying time. One IESF is to the left and a second is to the far right. Two others are not visible in this figure. Photo: Peter Weiss.

Chapter 6: Bioretention Practices

6.1 Description

Bioretention stormwater treatment practices utilize the chemical, biological, and physical properties of plants, microbes, and soils for capturing/reducing stormwater runoff and retaining/ removing pollutants from the runoff. This process is incorporated into many different types of filtration and infiltration stormwater management practices. Bioretention facilities can be divided into the following sub-categories, which will be discussed in more detail in this chapter:

- Rain gardens
- Infiltration basins (also discussed in Chapter 4)
- Filtration basins (also discussed in Chapter 5)
- Bioswales
- Filter strips

***(Bio)infiltration* → water goes to groundwater**

***(Bio)filtration* → water goes to underdrain and the stormwater management system**

In bioretention facilities, pollutants may be retained by adsorption, filtration, ion exchange, and uptake into plant matter. As discussed in Chapter 1, retained pollutants are stored within the practice and may be released at a later time. Stormwater in a bioretention practice may become groundwater if it infiltrates into the existing soil (infiltration). It may also be collected by an underdrain system (filtration), or overflow to an outlet during large events, or a combination thereof. It's important to note the difference between infiltration (water moving through the media towards the groundwater) and filtration (water moving through the media, collected by an underdrain, and conveyed to the downstream stormwater management system). When the rate of water entering a practice exceeds the infiltration or filtration rate, stormwater begins to pool on the surface of the media. If the pooled stormwater volume exceeds the design storage capacity of the practice, excess runoff may be bypassed through an overflow mechanism or spillway and into the conveyance system.

As per the MPCA, a properly designed and maintained bioretention facility will exhibit the following characteristics:

- Will not have standing water in the bioretention facility 48 hours after a rain event, in compliance with the MPCA's Construction General Permit.
- Will have healthy vegetation appropriate to the function of the practice and surrounding environment and be free of weeds.

Bioretention facilities often have pre-treatment to minimize clogging by the sediment carried in the stormwater runoff. Pre-treatment devices are intended to trap (i.e., retain) large sediment (~ > 100 microns), which reduces the required frequency of maintenance on the bioretention practice. Pre-treatment can consist of vegetated or rock filter strips, sediment forebays, sump manholes, or above ground or underground proprietary treatment devices such as grit chambers and proprietary settling devices.

Plants lose approximately 30-50% of their root structure annually, and this process produces small openings or pathways in the soil. The pathways can increase the infiltration rate of the practice so that more stormwater runoff is infiltrated. Thus, healthy vegetation in the bottom of a bioretention basin increases infiltration and reduces runoff volumes. Additionally, vegetation can reduce overland flow velocities, reduce erosion, and minimize the resuspension of retained solids. Vegetation also breaks down petroleum-based pollutants and may uptake phosphorus, nitrogen, and metals needed by the vegetation as micronutrients. Vegetation in a BMP needs to be tolerant to high chloride concentrations if the practice will receive runoff containing chloride such as occurs with many roads and parking lots. Typically, bioretention facilities are planted with a mix of native deep-rooted perennials, shrubs, and/or trees adapted to growing in periodically wet and dry conditions.

The soil or selected media of a bioretention practice may be the naturally existing soil or it may be a mix of specific components, such as sand and compost and sometimes additional material(s). Rain gardens and infiltration basins may also be covered with a layer of mulch. The mulch provides filtration, retains moisture, and may provide other pollutant retention processes such as adsorption and ion exchange. Microbial activity in the soil can also help lower concentrations of organic pollutants. Thus, bioretention practices can improve runoff water quality, but may, depending on conditions, increase runoff concentrations and/or pollutant loads. The key to preventing a bioretention practice from becoming an exporter of pollutants is regular maintenance, as discussed in Section 6.5.

The key to preventing a bioretention practice from becoming an exporter of pollutants is regular maintenance, as discussed in Section 6.5.

If the native soils are not conducive to infiltration, an "engineered" mixture comprising sand and compost, may be used to promote rapid infiltration and plant growth. Although it can help retain solids and dissolved metals, compost is naturally high in phosphorus and nitrogen, making it a common exporter of dissolved phosphorus and nitrogen (Morgan 2011, Paus et al. 2014, Erickson et al. 2022). The Minnesota Stormwater Manual (MPCA 2023) lists different media mixes for facilities with underdrains and those without (*Link Here*). Underdrains may be added to account for poor or non-infiltrating underlying soils, shallow bedrock, karst features, drinking water supply management areas or cases where clean stormwater is being harvested for reuse. Cleanouts and inspection/observation wells are frequently part of the underdrain system.

To prevent soil compaction, clogging, and negative impacts on vegetation from sand and road salt, bioretention facilities should not be used as dedicated snow storage or disposal areas. Also, salt application on bioretention soil has been shown to release both solids, which may lead to clogging, and other dissolved pollutants (Kakuturu and Clark 2015, Erickson et al. 2022).

6.2 Sub-categories of Bioretention Practices

6.2.1 Rain Gardens

Rain gardens are small-scale, shallow (typically 18” deep or less), vegetated depressions used to promote infiltration/filtration and treatment from the first flush of runoff from a parcel or small catchment area (Figure 6-1). Runoff typically enters the garden as sheet flow (Figure 6-2). Rain gardens can be planned and integrated into both new and existing developments. A rain garden combines shrubs, grasses, and/or flowering perennials in depressions that allow water to pool for 48 to 72 hours after a rain event. Water is retained in the ponding area until it either infiltrates or is removed via evapotranspiration. Rain gardens may be designed without underdrains so that stormwater infiltrates into the existing soil or they may be designed with an underdrain collection system. If an underdrain system is included, and infiltration is undesirable, the rain garden may be lined with an impermeable barrier. Impermeable barriers may be used to prevent contamination of underlying soils and aquifers and, when present, the practice acts as a filter. Besides the footprint of the practice and the water depth, the processes and operation of rain gardens and the larger infiltration basins discussed below are similar.

Figure 6-1: Typical rain garden that captures the first flush of runoff from a parcel or small catchment area. Photo: Brooke Asleson.

Figure 6-2: Sheet flow over rain garden pretreatment section. Photo: Andy Erickson.

6.2.2 Infiltration Basins

An infiltration basin is a constructed impoundment that captures, temporarily stores, and infiltrates the design water quality volume within an acceptable time period, typically 48 hours in Minnesota. Infiltration basins (Figure 6-3) contain a flat, densely vegetated floor situated over naturally permeable soils. Infiltration basins are typically used for drainage areas of five to 50 acres with land slopes below 20%. Typical maximum standing water depths range from two to six feet, including freeboard in the basin. Infiltration basins are sized to control runoff at a regional scale as opposed to bioretention basins that are intended to control runoff at a site scale (MPCA 2023).

Figure 6-3: Infiltration basin with natural grass covering. Photo: John Gulliver.

Infiltration basins function similarly to rain gardens but can generally treat larger areas than rain gardens because they have a larger footprint and a greater maximum water depth. In many cases, the vegetation in an infiltration basin, which could include trees and bushes, has a less manicured appearance than in a rain garden and may therefore require less frequent maintenance. This type of facility is suitable for areas where high recharge of groundwater is possible and would be beneficial. Because there is no underdrain, the in-situ soil needs to have a sufficient infiltration rate to accommodate the inflow levels. Infiltration basins, however, may be prohibited by a city's wellhead protection plan per Minnesota Department of Health regulations.

6.2.3 Filtration Basins

A filtration basin may look very similar to an infiltration basin from the surface; both are vegetated impoundments that capture and temporarily store stormwater runoff. A filtration basin differs in that stormwater is prevented from entering the groundwater system by an impermeable layer, such as a geosynthetic liner or clayey soil, and an underdrain collection system. The liner is a crucial element, designed to reduce the possibility of groundwater contamination. When runoff moves through the granular media of the facility and to the underdrain collection system, some treatment occurs. In the event of an accidental spill, the underdrain outlet can be plugged, and spill materials siphoned through the observation well and safely contained.

6.2.4 Bioswales

A bioswale is any vegetated open channel designed to convey stormwater and improve its water quality (Figure 6-4). The Minnesota Stormwater Manual (MPCA 2023) describes bioswales that may be dry or wet, or step pools on a steeper slope. The side slope of a swale can act as a filter strip and, in A or B type soils, can infiltrate a significant fraction of the runoff from an everyday rainfall event (e.g., ~1.5-inch storm). Thus, roadside swales can retain over 70% of suspended solids (Barrett 2004) and infiltrate a significant fraction of the annual runoff volume and associated dissolved pollutants (Ahmed et al. 2014, Garcia-Serrana et al. 2016). By retaining solids, swales also retain pollutants attached to the solids such as phosphorus and metals. Swales, however, do little to remove dissolved phosphorus, nitrogen, or dissolved metals and may even leach dissolved pollutants into the runoff, thus becoming a source of these pollutants.

Figure 6-4: Bioswale to accept road runoff, infiltrate stormwater, convey stormwater and improve the water quality of stormwater. Photo: John Gulliver

6.2.5 Filter Strips (pre-treatment)

Filter strips are densely vegetated, uniformly graded areas that accept sheet flow from impervious surfaces such as parking lots and roads (Figure 6-2 and 6-5). Filter strips trap sediments, infiltrate a portion of the runoff, and reduce runoff velocity. Grass filter strips are often used as a pretreatment practice just upstream of other stormwater management practices, such as filters, rain gardens, or bio in/filtration practices (USEPA 1999).

Figure 6-5: Field tests on the performance of a filter strip. Photo: John Gulliver.

Filter strips rely on the use of vegetation to slow runoff velocities, promote sheet flow, and filter sediment and other pollutants from stormwater. Whereas swales are concave, channelized, vegetated conveyance systems, filter strips provide treatment by sheet flow over gently sloped, laterally flat surfaces.

To be effective, filter strips require the presence of sheet flow across the entire strip (MPCA 2023). Once flow concentrates to form a channel, it effectively short-circuits the filter strip. The filter strip is typically an in-line practice, so it must be designed to withstand the full range of storm events and corresponding velocities without eroding. Filter strips can be as simple as a strip of turf and often have design velocities of less than 1 ft/s. Additionally; to be effective, the depth of flow should not be higher than the top of the vegetation. If designed correctly and over permeable soils, filter strips can provide infiltration and runoff volume reduction.

6.3 Benefits and Limitations of Bioretention Practices

6.3.1 Benefits

Reduce Pollutant Load. Bioretention practices can reduce pollutant loads through sedimentation, filtration, infiltration to groundwater (if no underdrains are present), biological activity in the soil, and plant uptake. The soil can filter solids and dissolved pollutants can be retained or removed through microbial processes and/or plant uptake. Because some fraction of the solids is retained, pollutants that have a fraction of their pollutant load attached to solid particles, such as phosphorus and metals, will also be partially retained. Because the vegetation and compost in a bioretention practice contains phosphorus and nitrogen and because plant matter dies and decomposes, bioretention practices can often release phosphorus and nitrogen. Bioretention practices can reduce the temperature of runoff and thereby can help minimize thermal impacts. They typically have a more positive impact on temperature compared to ponds in which water is often heated via direct sunlight.

Peak Flow Reduction. Bioretention practices can reduce peak flow rates in relation to the size of the practice. A relatively small rain garden, for example, will not reduce large storm peak flow rates to any noticeable extent. Large bioretention basins, or many y rain gardens dispersed throughout the upper reaches of a watershed, however, can reduce peak flow rates.

Volume Reduction. Bioretention practices that infiltrate water to groundwater will reduce the volume of stormwater runoff. The amount of volume reduction will depend on the infiltration capacity of the bioretention practice(s) and the number of bioretention practices implemented in the watershed. Bioretention practices with an impermeable liner and an underdrain collection system will not reduce the runoff volume.

Wildlife Habitat. Bioretention practices can provide wildlife habitat and aesthetic enhancement. These practices are attractive for wildlife such as birds, insects, pollinators, and other organisms.

Winter Operation. Bioretention practices, if designed appropriately for the conditions, have been shown to perform well in cold, winter climates (MPCA 2023).

6.3.2 Limitations

Clogging. Bioretention practices are susceptible to clogging by sediment, especially if vegetation is not established. Pretreatment practices upstream of bioretention can reduce the frequency and magnitude of clogging in bioretention practices.

Maintenance. To maintain healthy vegetation free of invasive species, bioretention practices may require more frequent maintenance compared to other practices. Watering and fertilization may be required in the first two years. The practices must be weeded on a regular basis during the growing season. Older, dying vegetation should be periodically removed from the practice to reduce the amount of phosphorus and nitrogen leaching into runoff.

Bioretention practices are susceptible to clogging by sediment, especially if vegetation is not established. Pretreatment practices upstream of bioretention can reduce the frequency and magnitude of clogging in bioretention practices.

Groundwater Protection. Infiltration may be limited or prohibited in areas over sensitive groundwater aquifers such as those protected by wellhead protection plans. All governing regulations must be followed. Contact the Minnesota Health Department for more information, if needed.

Karst Aquifers. Although bioinfiltration practices can be used to meet many stormwater management objectives, care must be taken when considering regions with karst geology, which may provide direct pathways for infiltrated stormwater to reach groundwater with little to no treatment. Also, infiltration into karst soils may create sinkholes. If karst soils are known to exist or may exist in an area, consult the Minnesota Stormwater Manual (MPCA 2023) for more information.

6.4 Assessment Activities – Bioretention Practices

As described in Chapter 1, assessment activities may involve visual inspection and/or capacity testing. Assessment activities corresponding to bioretention practices are described below.

6.4.1 Visual inspection

Visual inspection of a bioretention practice involves a site visit, photograph documentation, comparison to previous documentation, and looking for indicators of sub-optimal performance. Guidelines for visual inspection of Bioretention facilities are provided in Tables A-7a through A-7d.

According to the Minnesota Stormwater Manual (MPCA 2023), bioretention practices are required to drain within 48 hours. When conducting a visual inspection of a bioretention practice, this requirement should be considered along with the time of the last rain event. When standing water is observed more than 48 hours after the last large rain event, further evaluation of the practice, such as capacity testing, should be conducted to determine potential causes of failure.

Vegetation specified in the design of the bioretention practice should be documented in the original design plan with photographs or videos. After the vegetation is established, it should cover most of the practice. Annual photo or video records of the vegetation can be used to keep track of changes in health and migration of plant species over time. Annual photo or video records can also be used to document effects of channelization, sedimentation, and erosion. The Minnesota Stormwater Manual (MPCA 2023) provides guidance and resources for vegetation selection (Link Here). Vegetation should be evaluated on health, density, abundance, and location. Observe and record the presence of undesirable weed species including invasive plants and wetland plant species.

If the bioretention practice does not successfully sustain the desired vegetation, the soils may be retaining water for excessive periods of time, the vegetation may not be receiving enough water, the soil may be compacted limiting and root growth, or plants may have been killed by introduction of toxic substances (e.g., road salt, herbicides). When visual inspection of the vegetation indicates unsuccessful or unhealthy vegetation, the ideal conditions for each species should be examined and the soil properties (i.e., texture, compaction, sediment accumulation) should be investigated to determine the cause. If, after completion of the visual inspection, the potential cause(s) of failure are not determined, further assessment is recommended.

If the bioretention practice does not successfully sustain the desired vegetation, the soils may be retaining water for excessive periods of time, the vegetation may not be receiving enough water, the soil may be compacted and limiting root growth, or plants may have been killed by introduction of toxic substances (e.g., road salt, herbicides).

Excessive sediment accumulation may be evidenced by "sandbars," areas in which sediment deposition covers or chokes out established or developing vegetation, or large areas may be covered by layers of fine sediment or muck that minimizes infiltration, prevents healthy plant growth, and reduces stormwater storage capacity. Thus, bare areas in a bioretention practice may be the result of excessive periods of wet soils and standing water in the practice or it may be the result of excessive sedimentation and/or accumulation of fines on the floor of the practice. Either way, visual inspection should document and investigate the cause.

The practice should also be examined for erosion occurring near inlets, overflow structures, or along the side slopes, as eroded material deposited in the bioretention practice may cause structural instability.

6.4.2 Capacity testing for Bioretention Basins and Rain Gardens

Capacity testing can be used to assess infiltration rates or available sediment storage capacity of bioretention practices. Hydraulic conductivity and infiltration capacity tests are applicable. Simple visual evidence of sediment accumulation indicates the practice needs maintenance. A pretreatment system, such as erosion control, street sweeping, or sedimentation forebay could also be considered if not already present. If the practice already has a pretreatment system, visual inspection and necessary capacity or synthetic runoff testing should still be performed.

As previously discussed, the Minnesota Stormwater Manual (MPCA 2023) states that bioretention facilities should be designed to draw down to the base within 48 hours. If a bioretention practice does not infiltrate the water in time, the soil media may be clogged. Clogged media may cause flooding of surrounding areas or force untreated stormwater to bypass the bioretention practice. Underdrains, uncapping underdrains, or opening valves on underdrains will not increase infiltration through clogged media.

If the bioretention practice is not infiltrating stormwater at the desired rate, the soil profile should be established, including texture, color, moisture, and bulk density. For more information, see Methods of Soil Analysis (Klute 1986).

Saturated hydraulic conductivity (the rate of infiltration when the soil is saturated with water) can be estimated from soil texture classification (Clapp and Hornberger, 1978; Rawls et al., 1998; Saxton and Rawls, 2005). Table 6-1 provides saturated hydraulic conductivity values based on USDA soil texture from various authors. Note that infiltration rates are also dependent upon soil structure, determined by compaction, the presence of roots, etc. In the field, therefore, the ranges given in Table 6-1 can be exceeded.

Table 6-1: Ranges of saturated hydraulic conductivity (Ksat) and porosity for the USDA soil textural classes (Clapp and Hornberger 1978, Rawls et al. 1998, Saxton and Rawls 2005).

	Saxton and Rawls 2005		**Rawls et al. 1998**		**Clapp and Hornberger 1978**	
USDA Soil Textural Class	K_{sat} (ft/hr)	Porosity (m^3/m^3)	K_{sat} (ft/hr)	Porosity (m^3/m^3)	K_{sat} (ft/hr)	Porosity (m^3/m^3)
Sand	0.51-0.31	0.48-0.46	0.60-0.30	0.44-0.39	0.97	0.40
Loamy Sand	0.45-0.16	0.47-0.44	0.40-0.14	0.45-0.37	0.48	0.44
Sandy Loam	0.36-0.07	0.47-0.42	0.18-0.04	0.47-0.37	0.15	0.44
Loam	0.03-0.15	0.48-0.46	0.01-0.02	0.47-0.39	0.03	0.45
Silt Loam	0.04-0.22	0.48-0.46	0.05-0.01	0.49-0.39	0.01	0.49
Silt	0.04-0.11	0.49-0.47	--	--	--	--
Sandy Clay Loam	0.01-0.07	0.45-0.42	0.02-0.0094	0.44-0.37	0.03	0.42
Clay Loam	0.01-0.03	0.50-0.45	0.01-0.0024	0.48-0.40	0.01	0.48
Silty Clay Loam	0.02-0.03	0.53-0.49	0.0118-0.0165	0.50-0.43	0.0024	0.48
Sandy Clay	0.0003-0.0088	0.46-0.43	0.0035	0.39	0.0035	0.43
Silty Clay	0.0115-0.0118	0.55-0.50	0.0059	0.53	0.0012	0.49
Clay	0.01-0.0056	0.56-0.46	0.0071-0.0060	0.48-0.40	0.01	0.48

Hydraulic conductivity testing throughout the bioretention practice can be used to assess the spatial range of infiltration rates and to identify areas of small or large hydraulic conductivity. An infiltrometer and/or permeameter should be chosen and used to estimate hydraulic conductivity throughout the practice. An infiltrometer will measure near-surface infiltration rates and saturated hydraulic conductivity. A permeameter will measure similar properties, but in a borehole and at the depth below the borehole. For more information on this topic, see Erickson et al. (2013).

Saturated hydraulic conductivity values for bioretention practices should be compared to design specifications to determine if the practice is performing effectively. There are many techniques available for measuring infiltration capacity (Tecca, et al. 2021, 2022). See Gulliver et al. (2010) and Erickson et al. (2013) for additional information. It may be convenient to represent the practice with a single estimated value of saturated hydraulic conductivity based on the numerous point measurements taken. This can be done using a method developed by Weiss and Gulliver (2015). An example of capacity testing applied to bioretention facilities is provided in Asleson et al. (2009). If the design specifications are not available, the measured infiltration rate should be used to estimate the drain time of the design storage volume to determine if it is less than 48 hours, as demonstrated by Erickson et al. (2013). The infiltration rate should be measured periodically to determine if the bioretention practice infiltration capacity is stable or decreasing and, if decreasing, at what rate.

6.4.3 Capacity testing for Filter Strips and Swales

Filter strips and swales rarely maintain standing water because they are designed for stormwater conveyance, not stormwater storage. Nevertheless, infiltrometer and/or permeameter tests can be performed on filter strips and swales to determine infiltration rates. Some swales have berms or check dams to reduce flow velocities and store stormwater runoff temporarily, which increases sedimentation and the volume of runoff infiltrated. Hydraulic conductivity tests should be focused on locations where infiltration occurs or is likely to occur based on the design, such as upstream of a berm or a check dam.

6.4.4 Synthetic Runoff Testing of Bioretention Practices

Synthetic runoff testing is the application of synthetic stormwater runoff to assess stormwater infiltration rates, drain time, pollutant removal efficiency, or all the above. The reductions in peak flow and runoff volume can be estimated from the infiltration rate, specified storm intensity and duration, and watershed characteristics. Synthetic runoff testing can be applied to bioretention basins, rain gardens, filter strips, and swales (provided adequate access and water supply is available). Be sure to obtain all permissions and permits necessary to access property and water supplies, such as fire hydrants.

Synthetic Runoff Testing – Infiltration Basins and Rain Gardens. Synthetic runoff testing to determine the infiltration rate or drain time of infiltration basins and rain gardens involves filling the practice with synthetic stormwater and measuring the change in water level with respect to time. The flow rate of the water source (e.g., fire hydrant, water truck) should be significantly greater than the rate water infiltrates into the soil so that the basin or rain garden can be filled to the design storm volume in a reasonable time, typically less than one or two hours. If, however, the flow rate of the water source is not sufficient to fill the practice in a reasonable amount of time, pollutant removal efficiency can still be determined. Gulliver et al. (2010) and Erickson et al. (2013) provide details and examples for how to estimate infiltration rate and drain time of bioretention practices using synthetic runoff testing.

To determine if the practice is performing effectively, the measured drain time of the basin or rain garden should be compared to design specifications. The drain time can be measured periodically to determine if the infiltration rate of the practice is stable or decreasing and, if it is decreasing, at what rate.

The pollutant removal efficiency of a bioretention practice can also be estimated by adding a pollutant (e.g., sediment, phosphorus, etc.) to the synthetic stormwater, collecting effluent samples over time, and measuring the concentration of pollutant in the effluent samples.

Synthetic Runoff Testing – Filter Strips and Swales. Synthetic runoff testing is not recommended for typical filter strips or swales with a filter strip because these stormwater treatment practices typically lack inlet and outlet flow structures that allow for discharge measurement and pollutant sampling.

6.5 Maintenance Activities

Maintenance of bioretention practices can range from the relatively simple task of trash removal to more complicated tasks such as controlling invasive vegetation, removing sediment, and repairing and stabilizing eroded banks or deficient inlet or outlet structures. Less frequent maintenance may be required for dense and healthy vegetation. Guidelines for maintenance activities are provided in Tables A-7a through A-7d.

All maintenance activities need to be undertaken in a manner that does not lead to soil compaction. Compaction will reduce infiltration rates, limit root and plant growth, and could cause structural damage to an underlying drain tile system.

6.5.1 Maintenance Activities – Infiltration Basins and Rain Gardens

Infiltration basins and rain gardens can have an initial growing period of approximately three to five years before the vegetation becomes fully established. During that time, more frequent inspection may be warranted.

Infiltration basins and rain gardens can have an initial growing period of approximately three to five years before the vegetation becomes fully established. During that time, more frequent inspection may be warranted.

Bioretention practices require regular maintenance to remain effective. The required frequency of inspection and maintenance is dependent on the watershed land use (e.g., urban, rural, farm), construction in the watershed, and rainfall amounts and intensity. It is recommended, however, that visual inspection and any associated maintenance be performed at least once per year. Additional recommended maintenance may include annual inspection for sediment accumulation and removal. Hunt and Lord (2006) list maintenance requirements and corresponding frequencies for bioretention basins and rain gardens (Table 6-2).

Table 6-2: Maintenance requirements and frequencies for bioretention basins and rain gardens (modified from Hunt and Lord 2006).

Task	Frequency	Notes
Inspection and maintenance of pretreatment practices	Variable	Frequency and tasks depend on the pretreatment unit(s)
Pruning	1-2 times/year	Nutrients in runoff often cause bioretention vegetation to flourish
Mowing	2-12 times/year	Frequency is dependent on location and desired aesthetics
Mulching	1-2 times/year	--
Removal of mulch and top layer of soil	1 time every 2-3 years	Mulch accumulation reduces available water storage and decreases infiltration rates. The top layer usually is the cause of clogging and entire bioretention practices rarely need to be replaced.
Watering	1 time every 2-3 days for the first 1-2 months. As needed afterwards.	--
Fertilization	If necessary	One time spot fertilization
Remove and replace dead plants	1 time per year	Within the first year, 10% of plants die. Survival rates increase with time.
Miscellaneous upkeep	1 time per month	Weeding, trash collection, clearing overflow structures, etc.

If any level of assessment reveals that a bioretention practice is not adequately infiltrating runoff, the following steps should be taken.

1. Remove mulch, if present, and break up and/or remove the top layer of material.
2. If the previous step does not correct the situation, the entire practice may need to be replaced.

6.5.2 Maintenance Activities – Filter Strips and Swales

Filter strips and swales can retain suspended solids and reduce stormwater runoff volumes through infiltration. The required frequency of inspection and maintenance is dependent on the watershed land use (e.g., urban, rural, farm), construction practices in the watershed, and rainfall amounts and intensity. It is recommended, however, that visual inspection and any associated maintenance be performed at least once per year.

If infiltration rates or sediment retention rates of a filter strip or swale are unacceptable, the topsoil may have to be broken up and the surface reconstructed. Enhancing the health and density of vegetation can provide benefits by three mechanisms:

1. Decreasing water velocities to allow more time for infiltration,
2. Creating more flow paths (due to more roots) for the water to infiltrate into the soil,
3. Providing surfaces in the flow to enhance sedimentation.

Finally, decreasing the slope of a filter strip or swale, if possible, will slow velocities and allow for more sedimentation and more infiltration.

Landphair et al. (2000) stated that, other than typical mowing and trash pickup, maintenance requirements for roadside swales are minimal. However, immediate replacement of any dead, dying, or missing vegetation is imperative to prevent erosion and maintain infiltration.

6.6 Factors Affecting Performance

Factors that reduce the performance of and require maintenance for bioretention practices are typically sediment buildup, invasive vegetation, and trash. Table 6-3 lists factors most frequently causing deterioration in the performance of their bioretention practices according to responding municipalities.

Table 6-3: Percent of respondents who indicated the listed factor caused deterioration of bioretention practice performance (from Kang et al. 2008).

	Bioretention Basins and Rain Gardens	Filter Strips and Swales
Sediment Buildup	33%	21%
Trash	22%	26%
Pipe clogging	7%	5%
Invasive Vegetation	26%	26%
Bank Erosion	0%	11%
Groundwater level	7%	5%
Structural problems	0%	5%
Oil spill	4%	0%

6.7 Maintenance Costs of Bioretention Practices

The International Stormwater BMP Database (ISBD 2023) reports annual operating and maintenance costs for routine maintenance of stormwater management practices in 2018 dollars. The dollar amounts are based on actual costs entered into the database by users and are considered to be "ballpark" values. Bioretention (rain gardens) had a median value of $1960/year (range from $188/year to $9203/year) and grass strips (i.e., filter strips) had a median value of $1764/year ($245/year to $3416/year). No other maintenance cost information related to bioretention practices was reported.

6.8 Recommendations for Bioretention Practices

6.8.1 Assessment

Visual inspection and any associated maintenance should be performed at least once per year for all bioretention practices. If an assessment of runoff volume reduction potential or remaining sediment storage capacity is warranted, capacity testing is recommended; if the number of test locations is sufficient, this level of assessment provides accurate and location–specific data. Since capacity testing only assesses infiltration rates or volumes of retained sediment, synthetic runoff testing is recommended for bioretention practices when pollutant retention assessment is desired and there is an adequate available water supply. If the available water supply is insufficient (either due to total volume or flow rate), then monitoring should be considered. For more information on monitoring see Gulliver et al. (2010) and Erickson et al. (2013).

6.8.2 Maintenance

Bioretention practices can be effective in reducing stormwater runoff volume while also retaining suspended solids (and pollutants attached to the solids) and dissolved pollutants. They do, however, require regular maintenance if they are to remain effective. The required frequency of inspection and maintenance is dependent on the watershed land use (e.g., urban, rural, farm), construction practices in the watershed, and rainfall amounts and intensity.

For all bioretention practices it is important to maintain the desired vegetation in a healthy state at appropriate densities, because their roots will keep soil pores open. For practices that infiltrate stormwater it may be necessary to periodically break up the soil surface or scrape/remove the top layer to allow for or improve infiltration.

For all bioretention practices it is important to maintain the desired vegetation in a healthy state at appropriate densities, because their roots will keep soil pores open.

Chapter 7: Full-depth Permeable Pavement

7.1 Description

Full-depth permeable pavement is a pavement system that has several permeable layers. The bottom layer is usually the thickest, consisting of large (1-2 inch), angular gravel and used to temporarily store runoff until it either infiltrates into the existing subgrade or is conveyed out of the system through an overflow drain tile. The surface layer can be asphalt, concrete, concrete pavers (i.e., blocks), or permeable articulated concrete blocks (PACB). The first three are called porous asphalt, pervious concrete, and permeable interlocking concrete pavers (PICP), respectively. The design life of each permeable pavement type is 20-30 years (MPCA 2023). Porous asphalt and pervious concrete layers are permeable. Interlocking concrete pavers themselves are not permeable, rather water infiltrates into and through sand-filled spaces between the pavers. PACB, like PICP, are not permeable and the spaces between the blocks are left open rather than being filled with sand.

Another type of permeable pavement system, called open graded friction course or permeable friction course, is not included in this manual. This system consists of a layer of permeable pavement (typically asphalt) placed on top of a non-permeable, conventional pavement system. Water does not infiltrate down into a gravel storage reservoir or into the existing subgrade. Rather, it infiltrates into the top permeable layer and then moves laterally until it is discharged through the edge of the pavement.

Full-depth permeable pavements (referred to as permeable pavements from this point forward) reduce runoff volume through infiltration into the existing subgrade and can improve water quality but must have regular maintenance to remain effective. Also, due to the high air voids in the top layer, full depth porous asphalt and pervious concrete is typically weaker than conventional pavements. Thus, it is not recommended for heavy traffic loads or for use on high volume roadways. It can be used, however, in other applications such as sidewalks, low volume roads, highway shoulders, and parking lots.

Water quality is improved via filtration through the various permeable layers, with some pavement systems including a sand layer between the top pavement layer and the gravel reservoir solely to enhance filtration. Water quality can also be improved through settling of solids in the gravel reservoir and through microbial action.

Stormwater in a permeable pavement system may infiltrate into the existing soil and become groundwater, or it may be collected by a drain tile overflow system and be transported downstream in the conveyance system. The overflow drain tile is usually located some distance above the bottom of the gravel reservoir and is only needed to pass flows for storms larger than the design storm. Permeable pavement systems should be fully drained within 48 hours of a runoff event.

Although initial installation and construction costs are typically higher for permeable pavements, life cycle cost savings can be realized when considering the positive water quality impacts of permeable pavement and that, in some cases, the need for other stormwater management practices, such as basins (detention, retention, or infiltration), curbs, catch basins, and pipes, is reduced or eliminated (ASCE 2015, Izevbekhai and Schroeder 2017).

7.2 Types of Permeable Pavement

7.2.1 Pervious Concrete

In a pervious concrete system, the concrete layer is typically five to eight inches thick and there is no bedding layer. Variations in colors and textures are available. The pervious concrete layer is usually cast in place with a seven-day cure period in which the layer must be continuously covered. Pre-cast pervious concrete squares that can be placed on top of the pavement structure are, however, commercially available. The pre-cast option has the advantage that all concrete is cured equally and under controlled conditions.

Design guidance is available from the American Concrete Paving Association (ACPA 2009), ASCE (2015), and ACPA developed software, PerviousPave (2023).

7.2.2 Porous Asphalt

The top porous asphalt layer is typically three to four inches thick (but thicker pavement may be necessary for higher wheel loads) and is placed on top of a bedding layer of AASHTO No. 57 stone. The asphalt is cast in place with a 24-hour cure period. Colors range from dark grey to black. Design guidance is available from the National Asphalt Paving Association (NAPA 2008) and ASCE (2015).

7.2.3 Permeable Interlocking Concrete Pavements (PICP)

Permeable interlocking concrete pavers are approximately three inches thick and are manually or mechanically placed on top of a two-inch thick bedding layer of AASTHO No. 8 stone. No curing period is necessary. The pavers themselves are not permeable. Rather, sand-filled spaces between the pavers allow runoff to infiltrate into the underlying gravel reservoir. Some paving blocks are hollow, which allows for gravel or other media to be placed in the middle of the block. In some cases, this opening is used to grow vegetation. Hollow paving blocks allow for infiltration in the spaces between the blocks and in the middle, hollow portion of the block. A range of colors, textures, and patterns is available. Design guidance is available from Smith (2017) and ASCE (2015).

7.2.4 Permeable Articulated Concrete Blocks (PACB)

Permeable articulated concrete blocks are prefabricated, individual concrete blocks that can be used as a top pavement layer in a permeable pavement system. The blocks are typically much larger than PICP blocks and can be bound together into mats by nylon (or other material) rope. The mats allow for many blocks to be placed at one time by heavy machinery. A major difference between PACB and PICP is that the space between PACB is not filled with sand or any other material. This allows for higher rates of infiltration. It also makes maintenance easier because, unlike PICP, there is no gap material to replace after the pavement layer is vacuumed for maintenance. PACBs are available in a range of colors and patterns. Design assistance is usually provided by the manufacturer.

7.3 Benefits and Limitations of Permeable Pavement

7.3.1 Benefits

Space Savings. Permeable pavements can be used in dense urban areas that typically do not have space for other stormwater management practices such as ponds and bioretention practices.

Reduce Pollutant Concentrations and Loads. As the runoff filters downward through the permeable layers of the pavement system, contaminants are retained by physical filtration and by other means, thereby reducing contaminant concentrations. Through physical filtration, permeable pavements can retain solids and particulate forms of other pollutants that are attached to solid particles, such as phosphorus and metals. Although permeable pavements are less effective in reducing dissolved pollutants, biological activity may also reduce nitrogen and oil concentrations. Furthermore, infiltration into the existing subgrade provides additional water quality benefits by reducing pollutant mass loads conveyed downstream. Finally, because stormwater is stored below the surface and out of direct sunlight, permeable pavements also reduce runoff temperatures, especially compared to ponds, bioretention basins, and other practices that allow water to be heated by sunlight.

Peak Flow Reduction. Because permeable pavements temporarily store stormwater, they can reduce peak runoff flow rates for their catchment.

Volume Reduction. Permeable pavements store stormwater in an underground gravel reservoir and allow it to infiltrate into the existing subgrade thereby reducing the volume of runoff. Runoff volume reduction is not limited to well-draining soil subgrades. Drake (2013) found that permeable pavements installed over clayey soils that had underdrains with valves to restrict outflow reduced annual runoff volumes by 43%.

> ***Permeable pavements installed over clayey soils that had underdrains with valves to restrict outflow reduced annual runoff volumes by 43%.***

Reduced Winter Salt Load. Salt application is not recommended for pervious concrete because it can deteriorate the concrete, but salt can be applied to other permeable pavement types, often at a lower rate. The main reason is that snow and ice melted by the salt infiltrates into the pavement system and is removed from the surface. The salt, however, also infiltrates. Thus, more frequent salt applications may be necessary, and this can offset the benefit of low salt loading rates. NAPA (2008) states that, overall, porous asphalt can reduce the amount of salt needed for winter maintenance to a value between zero and 25% of what is typically required.

7.3.2 Limitations

Pavement strength. Due to the high void volume of the surface layer, porous asphalt and pervious concrete are not recommended for the driving lanes of high traffic volume roads or for applications that are subject to heavy wheel loads. Permeable pavement shoulders, however, have been found to be feasible and may be more cost-effective than other BMPs (Chai et al. 2012, Hein et al. 2013a).

Clogging. Permeable pavement systems are susceptible to clogging. To maintain sufficient infiltration rates, regular maintenance is required.

Maintenance. Permeable pavement systems require more maintenance than conventional pavement systems. Maintenance typically involves power washing and/or vacuuming. PICP has an additional inconvenience in that, upon vacuuming, the sand that fills the space between pavers must be replaced.

7.4 Maintenance Costs of Permeable Pavements

The International Stormwater BMP Database (ISBD 2023) reports annual operating and maintenance costs for routine maintenance of stormwater management practices in 2018 dollars. The dollar amounts are based on actual costs entered into the database by users and are considered to be "ballpark" values. Permeable pavements had a median value of $498 (range from $234 to $793) based on four reported values. No other maintenance cost information related to permeable pavements was reported, including the size and/or area of the practices.

7.5 Assessment Activities – Full Depth Permeable Pavement

Because permeable pavement systems physically strain solids from stormwater runoff, clogging occurs. Proper maintenance can partially restore infiltration rates, but rates should not be expected to return them to their original levels. Even in a properly maintained permeable pavement system, surface infiltration rates will gradually decrease over time. Surface infiltration rates of a properly constructed permeable pavement, however, are initially so high that this gradual decrease should not impact the performance of the system over its design life. This is because infiltration into the existing subgrade is usually the rate limiting step.

The exact procedure for using visual inspection to assess permeable pavements depends on the type of permeable pavement. If the pavement is a vegetated permeable pavement (i.e., hollow PICP with vegetation in the middle), then the approaches used for other vegetated stormwater treatment practices can be applied. Some indicators of inadequate infiltration capacity include dead or unhealthy vegetation during the growing season, standing water, or saturated surface soil for hours following a significant runoff event.

More involved observations include examining the soil profile for signs of persistent wet conditions in the surface soil or shallow subsurface soil. Such wet conditions indicate poor drainage conditions, which mean that infiltration capacities are lower than designed. Signs of persistent wet conditions in the soil are discoloration of the soil to a grayish tone and soil mottling. Mottling is an indication of anaerobic conditions resulting from persistent saturated or wet conditions.

For asphalt or concrete permeable pavements, indicators of poor infiltration performance are persistent standing water on the pavements following rainfall or evidence of sediment deposition on the surface.

For permeable pavement to function properly it must be well maintained. To know when maintenance is necessary, the pavement must be regularly assessed. Assessment activities corresponding to full-depth permeable pavement systems are described below.

7.5.1 Visual inspection

The MPCA (2023) provides guidance on visual inspection of permeable pavements and lists the following items as inspection points:

- The drawdown rate of water in the gravel reservoir should be measured at the observation well for three days following a storm event more than 1/2 inch in depth. If standing water is still observed in the well after two days, this is a clear sign that the system is not performing as desired and subgrade soil clogging is a problem.
- Inspect the surface for evidence of sediment deposition, organic debris, water staining, or ponding that may indicate surface clogging.
- Check inlets, pretreatment cells and any flow diversion structures for sediment buildup and structural damage.
- Inspect any contributing drainage areas for controllable sources of sediment or erosion.
- Inspect the condition of the observation well and make sure it is capped.
- Inspect the structural integrity of the pavement surface, looking for signs of surface deterioration, such as slumping, cracking, spalling, or broken pavers.

Guidance for visual inspection of permeable pavements is provided in Table A-8.

7.5.2 Capacity testing for Permeable Pavements

Capacity testing can be used to assess infiltration rates of permeable pavement systems. The American Society for Testing and Materials method, C 1701, should be used. The method results in an infiltration rate with units of length per time (e.g., in/hr) but the value only applies to the exact location and area tested. If the testing apparatus is moved, even slightly, significantly different values may be obtained.

Any areas of the pavement surface that were noted to have sediment deposition, organic debris, or in any other way appear clogged should be tested using the ASTM method. Other areas on the pavement surface should also be tested and their exact location recorded.

If the exact same location is tested before and after maintenance is performed, the results can be used to determine the effectiveness of the maintenance. Also, if locations are tested over time, the rate of clogging can be estimated, and future maintenance can be anticipated and scheduled/budgeted for accordingly.

7.5.3 Synthetic Runoff Testing of Permeable Pavements

Synthetic runoff testing can be used to determine the drain time of a permeable pavement gravel reservoir as well as the infiltration capacity (i.e., saturated hydraulic conductivity) of the surface layer of permeable pavement. Two different methods of synthetic runoff testing to determine the infiltration capacity (i.e., saturated hydraulic conductivity) of the permeable surface layer are available. The preferred method depends on whether water can be stored on the pavement surface with curbs or some other boundary.

If water can be stored on the surface of the permeable pavement at a depth of six inches or more and for a length of time necessary to measure the infiltration (> 1 minute), an external water source (e.g., fire hydrant or water truck) should be used to cover the pavement with six to 12 inches of water. In many cases, the pavement surface will be planar and sloped on a uniform grade, so curbs or some form of berm around the boundaries of the pavement will be required to store water at this depth. Knowing the thickness of the top layer of permeable pavement and the rate of drop of the infiltrating ponded water, it is possible to compute the saturated hydraulic conductivity of the surface layer using methods detailed in Gulliver et al. (2010) and Erickson et al. (2013).

Alternatively, if water cannot be stored on the surface of the permeable pavement by curbs or other boundaries, water can be applied at a metered rate through a sprinkler onto a specified area of the pavement surface. The sprinkler may be simply a hand-held device, or it may be held in a frame structure. The idea behind the water applicator is to determine the rate of application that causes runoff to occur in the application area. The flow rate through the applicator is increased to the point where runoff just begins to occur. The runoff will be evident by water flowing over the surface to the side of the application area. At the rate of application where runoff starts to occur, the flow rate should be reduced again until runoff stops. The infiltration capacity is, then, just the flow rate of water application divided by the application area.

The drain time for the gravel reservoir can also be determined using synthetic runoff testing if an external water supply can fill the reservoir to its design depth in a relatively short time (i.e., less than a few hours) and observation wells are available to monitor the water depth in the reservoir. If these conditions exist, the time required to drain the design depth can simply be observed and recorded. Additionally, the saturated hydraulic conductivity of the existing subgrade can be estimated using methods discussed in Chapter 4.

7.6 Maintenance Activities

In addition to proper construction methods, regular and proper maintenance is key to the long-term performance of a permeable pavement system. The most frequently cited issue impacting performance is surface clogging caused by organic matter and sediment. Power washing and/or vacuum sweeping are the two most recommended routine maintenance activities (Golroo and Tighe 2012b, Drake 2013) along with preventing sediment from adjacent areas from washing onto the pavement (Chai et al. 2012). Combinations of pressure washing and vacuum sweeping may also be used (Drake 2013, Hein et al. 2013b) and may be more

In addition to proper construction methods, regular and proper maintenance is key to the long-term performance of a permeable pavement system.

effective than a single maintenance method. Any solids removed during maintenance activities must be disposed of as required by all governing regulations.

Recommended frequency of maintenance ranges from at least annually (Drake 2013) to two to four times per year (Landphair et al. 2000, NJDEP 2004, Gunderson 2008). Actual required frequency for each permeable pavement system will vary depending on watershed characteristics such as tree cover, surrounding land uses, watershed area draining onto the pavement system, among other variables. Maintenance activities and considerations are discussed below.

Pressure washing – Pressure washing may push particles further into the pavement (Chopra et al. 2010, Henderson and Tighe 2012). To minimize this effect, pressure washing should be performed with the water striking the pavement surface at an angle less than 45 degrees above horizontal.

Periodic Vacuuming – The pavement surface is the first line of defense in trapping and eliminating sediment that may otherwise enter the stone base and soil subgrade. The rate of sediment deposition should be monitored and vacuumed with a regenerative air sweeper (Weiss et al. 2015) done at least two times per year. When vacuuming, mechanical brushes should not be used as they tend to push particles further into the pavement structure.

Salt and Sand – Minimize salt or sand for de-icing and traction in the winter and keep the landscaping areas well maintained to prevent soil from being washed onto the pavement.

Maintenance Agreements – Maintenance agreements should note which conventional parking lot maintenance tasks to avoid (e.g., sanding, re-sealing, re-surfacing, power-washing). Signs should be posted on parking lots to indicate their stormwater function and special maintenance requirements. When permeable pavements are installed on private residential or commercial property, owners must understand routine maintenance requirements. These requirements can be enforced via a deed restriction, drainage easement, maintenance agreement, performance bond, letter of credit or other mechanism enforceable by the local authority to help ensure that the permeable pavement is maintained and continues functioning.

When the maintenance activities discussed above fail to restore the infiltration performance of the pavement to acceptable levels, other, less frequent, maintenance activities may be warranted. These include drilling holes in the pavement surface to restore some capacity (Landphair et al. 2000) or milling porous asphalt (Winston et al. 2016), possibly with a new overlay of porous asphalt. If these actions fail to restore adequate surface infiltration, the entire surface or system may need to be replaced.

If areas of the surface pavement in porous asphalt or pervious concrete pavements show signs of deterioration or spalling, the porous pavement may be replaced with patches of conventional pavement (PDEP 2006, UDFCD 2010). Typically, the surrounding permeable pavement surface can compensate for a small loss in pervious area.

Recommended maintenance activities and frequencies for pervious concrete systems (modified from ACPA 2009 and ACI 2010) are given in Table 7-1. Although these guidelines are for pervious concrete pavements, they can be applied to other types of permeable pavement. Guidelines for maintenance activities are provided in Table A-8.

Table 7-1: Recommended maintenance activities and frequencies for pervious concrete

Activity	Frequency ACPA 2009	Frequency ACI 2010
Ensure that the pavement area is clean of sediment and debris	As needed	Monthly
Ensure that the pavement dewaters between storms	As needed	--
Mow upland and adjacent areas, and seed bare areas	As needed	As needed
Vacuum/sweep the pavement surface to keep it free of sediment	As needed	As needed
Inspect the surface for deterioration or spalling	Annually	Annually

7.7 Factors Affecting Performance

Keys to a successful permeable pavement installation include proper design, construction by a knowledgeable and experienced contractor, and maintenance (Weiss et al. 2015). Regarding maintenance, survey results (Kang et al. 2008) indicate that a majority of responding municipalities inspect their permeable pavements once a year or more. It is recommended, however, to conduct regular and frequent inspections. Detailed survey results on inspection frequency are given in Table 7-2.

Table 7-2: Percent of respondents who indicated the listed factor caused deterioration of permeable pavement performance (from Kang et al. 2008).

Factor	Response Rate
Sediment Buildup	67%
Trash	11%
Pipe clogging	11%
Invasive Vegetation	0%
Bank Erosion	0%
Groundwater level	7%
Structural problems	0%
Oil spill	11%
Mechanical problems	0%

7.8 Recommendations for Full depth permeable pavement

7.8.1 Assessment

Permeable pavements must be regularly inspected to ensure proper functioning. Required frequency of inspection is dependent on the watershed land use (e.g., urban, rural, farm) and rainfall amounts and intensity. However, it is recommended that visual inspection be performed a minimum of once per year.

Perform capacity testing to determine infiltration capacity at spot locations on the pavement surface using ASTM C 1701. Synthetic runoff testing can be used, if an adequate water supply is available, to determine the overall operation of a permeable pavement system (both overall surface infiltration and draw down of the internal gravel reservoir). For more information on assessment see Gulliver et al. (2010) and Erickson et al. (2013).

7.8.2 Maintenance

The required frequency of maintenance for permeable pavement systems is dependent on the watershed land use (e.g., urban, rural, farm), construction practices in the watershed, and rainfall amounts and intensity. To increase the longevity of permeable pavement, install pretreatment stormwater practices that remove large sediment and other solids upstream of the system and/or minimize runoff onto the pavement.

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Chapter 8: Stormwater Harvesting

8.1 Description

Stormwater harvesting, or stormwater reuse, involves the collection, treatment, and storage of stormwater runoff for an intended future use. Storage may occur in constructed vaults or in groundwater aquifers. To meet increased water demand amidst diminishing supplies, focus has turned to stormwater harvesting as a tool to help alleviate stresses on water supply systems.

Stormwater harvesting and reuse can ease demands on potable water supplies. Depending on the intended end use, harvested water can either be treated to potable standards or it can be treated to lower standards and used in non-potable applications such as groundwater recharge, irrigation, or recreation. In almost all situations, however, treatment to some extent is required. The extent of treatment depends mostly on the initial harvested water quality and intended use. Conventional stormwater management practices can be part of the treatment train but, even though these provide some level of water quality improvement, additional treatment is usually required before water is reused. The cost of stormwater harvesting is highly variable and dependent on size of the system, water quality, and intended use, among other variables. Literature has reported that, in some cases, harvested stormwater is much less expensive than the conventional potable water supplies (UF 2008), but in other cases it is much more expensive (Hatt et al. 2006). Similarly, the payback time on the capital costs of a harvesting system is estimated to be as low as three years to over 900 years (Hatt et al. 2006).

In almost all situations, however, treatment to some extent is required. The extent of treatment depends mostly on the initial harvested water quality and intended use.

Smart ponds (or real time control systems), which integrate weather forecasts into the operation of the harvesting system, can improve the performance of stormwater harvesting systems with respect to both volume of stormwater harvested and water quality treatment. The impact, however, is limited and may not increase the volume of available reuse water without additional components such as widespread use of SCMs throughout the watershed and large basins to promote infiltration for groundwater recharge (Parker et al. 2022).

Given the large variability in stormwater runoff quality, governing regulations, watershed characteristics, costs, and other features, each stormwater harvesting system must be considered and analyzed on a site-specific basis. Guidelines and procedures exist to help with the planning and design process. Typical steps are similar to those provided by the Minnesota Stormwater Manual (MPCA 2023), which include feasibility, pre-design, design, and implementation.

8.2 Benefits and Limitations of Stormwater Harvesting

8.2.1 Benefits

Reduce Stress on a Water Supply System. Stormwater runoff is a valuable resource that is often allowed to flow out of a watershed. Yet stresses on water supply systems mount due to limited supply and increasing demand. Harvested stormwater can be used in some applications as an alternative source to conventional water supply systems. This can alleviate some of the stress on a water supply system.

8.2.2 Limitations

Goonetilleke et al. (2017) listed the following potential limitations:

Variability. Rainfall is seasonal and variable and, therefore, unreliable.

Cost. It may be cost-prohibitive to construct a rain harvesting system, especially if groundwater storage is not available.

Treatment. Regardless of the intended use, harvested stormwater requires some level of treatment.

Available Technology. Current technology for water treatment may lack flexibility for treating stormwater.

Psychological and Political Barriers. The public may have psychological barriers to reusing stormwater and these may become political barriers. Other political barriers, such as lobbying efforts against rainwater harvesting and subsidies for other technologies, may exist.

Fletcher et al. (2008) cites other limitations such as inadequate guidance on risks, inadequate information on lifecycle costs, and the impact on secondary aspects (such as a reduced need for downstream stormwater management), lack of information on tradeoffs related to water–energy (such as that required for pumping and treatment), and limited data on environmental benefits.

8.3 Assessment and Maintenance Activities – Stormwater Harvesting

Due to the variability in stormwater harvesting systems, visual inspection must be performed on a site-specific basis. Capacity testing may be applicable to a harvesting system that incorporates one or more stormwater management practices. For example, a stormwater harvesting system may rely on infiltration to capture stormwater. See the corresponding chapter for more information on capacity testing for such components.

Maintenance activities will also vary on a site-specific basis and, like capacity testing, may involve activities that correspond to other stormwater management practices covered in this manual.

8.4 Minnesota Case Studies

The following case studies are adapted from those in the Minnesota Stormwater Manual (MPCA 2023, *Link Here*)

8.4.1 Stormwater Harvesting at Cottage Grove City Hall

In 2012 the City of Cottage Grove completed construction of the new City Hall and Public Safety complex, designed by Wold Architects. The building is situated in a growing part of the community, directly adjacent to Cottage Grove Ravine Regional Park, a natural resource and recreation amenity area which features unique habitat and a beloved fishing lake. In an effort to reduce water use and impacts on stormwater runoff, the building design incorporates a stormwater harvester system. The harvester reuses stormwater collected from the building's roof (Figure 8-1) for irrigation of the green space around the building and the Veterans Memorial fountain located at the building entrance. This system collects runoff from the 0.9-acre roof and stores it in an underground storage tank (Figure 8-2). From the storage tank, the water is filtered and treated with ultraviolet light then pumped through the irrigation system for use on the 7-acre City Hall grounds, and at the fountain. The purpose of the system is to provide the dual benefits of reducing the use of groundwater for landscape irrigation and minimizing stormwater runoff to Ravine Lake.

- **Total Drainage Area**: 0.9 acres of rooftop
- **Total Construction Cost**: $120,000
- **Pretreatment/Methods of Filtration**: Rainwater filter (screen to remove large particles leaves, debris, and sediment), Fine filter (filter fine particles, down to 5 microns), UV Treatment (provides microbial disinfection)
- **Documented Maintenance Practices**: Replacement of filter media and UV bulbs as needed, general winterization of irrigation system.
- **Pollutant Removal**: Runoff volume control = approximately 1.8 acre-feet (570,000 gallons) per year. MIDS calculator estimates pollutant reductions of approximately 1.5 pounds of phosphorus (0.85 pounds particulate phosphorus and 0.70 pounds dissolved phosphorus), and 282 pounds total suspended solids per year.
- **Special Design Features**: Rainwater Harvester Control Panel to regulate operation of systems, Irrigate planting beds on 7-acre site, education signage about system.

Figure 8-1: Photo of Cottage Grove City Hall building. Photo: Emmons and Olivier Resources.

Figure 8-2: Photo of tank for harvest and use system. Photo: City of Cottage Grove.

8.4.2 Stormwater Harvesting at Eagle Valley and Prestwick Golf Club, Woodbury

In 2014, the City of Woodbury, with funding from the South Washington Watershed District, constructed stormwater reuse for irrigation systems at Eagle Valley and Prestwick golf clubs. Previously, Eagle Valley Golf Course pumped 30 million gallons of well water annually to irrigate approximately 60 acres of golf course turf and landscaping. The reuse for irrigation project collects stormwater runoff from a 430-acre drainage area covering the golf course, surrounding neighborhoods, and Woodbury Drive into a storage pond on the course. Prestwick golf club regularly irrigates up to 75 acres of turf and landscaping. Previously, course managers pumped 35 million gallons of water annually from a course well to accomplish this. The stormwater reuse system can now supply approximately 17.5 million gallons of water from the storage pond annually.

Each system collects runoff from a large drainage area containing roads, housing developments, and a golf course and stores it in a centralized pond (Figure 8-3). A pump then draws water from the pond for use in golf course irrigation (Figure 8-4). The catalyst for the projects was the planned reconstruction of CSAH 19 (Woodbury Drive), changing it from a rural 2-lane road to an urban 4-lane road. The goals were to have no measurable downstream stormwater impacts from the road reconstruction project, with 99 lbs phosphorus removal per year, and 9.6 acre/ft per event volume reduction, and to help achieve Colby Lake's target TMDL standard to reduce phosphorus (TP) inputs by 30 lbs per year.

- **Total Drainage Area**: 430 acres (Eagle Valley), 130 acres (Prestwick)
- **Total Construction Cost**: $700,000 (funding from South Washington Watershed District/Clean Water Fund)
- **Pretreatment**: screen filter on intake pump
- **Documented Maintenance Practices**: winterize irrigation system each year, clean pump screen if it gets clogged (has not been needed during first three years of operation)

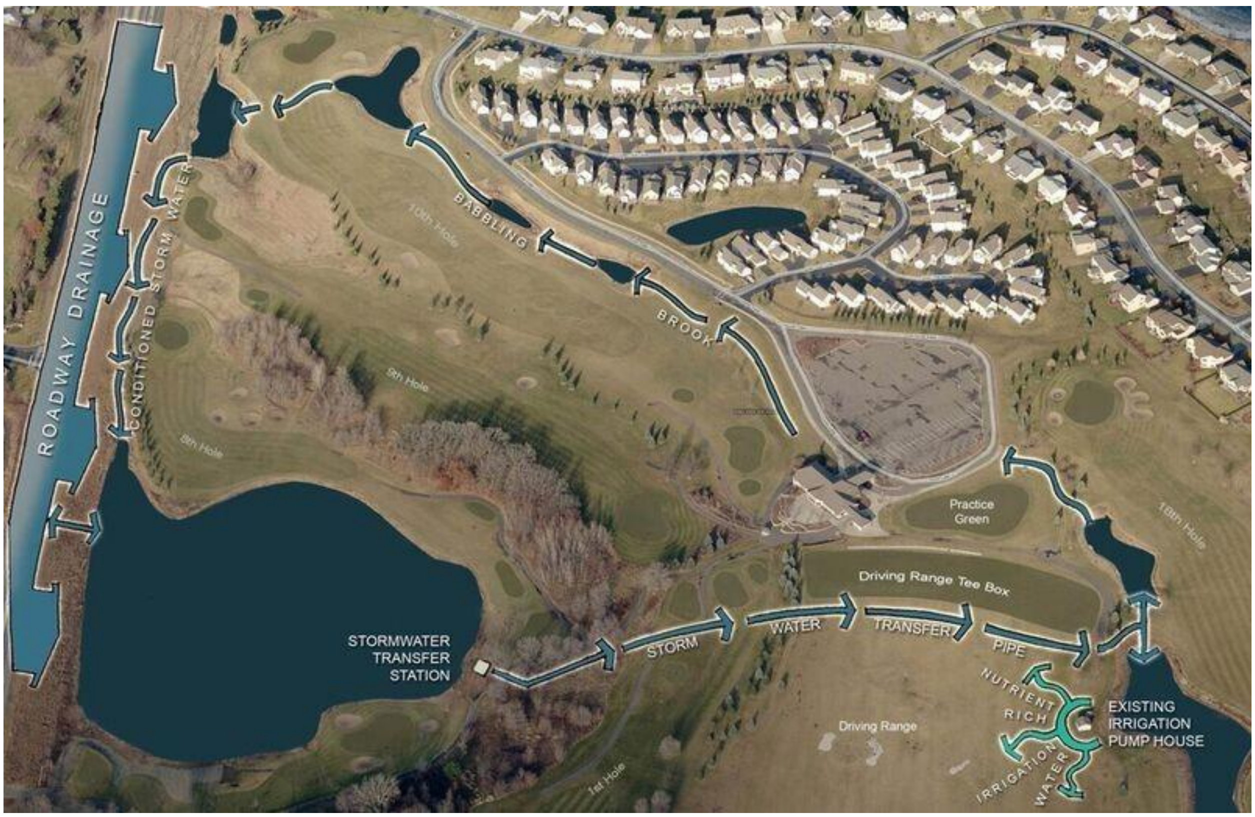

Figure 8-3: Plan for the harvest system showing storage and transport components. Photo: Emmons and Olivier Resources, HR Green, and Water in Motion.

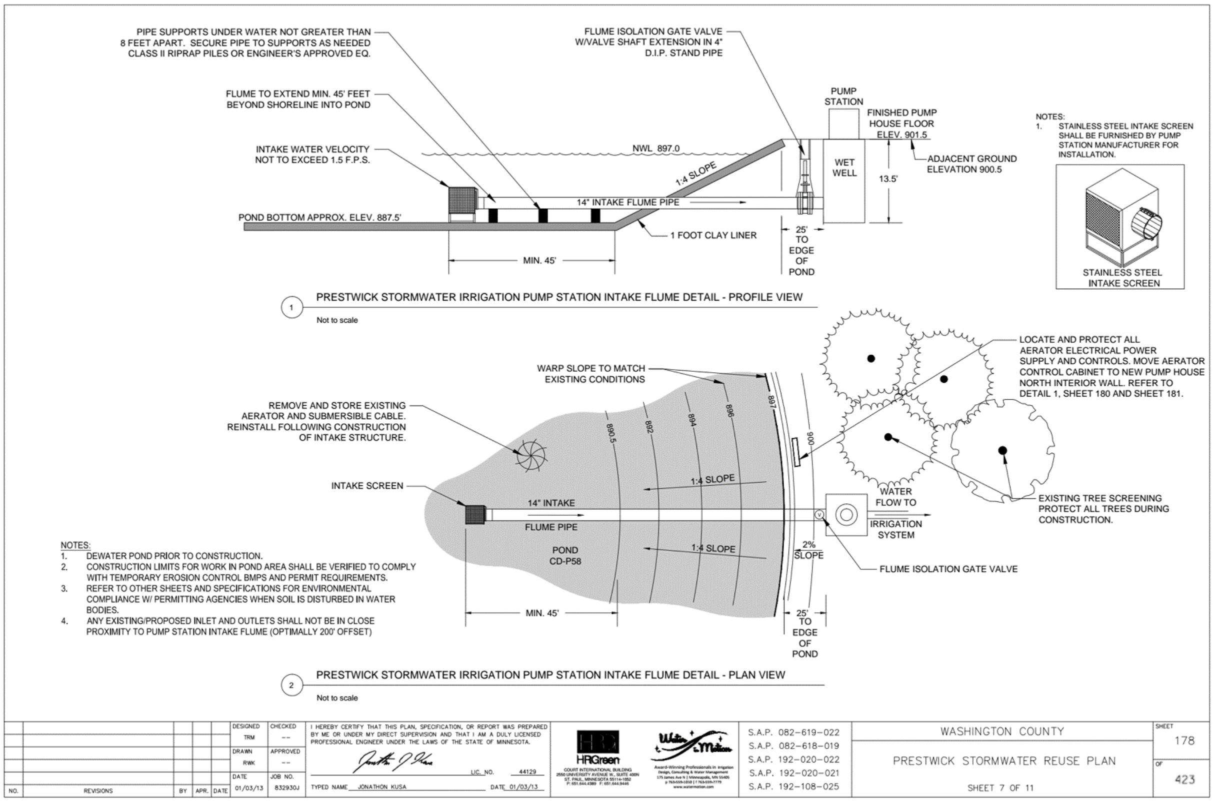

Figure 8-4: Irrigation pump station intake flume detail. Image: HR Green and Water in Motion.

8.4.3 Stormwater Harvesting at Carver County Harvest Estates Development

Club West Partners, the developer of Harvest Estates, worked with the Carver County Watershed Management Organization (CCWMO) to implement a stormwater harvest and use system that would meet stormwater, TP, and TSS reduction requirements (90% TSS and TP reduction, per CCWMO rules) for that sub-watershed. Completed in 2015, the harvest and use project utilizes stormwater runoff draining from Harvest Estates for irrigation of common areas within the development (Figures 8-5 and 8-6).

Stormwater is collected into three stormwater ponds. Two intake pumps draw stormwater from two of the three ponds to irrigate a central park and boulevard at the entrance of the development (Figure 8-7). By incorporating the harvest and use system into the construction of the new development, overall stormwater runoff impacts are partially mitigated and use of potable water for irrigation is reduced. Up to 22.2 million gallons of harvested stormwater can be used to irrigate the park and boulevards. The project goal is to harvest and use up to 12,500 cubic feet of stormwater per week, or equivalent to a depth of ½" of stormwater over the surface area of the new impervious paving in the development (18.8 acres total). The harvest and reuse system uses a 1.5-2.0 HP centrifugal stormwater pump, which is then transferred and managed through irrigation controller pedestals that allow for the efficient harvest and use of stormwater. The system reduces the need to pump irrigation water from conventional sources, with a bypass switch for municipal water only in cases of decreased rainfall. Harvested stormwater pumped from the two ponds goes through a filter system to remove sediment prior to irrigation uses. The modeled water quality benefits of the project are total phosphorus reductions up to 4.37 lb per year and TSS reductions up to 1,503 lb per year.

- **Project Designer**: Alliant Engineering
- **Total Drainage Area**:
  - Pond 1 = 28 acres
  - Pond 3 = 25 acres
- **Pond Size**:
  - Pond 1 = 18,600 sq ft
  - Pond 3 = 22,413 sq ft Irrigated area
  - Pond 1: 30,807 square feet
  - Pond 3: 42,267 square feet
- **Cost Savings Per Year**: $3,000 on irrigation water (compared to City potable water rates)
- **Pretreatment**: NURP pond and screen filter in intake pump
- **Methods of Filtration**: Filter Screens
- **Documented Maintenance Practices**: winterize irrigation system each year, clean clogged pump screen (annual startups and blow outs)

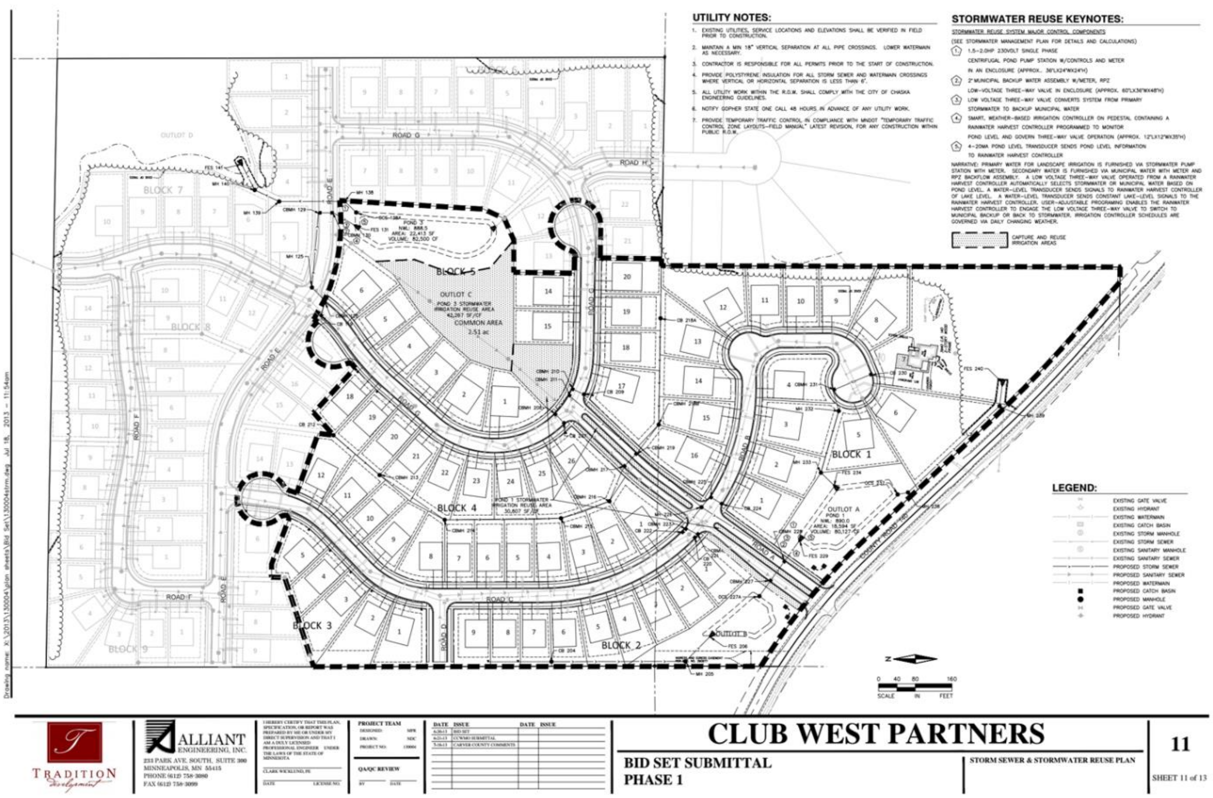

Figure 8-5: Carver County Club West storm sewer reuse plan. Image: Alliant Engineering.

Figure 8-6: Carver County stormwater harvesting site. Photo: DR Horton Homes.


Figure 8-7: Carver County irrigated area. Photo: Emmons and Olivier Resources.

Chapter 9: Meeting Stormwater Management Objectives

This chapter covers options for meeting specific stormwater management goals and how to best achieve desired goals and objectives. It is organized by the specific constituent to be treated, which is related to meeting Total Maximum Daily Load (TMDL) requirements. Maintenance considerations for each of the practices are described in the chapters relating to those practices.

9.1 Solids

9.1.1 Introduction

Stormwater runoff typically contains solid particles that are carried in the runoff. Solid particles increase water turbidity, prevent light from reaching aquatic vegetation, and can deposit on the floor of the water body, killing and preventing the reproduction of aquatic organisms and plants. A portion of some other pollutants, such as phosphorus and metals, attach to solid particles in stormwater runoff or are part of the solids, such as organic solids. Thus, solids are targeted for retention and/or removal in most stormwater management plans.

Solid particles in stormwater runoff can vary greatly in size from clay to sand or, in rare cases, even gravel. Practices that can retain solids include sedimentation-based practices (e.g., ponds and proprietary settling devices), filtration practices (e.g., filters, vegetative filter strips), and infiltration practices (e.g., bioretention, infiltration basins, vegetated swales).

Because a stormwater treatment practice's ability to retain a solid particle depends on the size of the particle, it is important to know the particle size distribution of solids in runoff. This varies with the size and intensity of the storm but, if known, will allow for reasonable expectations to be set regarding what fraction of the total solids load can be expected to be retained by the practice. For example, if the particle size distribution consists of mostly clays, a wet or dry pond should not be expected to retain a significant fraction of solids. The particle size distributions from several studies are given in Figure 9-1.

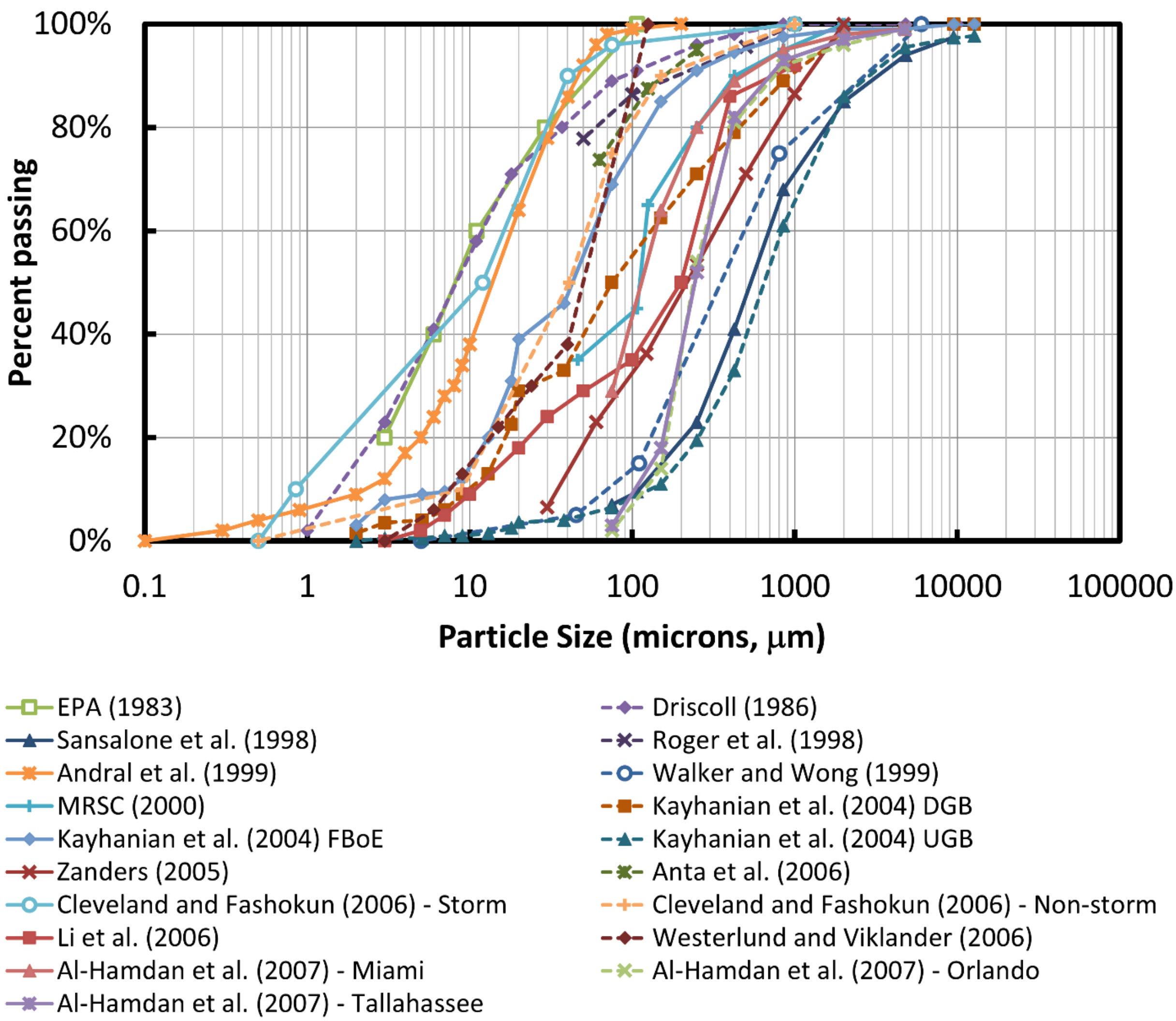

Figure 9-1: Particle size distributions from a variety of studies, indicating the wide range of possible particle size distributions. Image: Andy Erickson

9.1.2 Sedimentation Practices

Practices that incorporate sedimentation (i.e., settling, gravity separation) such as ponds will retain a fraction of the solids in stormwater runoff. The extent of retention depends on many variables, such as the hydraulic residence time of the practice, depth of the practice, the particle size distribution and composition of the solids in the runoff, and maintenance received by the practice, among others.

A conventional sedimentation-based stormwater practice will not retain a large fraction of particles in the clay and silt size range because their settling velocity is too small compared to the size of the basin. Typical proprietary sedimentation practices will not retain many solids smaller than fine sand (about 100 microns). Thus, it is important to know the particle size distribution of solids in runoff to ascertain what fraction of solids the practice can retain. If a large fraction of the solids are clays and silts, for example, a sedimentation practice cannot be expected to retain a significant fraction of the solids. More details on estimating retention by sedimentation-based practices can be found in Erickson et al. (2013).

A conventional sedimentation-based stormwater practice will not retain a large fraction of particles in the clay and silt size range because their settling velocity is too small compared to the size of the basin.

Research suggests that floating treatment wetlands (FTW), which consist of vegetation floating in a wet pond with roots dangling in the water, can retain smaller particles than other practices. The roots, which naturally grow a biofilm, can retain small solids that adhere to the biofilm. Thus, solids retention, especially for small solids, may be enhanced in wet ponds by installing FTWs.

9.1.3 Filtration Practices

Filtration practices typically retain smaller particles than sedimentation-based practices such as wet or dry ponds. Particles retained by a typical, 18-inch-thick stormwater sand filter can be as small as 6 to 40 microns (FHWA 2023). Thus, a sand filter can retain a larger fraction of the solid particles compared to a sedimentation-based practice. The particle size distribution of solids in the runoff is again important because it determines the fraction of sediment retained by a sand filter. One drawback is that filters require substantially more maintenance than most sedimentation practices.

9.1.4 Infiltration Practices (including bioretention)

When runoff infiltrates within a stormwater treatment practice, some particles will be retained on the floor of the practice and other particles will be retained (i.e., physically strained) by the soil media under the ground surface. Thus, even during a runoff event that exceeds the capacity of the infiltration practice and bypasses or overflows the practice, the solid mass load of the runoff event will be reduced.

9.1.5 Bioretention Practices

Bioretention practices such as rain gardens, vegetative filter strips, and vegetative swales can retain solid particles through sedimentation and filtering by the media and vegetation. For filter strips and swales, design recommendations typically limit water velocity and depth. Water velocities that are too large will keep solids in suspension, cause erosion, and allow a large portion of the flow to pass over the vegetation without receiving treatment.

9.2 Phosphorus

Phosphorus in stormwater is in either particulate or dissolved form. Particulate phosphorus is, by definition, filtered by a 0.45-micron filter. Any phosphorus that passes through a 0.45-micron filter is classified as dissolved. Dissolved phosphorus is composed of phosphate (soluble reactive phosphorus) and colloidal phosphorus, which is associated with particles smaller than 0.45 microns. Dissolved phosphorus is stated to be more than 90% bioavailable, while particulate forms are typically less than 25% bioavailable (MPCA, 2023). Therefore, dissolved phosphorus is more responsible for the algae blooms and plant growth that lead to eutrophication. Phosphorus associated with particulates must be degraded or released as phosphate before it becomes bioavailable.

Typically, 40 to 45% of the phosphorus in stormwater is in dissolved form, with the remaining fraction being particulate. The fraction of the phosphorus load that is dissolved, however, depends on many variables and can range from near zero to near 100% (Erickson et al., 2007). Because a fraction of dissolved phosphorus in stormwater attaches to solid particles, any stormwater management practice that retains solids will retain a fraction of the particulate phosphorus load. Dissolved phosphorus cannot be removed along with solids, however, and must be removed by other means, such as chemical precipitation or chemical adsorption. Infiltration may reduce dissolved phosphorus as well.

9.2.1 Sedimentation Practices

Because phosphorus attaches to solid particles or is contained in solid particles in runoff, any practice that retains solids will also retain some phosphorus. Thus, sedimentation-based practices (e.g., dry ponds, wet ponds) can retain a fraction of the phosphorus load. A typical sedimentation-based practice will retain little of the dissolved phosphorus load. However, vegetation (e.g., algae, duckweed) in a pond can convert phosphate into organic, particulate phosphorus.

Because phosphorus attaches to solid particles or is contained in solid particles in runoff, any practice that retains solids will also retain some phosphorus.

Practices with particulate-bound phosphorus retained in the settled sediment must not be subject to anaerobic conditions in the overlying water or the sediment may release phosphate from microbially degraded solids. If this happens, the practice may export phosphorus. Studies have shown that stormwater ponds as shallow as three feet deep may become anaerobic and release phosphorus (Taguchi et al. 2020). Key factors include age of the practice, wind sheltering by trees or buildings that prevent mixing of the water column, chloride concentrations in the water, which can increase water density and prevent mixing, and heating of the surface water, which can also prevent mixing. Without mixing, water near the sediment may not receive oxygen

Stormwater ponds as shallow as three feet deep may become anaerobic and release phosphorus.

from the surface. As microbes in the sediment use the oxygen in the water near the sediment, the water in contact with the sediment may turn anaerobic and release phosphorus.

9.2.2 Filtration Practices

Filtration practices will capture the particulate portion of phosphorus as described in Section 9.1. A conventional sand filter does little to retain dissolved phosphorus and should not be expected to do so. Amendments such as iron shavings, however, can be added to a sand filter media to retain dissolved phosphorus (Erickson et al. 2012). For more information, see the section on iron-enhanced sand filtration in Chapter 5. A properly maintained and functioning iron-enhanced sand filter can retain up to 80% of the dissolved phosphorus load.

9.2.3 Infiltration Practices (including bioretention)

When runoff infiltrates within a stormwater treatment practice, sediment can be captured on the floor of the practice and dissolved phosphorus will infiltrate into the existing soil with the water. Phosphorus that infiltrates can be broken down by microbial activity, taken up by roots of vegetation, or be retained on the soil particles, among other possibilities. Thus, phosphorus in infiltrated stormwater runoff is typically assumed to be removed from the conveyance system. Bioinfiltration (rain gardens, grasses swales, etc.) is especially effective for infiltration because the plant roots tend to keep the pores open allowing water to infiltrate. Practices with vegetation, compost, or other organic material, however, often export dissolved phosphorus as discussed below.

9.2.4 Biofiltration Practices (with underdrains)

Biofiltration practices, or any practice containing a significant amount of vegetation, compost, or other organic matter that also includes an underdrain should not be used to retain phosphorus, especially dissolved phosphorus. Organic matter typically contains phosphorus that will likely be released over time. Biofiltration media mixes often call for a fraction of compost in the mix, but compost has been shown to leach dissolved phosphorus (Erickson et al. 2022). If compost must be used, some have recommended using low phosphorus compost. Although plants may uptake phosphorus during the growing season and thereby reduce phosphorus, they will eventually die and release phosphorus upon decomposition. Thus, long-term phosphorus retention is difficult in biofiltration practices.

Biofiltration practices, or any practice containing a significant amount of vegetation, compost, or other organic matter that also includes an underdrain should not be used to retain phosphorus, especially dissolved phosphorus.

9.3 Nitrogen

Nitrogen in stormwater can be in the form of inorganic nitrogen or organic nitrogen. Inorganic nitrogen in stormwater runoff is in the form of ammonium, ammonia, nitrite, and nitrate, all of which are ions in solution that do not readily attach to solid particles. Thus, all inorganic nitrogen in stormwater is dissolved and therefore, removing solid particles from the water will not reduce inorganic nitrogen in the water.

To reduce the total inorganic nitrogen in stormwater runoff, the nitrogen must be retained (i.e., captured by some mechanism that holds it within the practice) or removed (i.e., transformed or removed from the practice). Retention can occur through 1) attachment to plant roots with possible assimilation into plant matter or 2) attachment to an engineered material or agent (such as activated carbon) that can bind some or all the forms of nitrogen. Removal of nitrogen can occur by 1) the physical removal of plant matter or a material/agent that previously retained nitrogen or 2) a two-step microbial process that ultimately converts dissolved nitrogen to nitrogen gas, which subsequently leaves the practice by escaping into the atmosphere. The first step of the microbial process, called nitrification, converts ammonia (NH_3^+) to nitrite (NO_2^-) and/or nitrate (NO_3^-) and occurs under aerobic conditions. The second step of the microbial process, called denitrification, converts nitrate to nitrogen gas (N_2) and only occurs under anaerobic conditions.

Organic nitrogen may be in the form of plant matter (e.g., grass clippings, leaves, etc.) or solid animal waste. The removal of organic nitrogen from stormwater can be achieved by floatation and skimming, filtration, or sedimentation (see Section 9.1). Because most of the effort targeting nitrogen retention or removal is geared toward inorganic nitrogen, which is more difficult to achieve, this section focuses on stormwater practices that can retain and/or remove inorganic nitrogen.

***Sedimentation practices* are not an efficient tool to reduce nitrogen in stormwater due to the slow diffusion rate in sediment media.**

***Standalone filtration practices* remove little to no inorganic nitrogen in stormwater.**

***Infiltration* of stormwater is an effective tool in removing nitrogen from surface stormwater, although the BMPs do not typically remove dissolved nitrogen from the water.**

9.3.1 Sedimentation Practices

Sedimentation practices are not an efficient tool to reduce nitrogen in stormwater due to the slow diffusion rate in sediment media. The anaerobic nature of the sediments in most sedimentation practices allows for conversion of nitrate and nitrite to nitrogen gas, which can be substantial (Morse et al. 2023). Diffusion from a sediment media is slow, however, so reduction of nitrate in the sedimentation practice may not be observed.

9.3.2 Filtration Practices

Standalone filtration practices remove little to no inorganic nitrogen in stormwater. Filtration practices with activated carbon amendments in the filter media can remove nitrogen, but the required frequency of media replacement to maintain retention capacity may make this practice cost-prohibitive (Erickson et al. 2016). Conventional sand filtration retains solid particles but will remove little to no inorganic nitrogen because inorganic nitrogen does not attach to the solid particles used in conventional sand filters. A cost-effective amendment for sand filter media to retain inorganic nitrogen has not been identified. Erickson et al. (2016), for example, found that the capacity of one activated carbon used for stormwater nitrate retention would be exhausted relatively quickly and, therefore, would not be cost-effective. A cost-effective amendment could make filtration an option for nitrogen reduction.

9.3.3 Infiltration Practices (including bioretention)

Infiltration of stormwater is an effective tool in removing nitrogen from surface stormwater, although the BMPs do not typically remove dissolved nitrogen from the water. It is assumed that the nitrogen is transported to groundwater. When runoff infiltrates within a stormwater treatment practice, organic nitrogen can be captured on the floor of the practice and dissolved inorganic nitrogen will infiltrate into the existing soil with the water. Nitrogen that infiltrates can attach to plant roots and be assimilated into plant matter, used by microorganisms, or travel with water as shallow groundwater flow, among other possibilities. Although the nitrogen traveling as shallow groundwater flow can reemerge at another location (and possibly enter a water body), the nitrogen in infiltrated stormwater runoff is often assumed to be transported to groundwater. Typical nitrogen concentrations in urban runoff are well below the drinking water limits for nitrogen. Thus, infiltration is one way to achieve nitrogen reduction.

9.3.4 Biofiltration Practices (with underdrains)

Nitrogen can be removed by biofiltration practices, but the practice must be specially designed for this pollutant removal or include plant harvesting. Biofiltration practices can retain nitrogen through root uptake and assimilation into plant matter. True removal, however, will only occur if the plant matter is harvested and removed from the practice. When vegetation remains in the practice, the assimilated nitrogen can be released upon plant death and decomposition, and if this happens, the practice may export nitrogen. Studies have shown that nitrogen retention can vary from large positive values (nitrogen reduction) to large negative values (nitrogen export). Inorganic nitrogen in a bioretention practice that is not retained by vegetation may change forms through microbial processes but may not be retained or removed. For example, microorganisms can convert ammonia to nitrite and nitrate (nitrification), but this does not retain or remove nitrogen from the practice. It only changes its form. True removal requires denitrification or plant harvesting.

Complete microbial removal of all nitrogen requires nitrification and denitrification and therefore, a biofiltration practice must have both an aerobic and an anaerobic zone. If both zones are provided in a single biofiltration practice, complete microbial removal of all nitrogen forms can occur because the nitrogen gas will leave the practice and enter the atmosphere. This can be accomplished by arranging the drain tile with an upturned elbow on the end or by using an elevated outlet to create an internal water storage zone and placing carbonaceous material in with the media (Brown and Hunt 2011). The water storage zone will become anaerobic, and denitrification can occur in the water that is stored in the media.

Complete microbial removal of all nitrogen requires nitrification and denitrification and therefore, a biofiltration practice must have both an aerobic and an anaerobic zone.

9.4 Metals

Metals in stormwater are classified as either particulate or dissolved. Particulate metals are defined as those that are retained on a 0.45-micron filter. Any metal that passes through a 0.45-micron filter is classified as dissolved.

A fraction of the ions of any metal in solution will attach to solid particles in stormwater runoff. The fraction of metal that will attach to solids is different for each metal and depends on the metal, characteristics of the solid particles, the pH of the water, and other variables. Any metal that attaches to a solid particle can be captured by stormwater management practices that retain solids.

The dissolved metal fraction, however, is not retained with solid particles. Dissolved metals can be retained by chemical adsorption, precipitation, or other means. Another method usually assumed to reduce dissolved metals is infiltration. All processes to reduce metal loads involve retention of the metals, not removal. Retained metals may be released under certain water chemistry conditions, such as low pH or high chloride levels. Metal removal will only occur if the material to which the metals have attached is removed from the practice. Thus, removal of sediment, mulch, compost, vegetation, etc. is necessary for metal removal. Such material should be disposed of according to all governing regulations.

9.4.1 Sedimentation Practices

Because a fraction of metals attaches to solid particles in stormwater, any practice that retains solids will also retain a fraction of the metal load. Thus, sedimentation-based practices (e.g., dry ponds, wet ponds) can retain a fraction of the metal load. A typical sedimentation-based practice will, however, retain little, if any, of the dissolved metal load.

9.4.2 Filtration Practices

A conventional sand filter does little to retain dissolved metals and should not be expected to do so. Amendments such as biochar, however, can be added to a sand filter media to retain dissolved metals.

9.4.3 Infiltration Practices (including bioretention)

When runoff infiltrates within a stormwater treatment practice, sediment-bound metals can be captured on the floor of the practice and dissolved metals will infiltrate into the existing soil with the water. Once in the soil, dissolved metals may be bound by microorganisms, become attached to and/or be taken up by roots, or be retained on the soil media, among other possibilities. Some practices such as bioretention also contain compost, mulch, and/or other organic material to which dissolved metal ions will attach. Thus, the metals in infiltrated stormwater runoff are typically assumed to be removed from the conveyance system. The soil, however, has a finite capacity to retain metals. Although studies have shown that metals infiltrating with water are typically retained in the top 50 cm of soil and that the soil can maintain the ability to retain metals for dozens (or even hundreds) of years, plans should be made for when soil metal adsorption capacity is exhausted. When this happens, metals may move deeper than 50 cm into the soil, potentially reaching the groundwater. Eventually, the soil may need to be replaced for continued metal retention capacity. Exhausted soil should be placed in an appropriate landfill.

9.4.4 Biofiltration Practices (with underdrains)

Biofiltration practices can retain both dissolved and particulate metals using the same processes as infiltration basins. Biofiltration practices, however, have a finite capacity to retain metals on the surface and within the media. Once capacity is exceeded, metals can be discharged to downstream systems and waterbodies through the underdrain. Thus, it is important to know the capacity of biofiltration practices and to plan for replacing media accordingly.

9.5 Chloride

Chloride is generally a conservative ion and is not removed or retained by any stormwater treatment practice. It is therefore difficult to treat once it gets into the stormwater system. The best means of reducing chloride is through source reduction; use less chloride-based salts and sweep up deicing salt remaining after snow and ice has melted on impervious areas. The chronic toxicity of chloride for the aquatic biota is set at 235 mg/L by the Minnesota Pollution Control Agency (MPCA 2023), and 250 mg/L is the point at which water begins to taste salty to many humans. These are relatively high concentrations, but in Minnesota a tremendous quantity of deicing salt (sodium chloride) is placed on driveways/parking lots/roads during the snowy season. Concentrations greater than 1000 mg/L are common in snowmelt runoff.

The best means of reducing chloride is through source reduction; use less chloride-based salts and sweep up deicing salt remaining after snow and ice has melted on impervious areas.

9.5.1 Sedimentation Practices

Chloride in runoff following snow melts can collect in the bottom of ponds because water laden with chloride is denser than water without. This can create an early seasonal stratification of ponds, setting the stage for temperature stratification later in the summer. Stratification is a precursor to low dissolved oxygen concentration in the bottom of ponds and subsequent phosphorus release from sediments.

9.5.2 Filtration Practices

Filtration practices will not remove or retain chloride.

9.5.3 Infiltration Practices (including bioretention)

Infiltration will remove chloride from surface waters, but then transmit it to shallow groundwater or to aquifers, where it can affect the aquatic biota over the seasons or pollute drinking water. Shallow groundwater flow can subsequently reemerge at other locations at any time during the year and, in the process, convey chloride to these locations.

9.5.4 Biofiltration Practices (with underdrains)

Biofiltration practices will not remove or retain chloride.

9.6 Pathogens

Microorganisms like fungi, bacteria, and protozoa are ubiquitous in stormwater. Some of these organisms can cause health problems for humans and other animals including intestinal problems or rashes and the spread of harmful viral infections. Many pathogens are present in the fecal matter of humans, domestic and wild animals, and can enter surface water bodies through runoff, storm sewer outfalls, septic systems, and direct animal defecation. *Escherichia coli* (*E. coli*), a bacterium that normally lives in the intestines of humans and other animals, is commonly used as an indicator of pathogens. MPCA regulations state that the geometric mean of five or more samples taken over a month should not exceed 126 per 100 mL and 1260 per 100 mL in any one sample (MPCA 2023).

Pathogen removal in stormwater best management practices depends on sediment retention, hydraulic residence time, and consideration of pathogen mortality in the practice. Because a portion of pathogens in stormwater attach to solid particles, any stormwater treatment practices that retain solids will retain a fraction of the pathogen load. Small sediments such as clays and silts, however, will likely not be retained by sedimentation-based practices. The most successful BMPs for pathogen removal tend to be sedimentation practices with long hydraulic retention times.

9.6.1 Sedimentation Practices

Because microbes attach to solid particles, any practice that retains solids (see Section 9.1) will also retain some pathogens. Captured *E. coli* can die off and most sedimentation practices do not have conditions that will encourage *E. coli* growth. The Minnesota Pollution Control Agency has cited the International Stormwater Database to provide an average bacterial removal of 70% in stormwater ponds and 75% in stormwater wetlands.

9.6.2 Filtration Practices

Filtration practices typically have a lower hydraulic residence time than stormwater ponds or wetlands, so less pathogen die-off will occur. The International Stormwater Database provides an average bacteria retention of 35% in filters, excluding vertical sand filters and filter strips. Media enhancements (e.g., biochar and similar charged compounds) can improve the retention of bacteria.

9.6.3 Infiltration Practices (including bioretention)

When runoff infiltrates within a stormwater treatment practice it is assumed that all the bacteria will die in the soil due to the long residence time before returning to surface waters. The international Stormwater Database lists 100% removal of bacteria for infiltration facilities.

9.6.4 Biofiltration Practices (with underdrains)

Biofiltration practices (bioretention with underdrains and a significant amount of vegetation, compost, or other organic matter) will have a short retention time before the water returns to the stormwater system. Bacteria die-off is thus less prevalent in biofiltration practices. The International Stormwater Database provides an average of 35% removal in biofiltration practices.

9.7 Organic Chemicals

Organic chemicals are compounds with at least one carbon-carbon bond and are common in nature. In this context, however, organic chemicals refer to those manufactured by humans and believed or suspected to be toxic and classified as chemicals of emerging concern (CECs). There are a variety of such chemicals, identified by acronyms such as TCE, and the large groupings of PAHs, PCBs, PFAS, etc. They are generally classified as hydrophobic (repels water) hydrophilic (likes water), volatile (prefers air) and non-volatile (prefers water). There are, of course, many levels in the hydrophobic-hydrophilic range and many levels of volatility (Lyman et al. 1990). An organic chemical with sufficient hydrophobicity will attach to solids in runoff, and one with sufficient volatility will transfer to the air. Most hydrophilic chemicals are also non-volatile, however, and are the most difficult to retain or remove from stormwater runoff.

9.7.1 Sedimentation Practices

Hydrophilic chemicals typically will remain in the water as dissolved compounds and will not be removed or retained by sedimentation. An addition of chemicals such as aluminum sulfate (alum) or a change in water chemistry can be utilized to remove some organic chemicals, depending upon their hydrophobicity.

9.7.2 Filtration Practices

A conventional sand filter does little to retain dissolved organic chemicals and should not be expected to do so. Amendments, such as alum, however, can be added to a sand filter media to retain hydrophilic compounds.

9.7.3 Infiltration Practices (including bioretention)

When runoff infiltrates within a stormwater treatment practice, sediment-bound organic chemicals can be captured on the floor of the practice and dissolved organic chemicals will infiltrate into the existing soil with the water. Organic chemicals that infiltrate can be broken down by microbial activity, taken up by roots of vegetation, or retained on the soil particles, among other possibilities. Thus, dissolved organic chemicals in infiltrated stormwater runoff are typically assumed to be removed from the conveyance system. Bioinfiltration (rain gardens, grass swales, etc.) is especially effective because the plant roots tend to keep soil pores open so that water can infiltrate.

9.7.4 Biofiltration Practices (with underdrains)

The availability of adsorption sites on organic material in biofiltration practices provides an excellent opportunity for organic chemical retention, depending on the chemical's hydrophobicity. In addition, microbial activity in biofiltration practices has the ability to transform organic chemicals by breaking chemical bonds to extract energy. The new chemical can be one which is either less or more toxic.

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