Performance Testing of Alternative Media for Use in Stormwater Biofilters

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Dedication

To my family, you are my strength and pride.

Abstract

This work included the *in situ* testing, laboratory characterization, and performance monitoring of biofilters amended with standard and alternative medias. Testing identified pertinent physical and water transport qualities of media that was compared between the methods to evaluate the predictive capacity of laboratory testing. Performance monitoring included a pilot test plot comparing compost and peat amended biofilters and a newly constructed peat biofilter.

Field and laboratory testing revealed a range of performance in existing biofilters but did not indicate over or under performance of biofilters amended with alternative medias. The results of the two methods showed promise for the use of laboratory methods in predicting field performance.

The monitoring at the pilot plot showed comparable infiltration capabilities between peat and compost. Both biofilters showed the ability to capture first flush rainfall events. The pilot plots showed clear impacts on infiltration efficiency based on initial soil moisture content and the duration of storm events. The newly constructed biofilter experienced similar impacts but also showed promise in meeting stormwater infiltration requirements.

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Chapter 1: Introduction

1.1 Introduction to Stormwater and Biofiltration Systems

Roadways are designed with systems to control and direct the flow of stormwater. The impermeable surface of the roadway and the engineered channeling of water changes the natural flow and infiltration of stormwater at the site. The reduction in stormwater infiltration leads to increased runoff and overall discharge volumes (Ebrahimian et al. 2016, Yang et al. 2013). The natural stormwater cycle is also impacted by the high efficiency of the conveyance systems. The primary goal of stormwater infrastructure is to move water offsite quickly which leads to increased peak runoff volumes that happen earlier during storm events. Roadways also tend to collect chemicals from treatments, debris from cars and chemical fertilizers which are flushed off by stormwater.

Low Impact Development (LID) has been used as a part of stormwater Best Management Practices (BMP) to reduce or eliminate the impact of roadways and stormwater control measures. LID strategies function to return or mimic the water movement and infiltration that sites experienced prior to construction (Yang et al. 2013). Biofiltration systems are one of the tools encompassed by LID. Biofilters cover stormwater management systems that use vegetation and various media to treat and infiltrate stormwater onsite (Davis et al. 2009).

For a biofilter to be effective, it's media must support the vegetation, pass water efficiently, and improve water quality by filtering pollutants. Media amendments are used as a part of biofilter designs to achieve the desired water passing and treatment characteristics. Amendments are selected from an understanding of how they perform over time to meet the infiltration, water treatment, and vegetation needs of a site.

1.2 Study Need and Motivation

Stormwater policy in Minnesota follows the National Pollutant Discharge Elimination System (NPDES). To meet these requirements, the Minnesota General Permit for Construction Stormwater states that new roadway projects must capture the first inch of rainfall (MPCA, 2013). Biofiltration systems are used as part of new road construction projects to comply with these standards. Biofilters must be able to handle the hydraulic and treatment demands where they are placed. The Minnesota Department of Transportation (MnDOT) has media mixture specifications which meets the NPDES standards and are used for current roadside soil amendments.

MnDOT media mixtures have been comprised of either compost or sand-compost mixtures. These combinations have known engineering and performance characteristics that make them suitable for field implementation. There is potential to meet the NPDES permitting requirements using alternative media to current MnDOT mix designs. Laboratory testing showed that peat has the potential to meet the physical and water transport needs of biofilters (Johnson et. al, 2017). Peat is a native soil to northern Minnesota. When encountered during new road construction it is often removed and hauled off site. Reusing peat onsite for stormwater control has the potential to meet regulations while reducing project costs.

1.3 Scope

This research included three primary applications that characterized the hydraulic capabilities of biofilter media. Sites were initially identified throughout the state where compost, muck, or peat had been used to amend native soils along roadways. A set of field tests were then selected to classify physical and hydraulic qualities of the identified biofilters. During field testing, samples were also taken for laboratory testing.

Media samples were then tested following the laboratory procedures established by Johnson et al. (2017). The results of field and laboratory testing were compared to evaluate the capacity of laboratory testing to predict field performance.

The final application of this research focused on performance monitoring of biofilters. Sensor arrays were designed and installed at two field sites to monitor soil moisture, rainfall, and temperature data. The field sites were then evaluated for the volume of water captured during rainfall events.

Chapter 2: Literature Review

2.1 Introduction

Stormwater conveyance systems are designed to protect infrastructure, such as roadways, from flooding and are designed to move water off site quickly. This changes the natural hydrology of these sites; a reduction in infiltration area causes an increase in stormwater runoff, which in turn increases the discharge volume (Ebrahimian et al., 2016, Yang et al., 2013). This cycle is further altered by the efficiency of conveyance system, causing peak runoff to be greater and earlier in a storm event. Roadways also cause an increase in pollutant load to receiving waters as particulates and chemicals from vehicles and roadway treatments are flushed in stormwater.

To reduce or eliminate theses impacts, there has been a move towards low impact development (LID) as a part of stormwater best management practices (BMP’s). These strategies work to return the predevelopment hydrology to sites (Yang et al., 2013).

Biofiltration systems are one of the tools encompassed by LID. This technology is the general name given to stormwater management systems that use vegetation and various media to treat and infiltrate stormwater onsite (Davis et al., 2009). Sizing and location are often determined based on roadway projects needs and right of way availability. For these systems to work effectively, the media used in construction must support the vegetation used as part of the treatment process, infiltrate water effectively, and improve water quality by filtering pollutants. The media must be selected from an understanding of performance over time in both a geotechnical, hydraulic, and water treatment capacity. Biofiltration systems are thus designed using spatial availability, knowledge of media characteristics, and vegetation properties.

2.2 Stormwater Policy

The Minnesota General Permit for Construction Stormwater issued under the NPDES outlines stormwater management requirements for new construction projects in state. The permit ensures that the stormwater impacted by construction activity will be handled in compliance with the Clean Water Act (CWA) of 1972. For new roadway projects to comply with permit requirements the first inch of runoff must be captured and treated on site (MPCA, 2013).

2.3 Biofilters

To meet requirements set forth by the CWA, as well as state regulations for stormwater management BMP’s are often implemented. As a part of BMPs, the use of LID and green infrastructure (GI) design is growing in popularity. These terms refer in part to stormwater management systems that mimic the predevelopment hydrology. LID and GI systems are designed to reduce runoff volumes and rates of stormwater by slowing and retaining runoff while also increasing infiltration (Yang et al., 2013; Ahmed et al., 2011).

As a subset of LID, biofiltration devices can be implemented as a part of stormwater BMPs. Biofilters are characterized by having highly permeable top soil, a mulch or thatch layer, water detention capabilities, and vegetation that can aide in pollutant reduction and water uptake (Davis et al., 2009). In the context of roadway construction, this type of technology is an ideal candidate for managing runoff due to sizing flexibility based of available right of way for implementation (ODOT, 2014b). Several types of biofilters include bioslopes, bioswales and vegetative filter strips. Each one of these technologies can be implemented individually or with other devices. The use of multiple LID options has proven to increase pollutant load reduction.

2.3.1 Bioslopes

Bioslopes, also referred to as ecology embankments or media filter drains, treat stormwater through infiltration and sheet flow control. These devices are placed in sloped sections along roadways, as shown in Figure 1, and can be used where right-of-way is limited (WSDOT, 2014). Bioslopes can be implemented as a single BMP for a site or in conjunction with other biofiltration devices. Figure 2 shows an example of a combined bioslope and vegetative filter strip, described in Chapter 2.3.2, system. A bioswale, described further in Chapter 2.3.3. can also be utilized with a bioslope to promote stormwater control as shown in Figure 3.

Figure 1. Existing bioslope in place along a highway in northern Minnesota.

Figure 2. Bioslope with vegetative filter strip (GDOT, 2014).

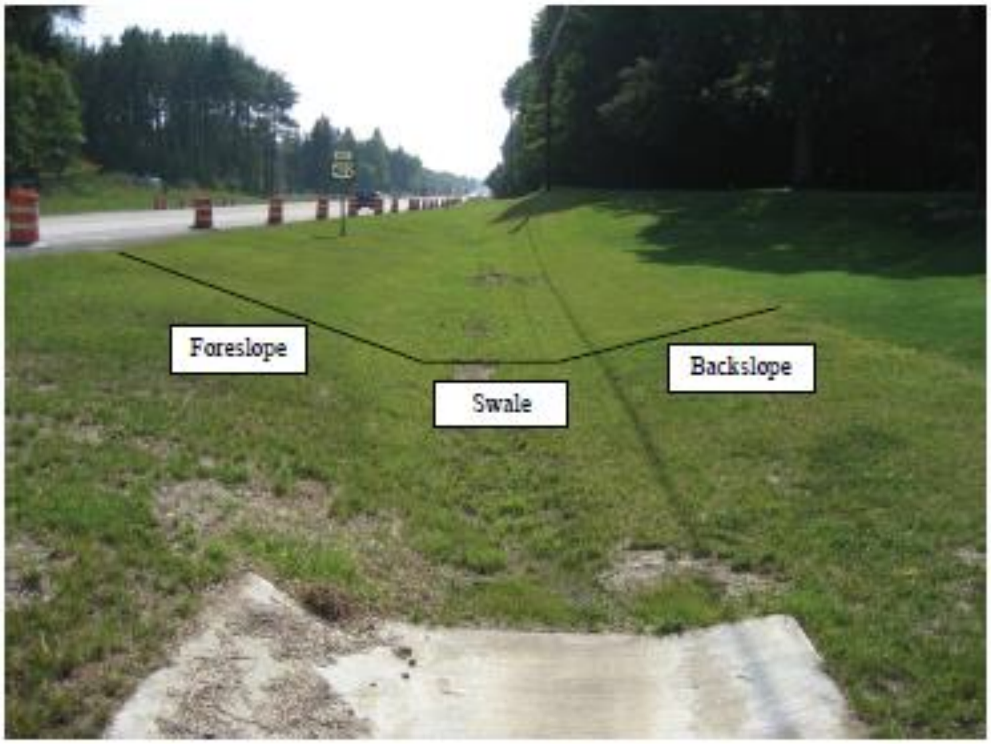


Figure 3. Biofiltration system with vegetated foreslope, backslope, and swale (Mitchell et al., 2010).

Various state DOT's have implemented types of bioslope designs. The Washington Department of Transportation (WSDOT) pioneered the development of this technology and has since created detailed design recommendations for various site conditions (NCHRP, 2013). WSDOT's work has also been influential in the creation of other state DOT's bioslope designs. This impact has caused commonalities in bioslope designs and features.

The WSDOT Highway Runoff Manual refers to bioslopes as media filter drains (MFD) and contains seven different design types. Each of these seven types of bioslopes have different capabilities and general applications. MFD Type 1 and Type 3 (detailed in

Figures 4 and 5) are designated for highway side slopes and can be implemented where right of way is limited or when roadways drain to wetlands. MFD Type 2, as seen in Figure 6, is intended for use in any type of linear depression such as highway medians or roadside ditches. In cases where stormwater flow from roadways cannot be conveyed as sheet flow MFD, Type 4, depicted in Figure 7, or Type 5, depicted in Figure 8, are ideal. These designs work particularly well for when stormwater is captured and conveyed via other systems such as pipes to the bioslope. The final two designs, MFD Type 6 and Type 7, shown in Figures 9 and 10, should be implemented in cases where runoff needs to be captured and conveyed. These final two types of bioslopes are put in place downstream of detention systems (WSDOT, 2014).

Several of the design types include a perforated pipe feature that ensures free flow through the MFD. For several of the designs the underdrain is the only distinguishing feature. Type 3 for instance, includes the underdrain whereas Type 1 does not have it. The perforated pipe is only required were free flow of stormwater cannot be established with the permeable media alone (WSDOT, 2014).

There are constraints and physical limitations on bioslope designs to ensure they can manage stormwater runoff effectively. The degree of the slope controls the velocity of the runoff and affects the infiltration capacity of the bioslope. WSDOT (2014) recommends a maximum slope of 25% for MFD Types 1 through 3 to promote infiltration and slope stability. MFD Types 4 through 7 contain a slotted pipe flow spreader for routing flow from adjoining of roadways which cause increased flow volumes over the course of the bioslope. To accommodate the increased flow volume WSDOT (2014) recommends that the slope on Types 4 through 7 be limited to 12.5%.

For stormwater routed from adjoining roadway sections to the bioslope, GDOT (2016) and WSDOT (2014) both recommend limiting the length of the flow path 150 feet.

Seasonal groundwater levels must also be determined at placement sites. Shallow groundwater can lead to pooling inside of the bioslope media reducing treatment capability (WSDOT, 2014). A high seasonal water table will constrain the dimensions of the bioslope or require additional drainage features.

Bioslopes have also been implemented as a part of as a stormwater BMP in Oregon and Georgia. These designs are based off the WSDOT Highway Runoff Manual and have a similar design to MFD Type 1. In the Georgia department of transportation (GDOT) design (Figure 11), there is not a recommended non-vegetated zone adjacent to the highway or recommended vegetation over the ecology mix (GDOT, 2016). The Oregon department of transportation (ODOT) design (Figure 12) includes an inlet system in the bioslope to aid in controlling stormwater flow (ODOT, 2014).

Bioslopes have various components which contribute to stormwater treatment and conveyance. Common components include a non-vegetated zone, vegetated filter strip, conveyance system, media filter drain, compost blanket and vegetation. The non-vegetated zone lies adjacent to the roadway and should be between one to three feet in width depending on available right of way (WSDOT, 2014). The non-vegetative zone aids in dispersion and sheet flow development of runoff to the bioslope. Vegetated filter strips are considered in their own class of BMP but are often included in bioslope designs to deliver pretreatment and further control sheet flow. Conveyance systems are implemented to ensure free flow of water through the bioslope media and include perforated pipe placed in highly permeable media (WDOT, 2016; ODOT, 2014; GDOT

2016). A media filter drain is used along with a conveyance system to aid in stormwater dispersion through base course media (WSDOT, 2014). The WSDOT (2014) recommends the use of a compost blanket placed over the media filter drain mix to control erosion and encourage grass growth. Compost blankets can potentially leach nitrogen and phosphorous and are not suitable for areas that are sensitive to these chemicals.

The media mixture used in the filter bed determines the performance of the bioslope. Components recommended for use in the filter bed include crushed rock, dolomite, gypsum, and perlite (GDOT, 2016; WSDOT, 2014). The rock works as a support system for the media. The dolomite and gypsum are recommended to treat heavy metals present in stormwater runoff. The perlite promotes moisture retention (WSDOT, 2014). The ratios of each component used in the mixture ensure that the filter bed will infiltrate stormwater predictably. WSDOT (2014) estimates the infiltration rate of its recommended media mixture at 50 inches per hour when initially installed, as shown in Table 1. Particulate accumulation has been shown to decrease this value over time to 28 inches per hour (WSDOT, 2014). With a factor of safety included value, an infiltration rate of 10 inches per hour is recommended for sizing design of the media filter bed.

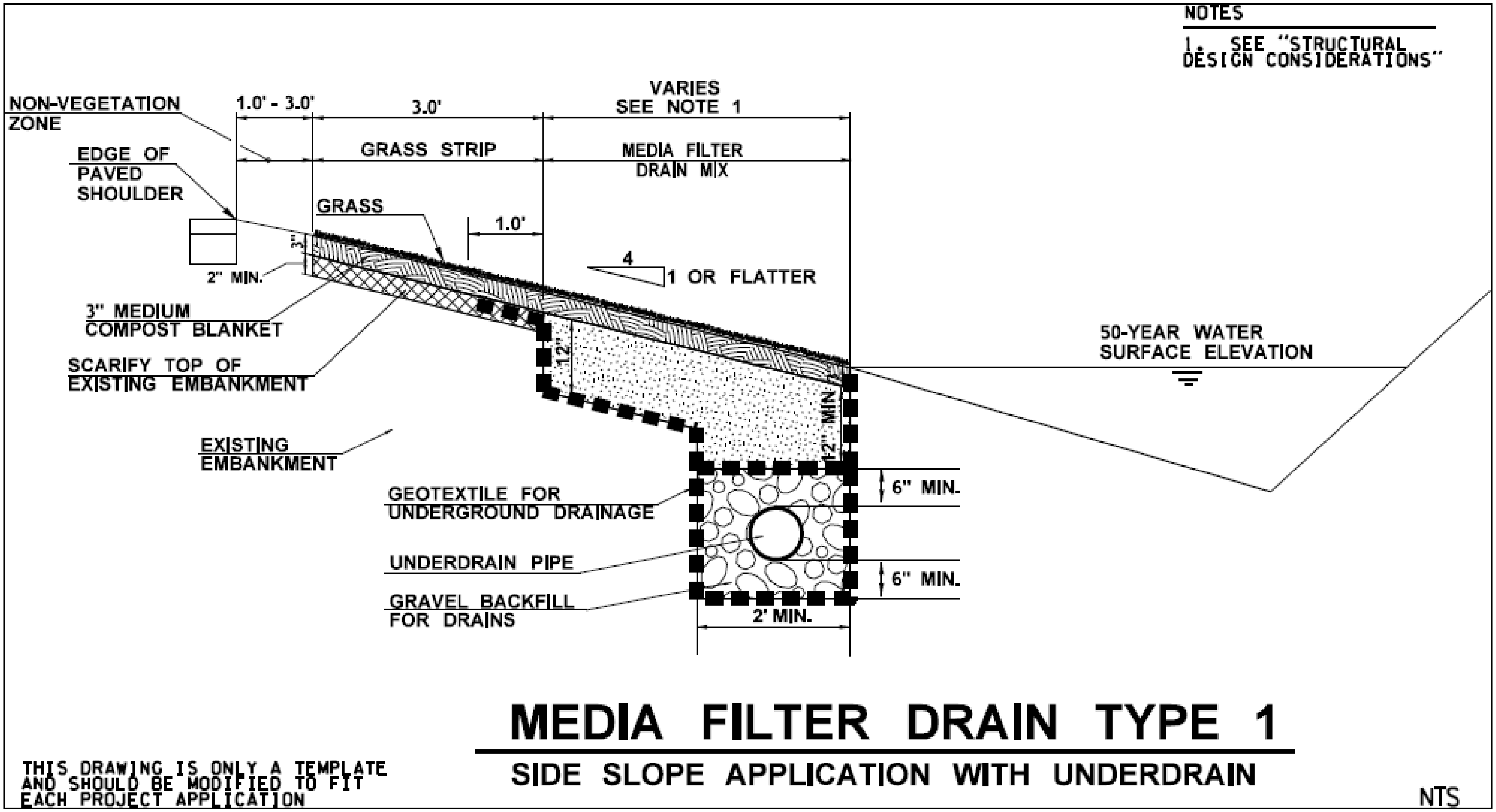


Figure 4. Cross section of Media Filter Drain Type 1 (adapted from WSDOT, 2014).

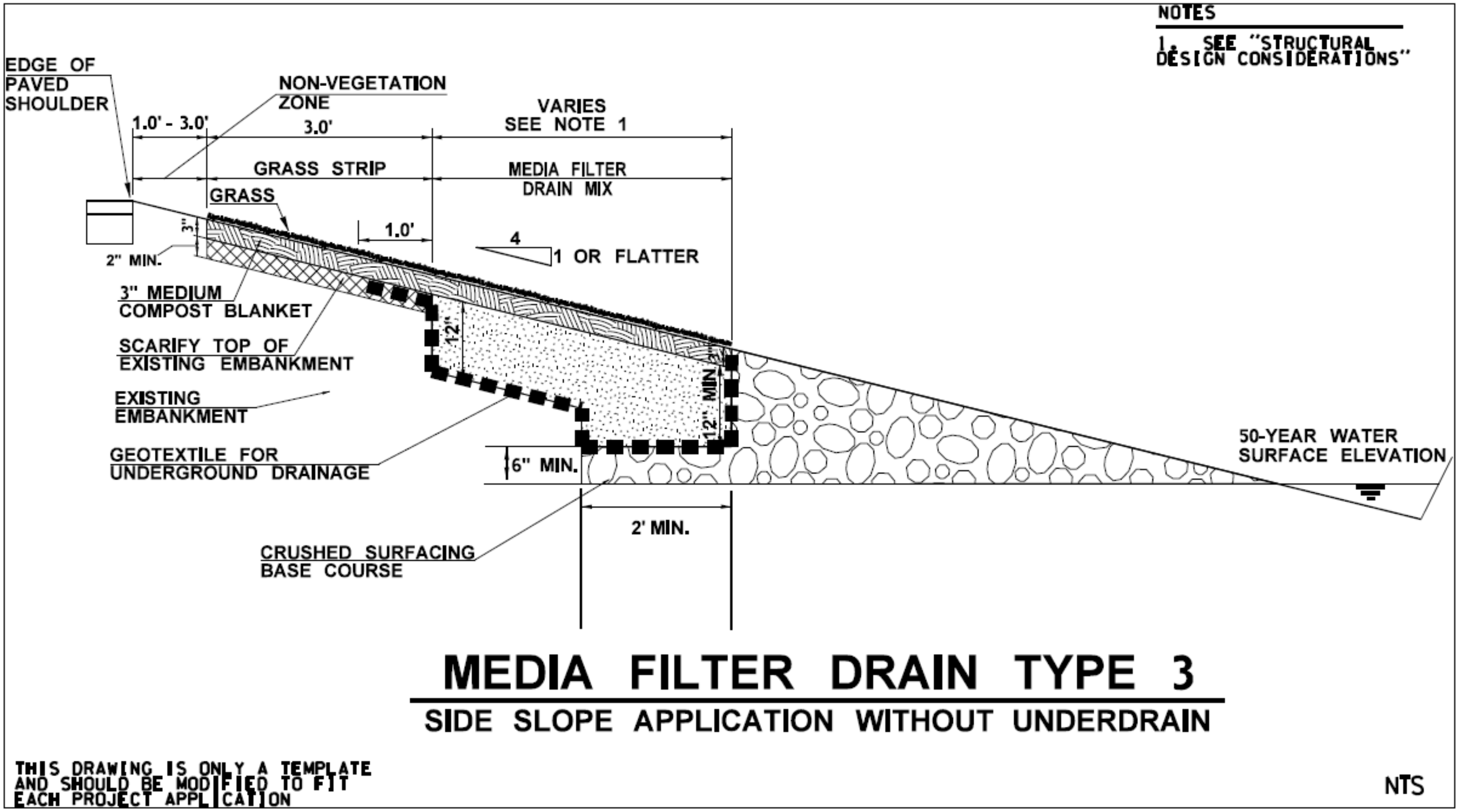


Figure 5. Cross section of Media Filter Drain Type 3 (adapted from WSDOT, 2014).

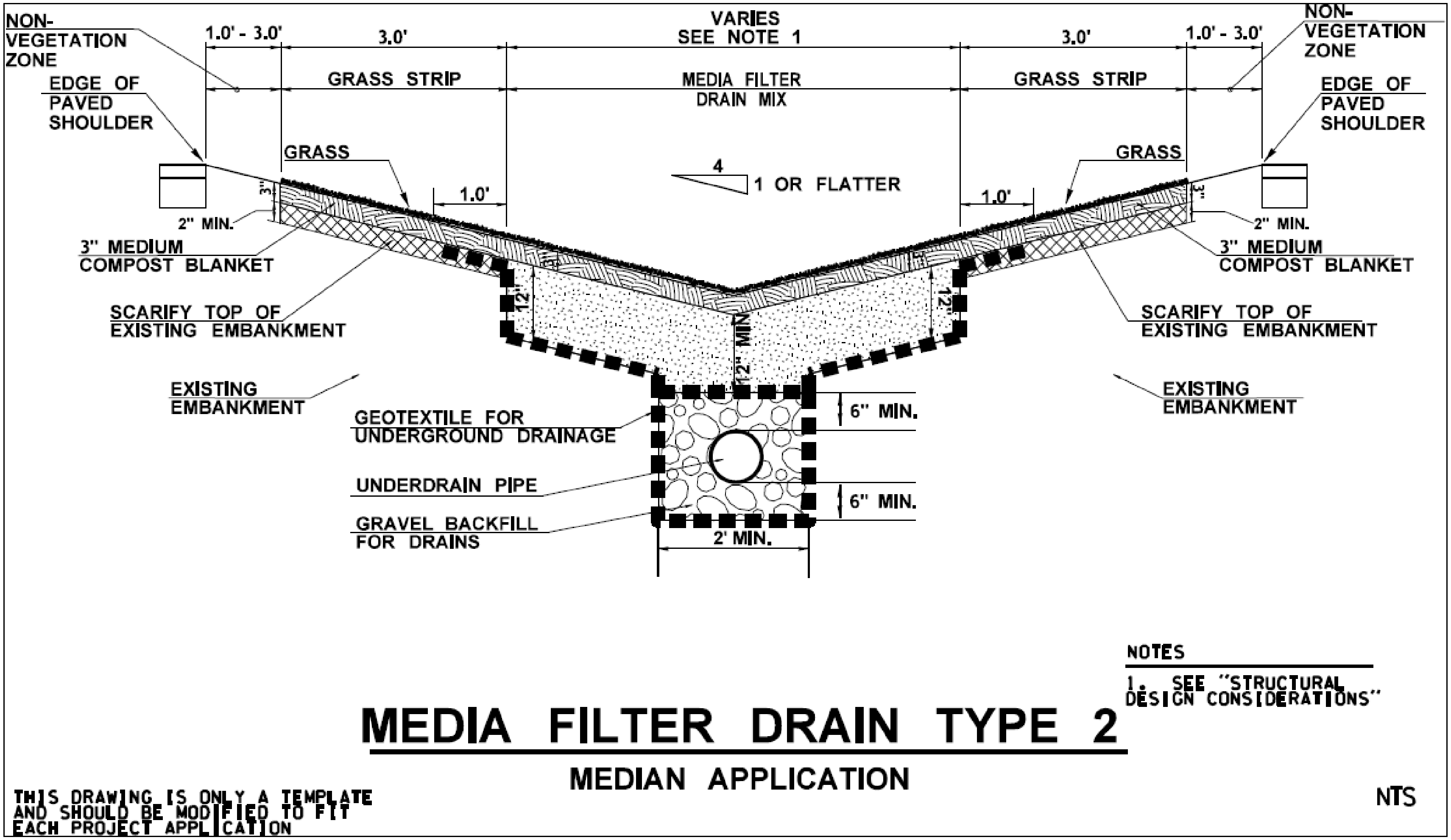
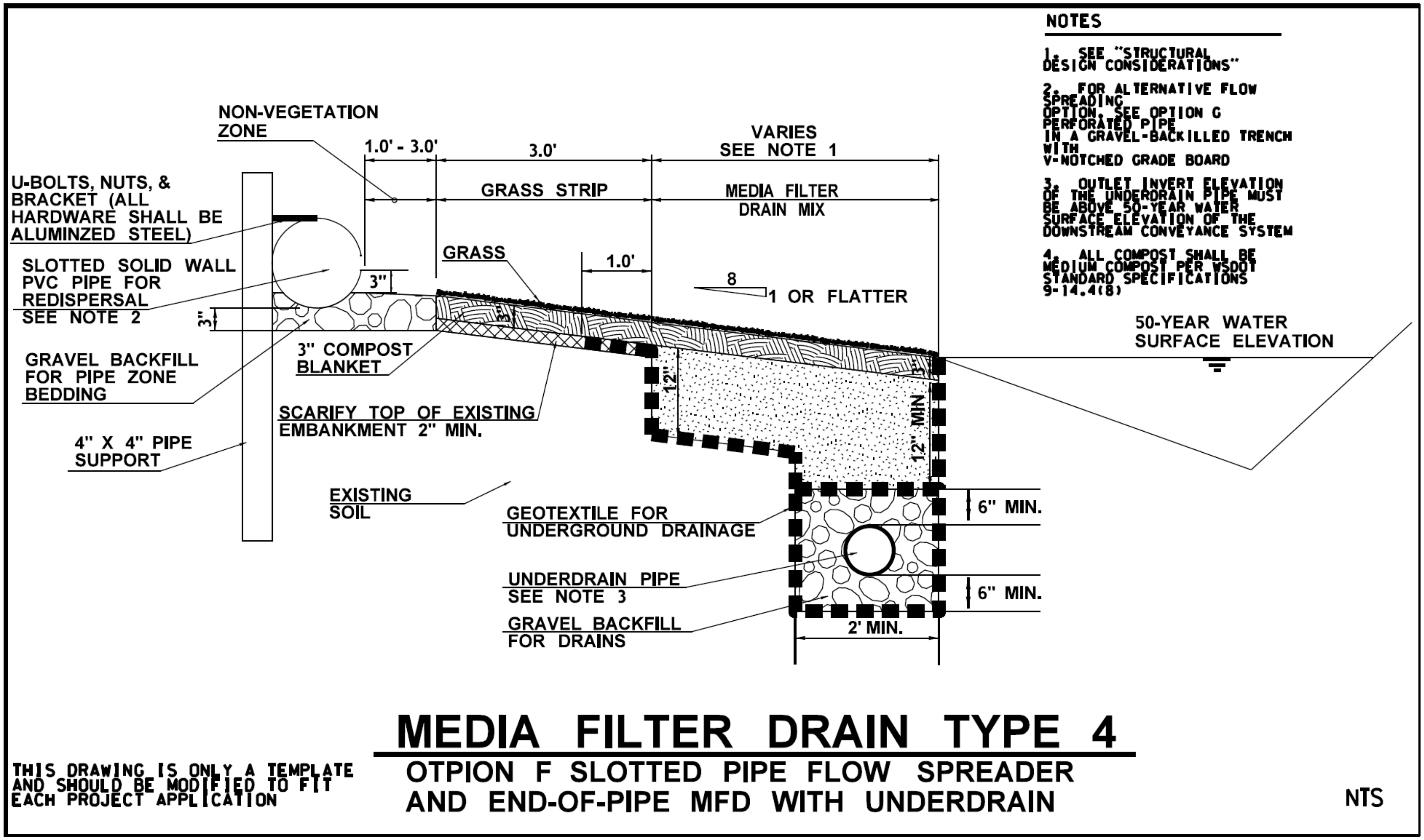


Figure 6. Cross section of Media Filter Drain Type 2 (adapted from WSDOT, 2014).



NOTES

1. SEE "STRUCTURAL DESIGN CONSIDERATIONS"
2. FOR ALTERNATIVE FLOW SPREADING OPTION, SEE OPTION G PERFORATED PIPE IN A GRAVEL-BACKILLED TRENCH WITH V-NOTCHED GRADE BOARD
3. OUTLET INVERT ELEVATION OF THE UNDERDRAIN PIPE MUST BE ABOVE 50-YEAR WATER SURFACE ELEVATION OF THE DOWNSTREAM CONVEYANCE SYSTEM
4. ALL COMPOST SHALL BE MEDIUM COMPOST PER WSDOT STANDARD SPECIFICATIONS 9-14.4(8)

THIS DRAWING IS ONLY A TEMPLATE AND SHOULD BE MODIFIED TO FIT EACH PROJECT APPLICATION

MEDIA FILTER DRAIN TYPE 4

OTPION F SLOTTED PIPE FLOW SPREADER AND END-OF-PIPE MFD WITH UNDERDRAIN

Figure 7. Cross section of Media Filter Drain Type 4 (adapted from WSDOT, 2014).

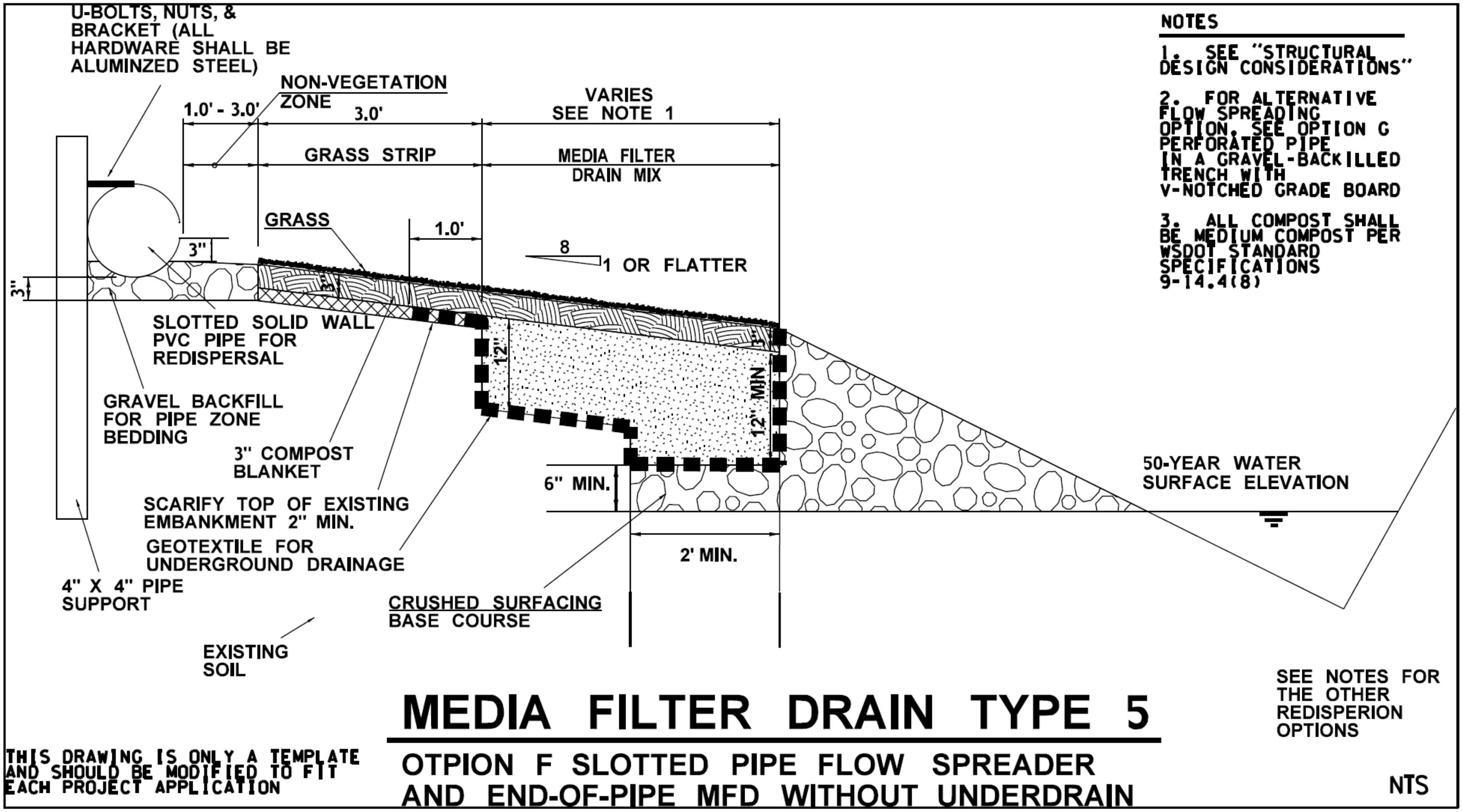
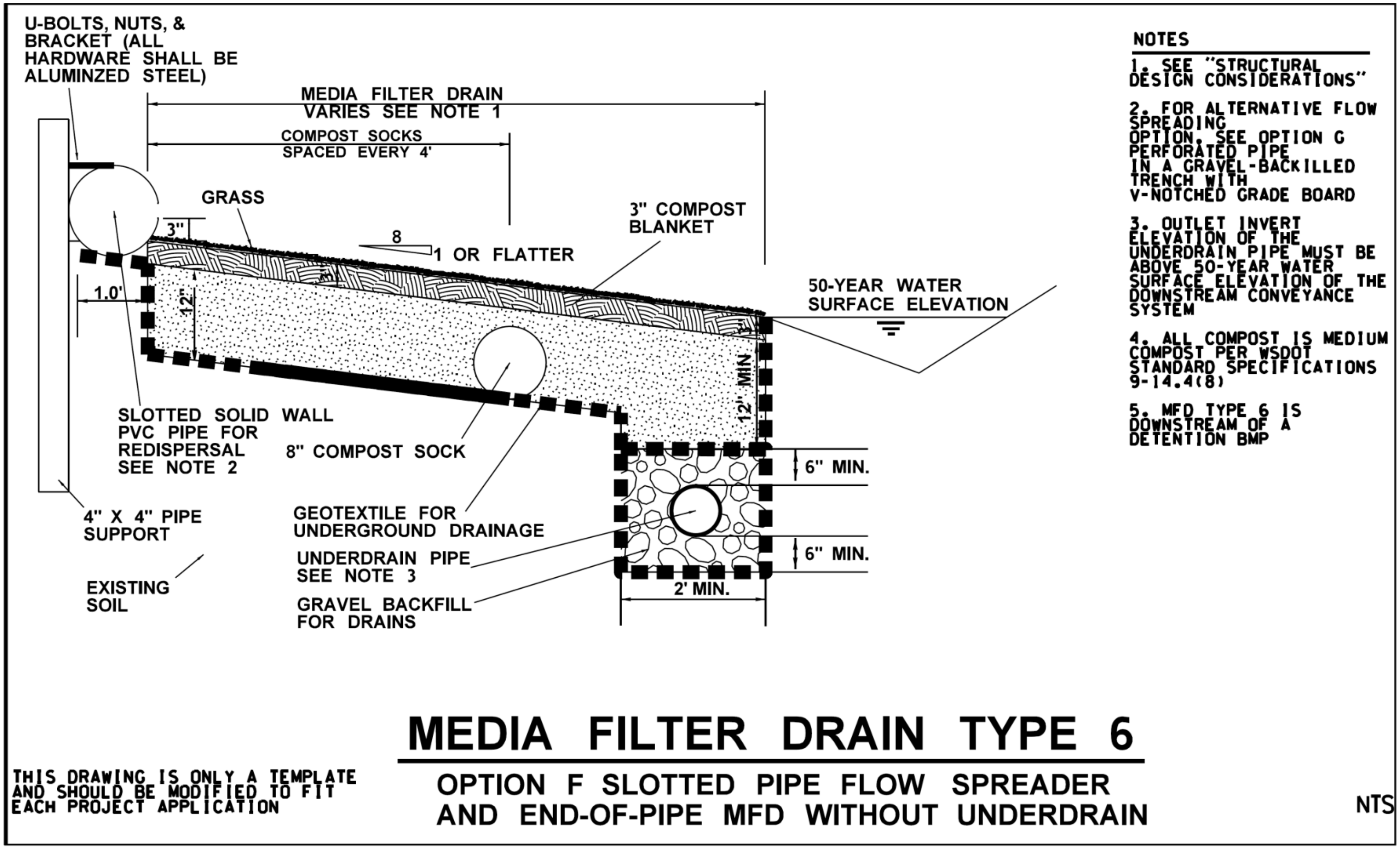


Figure 8. Cross section of Media Filter Drain Type 5 (adapted from WSDOT, 2014).



NOTES

1. SEE "STRUCTURAL DESIGN CONSIDERATIONS"
2. FOR ALTERNATIVE FLOW SPREADING OPTION, SEE OPTION G PERFORATED PIPE IN A GRAVEL-BACKILLED TRENCH WITH V-NOTCHED GRADE BOARD
3. OUTLET INVERT ELEVATION OF THE UNDERDRAIN PIPE MUST BE ABOVE 50-YEAR WATER SURFACE ELEVATION OF THE DOWNSTREAM CONVEYANCE SYSTEM
4. ALL COMPOST IS MEDIUM COMPOST PER WSDOT STANDARD SPECIFICATIONS 9-14.4(8)
5. MFD TYPE 6 IS DOWNSTREAM OF A DETENTION BMP

THIS DRAWING IS ONLY A TEMPLATE AND SHOULD BE MODIFIED TO FIT EACH PROJECT APPLICATION

Figure 9. Cross section of Media Filter Drain Type 6 (adapted from WSDOT, 2014).

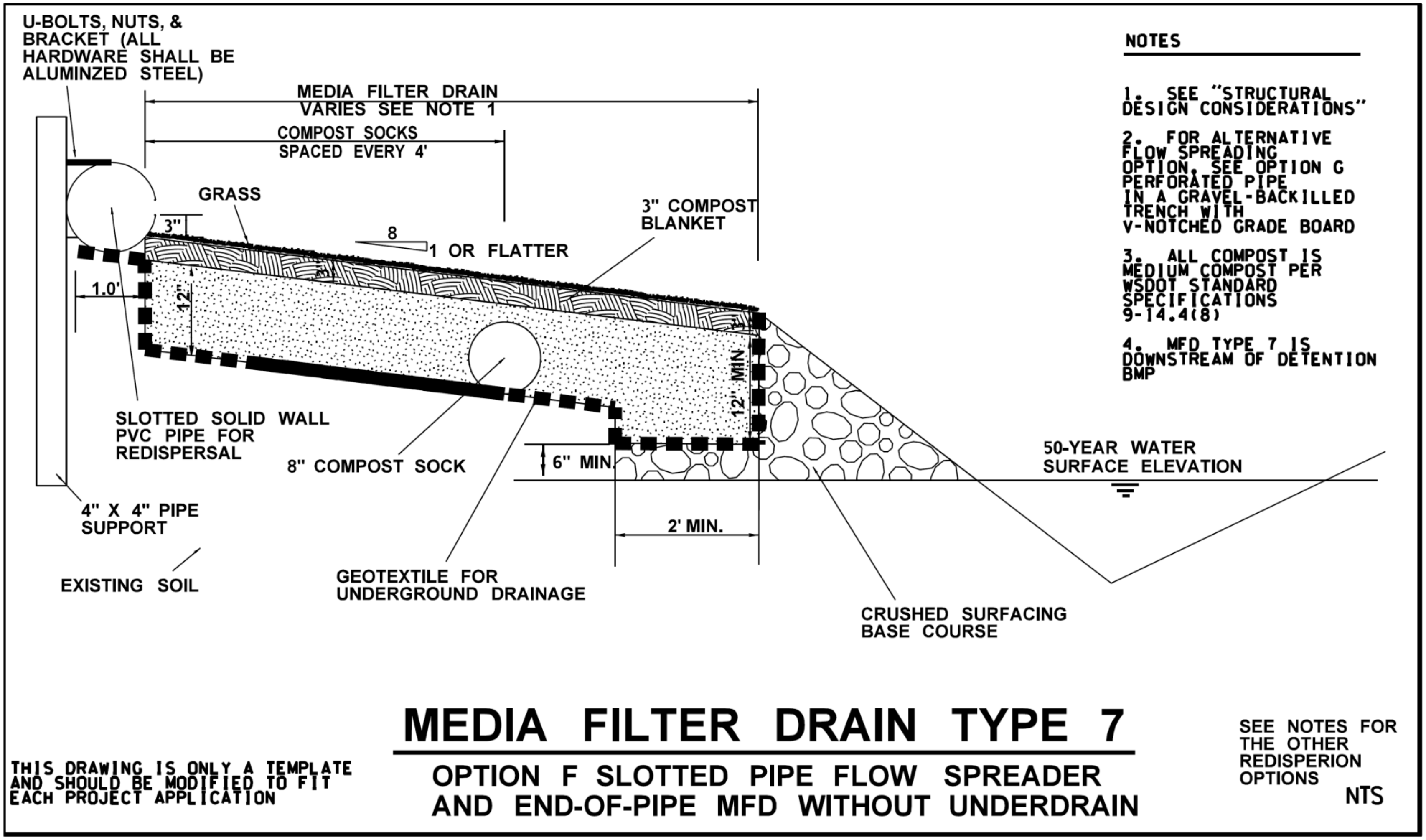


Figure 10. Cross section of Media Filter Drain Type 7 (adapted from WSDOT, 2014).

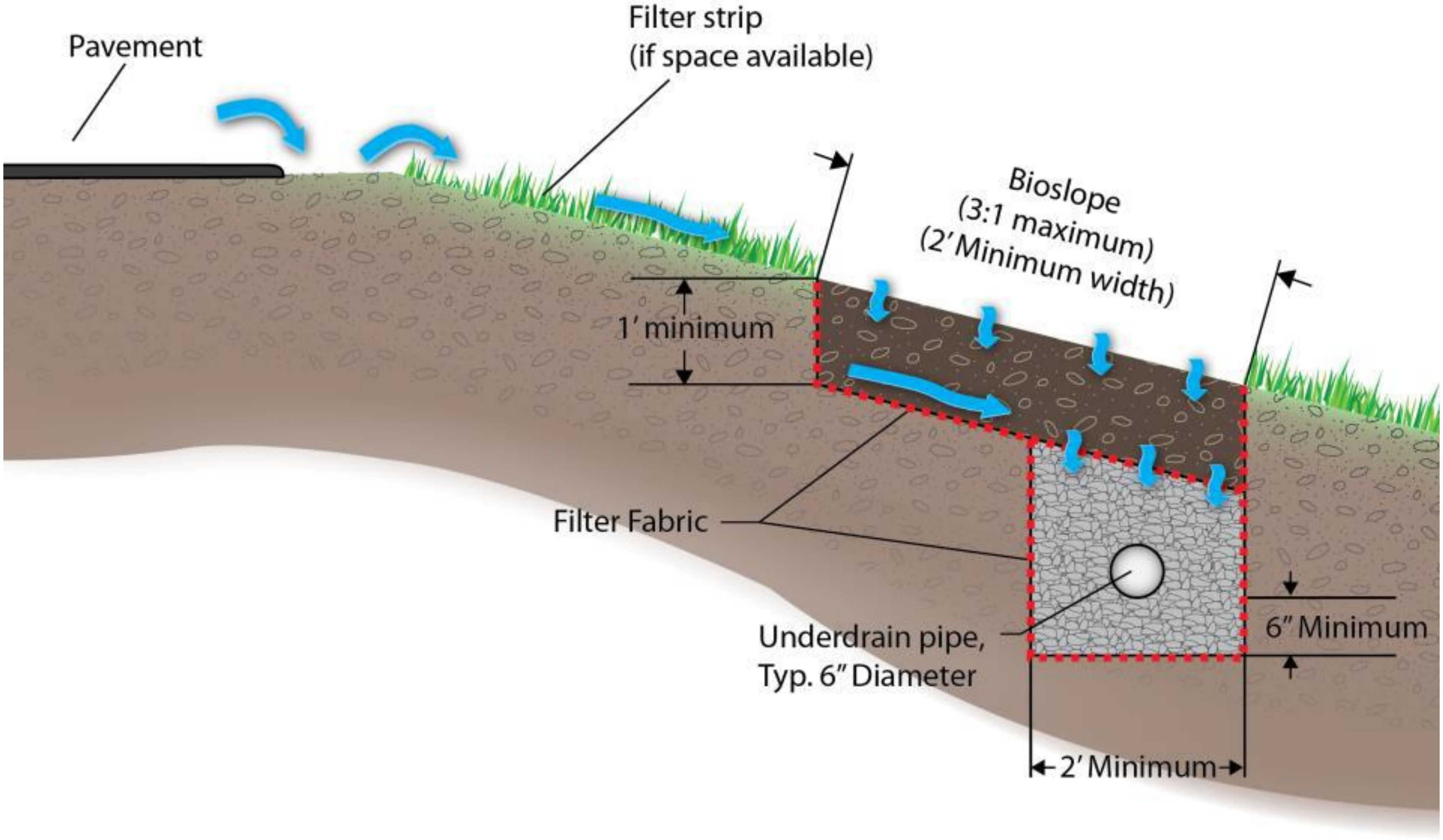


Figure 11. Cross section of bioslope design with flow depiction (adapted from GDOT, 2016).

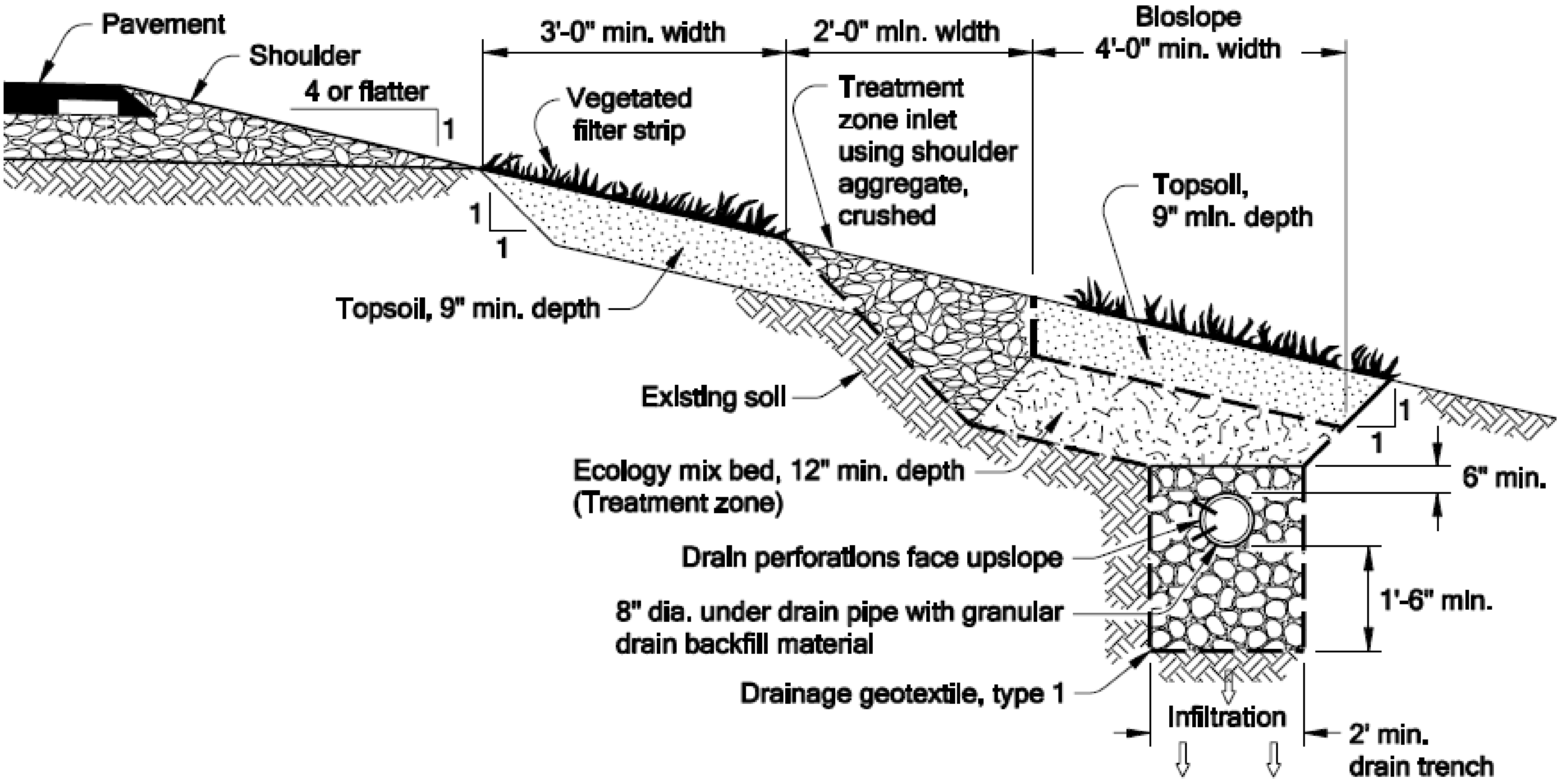


Figure 12. Cross section of bioslope design (adapted from ODOT, 2014).

Table 1. Bioslope media mixture components (adapted from WSDOT, 2014 and GDOT, 2016).

Soil Amendment	**Quantity**
Aggregate: • Crushed screenings 3/8-inch to U.S. No. 4 Sieve • No recycled material • Non-limestone material mineral aggregate	3 cubic yards
Perlite: • Horticultural grade • 30% maximum passing U.S. No. 18 Sieve • 10% maximum passing U.S. No. 30 Sieve	1 cubic yard
Dolomite: $CaMg(CO_3)^2$ (calcium magnesium carbonate) • Agricultural grade • 100% passing U.S. No. 8 Sieve • 0% passing U.S. No. 16 Sieve	10 pounds
Gypsum: Non-calcined, agricultural gypsum CaSO4•2H2O • Agricultural grade • 100% passing U.S. No. 8 Sieve • 20% passing U.S. No. 20 Sieve	1.5 pounds

The dimensions of the media filter bed are determined from the runoff flow from the pavement to the bioslope. The filter bed is typically the length of the roadway section being treated and should have a minimum depth of 12 inches (GDOT, 2016; ODOT, 2014; WSDOT 2014). The width is based on the treatment requirements of the bioslope. The minimum width varies depending on the design guide used and the bioslope configuration. WSDOT and GDOT require a minimum of two feet (GDOT, 2016; WSDOT, 2014), whereas ODOT (2014) requires four feet. Ultimately, the bioslope must be sized such that the water quality volume peak flow is less than or equal to the volume which the slope is capable of infiltrating. Water quality peak flow is found from regional rainfall event data and the design storm intensity. State DOT’s have regional recommendations and software to determine this value (Caltrans, 2011; WSDOT, 2014).

The infiltration flow can be determined from based on the media’s infiltration rate and the basic geometry of the bed (Equation 1) (WSDOT, 2014).

Equation 1. For determining infiltration flow with variable width (adapted from WSDOT, 2014).

$$Q_{Infiltration} = \frac{LTIR * L * W}{C * SF}$$

Where $Q_{infiltration}$ is the infiltration flow rate in cubic feet per second, LTIR is the long-term infiltration rate with a recommended design value of 10 inches per hour, L is the length of the bioslope in feet, W is the width of the bioslope in feet, C is a conversion factor of 43200 inches per hour to feet per second, and SF is a safety factor equal to one unless extremely high sediment loads are expected.

There are several approaches for finding a value for width and ultimately the infiltration flow rate. The width is initially assumed as two feet for the equation. If this produces a value for infiltration flow rate that is lower than the runoff from the highway, the width should be increased to the next whole value and the infiltration determined again (WSDOT, 2014). Alternatively, width can be solved for by rearranging Equation 1 when a design value for the water quality volume peak flow is known. A calculated bed width of less than two feet must be rounded to this value (GDOT, 2016).

2.3.2 Filter Strips

Filter strips, as represented in Figure 13, are implemented alongside roadways for water treatment, increased infiltration and runoff volume control (Bloorchian et al., 2016). These devices are designed with a shallow cross slope to slow the runoff velocity of stormwater from roadways, controlling discharge rates and aiding in sediment removal. Filter strips can also be implemented as a pretreatment measure when combined with another BMP technology such as bioslopes or bioswales (WSDOT, 2014).

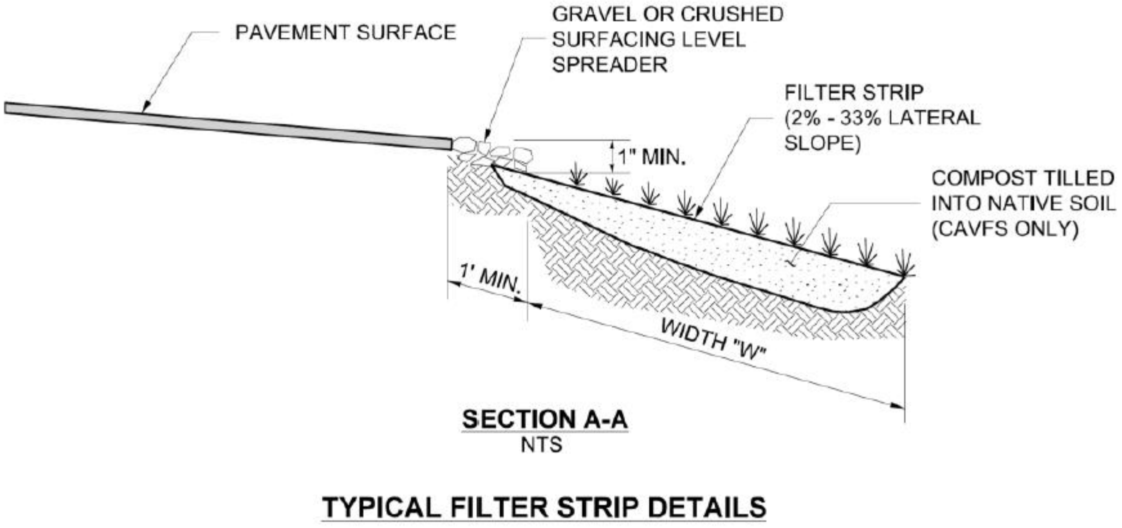


Figure 13. Typical filter strip details used by WSDOT (2014).

To meet stormwater filtration and runoff control needs, vegetative filter strips have several common features. A shallow cross slope is recommended to control runoff velocity and aid infiltration. The ODOT (2014) recommends a maximum slope of 15%. The WSDOT gives this same recommendation for maintaining sheet flow conditions but cites the use of slopes up to 33% percent for creating concentrated flows and as low as 2% to produce standing water. If erosion control is a primary concern, then a shallower slope will help to control flow velocity (WSDOT, 2014). For effective stormwater conveyance longitudinal slopes are recommended to be between 2% and 6% (ODOT, 2014; VDOT, 2013; WSDOT; 2014).

The dimensions for vegetative filtration strips should be determined from the size of the treatment area as well as design storm flows. In general, length is limited to 150 feet as flow paths longer than this tend to concentrate flows. Optimal lengths range between 80 to 100 feet for roadway treatment sections (VDOT, 2013; WSDOT 2014). The depth of the media bed varies depending on implementation of the filter strip as a combined BMP or as the primary treatment feature. A minimum depth of one foot is used by WSDOT for both cases (WSDOT, 2014). ODOT recommends a minimum depth of nine inches for a combined BMP and eight inches for a primary BMP.

When a vegetated filter strip is constructed as the primary treatment BMP, the design guides vary on determining width. ODOT uses a tabulated set of widths, shown in Table 2, which are designated based on existing embankment slopes and contributing pavement widths. The Virginia Department of Transportation (VDOT) recommends the width of the filter strip be the greater value between 0.2 times the filter strip length and eight feet (VDOT, 2013). WSDOT and GDOT utilize sizing methods based on regional water quality volume peak flow values (GDOT, 2016; WSDOT, 2014).

Table 2. Vegetative filter strip width determination from cross slope and pavement width (adapted from ODOT, 2014).

filter strip slope (%)	**filter strip width for 20 ft pavement width**	**filter strip width for 30 ft pavement width**	**filter strip width for 40 ft pavement width**	**filter strip width for 50 ft pavement width**	**filter strip width for 60 ft pavement width**
2	5	8	10	13	15
5	7	10	14	17	20
10	10	15	20	25	30
15	14	20	27	33	40

2.3.3 Bioswales

Bioswales, as seen in Figure 14, are another infiltration system included in the broader biofilter category. Several commonly used terms for bioswales include vegetated swale, enhanced swale, compost amended swale, and biological filtration canal. The Environmental Protection Agency (EPA) describe bioswales as, “a broad, shallow channel with a dense stand of vegetation covering the side slopes and bottom (EPA, 1999).” As a biofilter, swales are designed to infiltrate stormwater through their side slopes and channel bed while also conveying stormwater flow. This decreases runoff volume and slows stormwater velocity. In storm events where bioswale media becomes saturated the swale can become a retention system to hold and further treat stormwater (Jurries, 2003).

Figure 14. Bioswale with designed outflow into a detention pond (adapted from ODOT, 2014).

Bioswales can also be differentiated into dry or wet swales based on treatment conditions at the site. A dry swale is a traditional bioswale whereas a wet bioswale is used in situations where the bed soil will tend to be saturated based on flow conditions, a high groundwater table, or seeps (WSDOT, 2014). A compost amended swale is the term given to a bioswale which has had compost or other media additives mixed into the native soils to improve plant growth, infiltration, and pollutant removal (WSDOT, 2014).

Bioswales are designed specifically to treat the first flush pollutant laden flows that occur during storm events. To size a bioswale an average storm fall event must be selected. The value chosen is typically greater than 90% of rainfall events that the bioswale will be used to treat. A two-year 24-hour storm event is the minimum flow volume used for designs. A five-year or ten-year 24-hour storm event are also commonly used in the bioswale design process to fulfill the treatment requirements (Jurries, 2003).

The runoff velocity through the bioswale is also considered in design. High velocities can cause the channel bed to erode and reduce the treatment efficiency. Low velocities can result in standing water in the channel bed which can negatively impact vegetation and thus the pollutant uptake capabilities. The recommended flow velocities range from 1.5 feet per second as a minimum to 5 feet per second as a maximum. The water quality design storm event is used to calculate the minimum flow velocity. The peak flow storm event is used to calculate the maximum flow velocity (Jurries, 2003). The minimum and maximum flow velocities are then used to size the width of the bioswale.

The bioswale design process must also consider vegetation as it impacts stormwater treatment and flow. Vegetation aids in pollutant removal, particulate settling, and ion exchange (Jurries, 2003). When selecting vegetation, application and location is considered. A wet swale, which experiences long periods of standing water, requires different vegetation than a dry swale (GDOT, 2016; WSDOT, 2014). The flow of stormwater through the swale is impacted by the roughness of the swale which is a function of the vegetation present (WSDOT,2014). DOT guides recommend the use of native varieties of plant species that will be able to handle the treatment needs and soil moistures (Caltrans, 2011; GDOT, 2016; Jurries, 2003; ODOT, 2014; WSDOT, 2014).

Bioswales have common geometric features designed to control stormwater flow. The longitudinal slope of the bioswale lies along the channel bed and directly impacts flow velocity. To avoid erosion and improve water residence time for treatment purposes, the longitudinal slope is recommended between 1% and 6% (Jurries, 2003; ODOT, 2014). The cross-sectional geometry of a bioswale falls into one of four categories: square, parabolic, triangular, or trapezoidal. The trapezoidal geometry, shown in Figure 15, is the most common used bioswale designs due to constructability, ease of maintenance, and hydraulic performance (Jurries, 2003). Regardless of the cross-sectional shape, the depth of the canal is designed to convey the peak water quality flow that is determined for the site. A free board, measured from the top of the swale's side slope to the surface of the water quality design flow, is also included in the swale depth to protect against overflow (ODOT, 2014). Recommendations on free board depth vary from six inches above the water quality design flow (GDOT, 2016) to one foot (ODOT, 2014; WSDOT, 2016) based on design storm events.

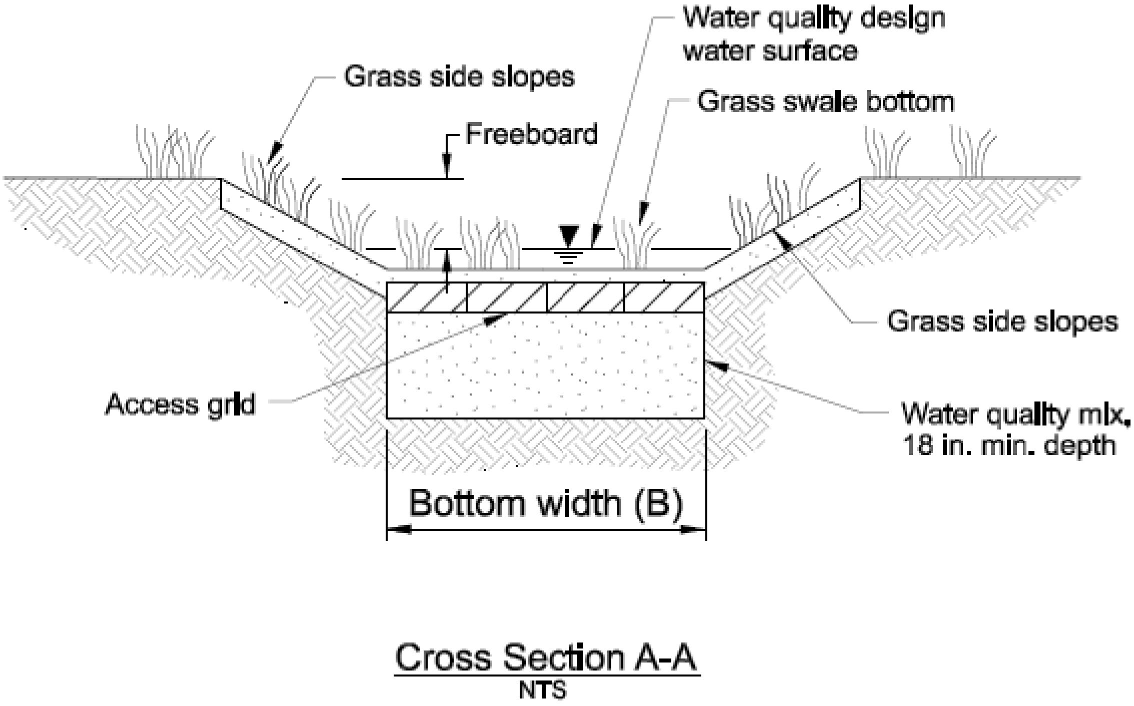


Figure 15. Typical cross section of a trapezoidal bioswale design (Adapted from ODOT, 2014).

In addition to the geometric features that control flow, the length, side slopes, and width of a bioswale must also be determined. The time that it takes for stormwater to travel the length of a bioswale is referred to as residence time. The residence time is correlated to treatment capabilities, as higher contact time between vegetation and stormwater allows for greater pollutant uptake (Jurries, 2003). The length recommended by both ODOT (2014) and WSDOT (2016) is a minimum of 100 feet with no maximum given. Other departments, such as GDOT (2016) and Caltrans (2011), give their recommended lengths, which can be found using Equation 5, based on minimum stormwater residence time of five minutes. Side slopes which convey runoff from roadways are recommended at or below 33.3% to control flow velocities and ensure slope stability (Caltrans, 2011; GDOT, 2016; ODOT, 2014; WSDOT, 2014). For bioswales with a trapezoidal cross section, the minimum recommended bed width is two feet, allowing for stormwater conveyance and basic maintenance such as mowing (ODOT, 2014). Recommended maximum widths vary between six and ten feet from various DOTs for dry swales and up to 25 feet for a wet swale (Caltrans, 2011; GDOT, 2016, ODOT, 2014; WSDOT, 2014). GDOT (2016) describes width as a function of regional geology, or bioswale media, which controls stream braiding.

There are several optional bioswale design features to control flow including check dams, inlet flow spreaders and underdrains. Check dams, shown in Figure 16, can be constructed of concrete, rock, mounded soil, boards, or nailed compost logs (Caltrans, 2011; Jurries, 2003; WSDOT, 2014). Check dams are used to cause water to pool in sections of the bioswale, decreasing flow velocity and increasing residence time (Jurries, 2003). Inlet flow spreaders, shown in Figure 17, are also recommended to control incoming flow velocity and produce sheet flow. Inlet flow spreaders are used in systems that have directed flow into the bioswale via pipes or curbs (Caltrans, 2011; Jurries, 2003; ODOT, 2014). Bioswales may also utilize an underdrain to help water flow through the swale media and reduce ponding. ODOT (2014) recommends the use of an underdrain for bioswales placed in poor draining media or with a slope less than 1.5%.

Figure 16. Vegetated swale with temporary check dam along a California highway (Caltrans, 2017).

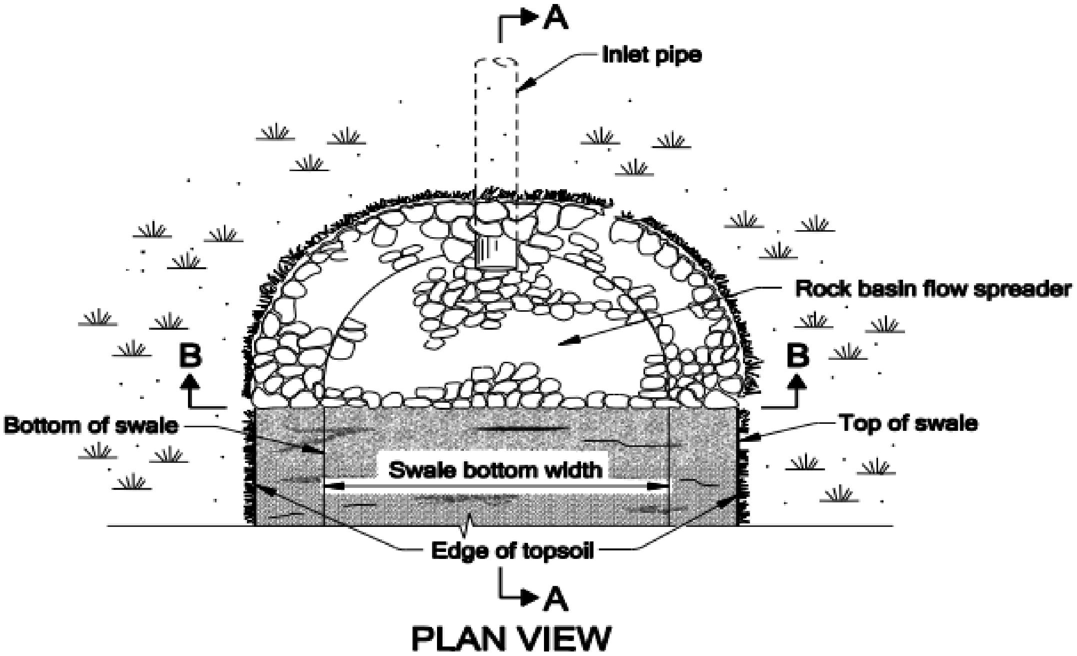


Figure 17. Typical flow spreader design used by ODOT (2014) for inlet flow control.

2.4 Biofiltration Media

Pollutant treatment, infiltration capabilities, and vegetation requirements control media recommendations for stormwater biofiltration systems. Soil amendments can be added to native soils when performance qualities are not met. Compost is widely recommended as a soil amendment for its treatment and infiltration capabilities (Jurries, 2003). As the use of biofilters for stormwater management increases, the demand for alternative medias has also increased. An ideal product for this purpose would be low cost and easily obtained.

Compost is widely used as a biofiltration amendment due to its established performance characteristics. Compost is recommended by various DOT's for erosion control, to aid in vegetation establishment, to improve infiltration capabilities, and for pollutant treatment. Recommendations for addition of compost into biofilters range from addition into the top soil via tilling to placement of a compost blanket over native soils (Caltrans, 2011; GDOT, 2016; ODOT, 2014; WSDOT, 2014).

The primary concern of using of compost as a soil amendment is in nutrient leaching. The WSDOT (2014) designates that compost should not be added to phosphorus sensitive sites. Nitrogen and phosphorus leaching are of concern for their potential impact on receiving waters (Faucette et al., 2007).

Peat is alternative to compost as a soil amendment used in biofiltration systems. Peat has been shown to be effective for increasing infiltration, aiding in vegetation establishment, and for water treatment. In northern Minnesota peat is often removed during the process of road construction, making it a readily available material in this (Johnson et al., 2017). Peat is defined as a mixture of soil and decomposed organic material that is both physically and chemically complex. Muck is considered to have similar qualities to peat but to contain highly decomposed form of organic content which result in low hydraulic conductivities of the soil (Bieber and Elfering, 2004).

Peat has qualities which make it ideal for stormwater treatment applications. Farnham and Brown (1972) show peat to be effective in reducing phosphorous concentrations in water. Peat supports high levels of cation exchange due to its acidic nature, while also having a high buffering capacity, and a high absorptive surface level. These qualities make it effective at removing heavy metals in stormwater runoff (Biesboer and Elfering, 2004).

The treatment and infiltration capabilities of peat are variable based on several factors. Peat itself is differentiated based on the levels of organic decomposition, botanical origin, level of acidity, and absorbency (Biesboer and Elfering, 2004). These qualities in turn affect peat's performance capabilities as a soil amendment. The level of decomposition of peat has been related to reductions in infiltration capacity (Pitt et al., 1997).

2.5 Conclusion

LID technology is effective for managing stormwater and meeting treatment criteria for roadway projects. Biofilters are one LID treatment method that is characterized by enhanced media, vegetation or site geometry that is intended to control stormwater runoff and treat water onsite. Several examples of biofilters include bioslopes, filter strips, and bioswales.

Compost is commonly used for amending native soils for biofilters. Various DOT's recommend its use in biofilters due to control erosion, aid in plant growth, and to improve infiltration in native soils. Peat has shown promise as an alternative media amendment to compost. Peat can support plant growth and aide in pollutant removal but has variable water transport characteristics.

Chapter 3: Methodology

3.1 Introduction

Chapter 3 describes the methods used to characterize the hydraulic capabilities of biofilter media and the instrumentation program used for performance monitoring. *In situ* testing was conducted on biofilters amended with either compost, peat, or muck. Other details about these sites, including the time of construction and the source of media amendments, have been detailed to potentially identify the effect of aging on hydraulic performance. The *in situ* tests characterized the saturated hydraulic conductivity, soil relative density, and soil moisture content at each site. Samples taken from the field were then tested in a laboratory setting; media was formally classified and then retested for saturated hydraulic conductivity.

Johnson et al. (2017) conducted a field pilot test comparing peat to compost as a biofilter media amendment. Soil moisture content and rainfall data was recorded at the site to assess the water transport capabilities of the two amendments. Monitoring of the site was continued in this phase of research. The same monitoring approach was implemented at a newly constructed biofiltration system which utilized peat to enhance native soils. Details about the construction of both sites and the instrumentation schemes are also presented in this chapter.

3.2 Site Identification

Over the last three decades MnDOT has constructed biofilters along roadways to comply with MPCA stormwater regulations. Nine locations, several with multiple biofilters, were identified for field testing and sample collection. The construction date and media used to amend the biofilters was also determined and summarized in Table 3. The locations of the biofilters included in this project are summarized in Figure 18.

Table 3. Site identification, year of construction, and biofilter media amendment.

Site	**Approximate Year of Construction**	**Media Used in Biofilter**
Chaska	2009	Compost
Cloquet	1990	Muck
Cook	2014	Peat
Crosby	1998	Peat
Grand Rapids	1998	Peat
Gilbert Lake	Unknown	Compost
Keene Creek	2012	Compost
Lilydale	2008	Compost
Silver Cliff Creek	2000	Compost

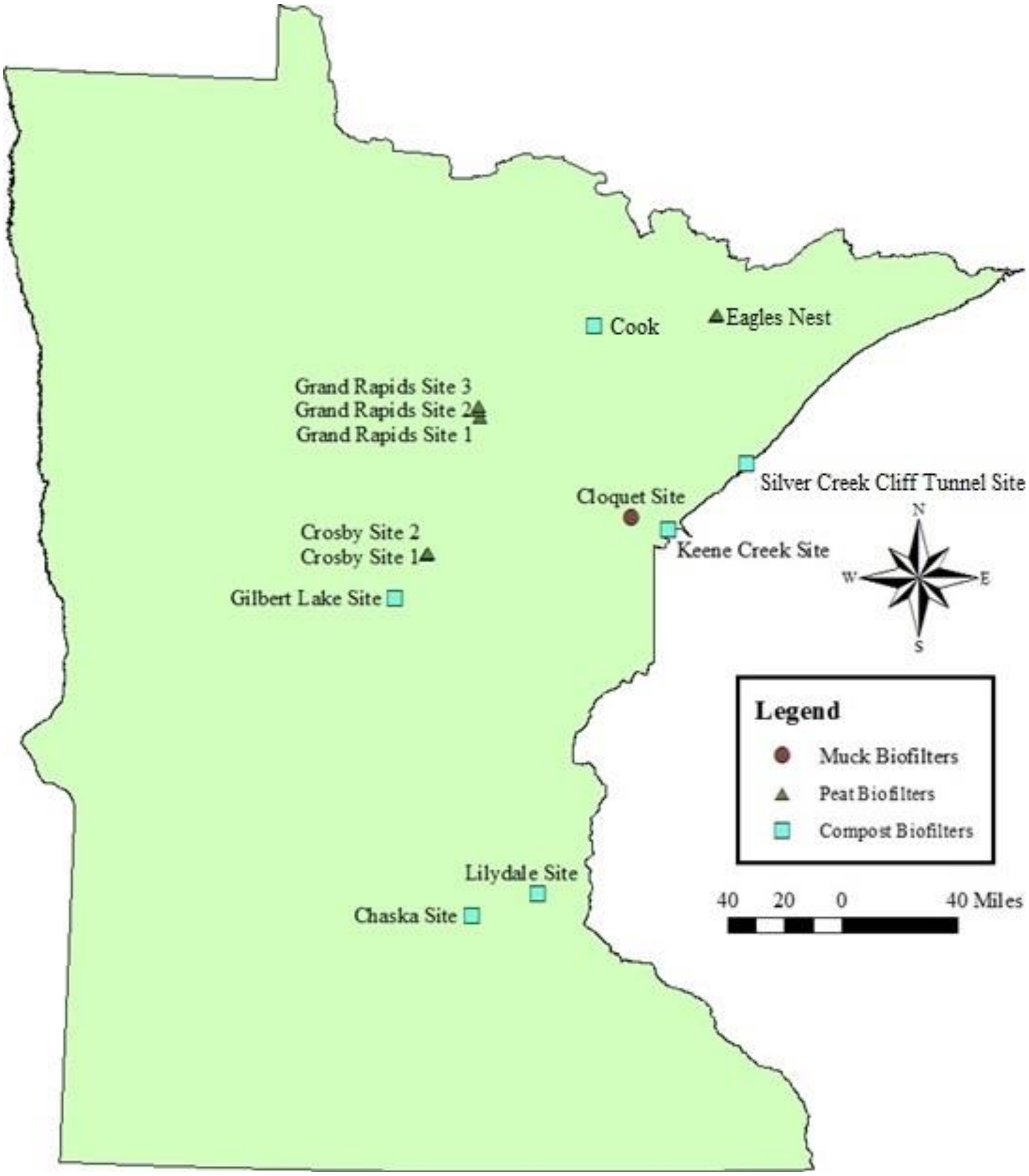


Figure 18. Map of biofilters included in this project.

3.2.1.1 Chaska Site

A biofilter was identified in the city of Chaska, on North Chestnut Street (County Road 41), to the south of Walnut Court as shown in Figure 19. The media used at this site was reported as a compost of unknown source. The biofilter was constructed in 2009.

Figure 19. Aerial view of the biofilter located in Chaska, Minnesota.

In situ testing was done at the Chaska site in September of 2018. The field investigation showed two distinct sections of the biofilter: a maintained grassed portion with a mild slope and a densely vegetated area with a more extreme slope as shown in Figure 20. The densely vegetated section had a significant root structure in the top soil that made testing in this area impossible without significant disturbance of the media. Testing was conducted in the maintained grass section of the biofilter. Sandy soils containing some gravel, shown in Figure 21, were encountered at the site.

Figure 20. Ground view of the Chaska biofilter.

Figure 21. Characteristic soil profile from the Chaska biofilter.

3.2.1.2 Cloquet Site

Another biofilter was identified north of the city of Cloquet, along Highway 33, where the Pine River parallels the road as seen in Figure 22. Locally sourced muck was used to amend the biofilter when it was constructed in 1990.

Figure 22. Aerial view of the biofilter located north of the city of Cloquet, Minnesota.

Field testing was conducted in August of 2018 at the Cloquet biofilter. The site had a relatively uniform and shallow slope. The biofilter included a maintained grass strip that extended for approximately 10 feet from the roadway and transitioned into a section of taller grass and reeds as shown in Figure 23. Testing was conducted in the more densely vegetated portion of the slope to ensure measurements were taken in amended soils. Prior to testing, vegetation was cut to a height of several inches and debris was cleared from the area. The biofilter media sampled at the site consisted of sandy soils with some gravel as shown in Figure 24.

Figure 23. Ground view of the Cloquet biofilter.

Figure 24. Characteristic soil profile from the Cloquet biofilter.

3.2.1.3 Cook Site

South of the city of Cook, there is a biofilter which runs along the west side of Highway 53, as shown in Figure 25. Peat was sourced from the wetland along the highway to amend the biofilter which was constructed in 2014. Sections of new pavement on south bound Highway 53 correspond to where the slope has been amended.

Figure 25. Aerial view of the biofilter located south of the city of Cook, Minnesota.

Field testing was conducted at the Cook site in August of 2018. The site had relatively shallow sloping, uniform, topography as seen in Figure 26. The biofilter had a maintained section of grassed slope which extended for approximately 15 feet from the roadway. The maintained section was followed by a section of tall grass that was approximately 5 feet in width which ran into a wetland area. Testing was conducted in the maintained section of the biofilter. Small plots were prepared for testing by first cutting grass to a height of several inches and removing debris from the area. The soil sampled at the site was comprised primarily of clay and organics as shown in Figure 27.

Figure 26. Ground view of the Cook biofilter.

Figure 27. Characteristic soil profile from the Cook biofilter.

3.2.1.4 Crosby Sites

There are two biofilters located north of the city of Crosby on Highway 6 as shown in Figure 28. Both biofilters can be found to the south of County Road 30 (Moritz Road) on Highway 6 north of Olander Road. The first biofilter, Crosby Site 1, is located on either side of Highway 6 from Olander Road extending north to where the tree line comes close to the road. The second biofilter, Crosby Site 2, can be found north of the first biofilter location, on the east side of Highway 6, starting at the private drive and ending where tree cover comes close to the road.

Peat was used as the media amendment at both biofilter locations along Highway 6. The aerial view of the site, as seen in Figure 28, shows that the biofilters are located along areas with no tree cover. These areas have been identified as wetlands and as the source of the peat used to amend the sites. The biofilters were constructed in 1998.

Figure 28. Aerial view of biofilters located near the city of Crosby, Minnesota.

In situ testing was conducted at the Crosby biofilters in August of 2018. Both biofilters had a moderate slope and were vegetated with un-maintained grass that extended from the shoulder of the road for approximately 15 feet. The sloped sections of both sites ran into a wetland area which could be identified by the cattails and reeds as shown in Figure 29. Test plots were prepared in the biofilter by trimming grass to a height of several inches, followed by the removal of the debris. Soil sampled from the biofilters were uniform and sandy as shown in Figure 30.

Figure 29. (a) West portion of Crosby Site 1. (b) East portion of Crosby Site 1. (c) Crosby Site 2.

Figure 30. Characteristic soil profile from the Crosby biofilters.

3.2.1.5 Gilbert Lake Site

A biofilter was constructed in the city of Brainerd between the east shore of Gilbert Lake and Riverside Drive, pictured in Figure 31. The roadside section was amended with compost, source unknown, and was indicated as having a steep grade. The time of construction is not known for this biofilter.

Field investigation and testing was conducted in August of 2018. Much of the biofilter was found to have a steep slope (between approximately 60 to 70 degrees) and was deemed unsafe for testing. A section of the biofilter towards the southeast shore of Lake Gilbert, shown in Figure 32, and several sites near the road with moderate slopes were selected for field testing. Although grass was maintained along the road, the sites were initially prepped for testing by trimming grass to several inches in height and then removing debris. Soil samples taken at the site included sands with some larger sized aggregate as shown in Figure 33.

Figure 31. Aerial view of the location of the Gilbert Lake site.

Figure 32. Ground view of the Gilbert Lake site.

Figure 33. Characteristic soil profile from the Gilbert Lake biofilter.

3.2.1.6 Grand Rapids Sites

There are 3 biofilters located north of the city of Grand Rapids on Highway 38, as shown in Figure 34. The southernmost biofilter on Highway 38, Grand Rapids Site 1, is located on the west side of the road between Town Line Road (County Road 61) and a private drive. The second biofilter, Grand Rapids Site 2, is located on the east side of Highway 38 north of County Road 177 and spans approximately a quarter of a mile. The northern most biofilter, Grand Rapids Site 3, is located on the east side of Highway 38 between a private drive and County Road 325. All biofilters along Highway 38 utilized locally sourced peat for the media amendment and were constructed in 1998.

Figure 34. Aerial view of multiple biofilter locations north of Grand Rapids, Minnesota.

Field testing was conducted at the Grand Rapids sites in August of 2018. The 3 sites all had mild slopes and a grassed section that extended for approximately 10 feet from the road as shown in Figure 34. Prior to testing, grassed sections of the slope were cut to several inches in height and debris was cleared. Soils sampled at the site were uniform and sandy as shown in Figure 35.

Figure 35. (a) Grand Rapids Site 1. (b) Grand Rapids Site 2. (c) Grand Rapids Site 3.

Figure 36. Characteristic soil profile from the Grand Rapids biofilters.

3.2.1.7 Keene Creek Site

A biofilter was constructed in the city of Duluth, along Cody Street. Figure 37 shows the biofilter location on the southern section of the culvert over Keene Creek. The biofilter was amended with compost from an unknown source and was finished in 2012.

Figure 37. Aerial view of the biofilter on Cody Street in Duluth, Minnesota.

Field testing was conducted at the Keene Creek biofilter in August of 2018. The site had relatively uniform topography, as shown in Figure 38, with a moderate slope. The media sampled at the site was found to be sandy with some larger sized aggregate as shown in Figure 39.

Figure 38. Ground view of the biofilter located over Keene Creek in Duluth, Minnesota.

Figure 39. Characteristic soil profile from the Keene Creek biofilter.

3.2.1.8 Lilydale Site

There is a single, small spanning, biofilter located in the city of Lilydale. The biofilter can be found off Highway 13 West (Sibley Memorial Highway) on the north section of the road and can be identified by a clearing in the tree cover as seen in Figure 40. Compost, from an unknown source, was indicated as the media amendment used at the site. The biofilter was constructed in 2008.

Figure 40. Aerial view of the biofilter located along the Sibley Memorial Highway in Lilydale, Minnesota.

Field testing was conducted at the Lilydale site in September of 2018. The biofilter had a shallow sloped section with a maintained grassed area which fed into a much steeper, densely vegetated section as shown in Figure 41. Vegetation at the site was trimmed to several inches in height and debris was cleared prior to testing. Soils sampled from the site included sands and some coarse aggregate as shown in Figure 42.

Figure 41. Ground view of the Lilydale biofilter.

Figure 42. Characteristic soil profile from the Lilydale biofilter.

3.2.1.9 Silver Creek Cliff Tunnel Site

The Silver Creek Cliff Tunnel, north of the city of Two Harbors, on Highway 61 marks the location of another biofilter, shown in Figure 43. The biofilter runs along both sides of the walking trail, a section of old Highway 61, which runs parallel to the Silver Creek Cliff Tunnel. Compost from an unknown source was used to amend the site. The biofilter was constructed in 2000.

Figure 43. Aerial view of the Silver Cliff Creek biofilter.

Field testing was conducted at the Silver Creek Cliff biofilter site in August of 2018. The biofilter extends over approximately a half of a mile along both trail sections and a short section of roadway as seen in Figure 35. The broader section of the biofilter has a moderate slope, sections along the trail are relatively flat. Sections of the biofilter along the trail and further north by the parking lot contained high amounts of gravel that made testing difficult. Sampling was carried out at the trail access point. Vegetation was initially cut to several inches in height and cleared from locations prior to testing. Soils from the site were sandy and contained some coarse aggregate as shown in Figure 45.

Figure 44. Biofilter along trail (left) and at the south trail access point (right) at the Silver Creek Cliff Tunnel.

Figure 45. Characteristic soil profile from the Silver Creek Cliff biofilter.

3.3 *In Situ* Testing

An *in situ* testing regimen was developed to establish the hydraulic capabilities of each biofilter. Testing was done to determine the saturated hydraulic conductivity, relative density, and the moisture content of the soil at each site. These parameters were considered as primary factors controlling the water transport abilities of each biofilter. Samples were also collected from field sites for laboratory testing.

3.3.1 *In Situ* Hydraulic Conductivity Testing

The ability for a biofilter to capture and treat stormwater runoff is largely dependent on the infiltration capabilities of its media. *In situ* hydraulic conductivity testing gives discrete values which can be used to estimate water passing performance. *In situ* testing measures infiltration by causing water to move into the soil under constrained conditions until the soil becomes saturated and this rate becomes constant as represented in Figure 46. The saturated hydraulic conductivity is the lowest rate of infiltration that a site will experience and is used as a conservative value for design purposes by MnDOT (2018).

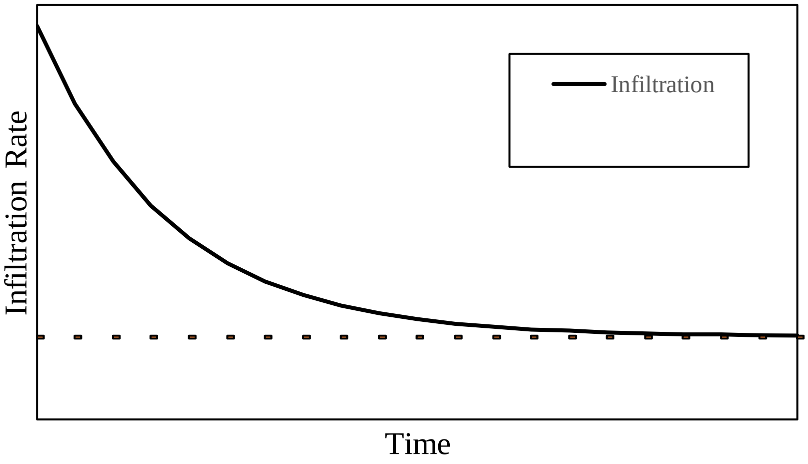


Figure 46. Correlation between constant infiltration and saturated hydraulic conductivity.

Figure 47. Modified Philip-Dunne Infiltrometer.

The primary device used for *in situ* hydraulic conductivity testing was the MPD infiltrometer, shown in Figure 47. The Saint Anthony Falls Laboratory (SAFL) produced a manual for device operation (Ahmed and Gulliver, 2012) which was followed during testing. The MPD determines surface values of saturated hydraulic conductivity with specific applications in stormwater BMP's (Nestingen, 2007). This method uses small volumes of water, has a relatively short run time, and device sampling can be run concurrently (Ahmed et al., 2014). Four tests were conducted at each site along with moisture content sampling per the MPD test procedure. Running multiple tests gave insight into the spatial variability of hydraulic conductivity and aided in determining each site's representative saturated hydraulic conductivity.

3.3.2 Dry Unit Weight

The *in situ* dry unit weight of the biofilter media was determined using the sand cone test which followed ASTM D1556 (ASTM, 2015). Part of the testing procedure involves the collection of soil at the site for the determination of the dry unit weight of the soil and the moisture content at the time of sampling. The dry unit weight of media samples taken from field sites were used to replicate field conditions during laboratory testing.

3.4 Laboratory Testing

Samples collected in the field were evaluated using the laboratory testing procedure developed by Johnson et al. (2017). The various tests conducted determined media classification, compaction properties, and hydraulic conductivity. These tests characterized relevant engineering properties and the water transport capabilities of media samples. The performance of alternative amendments was then compared to standard MnDOT media mixes (Johnson et al, 2017). This phase of research compared the results of laboratory and *in situ* testing to determine the ability for laboratory testing to accurately predict field performance. The results of laboratory testing and subsequent comparison to field results is presented in Chapter 4.

3.4.1 Media Sampling

An approximate volume of 15 gallons of media was taken at each site for laboratory testing. Each site was sampled at three locations. The media was obtained by removing the overlying layer of vegetation from a section of biofilter and excavating to the depth of amended soil. This method prevented excessive amounts of vegetation from entering the samples while also avoiding underlying, unamended soils. Samples were processed using a soil mixer to mitigate the effect of site variability on laboratory test results.

3.4.1 Media Classification

The Unified Soil Classification System (USCS), following ASTM D2487 (2017), was used to categorize media samples. The USCS method determines soil classifications using results from soil sieving and Atterberg limit tests. Using the procedure defined for the USCS method, sieving was conducted according to ASTM C136 (2014). Samples found to contain greater than five percent fines by mass (taken as media passing the No. 200 sieve) required additional testing to determine their Atterberg limits, found using ASTM D4318 (2017).

Prior to conducting these tests, ASTM D2487 (2017) requires samples identified as containing primarily organic material, peat soils, to be classified instead using ASTM D4427 (2018). This system uses the fiber content, ash content, pH, and absorbency of samples to determine appropriate designations for media. The fiber content of peat was found using ASTM D1997 (2013). The test for ash content was conducted according to ASTM D2974 (2014). The pH and absorbency of samples were determined following ASTM D2976 and D2980, respectively.

3.4.2 Compaction Testing

Compaction testing was used to identify the maximum dry density and optimum water content of media samples. This testing followed ASTM D698 (2012), commonly referred to as the standard Proctor test. For media sampled at various treatment sites, the sand cone test was used to determine the *in situ* relative density of soils following ASTM D1556 (2015). The relative density values were then used in laboratory testing to replicate field conditions. Peat samples that were taken as potential treatment amendments were disturbed prior to collection and no data existed for *in situ* relative density. The results of compaction testing were used to test peat samples at 85% of maximum dry density in hydraulic conductivity testing.

3.4.3 Laboratory Hydraulic Conductivity Testing

The falling head and constant head tests were used to determine the saturated hydraulic conductivity of media samples in a laboratory setting. These tests were intended to replicate field conditions and saturated hydraulic conductivities found during *in situ* testing. The constant head test was conducted according to ASTM D2434-06 (2006), the constant head test followed the testing procedure from Germaine and Germaine (2009).

The dry unit weight of samples, described in Chapter 3.2.3, was used to simulate field density of media in hydraulic conductivity testing. The sand cone test determined a moist unit weight and corresponding moisture content. Equation 6 shows how this is used to find the dry unit weight of soils. This equation can be rearranged to solve for the moist unit weight of a soil given moisture content. This was done to media samples prior to hydraulic conductivity testing to account for changes in moisture content during storage.

Equation 2. Weight volume relationship equation for dry unit weight of soil.

$$\gamma_{field} = \frac{\gamma}{1 + w}$$

Where γ_{field} is the dry unit weight of soil, γ is the moist unit weight of the soil in the field, and w is the moisture content of the soil as a percentage.

Compaction testing was conducted to determine 85% maximum dry density for peat samples that were collected from the Eagles Nest site. This level of compaction was determined in the first phase of testing to be an ideal value to mimic field conditions (Johnson et al., 2017).

3.5 Instrumentation and Monitoring

In situ and laboratory testing was conducted to characterize the water transport capabilities of biofilter media and inform the design of new media mixes. To fully characterize the performance of new mix designs, field implementation was required. Utilizing the results from the first phase of laboratory testing, a pilot test program was initiated and monitored using a data collection system record soil moisture and rainfall values. The data collected from the test plots was used to correlate increases in soil moisture to rainfall and compare various media mixes' infiltration ability. A newly constructed biofilter, amended with an alternative media recommended from the first phase of testing, was also selected for monitoring. The new biofilter was monitored using the same method of instrumentation and data acquisition.

3.5.1 Field Pilot Test

The pilot test started in the first phase of research compared compost and peat as biofilter media amendments. Testing was conducted at the Natural Resource Research Institute (NNRI) in Hermantown, Minnesota shown in Figure 48. A sloped section, adjacent to a parking lot, shown in Figure 49, was identified as an ideal location for constructing test plots. Following MnDOT (2016) guides, soils were mixed volumetrically in one-part native soils to one-part amendment. A total of six media beds were prepared with three containing native soil amended with compost and three containing native soil amended with peat. Each media bed measured three feet by three feet and contained a layer of engineered soil which was placed over a prepared sand drain layer as shown in Figure 50. An under drain was also placed at the bottom of each bed to promote drainage and to allow for sample collection.

Figure 48. The location of the NRRI pilot test plot.

Following construction, the site was instrumented with monitoring equipment. A data acquisition unit, shown in Figure 51, was installed to regularly sample soil moisture, rainfall, and ambient temperature. A single soil moisture probe, pictured in Figure 52, was placed centrally in each of the six media beds. The rain gauge, shown in Figure 53, and temperature probe, shown in Figure 54, were both placed in a central location near the data collection unit. Sensors were set to take samples once every 15 minutes. A solar panel, shown in Figure 55, was used to ensure a consistent power for the data acquisition unit.

Figure 49. Field pilot test plot at NRRI.

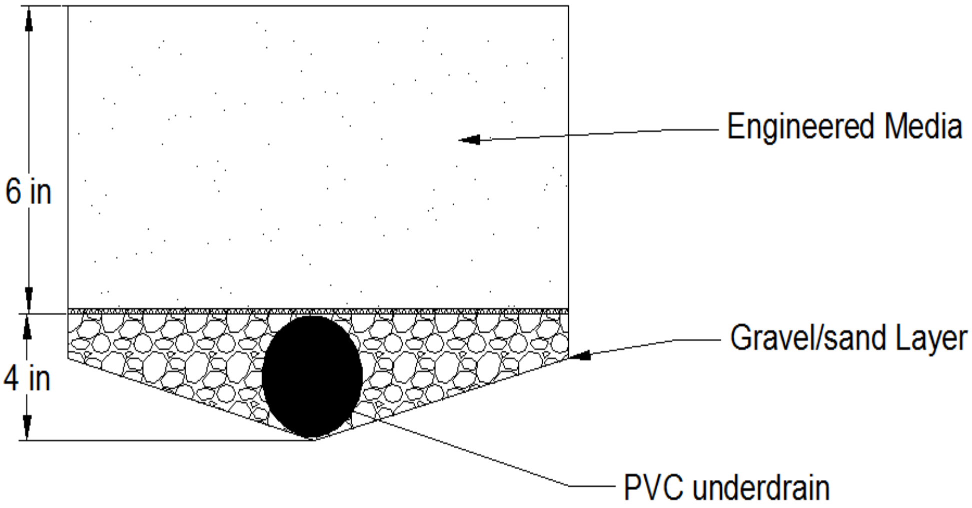


Figure 50. Cross section of media bed design (adapted from Johnson et. al, 2017).

Figure 51. Data acquisition unit used to record soil moisture, rainfall and temperature during monitoring.

Figure 52. Typical soil moisture probe used for monitoring.

Figure 53. Rain gauge monitoring unit.

Figure 54. Temperature probe with solar shield.

Figure 55. Solar panel used to sustain long term monitoring.

3.5.2 New Construction

Large scale field testing was required to verify the performance results shown from the pilot test and media characterization done by Johnson et al. (2017). The Eagles Nest Lake Area (Eagles Nest) project was identified in coordination with MnDOT as an ideal site for the development of a new biofilter. The Eagles Nest project realigned and updated a 5.7 mile stretch of Highway 1/169 west of Ely, Minnesota shown in Figure 56. Peat was considered readily available at the site, as wetlands and bogs are common to this region.

Figure 56. Location of the Eagles Nest Lake Area project in northern Minnesota.

3.5.2.1 Eagles Nest Peat

A site visit was conducted in June of 2017 to collect samples of potential peat amendments for the new biofilter. Three sites containing distinct grades of peat were identified at the project location. Site 1 was considered a low grade peat, Site 2 was considered a medium grade, and Site 3 was considered a high grade peat. Typical samples from the sites are shown in Figure 57. Media characterization was conducted following the methods discussed in Chapter 3.4.

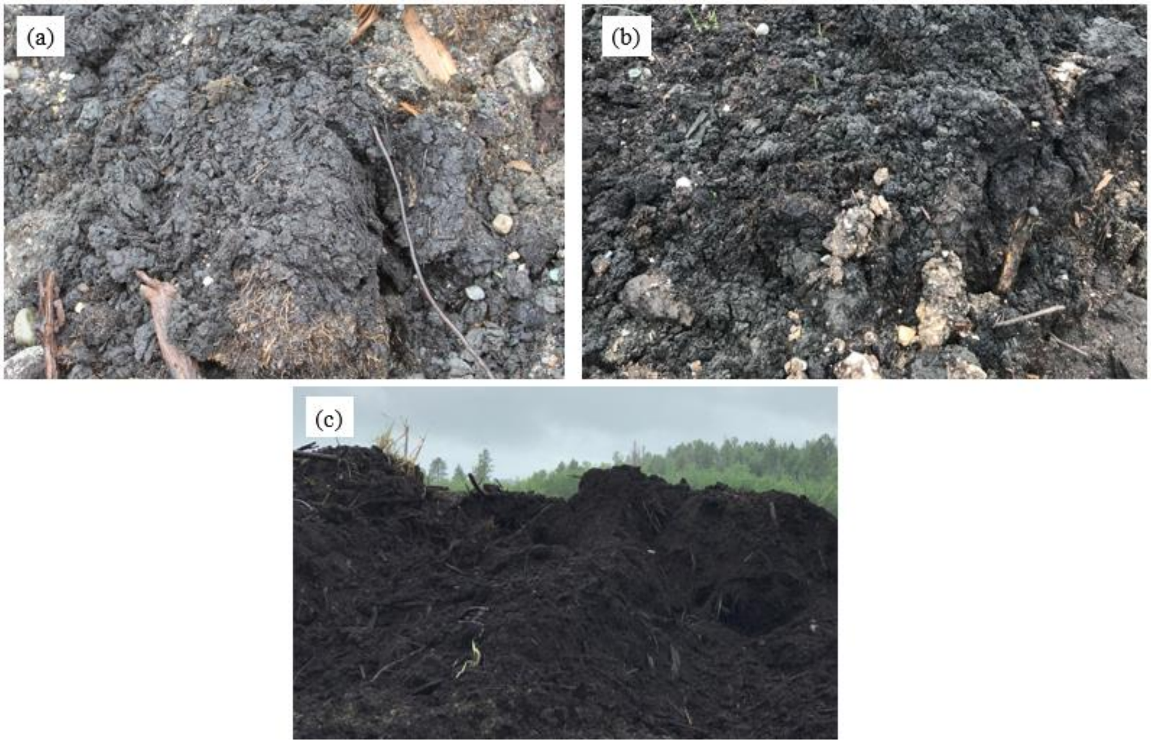


Figure 57. (a) Site 1 peat sample. (b) Site 2 peat sample. (c) Site 3 peat sample.

3.5.2.2 Eagles Nest Biofilter Design

Typical construction of the biofiltration system implemented at the site included a peat amended bioslope which flowed into a bioswale. Peat, shown in Figure 58, that was excavated from sections of the site was placed on slopes adjacent to roads at a depth of four inches and seeded. An infiltration bench, shown in Figure 59, was placed at the toe or cutoffs of sloped sections along the roadways. The swales contained an 80:10:10 by volume, mixture of sand, peat, and compost. A perforated pipe underdrain system was also placed at the bottom portion of the swale to promote drainage. The underdrain system was sleeved in a permeable membrane, as shown in Figure 60, surrounded by a layer of crushed rock and then wrapped in geomembrane to protect against silt clogging. An overflow outlet was also placed in each swale system to direct high volumes flows to zones of the slope designed to be erosion resistant.

Figure 58. Typical sample of peat used at the Eagles Nest Project site.

Figure 59. Bioswale construction at midpoint of hillside.

Figure 60. Permeable membrane sleeve and geomembrane placed at site to protect underdrain from clogging.

A section of bioslope, and adjacent bioswale, was selected for instrumentation and monitoring which began in August of 2018. The area monitored spanned over a 200-foot length of road and a 75-foot length of hillside. A set of nine soil moisture probes were placed at each end of the monitored slope area, in the center of the span and distributed throughout the swale as shown in Figure 61. A single rainfall gauge placed at the centrally located monitoring station and a temperature probe at the station monitoring the swale. Soil moisture and rainfall data was recorded to correlate changes in moisture with water uptake of the biofilter as with the pilot test. The temperature data allowed for periods of freezing temperatures to be identified and not included in the final analysis. Each monitoring station was connected to a solar panel to ensure a constant supply of power throughout deployment.

3.6 Conclusion

Chapter 3 summarizes the field and laboratory testing used to determine the hydraulic capabilities of biofilters and the instrumentation used for performance monitoring. The *in situ* testing conducted included relative density, moisture content and saturated hydraulic conductivity. These parameters were determined to be the key indicators to the infiltration capabilities of each biofilter and were important for making comparisons with laboratory testing. The laboratory characterization included formally classifying each media sample, compaction testing for disturbed media, and hydraulic conductivity testing.

The field monitoring portion of this research included a pilot test initiated by Johnson et al. (2017) and the monitoring of a newly constructed biofiltration system. Both monitoring schemes included soil moisture probes, rain gauges, temperature probes, a data acquisition unit, and a solar panel. These systems were designed to record the changes in moisture content in biofilter soils to correlate with the rainfall values. A detailed analysis of the data recorded and the results from field and laboratory testing will be discussed in the following chapter.

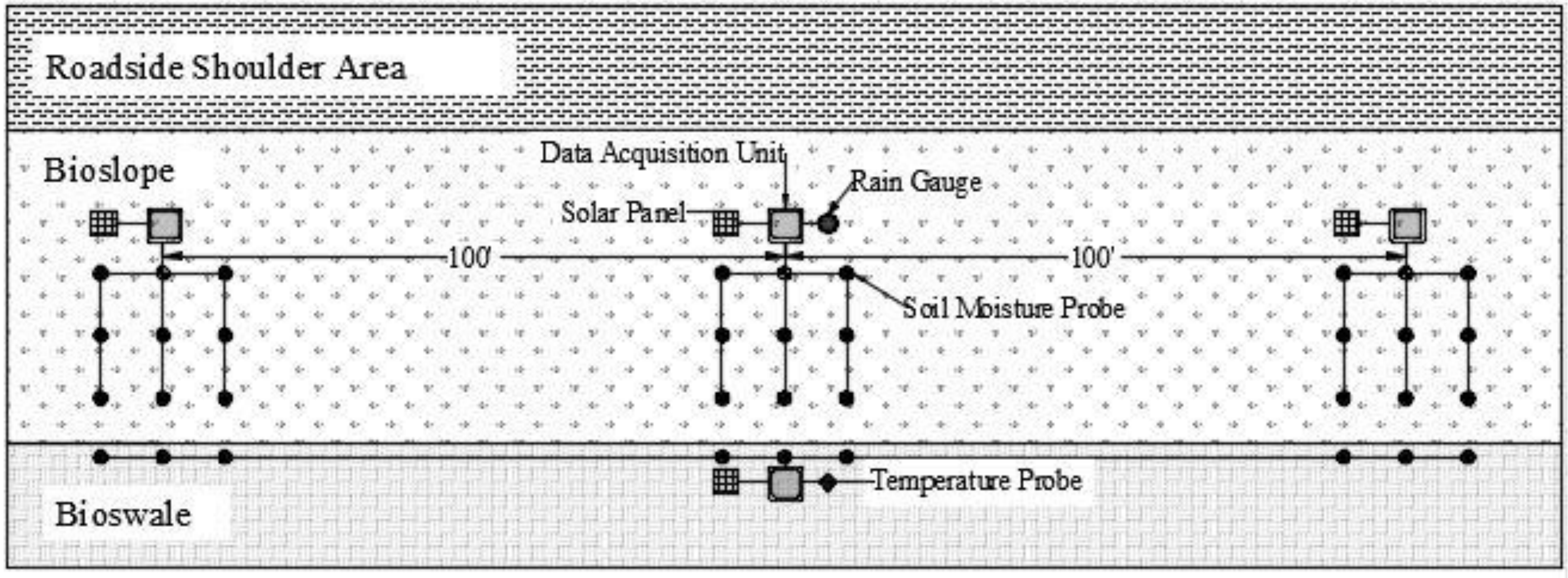


Figure 61. Biofiltration system monitoring schematic.

Chapter 4: Results

4.1 Introduction

Chapter 4 presents the results of *in situ* testing, laboratory characterization, and site monitoring. The *in situ* testing focused on identifying the site specific conditions of each biofilter, this included determining the relative density and the saturated hydraulic conductivity at each site. During laboratory testing, samples were first formally classified and then tested for saturated hydraulic conductivity. *In situ* and laboratory testing results are compared to assess the predictive capacity of laboratory methods. The time of construction and *in situ* saturated hydraulic conductivity is also used to determine the effect of age on biofilter performance.

Chapter 4 also evaluates the data collected from the pilot test plot and the newly constructed biofilter. Soil moisture and rainfall data was recorded at the sites to evaluate the systems' infiltration during storm events. A comparison between peat and compost amended biofilters is presented for the test plot. The new peat amended biofilter was analyzed for its ability to infiltrate the first inch of rainfall runoff and for spatial variations in infiltration capability.

4.2 *In Situ* Testing

In situ testing was conducted to characterize the water transport characteristics of each biofilter. The relative density and saturated hydraulic conductivity were considered primary factors influencing the infiltration capabilities at each site. The results of laboratory testing are discussed in this section along with a comparison to previous laboratory characterization.

4.2.1 Dry Unit Weight

The dry unit weight for each biofilter was determined to aid in reproducing field conditions during laboratory testing. The sand cone method, following ASTM D1556 (2015), was used to find the dry unit weight and moisture content at each site. Table 4 contains a summary of the test results.

Table 4. Results of in-situ relative density testing.

Sample Location	**Field Dry Unit Weight of Media (g/cm^3)**	**Field Dry Unit Weight of Media (lb/ft^3)**	**Moisture Content (%)**
Chaska	1.44	89.89	16.85
Cloquet	1.59	99.26	3.67
Cook	1.55	96.78	2.55
Crosby Site 1	1.32	82.41	20.42
Crosby Site 2	1.15	71.78	5.06
Grand Rapids Site 1	1.23	76.78	4.31
Grand Rapids Site 2	1.55	96.78	0.85
Grand Rapids Site 3	1.40	87.41	5.40
Gilbert Lake	1.08	67.41	9.74
West Duluth	1.29	80.52	10.35
Lilydale	1.05	65.56	20.47
Silver Creek	1.74	108.63	5.89
Eagles Nest Trench	1.27	79.30	16.85
Eagles Nest Slope	1.36	84.90	19.75

4.2.2 Hydraulic Conductivity

The MPD infiltrometer was used to find the saturated hydraulic conductivity for each biofilter. Testing followed the guidelines given by Ahmed and Gulliver (2012). The average value for saturated hydraulic conductivity is given for each site in Table 5. The value of saturated hydraulic conductivity of sandy soils were consistent with the laboratory values found by Johnson et al., shown in Table 6. The Silver Creek Cliff biofilter had the highest saturated hydraulic conductivity at 1.30 $*10^{-1}$ cm/s, this site also had a significant coarse aggregate content (see Appendix 1). The Cook biofilter was identified as a peat soil, being comprised primarily of organics and also containing clays. Soil from the Cook site still preformed with a saturated hydraulic conductivity consistent with the peat specimen characterized in Table 6.

Table 5. Results of MPD infiltrometer testing.

Sample Location	***In Situ* Saturated Hydraulic Conductivity (cm/sec)**
Chaska	$1.24*10^{-3}$
Cloquet	$4.13*10^{-2}$
Cook	$3.57*10^{-2}$
Crosby Site 1	$5.07*10^{-3}$
Crosby Site 2	$1.45*10^{-2}$
Grand Rapids Site 1	$2.90*10^{-2}$
Grand Rapids Site 2	$3.24*10^{-2}$
Grand Rapids Site 3	$1.36*10^{-2}$
Gilbert Lake	$2.76*10^{-2}$
Keene Creek	$1.31*10^{-3}$
Lilydale	$2.05*10^{-3}$
Silver Creek Cliff	$1.30*10^{-1}$
Eagles Nest Slope	$1.25*10^{-2}$
Eagles Nest Trench	$1.21*10^{-2}$

Table 6. Saturated hydraulic conductivity of various media (adapted from Johnson et al. 2017).

Media	Saturated Hydraulic Conductivity (cm/sec)
Sand	$6.0*10^{-3}$
Compost	$4.5*10^{-5}$
Peat	$3.9*10^{-3}$
Muck	$7.0*10^{-6}$

4.3 Laboratory Testing

The laboratory testing program was developed to replicate field conditions and characterize the infiltration characteristics of the biofilter media from each site. Media samples were first formally classified, and the hydraulic conductivity was revaluated.

4.3.1 Media Classification

The Unified Soil Classification System (USCS) following ASTM D2487 (2017) was used to formally identify the biofilter media samples. This was done to help describe samples and to aid in selecting the appropriate laboratory permeability test for each media. Soil samples were first dried and then sieved following ASTM C136 (2014). Most of the samples could be classified at this stage of testing as either poorly graded sands (symbol, SP) or well graded sands (symbol, SW). See Appendix 1 for media gradation results. The Atterberg limit testing, following ASTM D43189 (2017), was done on samples containing 5% or more fines to determine their sub classifications. The results of all media classification are shown in Table 7.

The USCS method requires soils that have a high organic content (over 50% by visual inspection) to be classified according to the standard for peat soils. ASTM D4427 (2018) was used to classify media sampled from the Cook biofilter which had a high organic content. The standard classification for peat requires additional testing to determine specific qualities of the peat which have by summarized in Table 8. The media sampled from the Cook biofilter was formally classified as a sapric, high ash, basic, and slightly absorbent peat.

Table 7. USCS designations for the biofilter media samples.

Sample Location	**USCS Classification**
Chaska	Poorly Graded Sand (SP)
Cloquet	Poorly Graded Sand (SP)
Cook	Peat (PT)
Crosby Site 1	Poorly Graded Sand (SP)
Crosby Site 2	Poorly Graded Sand with Silt (SP-SM)
Grand Rapids Site 1	Poorly Graded Sand (SP)
Grand Rapids Site 2	Poorly Graded Sand (SP)
Grand Rapids Site 3	Well Graded Sand with Silt (SW-SM)
Gilbert Lake	Poorly Graded Sand (SP)
West Duluth	Well Graded Sand (SW)
Lilydale	Poorly Graded Sand (SP)
Silver Creek	Well Graded Sand (SP)
Eagles Nest Slope	Poorly Graded Sand (SP)
Eagles Nest Trench	Poorly Graded Sand (SP)

Table 8. Standard parameters required for the classification of peat soils.

Parameter	ASTM Standard
Fiber Content	D1997 – 13
Ash Content, pH	D2974 – 14
Absorbency	D2980 - 04

4.3.2 Hydraulic Conductivity

Laboratory permeability characterization was conducted using the constant head and falling head tests. The constant head test followed ASTM D2434 (2006) which is specified for, “granular soils containing not more than 10 % soil passing the 75-m (No. 200) sieve.” The falling head test followed the methods developed by Germaine and Germaine (2009) and was used to test the permeability of peat soils. The results of testing are summarized in Table 9. The saturated hydraulic conductivity determined for the biofilters were at or above that of sandy soils, shown in Table 6, indicating strong infiltration capabilities. There was no clear performance difference between peat and compost amended biofilters.

4.4 Comparison of Methods

The laboratory characterization methods were developed as a potential predictive tool for evaluating the performance of biofilters (Johnson et al. 2017). Looking at a comparison of the results from both methods, as presented in Figure 62, there did not appear to be a clear trend for laboratory testing over or under predicting field performance. There is the potential that relative density at the various sites was not robust enough to account for the high variability that can be encountered in any field site’s media. Due to the high variability of hydraulic conductivity the results found that were within an order of magnitude between the two methods could be considered relatively the same.

Table 9. The results of laboratory permeability testing.

Sample Location	**Laboratory Saturated Hydraulic Conductivity (cm/sec)**
Chaska	$5.63*10^{-3}$
Cloquet	$8.31*10^{-3}$
Cook	$8.05*10^{-3}$
Crosby Site 1	$8.97*10^{-3}$
Crosby Site 2	$1.68*10^{-2}$
Grand Rapids Site 1	$6.61*10^{-2}$
Grand Rapids Site 2	$8.82*10^{-3}$
Grand Rapids Site 3	$6.66*10^{-3}$
Gilbert Lake	$1.00*10^{-2}$
Keene Creek	$2.53*10^{-2}$
Lilydale	$3.70*10^{-3}$
Silver Creek Cliff	$7.62*10^{-2}$
Eagles Nest Slope	$1.59*10^{-3}$
Eagles Nest Trench	$3.86*10^{-3}$

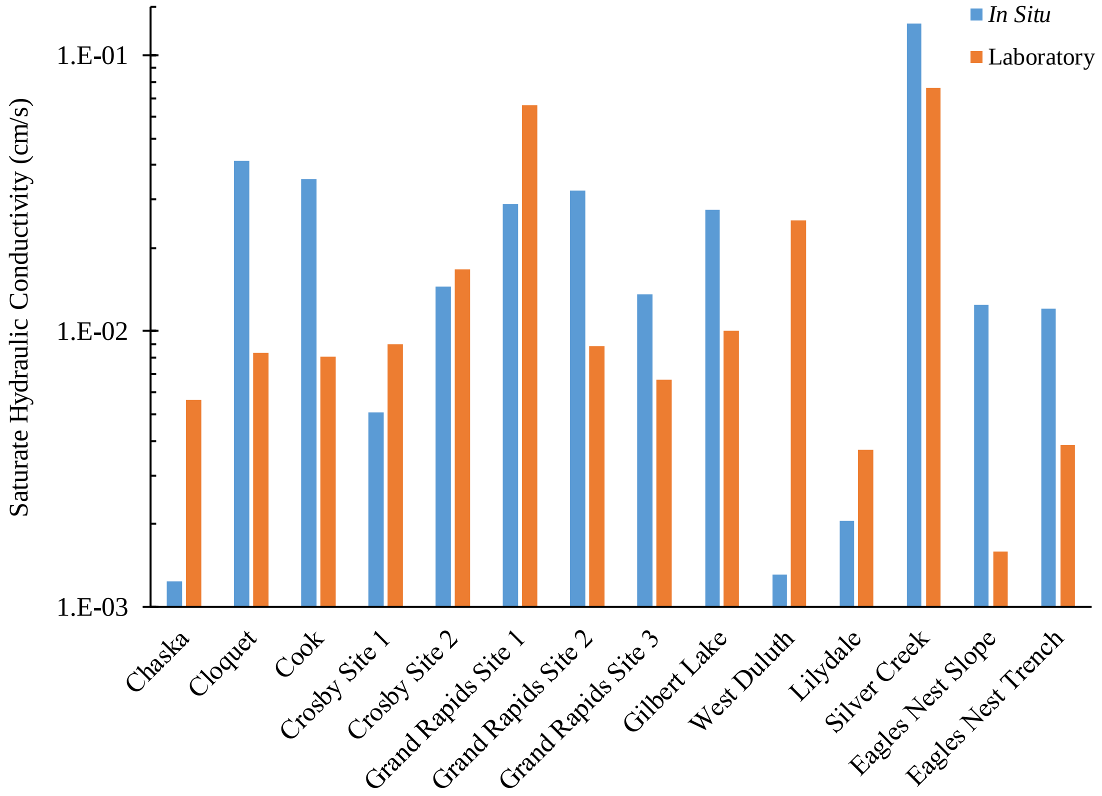


Figure 62. Comparison of *in situ* and laboratory hydraulic conductivity testing.

4.5 Effects on Biofilter Performance

Understanding how biofilters preform over time is a key aspect to determining the life cycle cost and viability these systems. Biofilters included in this study were investigated one time post construction (the summer of 2018). An evaluation of the change in saturated hydraulic conductivity over time for individual biofilters was not possible due to the length of this work. Biofilters have instead been compared by the year of their construction and their measured infiltration rates which has been represented in Figure 63. This comparison does not lead to a significant relationship between the age of a biofilter impacting performance.

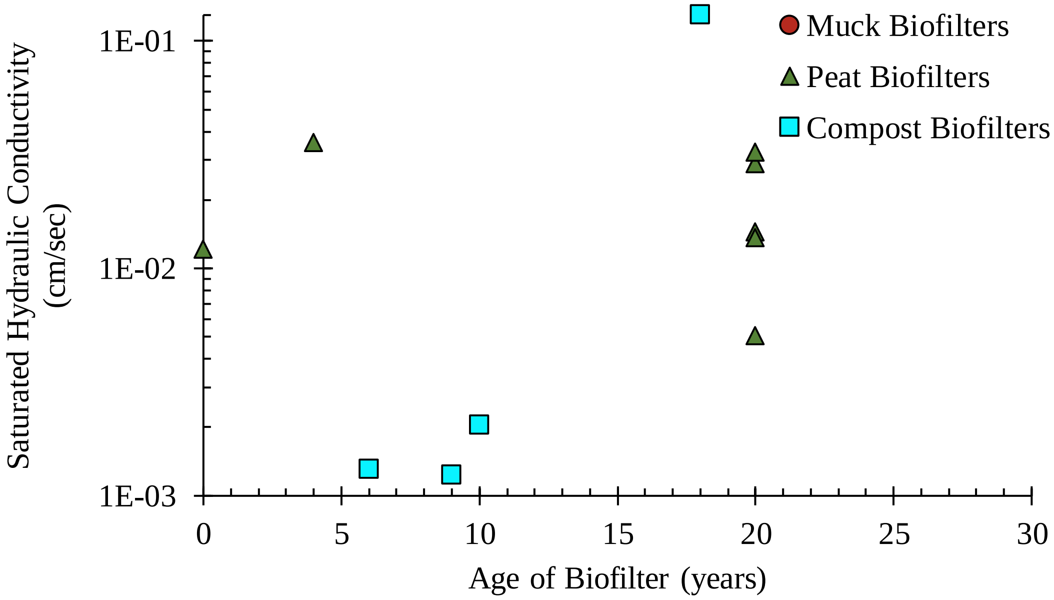


Figure 63. The saturated hydraulic conductivity versus the age of the various biofilters

4.6 Performance Monitoring NRRI

NRRI, located in Hermantown Minnesota, was selected as an ideal location for the development of a pilot test plot in the spring of 2017. The plot included three beds of native soils amended with compost and three amended with peat. The site was then instrumented with a soil moisture probe for each bed, a rain gauge, a temperature probe, and a solar panel to ensure a constant power source for the array. A more detailed description of the site and the monitoring set up is given in Chapter 3.4.1.

This instrumentation scheme allowed for correlations between rainfall data and changes in soil moisture content as shown in Figure 64. The site was evaluated from April to October in 2017 and in the following year from May to November. The temperature probe was used to identify freezing temperatures at the site which indicated periods that should not be analyzed.

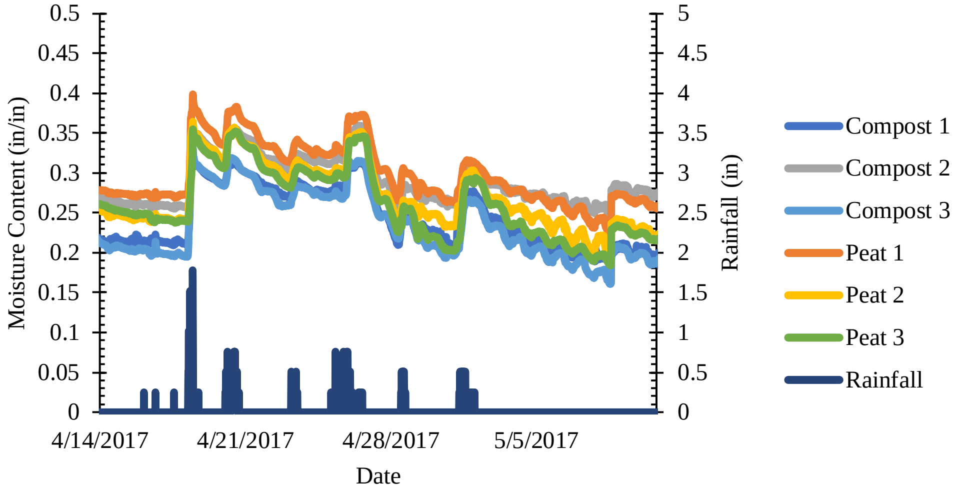


Figure 64. Soil moisture and rainfall event data for the NRRI test plot during the spring of 2017.

The readings at the site were analyzed for pre-rainfall event moisture content and peak moisture content for each plot. The change in moisture content for each rainfall event was calculated as average from the respective compost and peat plots. Figures 65 and 66 summarize the average moisture content change for peat and compost plots during rainfall events in 2017 and 2018 respectively. The comparison of average increase in moisture content indicates that peat and compost experienced comparable moisture increases for the period monitored.

It should be noted that the field site experienced equipment tampering during the summer of 2018. One of the soil moisture probes placed in a compost amended bed was destroyed June 6th, 2018. The probe was replaced September 15th after the discovery of tampering was made. Averages for soil moisture were taken from the remaining two soil moisture probes during the time when the third probe was broken.

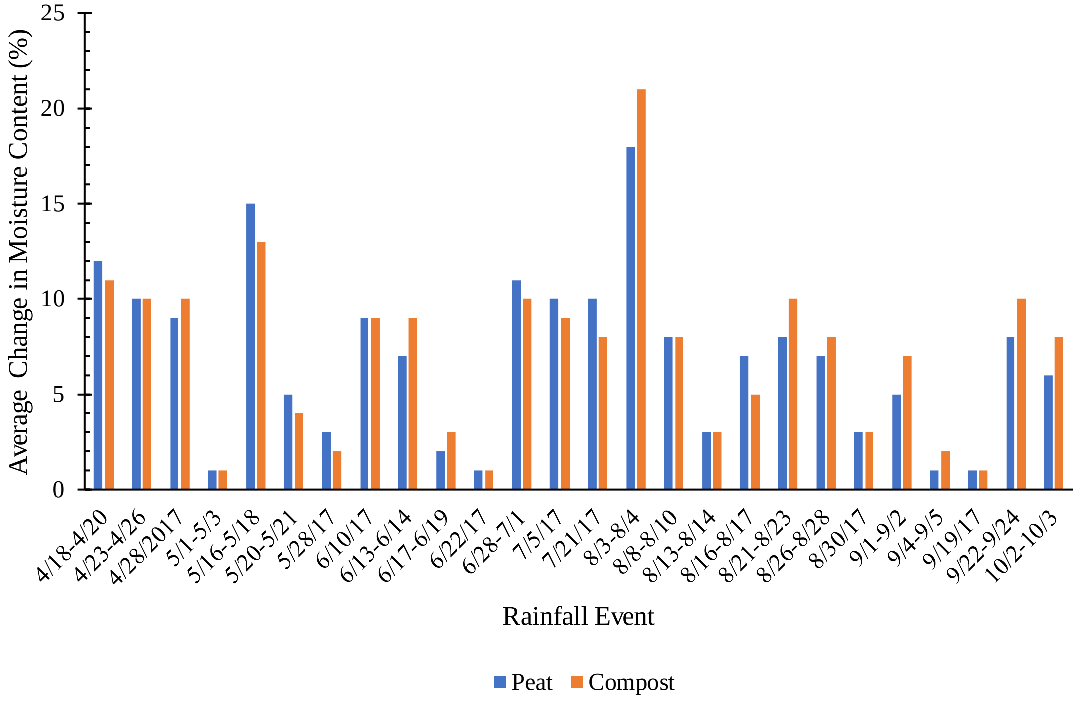


Figure 65. Comparison of water absorption for the NRRI pilot plot for 2017.

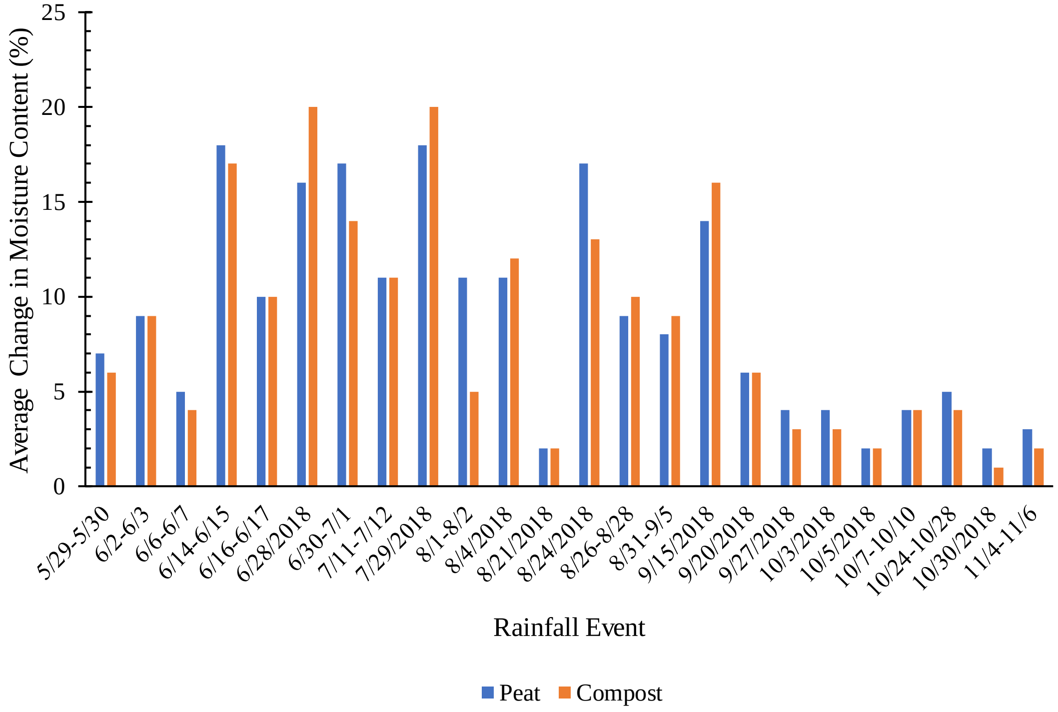


Figure 66. Comparison of water absorption for the NRRI pilot plot for 2018.

The soil moisture data was also analyzed using several methods to determine the amount of water captured by the biofilter media during storm events. The data was initially aggregated by using rain gauge and soil moisture readings to identify the date and duration of storm events. Soil moisture data was then averaged for the peat plots and compost plots at each time step for the identified storm events. The minimum soil moisture value was then found for each event and was considered as the initial moisture content. A summation of rainfall readings was used to determine the total rainfall for each event.

The soil moisture data was then evaluated using weight volume relationships to determine the height of water captured by each biofilter during storm events. This process included using the depth of media for the biofilters (6 inches), assuming a total evaluated volume of 1 cubic foot, and assuming a specific gravity of 2.65 for both medias. The height of water captured was then determined for each time step during the various storm events.

The first method used to evaluate the water capture ability of the biofilters was a summation of the change in height of water for each storm event. Positive values for change in water caught corresponded with water absorption or infiltration, negative values corresponded with the soil drying. Negative values for change in water caught were common in rain events that were intermittent and occurred over long time periods. The drying effect was deemed to skew the biofilter capture ability and produce underestimated values for performance.

A summation of only positive change in height of water captured values was conducted to eliminate the drying effects impact on the performance analysis. The values of captured water were then compared to total rainfall for each storm event. There were a considerable number of storm events for both biofilters that showed captured water values that were higher than total rainfall values. This could have resulted from the biofilter media having a much higher hydraulic conductivity than surrounding soil, causing water to flow into the biofilter from surrounding soil. There is also the possibility that in high intensity rainfall events, native soils became saturated and overland flow began to direct additional stormwater to the biofilters. Without a way to distinguish additional water volumes from actual capture volumes the positive summation value was found to overestimate biofilter performance.

The data was also analyzed by taking the difference in pre and post rainfall moisture content to determine the height of water captured. A ten point average was taken for moisture contents just prior to rainfall occurring and following the end of the storm event. The total height of water captured was then compared to rainfall values. The pre and post difference method produced reasonable capture values for storm events that were short in duration with constant rainfall throughout the event. The data for long duration or intermittent storm events showed capture values that were consistently lower than total rainfall values. The initial moisture content for all storms fell within the ten point average taken for the pre event value. The peak moisture content value tended to happen prior to the end of storm events. Often, soil drying would already have begun to occur and the ten point post event average was significantly lower than the peak moisture content value. The difference between the pre and post averages for long duration and intermittent storms produced artificially low capture values due to the drying effect. The pre and post average difference method was not suitable for evaluating the majority of storm events which occurred due to the events with skewed capture values.

To alleviate the effect of low post event moisture content values on the analysis the data was evaluated using the difference between the minimum and maximum soil moisture content values. The minimum and maximum difference method did have storm events where the determined height of water captured was greater than the rainfall total. The increased capture capacity could be explained again by either increased infiltration capacity absorbing water from adjoining native soil or potentially by overland flow directing additional water to the biofilters. The minimum and maximum difference method was considered to be the best representation of biofilter capture capacity and was used for the following analysis.

Figure 67 shows rainfall event totals as compared with water captured by the biofilters. The data indicates a near one to one relationship during smaller volume rainfall events where the biofilters were able to efficiently infiltrate rainfall. The data becomes less grouped as rainfall volume increases. The greater rainfall events do not have the same linear relationship that the smaller events have. The larger event data appears to experience a limited infiltration rate which is potentially linked to the saturated hydraulic conductivity of the media. During lower intensity events there are points that indicate a height of water caught that is greater than the event rainfall intensity. Due to the increased infiltration capability of the biofilter media there is the potential that moisture was absorbed from the surrounding soil and caused artificially high values. Peat and compost had comparable results in this comparison with no clear over or under performer.

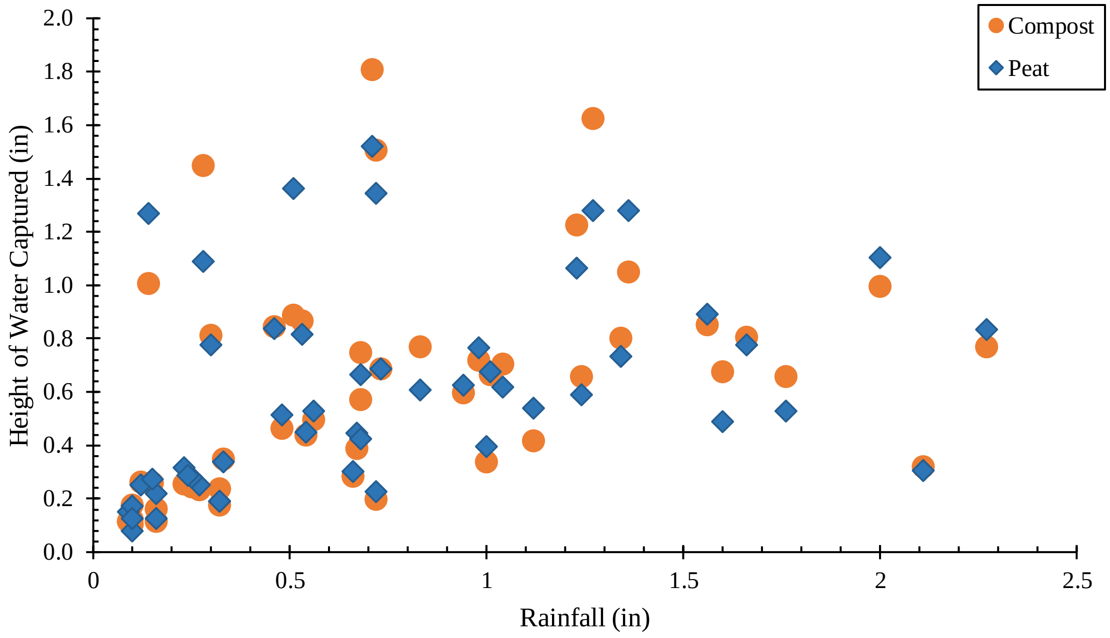


Figure 67. Comparison of rainfall total with water captured by peat and compost amended biofilters.

The soil moisture data was also analyzed for the effect of the initial moisture content on biofilter infiltration capabilities. The amount of water captured by each biofilter was normalized against rainfall totals and plotted against initial moisture content for the respective events as shown in Figure 68. There is some variance in the data with a clear trend around a value of one for the ratio of height of water captured to rainfall total which is ideal for biofilter performance. Lower initial moisture content values did coincide with unusually high values of normalized infiltration which could be attributed to the same phenomenon discussed above. There is a clear trend in the data at higher initial moisture contents to a less varied and lower infiltration performance. The end behavior of this plot also alludes to a limiting saturation point for the media that controls the infiltration capabilities.

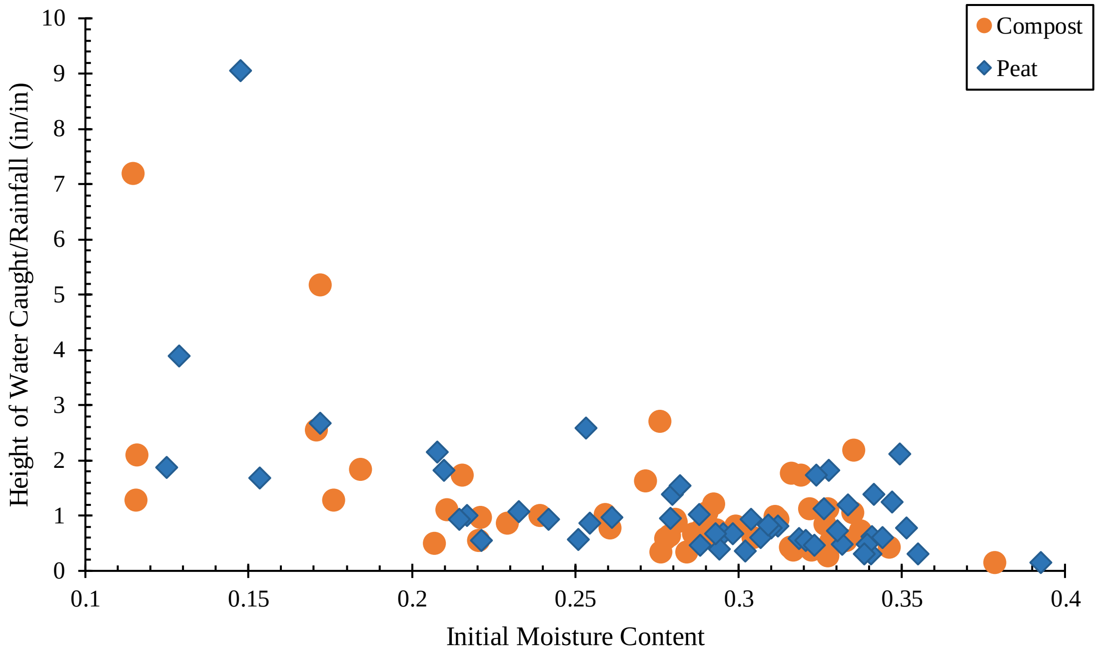


Figure 68. Initial soil moisture content compared to normalized rainfall and infiltration data.

Prolonged storm events also appeared to have an impact on the infiltration capabilities of the biofilters. Figure 69 shows the amount of water caught by each biofilter compared with the duration of storm events. Figure 70 evaluates the normalized storm event data (height of water caught divided by rainfall total) against time. These two comparisons of the data show very similar behavior between the peat and compost amended biofilters with no clear superior performance. Both biofilter types seemed to experience a wide range of infiltration capabilities during short duration events with more consistent (or limited) behavior during longer duration events. The high absorption capabilities and limiting saturation behavior is the most likely reasons for this behavior.

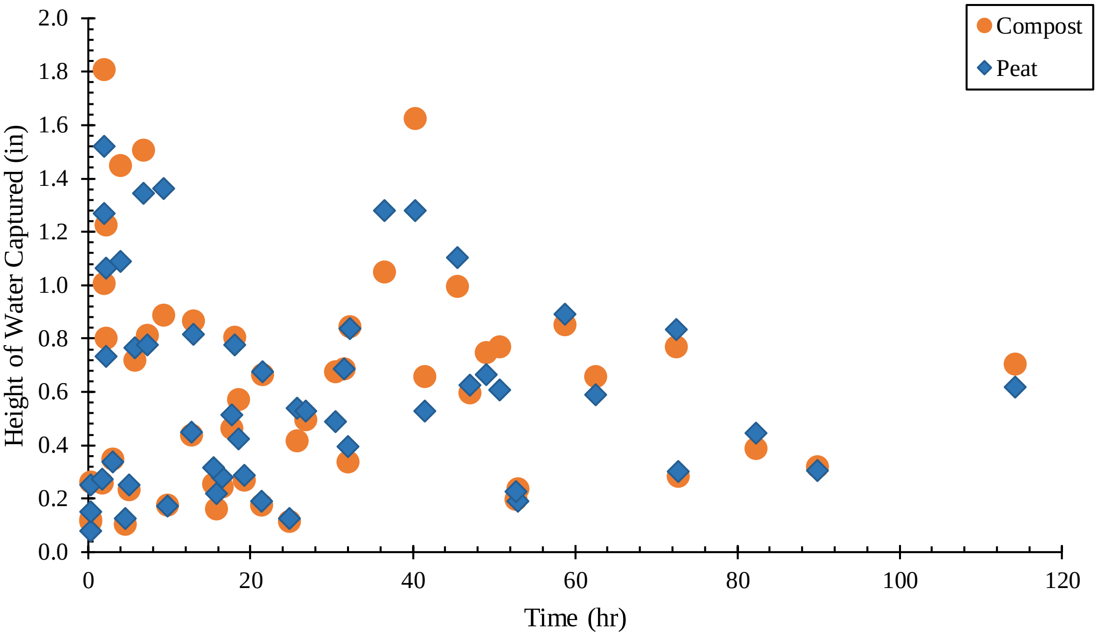


Figure 69. Infiltration compared to rainfall event duration.

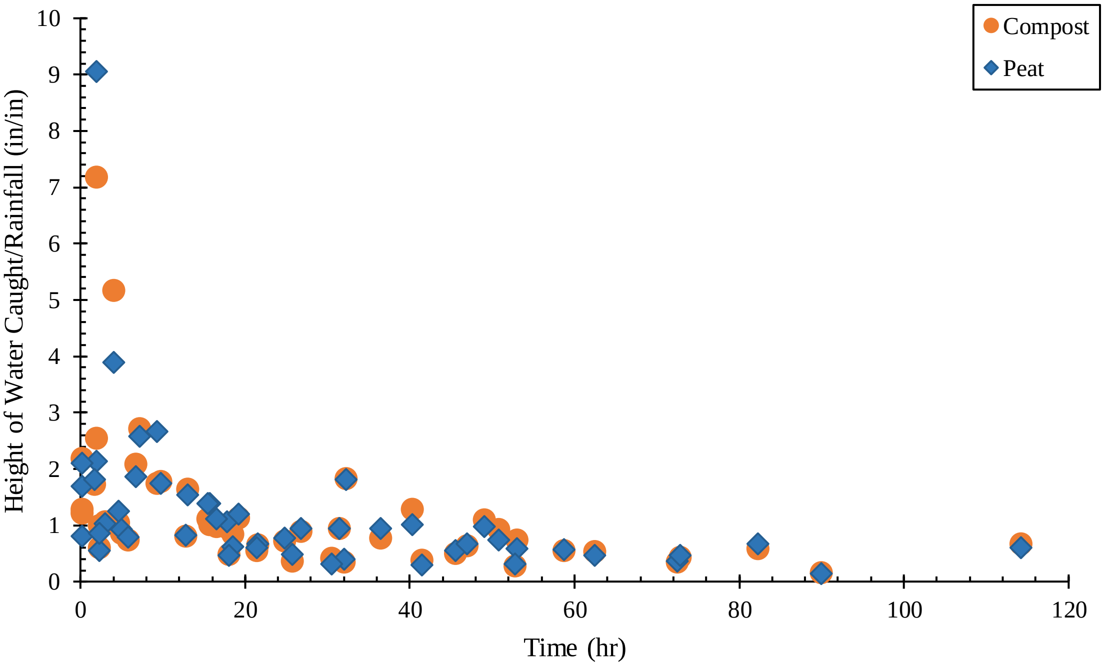


Figure 70. Normalized rainfall and infiltration data compared with rainfall event duration.

4.7 Eagles Nest

The recommendations of Johnson et al. (2017) led to the selection of the Eagles Nest project for the construction of a new peat amended biofilter. The site was ideally located in a native wetland area where peat would be readily available. Potential media amendment samples were taken during initial construction at the site for characterization. The results of testing were compared to previous classification of biofilter amendments and current MnDOT standards. Following initial construction at the site, a section of the biofilter was selected to be characterized and instrumented. Soil moisture probes, a rain gauge, and a temperature probe were placed at the site for continuous monitoring following completion of the project in August 2018. A more detailed description of the site and the monitoring set up is given in Chapter 3.4.2.

4.7.1 Characterization of Eagles Nest Peat

A site visit was conducted during early phases of construction at the Eagles Nest project to collect samples of potential peat amendments for the new biofilter. Three sites containing distinct grades of peat were identified at the project location, see Chapter 3.5.2.2 for detailed description. Samples were taken from each site and characterized using laboratory methods described in Chapter 3.3. The results of testing were then compared to current MnDOT media amendment standards and previous characterization of biofilter amendments from Johnson et al. (2017).

Grade 2 Compost is designated by MnDOT (2018) for filter topsoil borrow, or filtration media. Specification 3890 gives a physical description of compost as, “a natural hummus product,” being similar in texture to peat. Grade 2 Compost is considered a planting medium that must comply with the requirements outlined in Table 10. To improve the infiltration characteristics of compost MnDOT requires compost to be mixed with sand for filter topsoil applications. Current mixture recommendations range from 40% to 60% compost with 60% to 40% sand.

Table 10. Grade 2 Compost requirements specified by MnDOT (2018).

Requirement	Range
Organic matter content	≥ 30 %
C/N ratio	6:1 – 20:1
NPK ratio	1:1:1
pH	5.5 – 8.5
Moisture content	35% – 55%
Bulk density	700 lb per cu. yd – 1600 lb per cu. yd
Inert material*	< 3% at 0.15 in
Soluble salts	≤ 10 mmho per cm
Germination test**	80% – 100%
Screened particle size	≤ ¾ in

* Includes plastic bag shreds.

** Germination test must list the species of Cress or lettuce seed used.

The peat sample required alternative testing for proper classification. ASTM D4427 (2018) was followed to characterize the media and required conducting fiber content testing (ASTM, 2013), ash content (ASTM, 2014), and absorbency testing (ASTM, 2017). Results of these tests classified Site 1 as sapric, high ash, slightly acidic, slightly absorbent peat. Site 2 classified as sapric, high ash, moderately acidic, slightly absorbent peat. Site 3 classified as sapric, high ash, slightly acidic, slightly absorbent peat. The peat sampled in previous research was also identified as sapric, high ash, slightly acidic, and slightly absorbent peat (Johnson et al., 2017). A summary of the classification testing results is given in Table 11.

Table 11. Summary of results for the classification of peat samples from Eagles Nest.

Testing Parameter	**Site 1**	**Site 2**	**Site 3**
Fiber Content	3%	16%	23%
Ash Content, pH	95.2%, 6.8	75%, 5.2	57%, 5.6
Absorbency	65.99%	72.74%	186.42%

Compaction testing was conducted following physical classification to determine the maximum dry density and optimum moisture content of each media. The standard Proctor test was conducted following ASTM (2012) to determine the compaction curve for each peat sample. Figures 71-73 represent the results of compaction testing conducted with a summary of the optimum moisture contents and dry densities shown in Table 12.

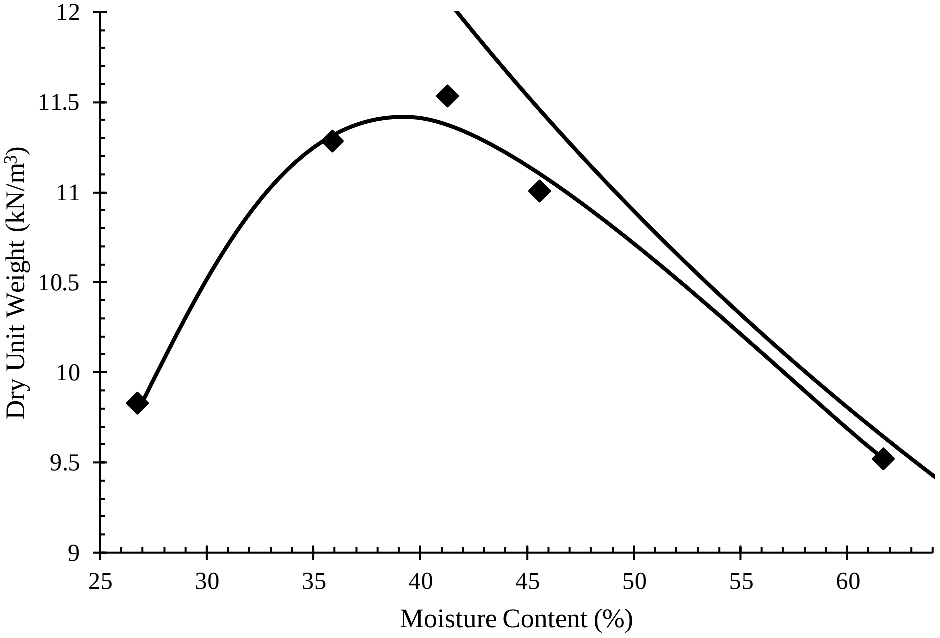


Figure 71. Compaction testing results for Site 1.

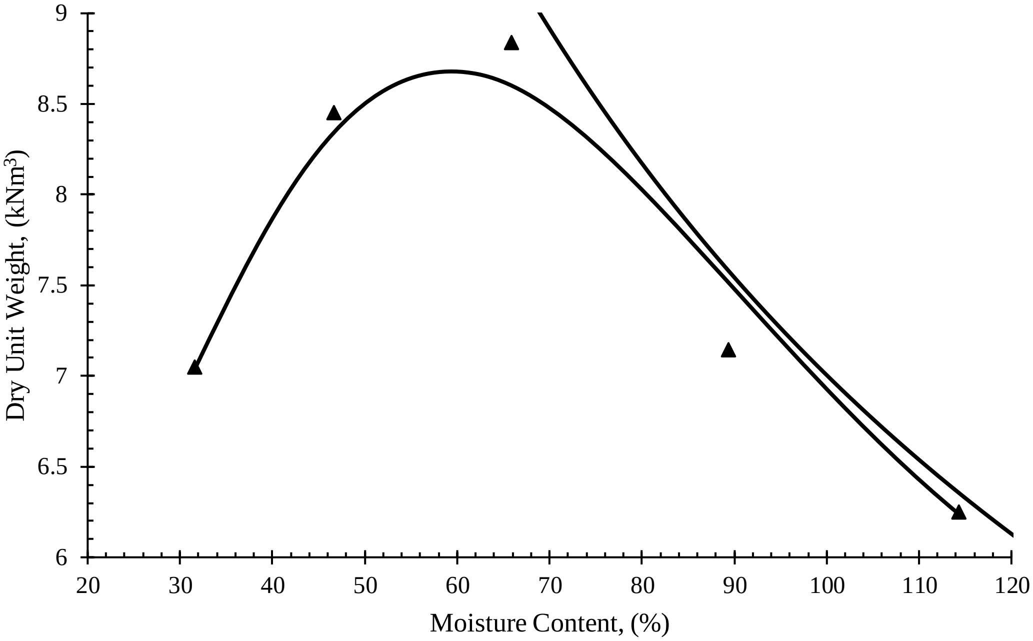


Figure 72. Compaction testing results for Site 2.

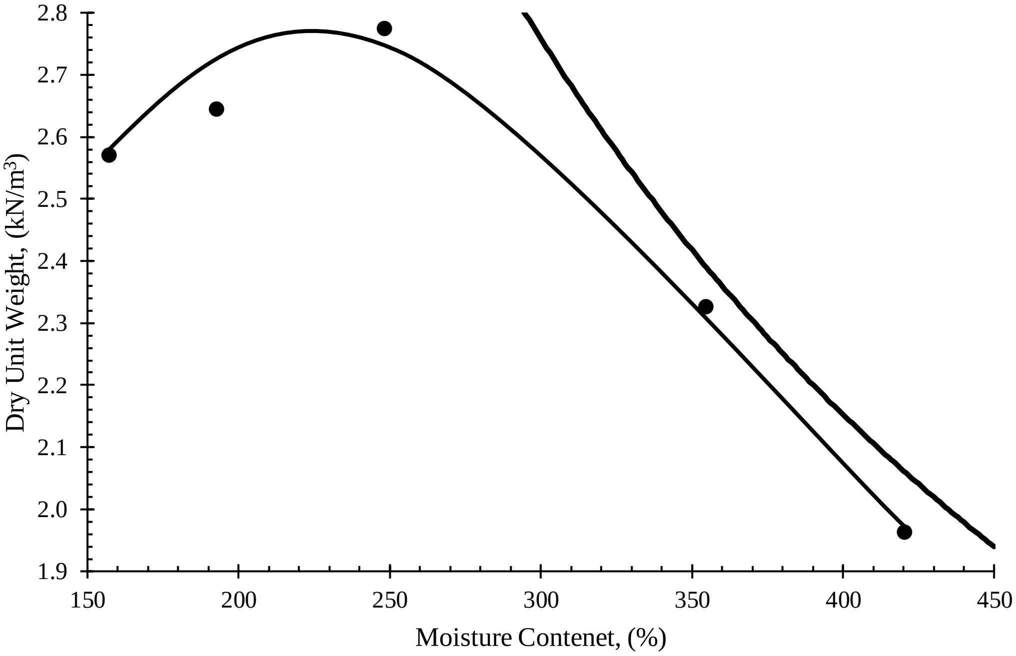


Figure 73. Compaction testing results for Site 3.

Table 12. Results of compaction testing.

Peat Sample	Maximum Dry Density (kN/m^3)	Optimum Moisture Content (%)
Site 1	11.6	39%
Site 2	9.61	55%
Site 3	2.81	235%

These results of compaction testing were used to determine a relative density of 85% for each peat sample for use in hydraulic characterization of the media. This method followed the procedure outlined by Johnson et al. (2017) that was designed to replicate field conditions during the laboratory characterization of biofilter media samples. The hydraulic conductivities of the three peat samples were then determined using the falling head test following the method given by Germaine and Germaine (2009).

The results of testing are summarized in Table 13, the previous characterization of peat and MnDOT grade compost are presented in Table 6. These tests showed that the peat samples from the three Eagles Nest sites had hydraulic conductivities that were slightly lower than the previously characterized peat but were still comparable to MnDOT grade compost.

Table 13. Saturated hydraulic conductivities of peat samples from Sites 1-3.

Peat Sample	Saturated Hydraulic Conductivity (cm/sec)
Site 1	$3.5*10^{-4}$
Site 2	$2.8*10^{-5}$
Site 3	$1.7*10^{-5}$

4.7.2 Performance Monitoring

Instrumentation was installed at the Eagles Nest in August of 2018. A total of 12 rainfall events were recorded for the Eagles Nest site during the time that instrumentation was deployed. It should be noted that the rain gauge placed at the site initially malfunctioned and was unable to record data for the first several weeks of deployment. A detailed analysis of the data for the site also revealed issues with the two of the soil moisture probes that were consistent with faulty sensors. Figure 74 shows the labeling scheme used to identify the sensors at the site and the faulty sensors which were excluded from the data analysis.

Changes in moisture content were evaluated in a similar manner to the pilot plot. Changes in soil moisture data was initially analyzed for the site for a total of 11 rainfall events. Figure 75 summarizes the average soil moisture increases for different sections of the biofiltration system for each storm event. There was not a clear trend for soil moisture adsorption corresponding to location on the slope. The data instead seems to reflect a high variability in hydraulic conductivity across the site.

Physical properties of the media were used along with weight volume relationships to evaluate the height of water captured for storm events at the site. The data was aggregated and analyzed in a similar manner to the pilot plot discussed in Chapter 4.6. Soil moisture values for the site were determined by taking a global average of probes placed on the slope. Values from the bioswale were not considered due to the difference in media and geometry. The minimum and maximum difference method was used to determine biofilter stormwater capture performance.

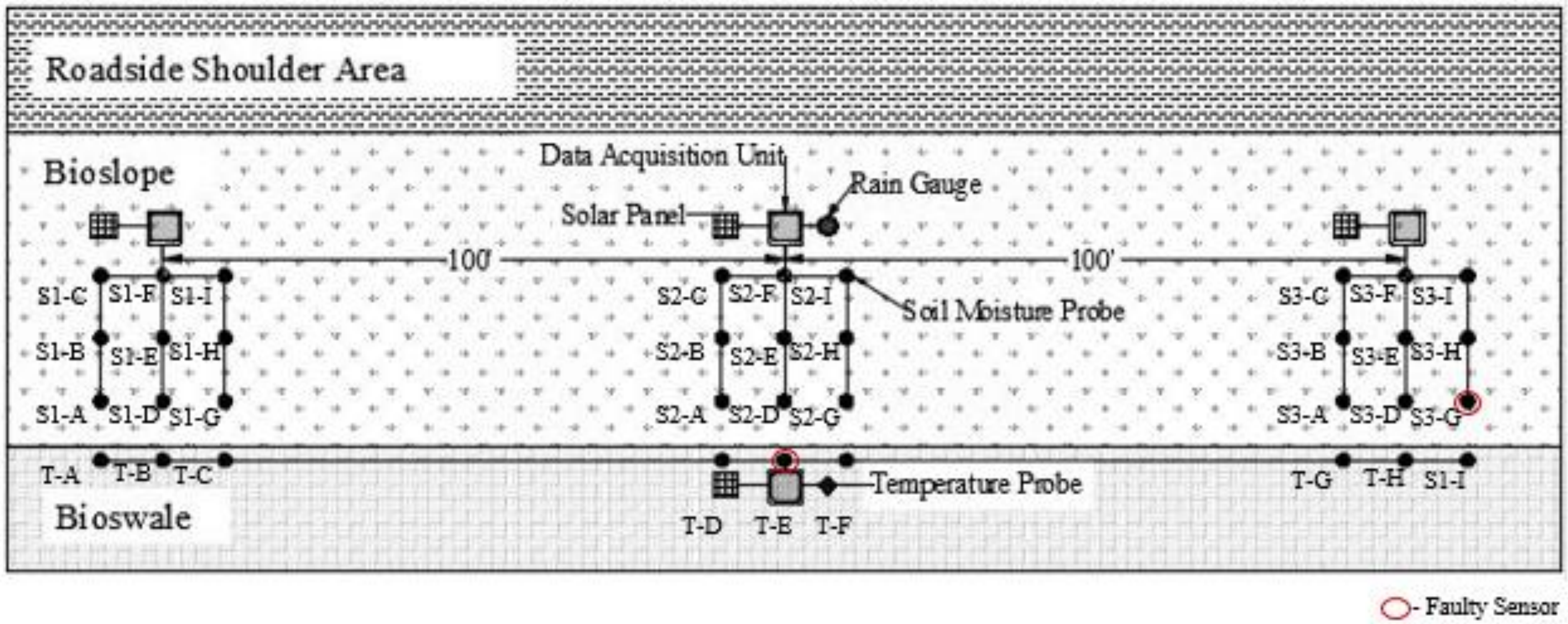


Figure 74. Sensor labeling scheme with faulty sensors identified.

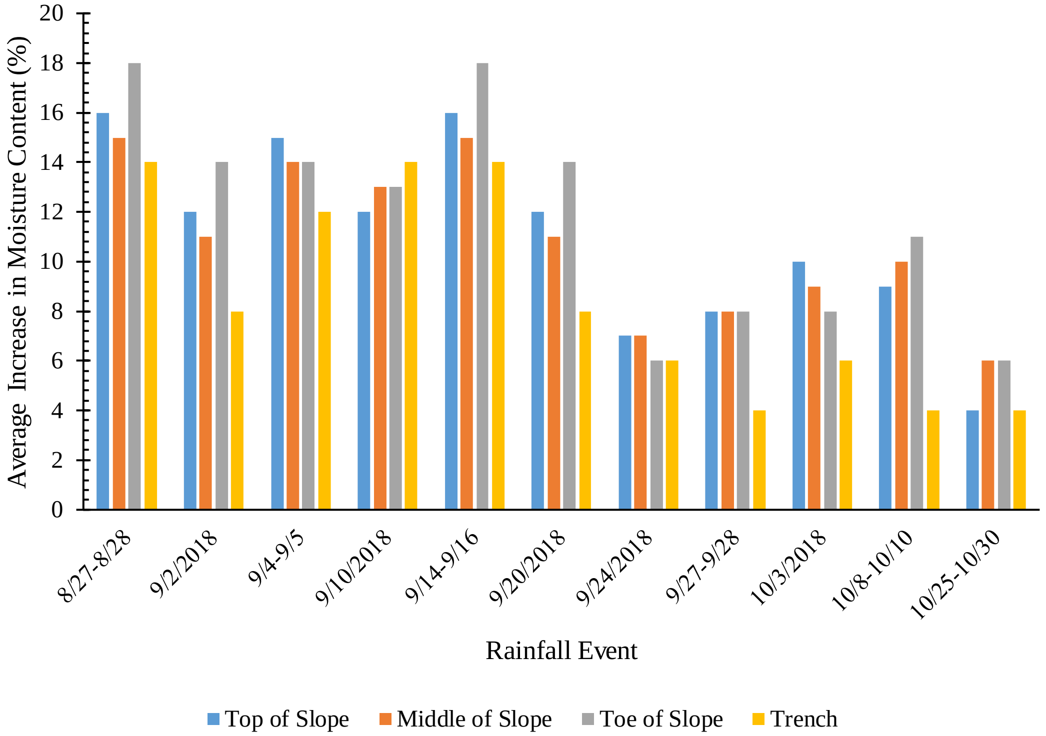


Figure 75. Comparison of water absorption over the course of the slope for the Eagles Nest biofiltration system.

Figure 76 represents the height of water captured against total rainfall for each storm event with values from the pilot plot given for reference. The capture results from the Eagles Nest data shows results consistent with the pilot plot biofilters. Lower volume rainfall events experienced near one to one capture rates with higher volume events somewhat having a less linear relationship. Similar to the pilot test biofilters, the initial linear relationship indicates the ability to infiltrate the first inch of rainfall during storm events.

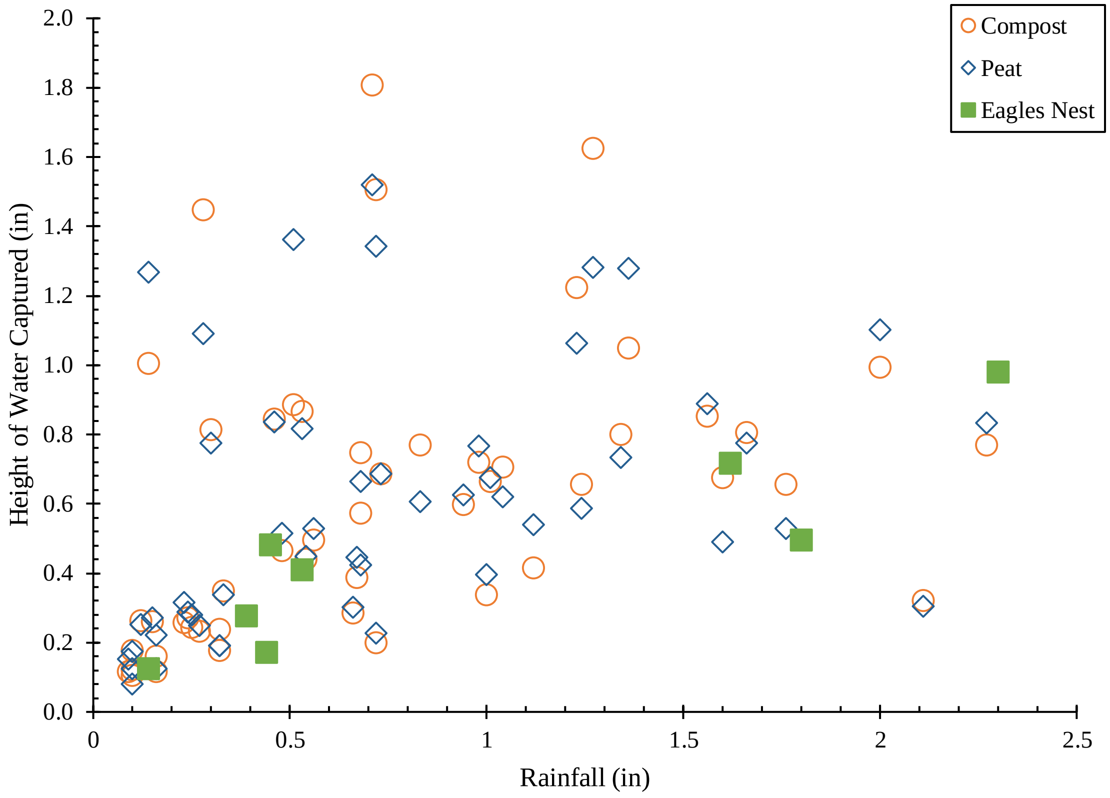


Figure 76. Comparison of water absorption against rainfall events.

The majority of the rainfall events recorded at the Eagles Nest site had a relatively high initial moisture content as compared to the pilot plot. Figure 77 gives a comparison of normalized infiltration against moisture with most of the data grouped around an initial moisture content of 30%. More data is required to accurately assess the low moisture content behavior of the site although the one recorded event did appear to not be able to efficiently the rainfall event. In this case, the peat at the site could have potentially dried to a point were hydrophobic conditions were activated in the soil, causing slowed water transport response.

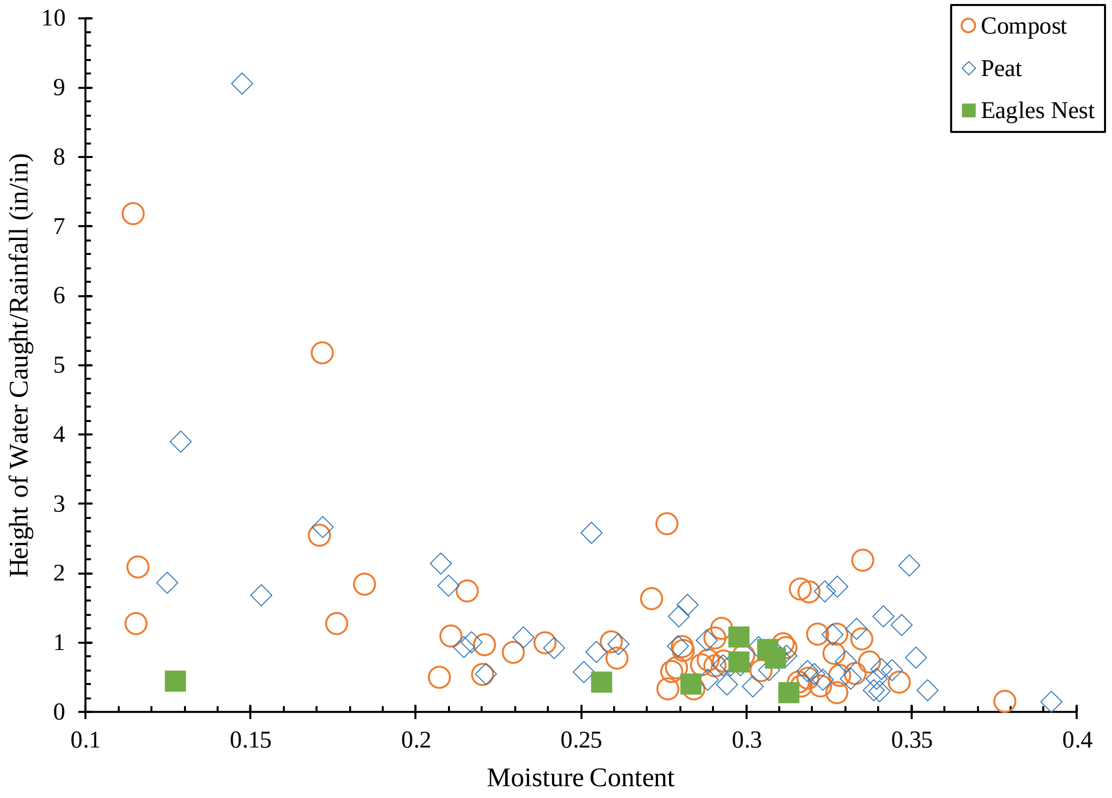


Figure 77. Comparison of normalized rainfall event data against initial moisture content.

The duration of rainfall events did appear to have a similar behavior at the Eagles Nest site as at the pilot plot. Figure 78 shows scattered data during short duration storms with values that tend towards approximately 0.5 inch of rainfall caught for longer duration storms. More data is needed to accurately assess the behavior for longer duration storms.

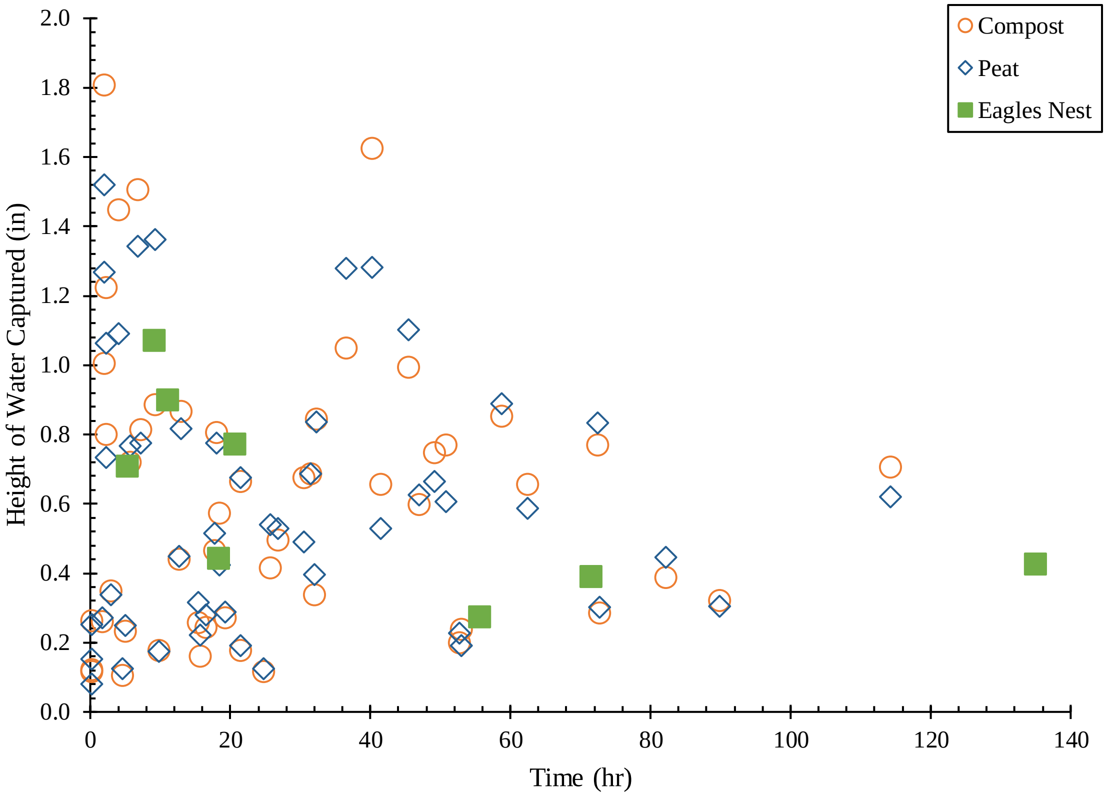


Figure 78. Comparison of water captured against rainfall event duration.

A normalization of the water caught with rainfall height against storm duration gives varied results. Figure 79 shows the majority of the storms infiltrating at or above a ratio of one which would point towards being able to capture first flush behavior during rainfall events. When compared with Figure 76 the site data would point towards higher initial moisture content conditions that were still capable of efficiently infiltrating rainfall.

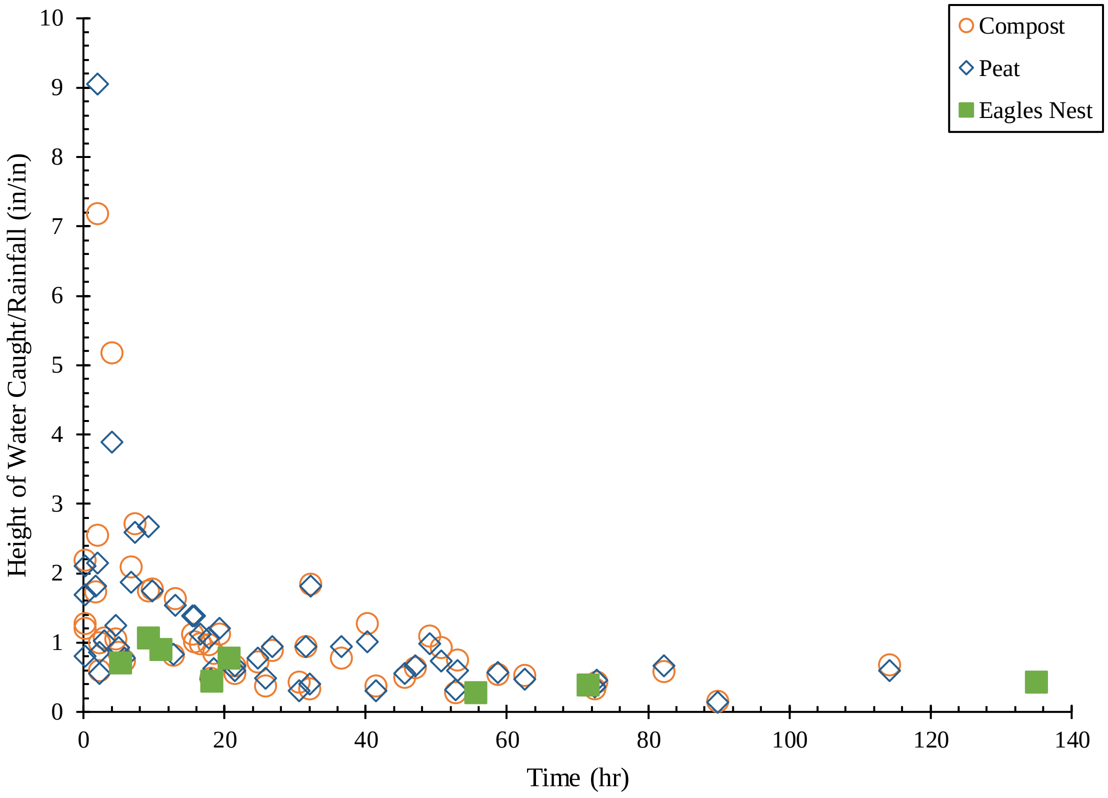


Figure 79. Normalized rainfall event data compared with event duration.

4.8 Conclusion

Chapter 4 discussed the results of field characterization, laboratory testing, and performance monitoring of biofilters amended with standard and alternative medias. *In situ* testing identified the relative density and saturated hydraulic conductivity of each site. Laboratory testing was designed to replicate field conditions, saturated hydraulic conductivity was evaluated in this setting and the results of the two methods were compared.

The data collected during long term field monitoring was also discussed in Chapter 4. An analysis of the field pilot test initiated by Johnson et al. (2017) and continued in this phase of research was evaluated to compare the performance of peat and compost amended biofilters. A similar monitoring approach was used at the site of a new peat amended biofiltration system. An evaluation of rainfall events at the site was conducted to determine water transport capabilities.

Chapter 5: Conclusions

5.1 Introduction

Chapter 5 details the results of *in situ* testing, laboratory characterization, and performance monitoring of biofilter media. Conclusions are presented from the results of data analysis and recommendations are given for biofilters and the use of alternative medias. Future work and project extensions included the continued monitoring of both the pilot plot and the Eagles Nest site are also discussed.

5.2 Conclusions and Recommendations

In comparing the results of *in situ* and laboratory testing, there was not a clear trend for laboratory methods over or underpredicting field performance. The methods, although showing some variations, did produce comparable values for saturated hydraulic conductivity for the various sites. The laboratory methods can be used conservatively to predict field performance with the understanding that saturated hydraulic conductivity can be highly variable for sites.

Performance monitoring at the pilot plot showed comparable field performance between compost and peat amended biofilters. The initial moisture content and the duration of the rainfall events recorded at the site appeared to have the largest impact on biofilter infiltration performance. The data reflected saturated hydraulic conductivity as a limiting factor for both media amendments. Early trends in the effects of initial moisture content and duration of rainfall events on infiltration efficiency should be reinforced with continued monitoring at the site. Future data sets could also give insight into the effect of aging on biofilter performance.

The data collected from the Eagles Nest site showed the potential for the biofilter to capture first flush rainfall events. The biofilter did show some underperformance for rainfall capture rate as compared to the pilot plot, understanding that the Eagles Nest site has a less robust data set to draw from. Continued monitoring at the site is required to draw more concrete conclusions and determine trends for the biofilter media performance.

5.3 Future Work

This research evaluated standard and alternative biofilter media performance using *in situ testing*, laboratory characterization, and performance monitoring. Continued monitoring of the both the pilot test and the Eagles Nest biofilter will provide insight into the long term performance of biofiltration systems. The identification and characterization of additional alternative biofilter media amendments is the next step in this work.

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Appendix 1

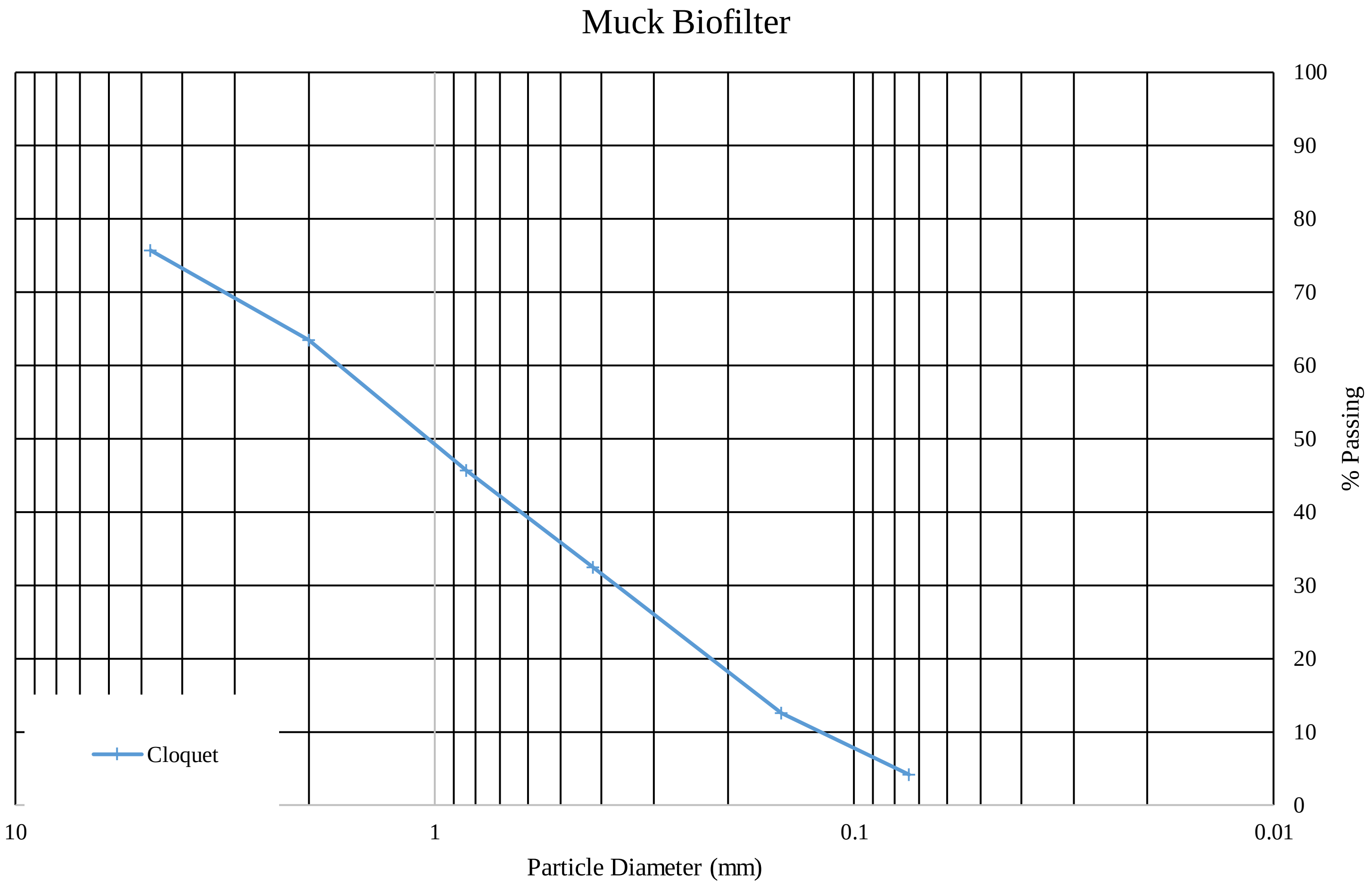

Figure 80. Soil gradation for the muck amended biofilter.

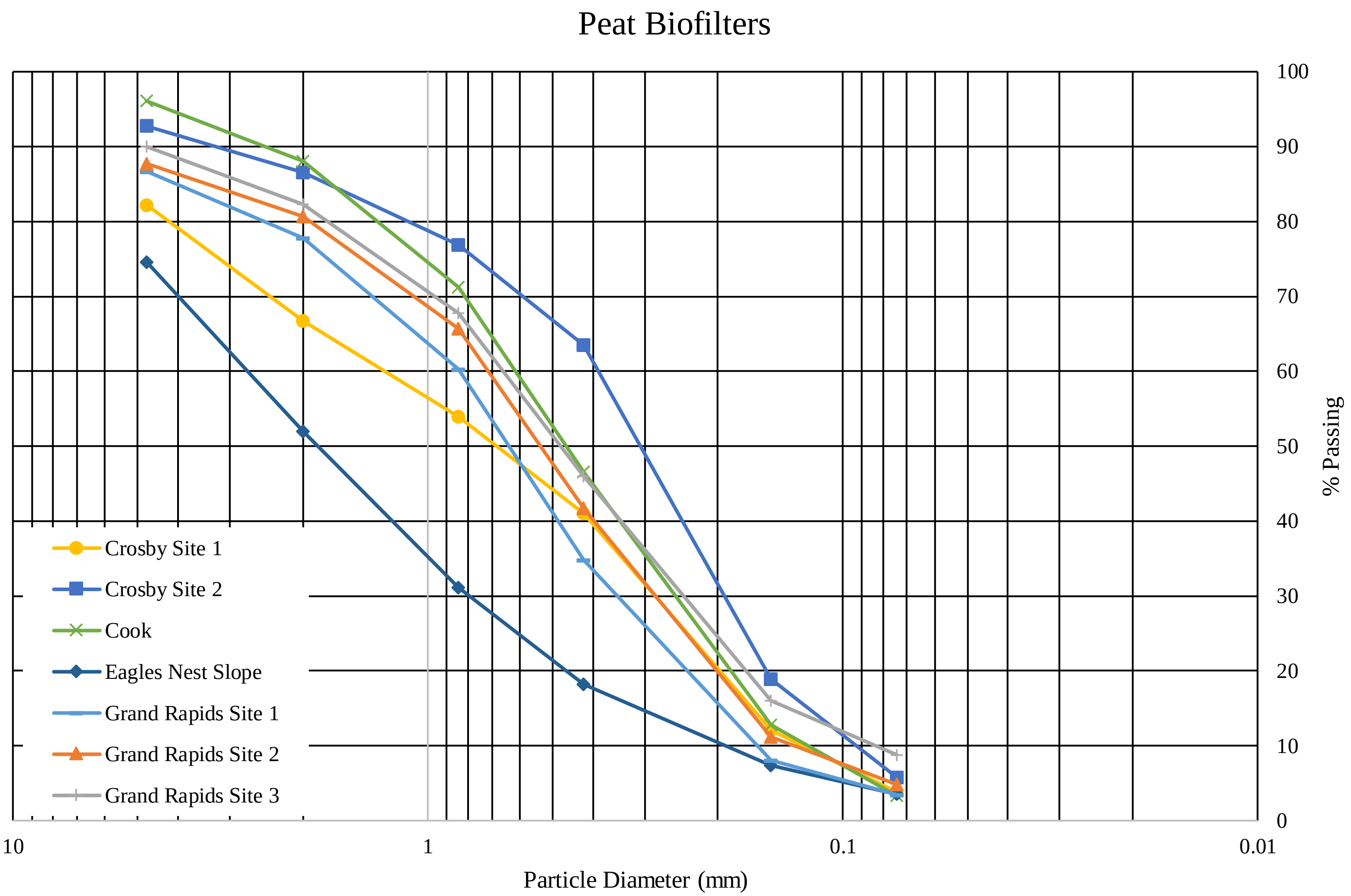

Figure 81. Soil gradation for the peat amended biofilters.

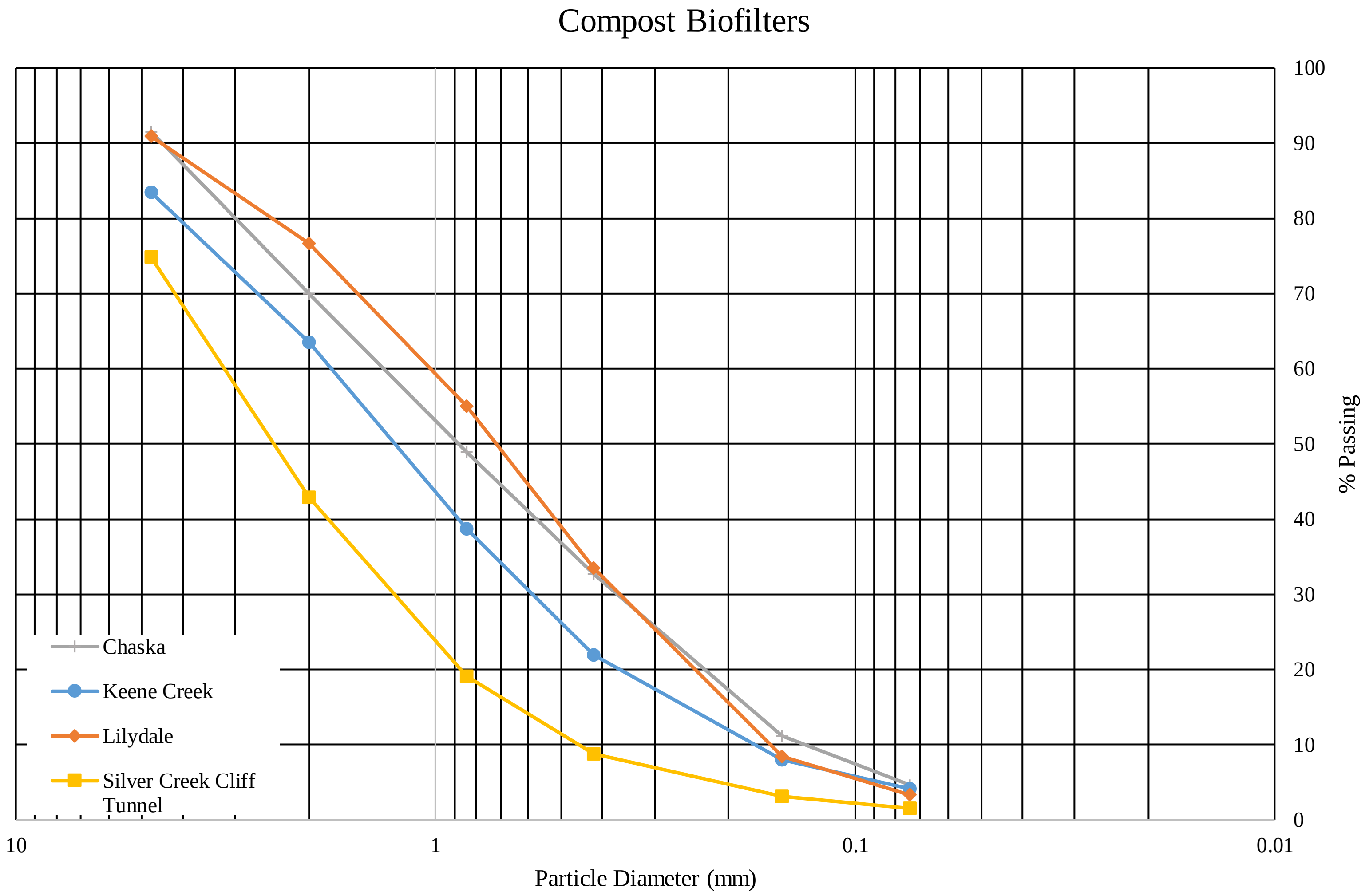

Figure 82. Soil gradation for the compost amended biofilters.