DEPARTMENT OF TRANSPORTATION

Development and Regionalization of *In Situ* Bioslopes and Bioswales

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16. Abstract (Limit: 250 words)

This project is a multi-disciplinary investigation into the use of alternative media for biofiltration systems in Minnesota. Over the last thirty years, the Minnesota Department of Transportation (MnDOT) has implemented biofilters along roadways as a stormwater control measure. These systems must be able to infiltrate and treat the first inch of rainfall onsite to meet state and national regulations. The performance of a biofilter is largely based on its media's ability to infiltrate water, sustain vegetation, and capture pollutants. To date, MnDOT has relied on sand and compost mixtures for biofilter media components. An early phase of this work identified peat as having similar performance characteristics as compost, making it an ideal alternative. A laboratory testing program was also developed during the early phase of work to determine media properties that could be used to predict biofilter performance. This project focused on characterizing existing biofilters using in situ testing and comparing results to laboratory testing. The comparison of the two methods demonstrated the predictive capabilities of the laboratory regime. This project also included the instrumentation and monitoring of field sites including a newly constructed peat amended biofilter. Findings from this work determined the validity of using peat for future biofilters and can aid in identifying and characterizing other alternative media.

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FINAL REPORT

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EXECUTIVE SUMMARY

BIOLOGY

Soil samples were collected from the various biofilters included in this research and analyzed for their ability to sustain vegetation. Samples were evaluated for their macro and micro nutrients, organic matter (O.M.), pH, and soluble salts (E.C.). The makeup of each sample was then used to determine deficiencies or excessive levels of the various characteristics. Most samples had some deficiency, with the most common being low organic matter. The vegetative cover at each biofilter site was also surveyed during field visits. Weedy species such as common tansy, field thistle and reed canary grass were common, likely due to their ability to adapt to suboptimal conditions.

CIVIL ENGINEERING

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 were then 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 reveal 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 regulations.

ENVIRONMENTAL ENGINEERING

Soil samples were collected from newly constructed and existing stormwater biofilter sites. Their performance in pollutant retention capacity was evaluated through laboratory batch tests. Both compost and peat can remove copper, lead and zinc by more than 85%. Lead retention was not affected by soil age and was kept at constant high ratio. However, the adsorption capacities of copper and zinc were negatively related with soil age and estimated that the retention capacity would be depleted after approximately 66 years for copper and 102 years for zinc. Compost leached a significant amount of phosphate, while peat can retain small amounts of phosphate at around 10-20%. The retention capacity of peat would be depleted after approximately 7 years.

One experiment test site was constructed in the Natural Resource Research Institute’s (NRRI) parking lot in late 2016. Since then, the leachate solutions were collected and analyzed. From the monitoring conducted over the past two years, no significant changes of water quality were observed over time, implying that long-term monitoring is needed. The major difference between compost and peat is PO_4 leaching, which has concentrations in the range of 1,000-5,000 µg/L for the compost sites and generally below 100 µg/L for the peat sites. These results suggest that peat is a good alternative to compost for treating metals and phosphate.

The newly constructed Eagles Nest road site was monitored for leachate collected from the bank and from the trench. Due to the timeline of construction, only four events were sampled, and no clear conclusion could be made from the limited data. Long-term monitoring would help improve the understanding of the applications of peat for stormwater management.

CHAPTER 1: INTRODUCTION

Stormwater conveyance systems are designed to protect infrastructure from flooding and 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). The cycle is further altered by the efficiency of conveyance systems, which attempt to move stormwater quickly causing peak runoff to be greater and to happen earlier in a storm event. Roadways also cause an increase in pollutant load to receiving waters as particulates and chemicals from vehicles as well as roadway treatments are flushed off in stormwater.

Low Impact Development (LID) has been implemented as a part of stormwater best management practices (BMP) to reduce or even eliminate these impacts. LID strategies work to return the predevelopment hydrology to sites (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, its 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 these desired attributes

Amendments are selected from an understanding of how they perform over time in hydraulic capacity. Biofiltration systems are thus designed using spatial availability, knowledge of media characteristics and vegetation properties.

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 put in place as part of new road construction projects to comply with these standards. As such, biofilters must be able to handle the hydraulic demands where they are implemented. The Minnesota Department of Transportation (MnDOT) has media mixture specifications that meet 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.

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 their water transport capabilities during rainfall events.

CHAPTER 2: BACKGROUND

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 2.1 Existing bioslope in place along a highway in northern Minnesota.

Figure 2.2. Bioslope with vegetative filter strip (GDOT, 2014).

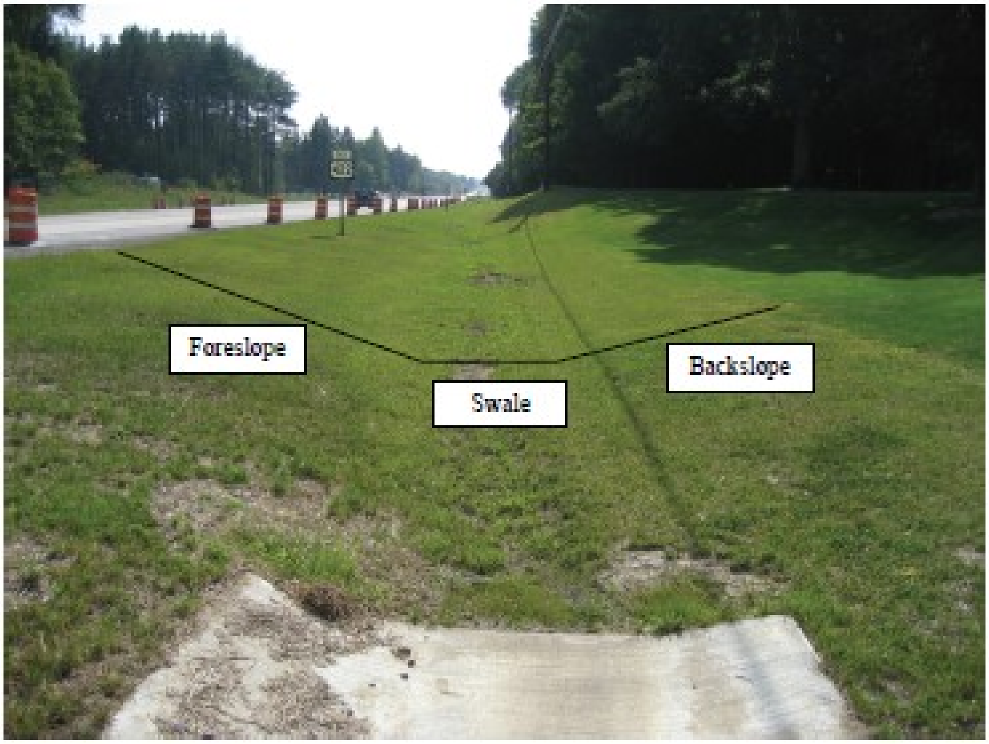


Figure 2.3. Biofiltration system with vegetated foreslope, backslope, and swale (Mitchell et al., 2010).

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.

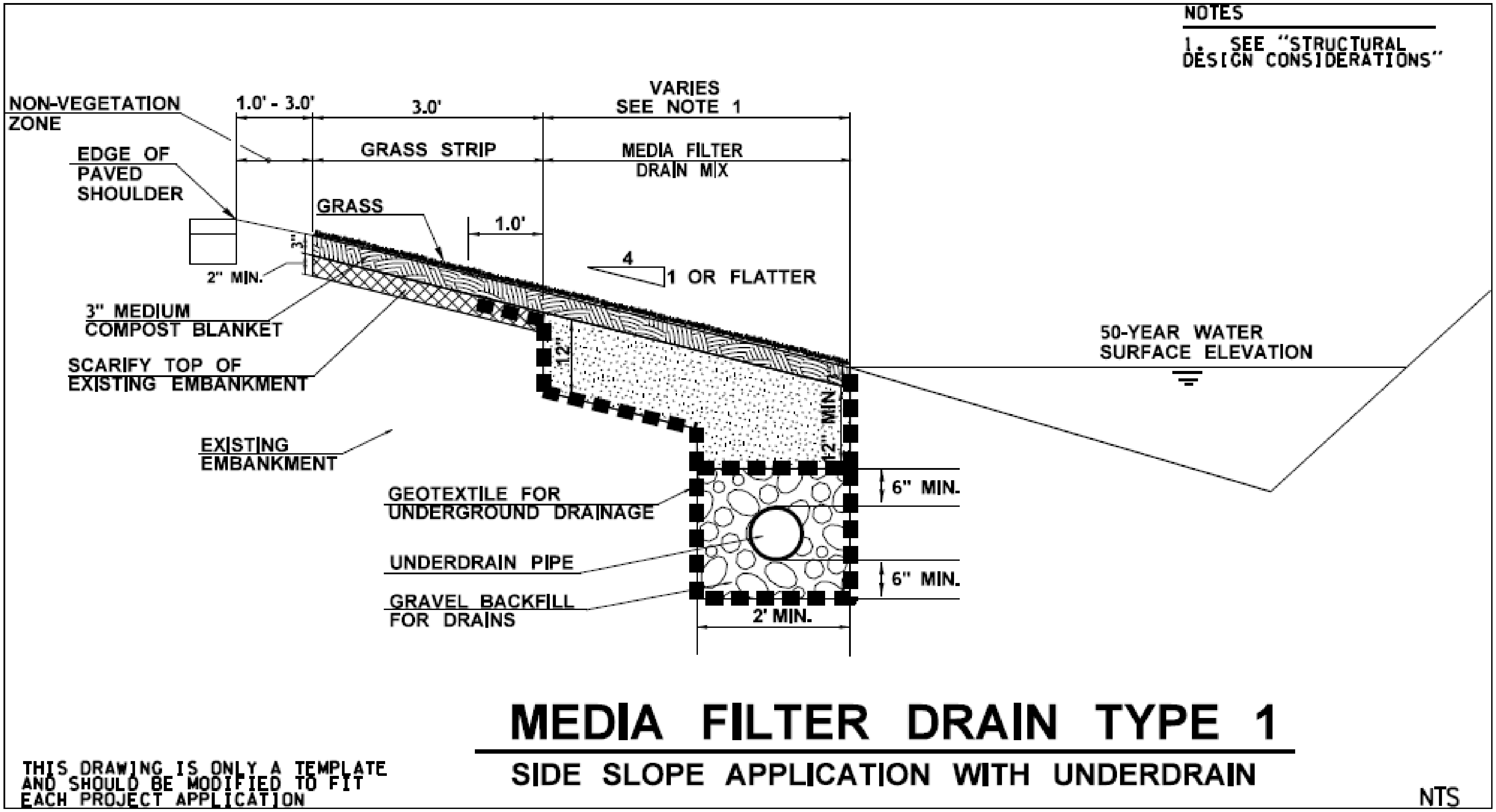


Figure 2.4. Cross section of Media Filter Drain Type 1 (adapted from WSDOT, 2014).

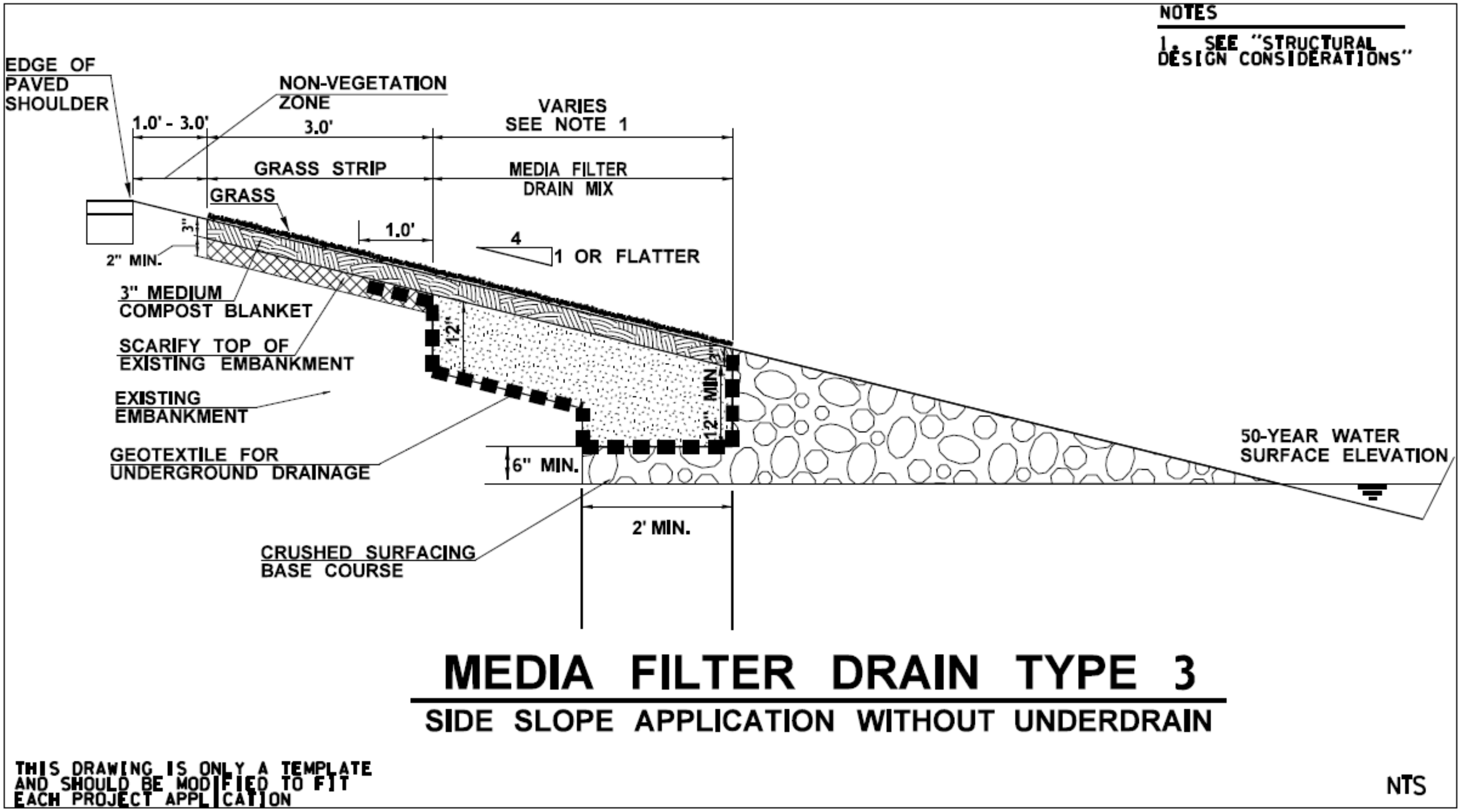


Figure 2.5. Cross section of Media Filter Drain Type 3 (adapted from WSDOT, 2014).

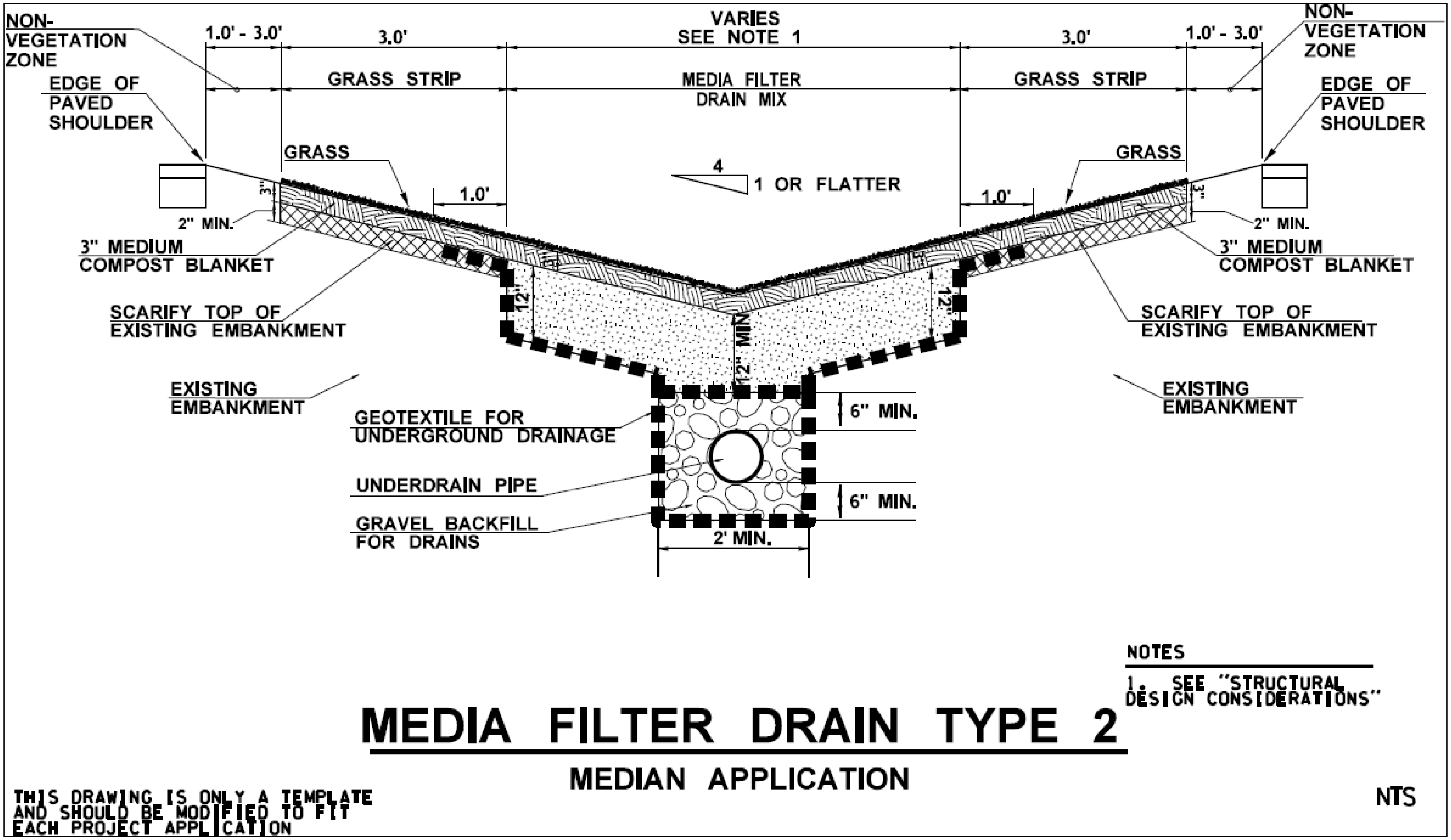


Figure 2.6. Cross section of Media Filter Drain Type 2 (adapted from WSDOT, 2014).

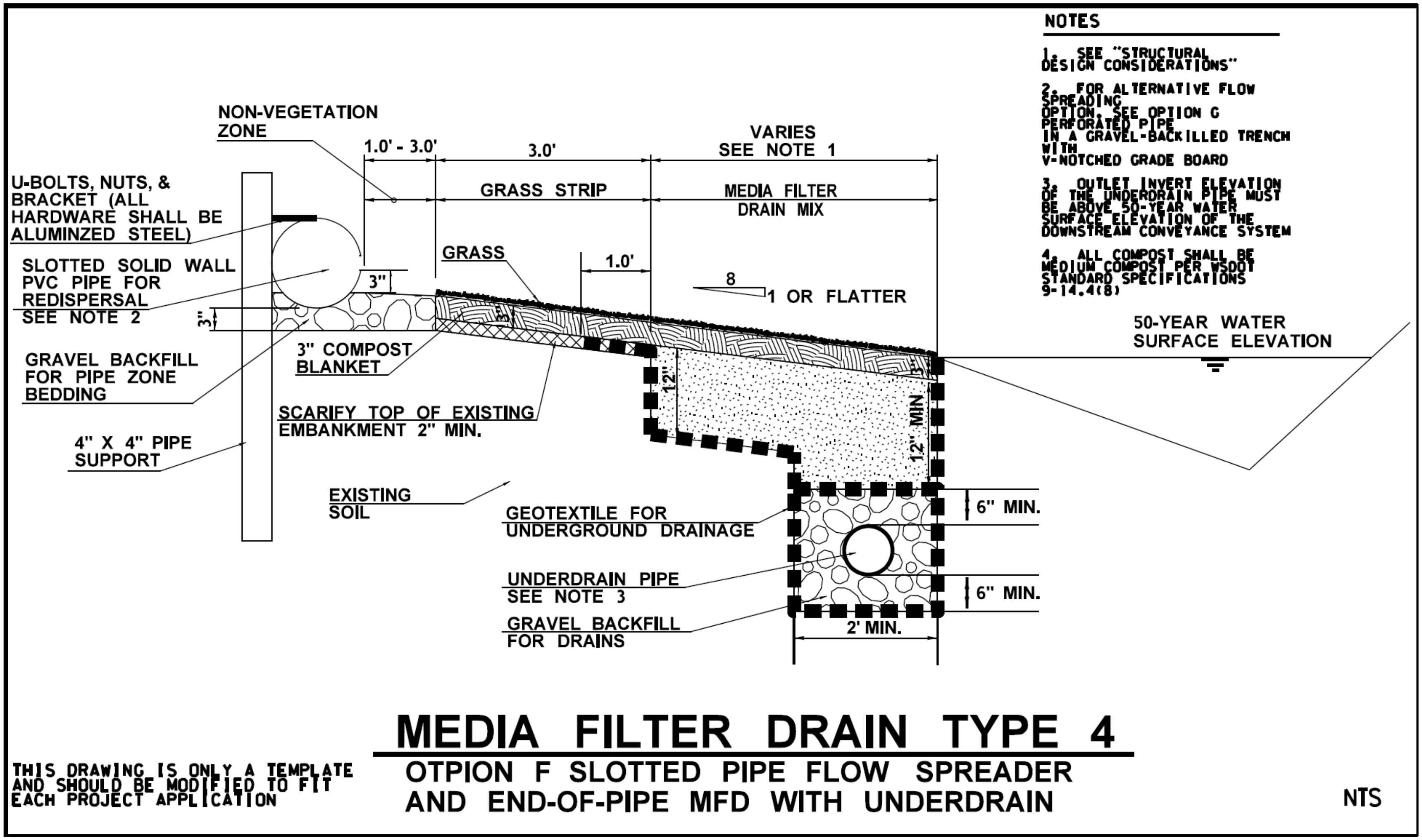


Figure 2.7. Cross section of Media Filter Drain Type 4 (adapted from WSDOT, 2014).

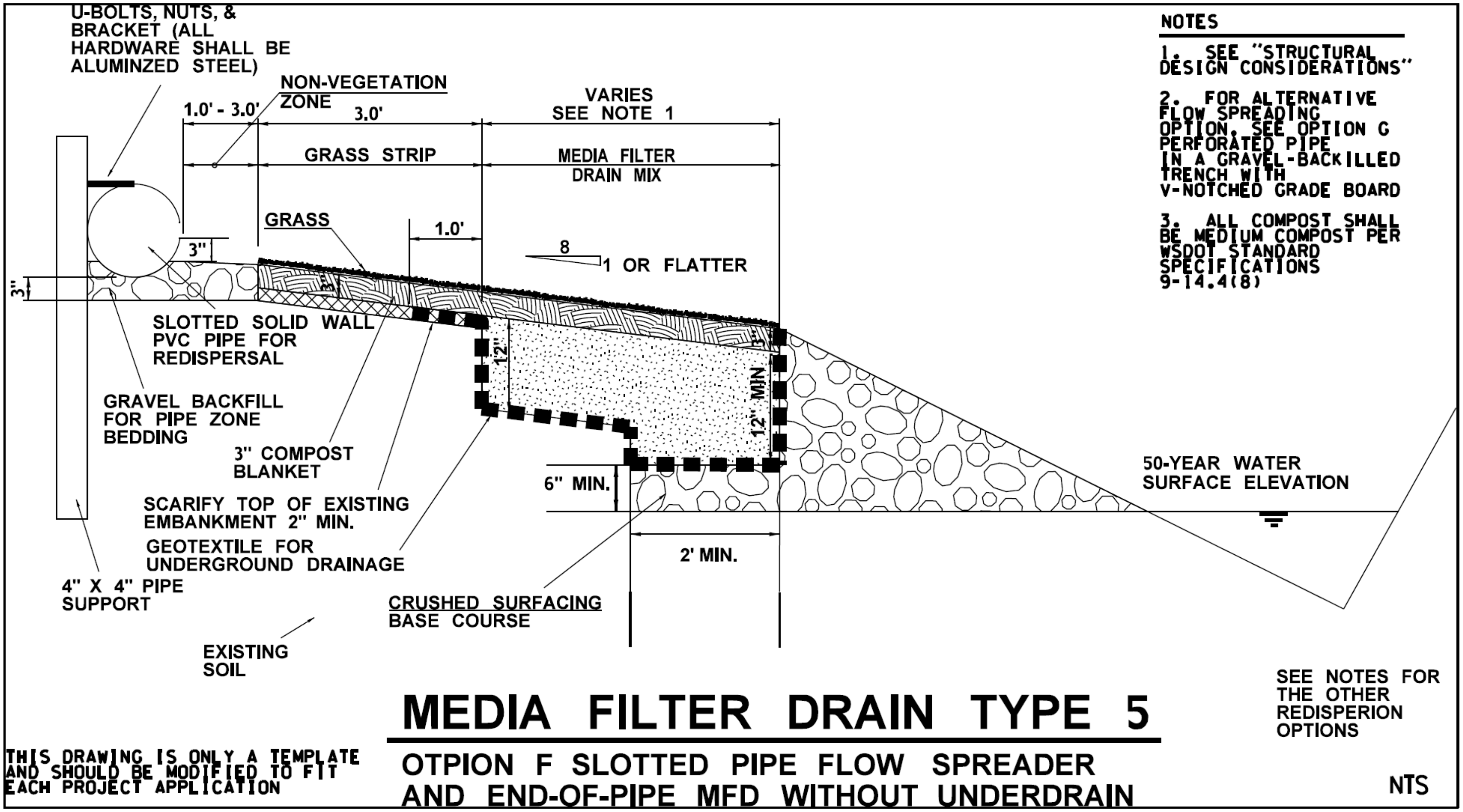


Figure 2.8. Cross section of Media Filter Drain Type 5 (adapted from WSDOT, 2014).

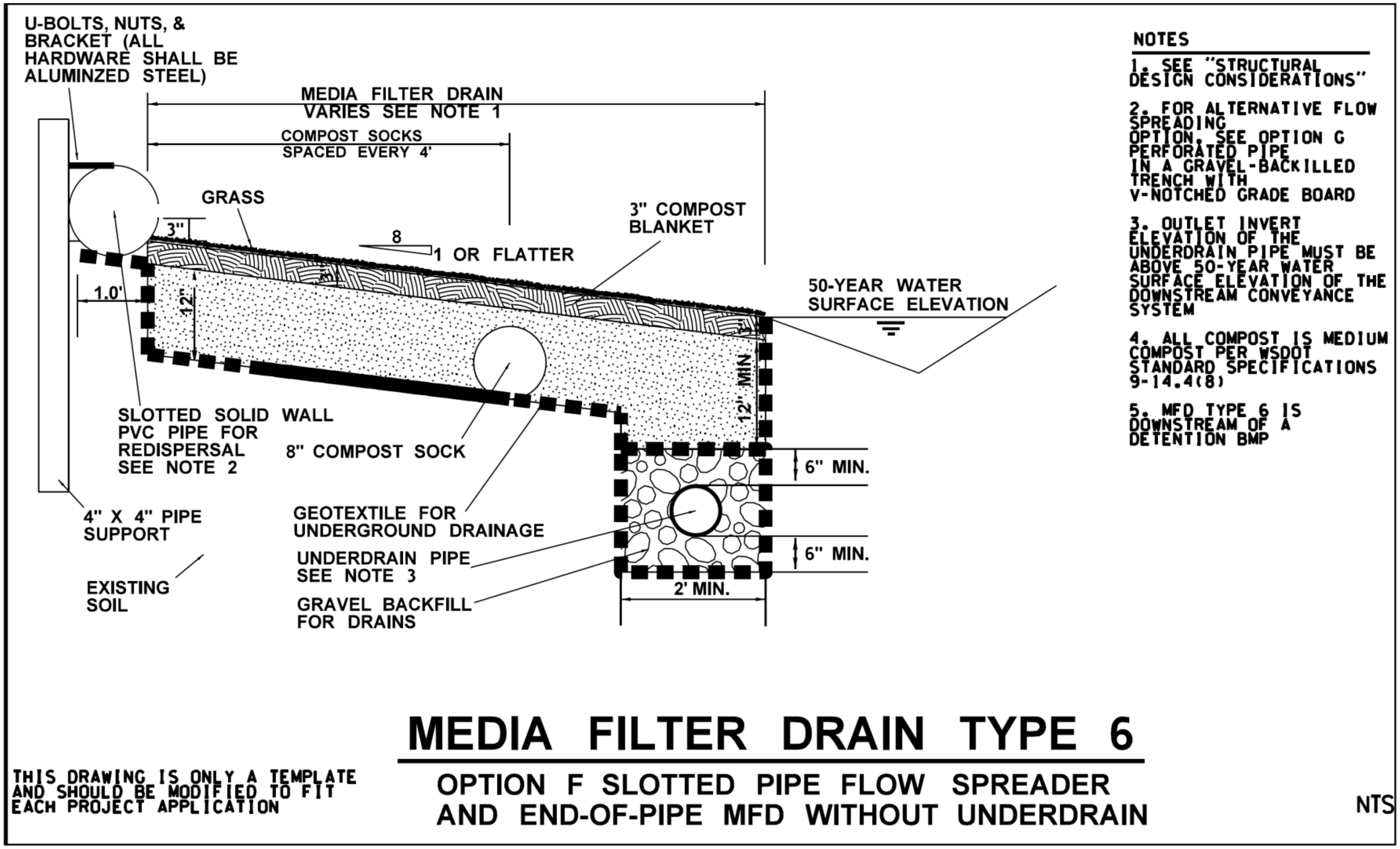


Figure 2.9. Cross section of Media Filter Drain Type 6 (adapted from WSDOT, 2014).

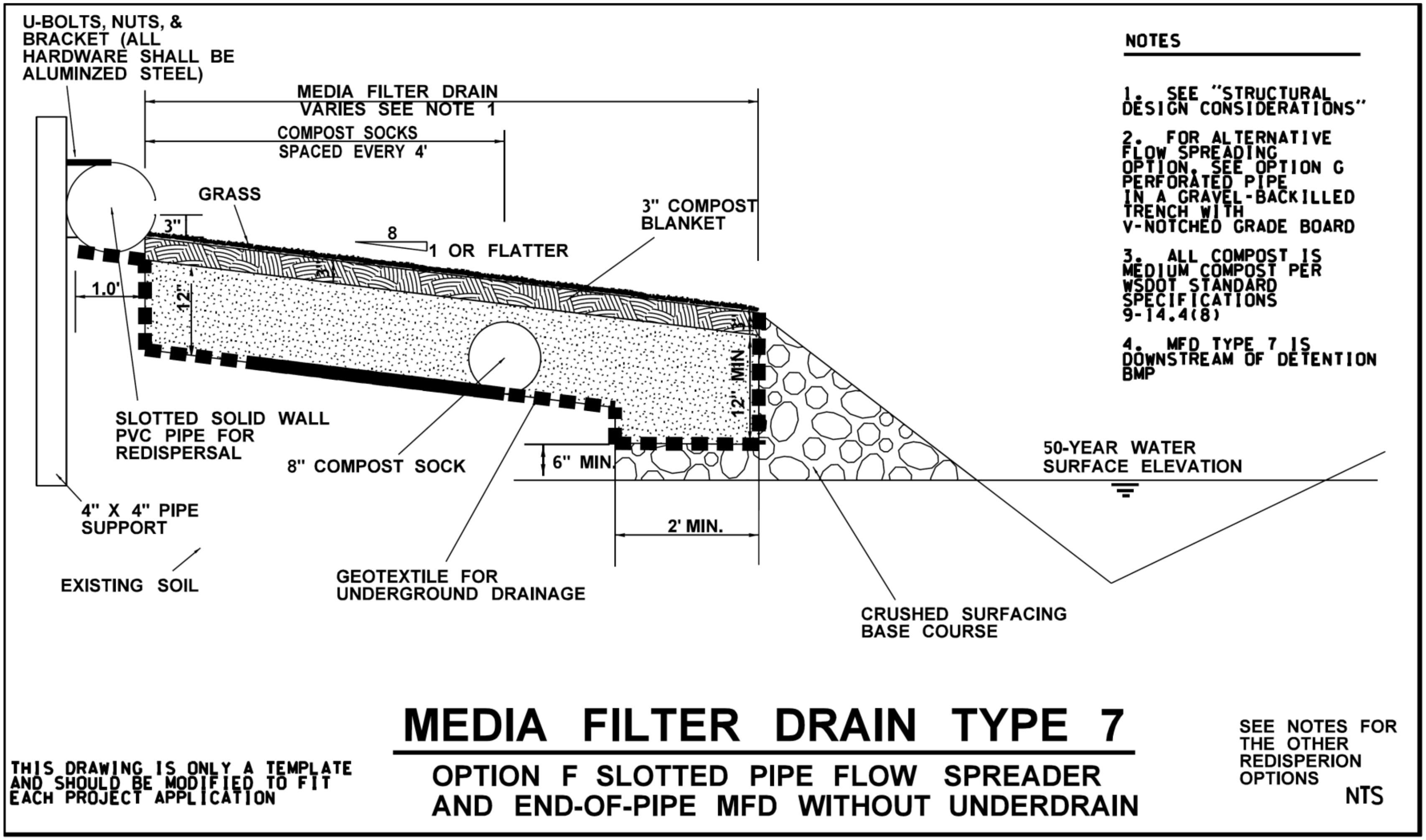


Figure 2.10. Cross section of Media Filter Drain Type 7 (adapted from WSDOT, 2014).

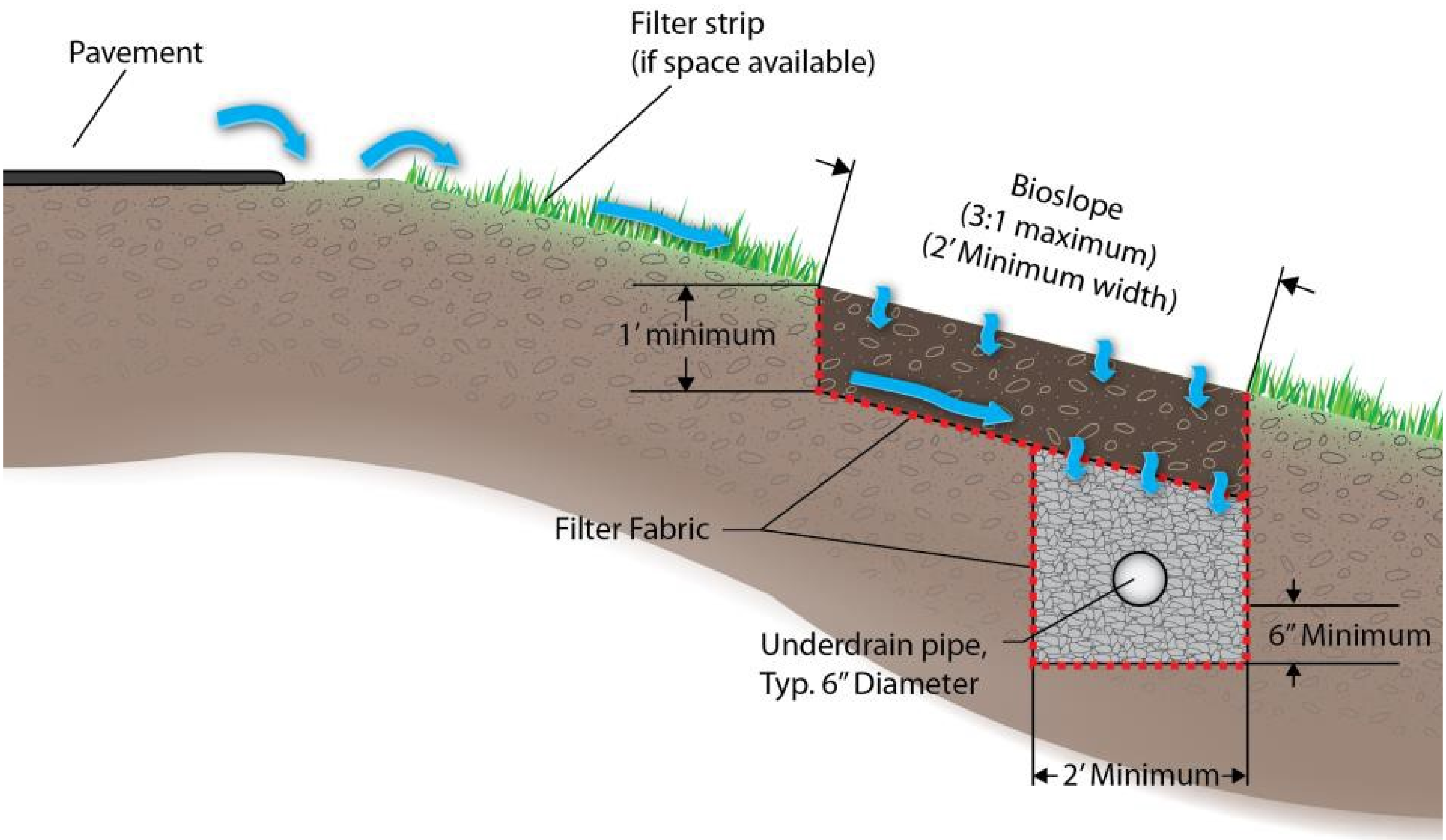


Figure 2.11. Cross section of bioslope design with flow depiction (adapted from GDOT, 2016).

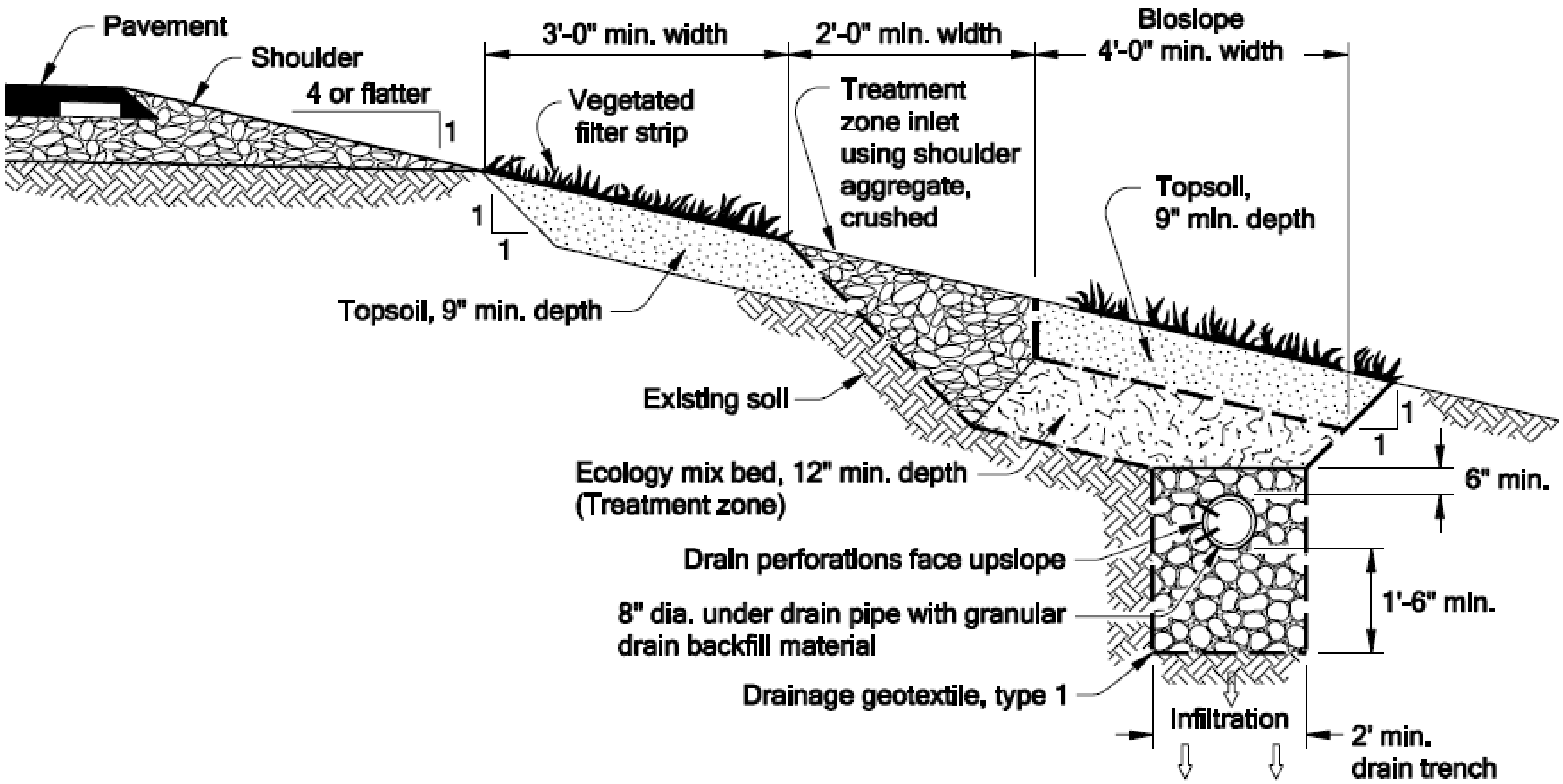


Figure 2.12. Cross section of bioslope design (adapted from ODOT, 2014).

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).

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).

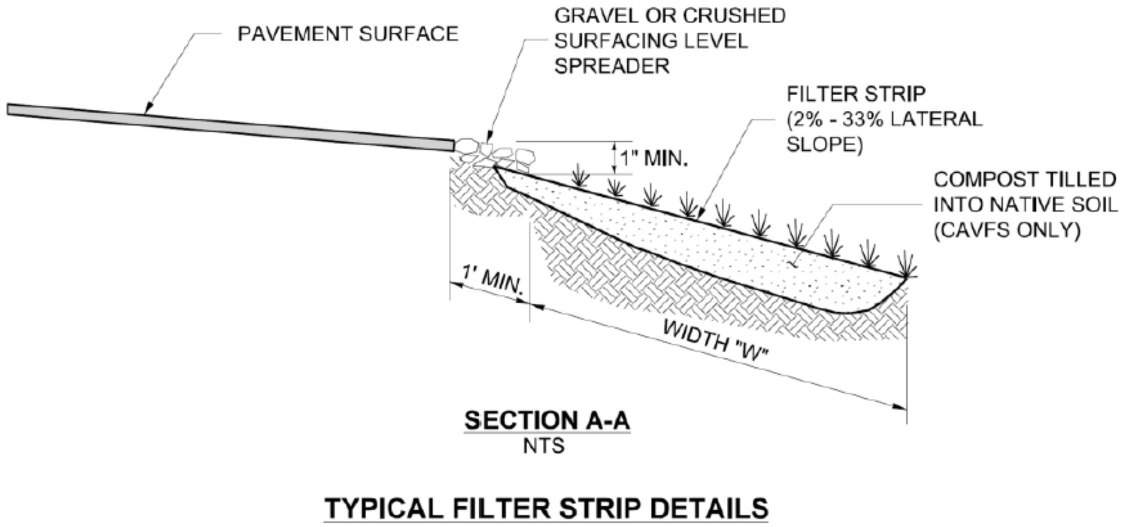


Figure 2.13. Typical filter strip details used by WSDOT (2014).

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).

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).

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

Figure 2.14. 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.

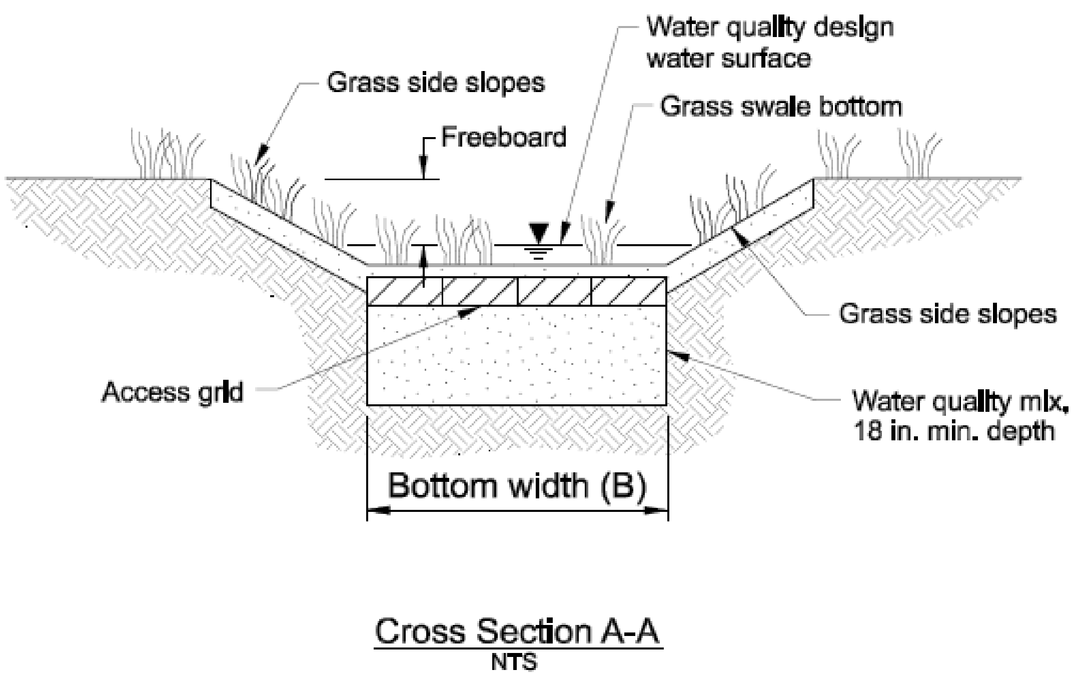


Figure 2.15. Typical cross section of a trapezoidal bioswale design (Adapted from ODOT, 2014).

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 2.16. Vegetated swale with temporary check dam (Caltrans, 2017).

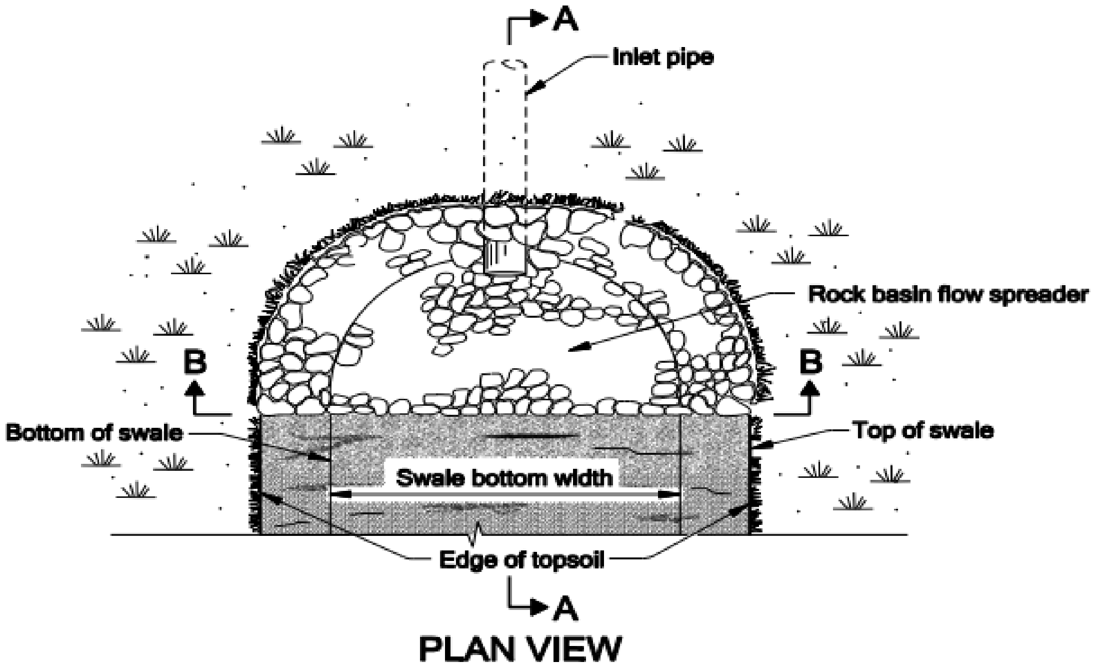


Figure 2.17. Typical flow spreader design used by ODOT (2014) for inlet flow control.

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: SITE SELECTION

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

3.1 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.

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.

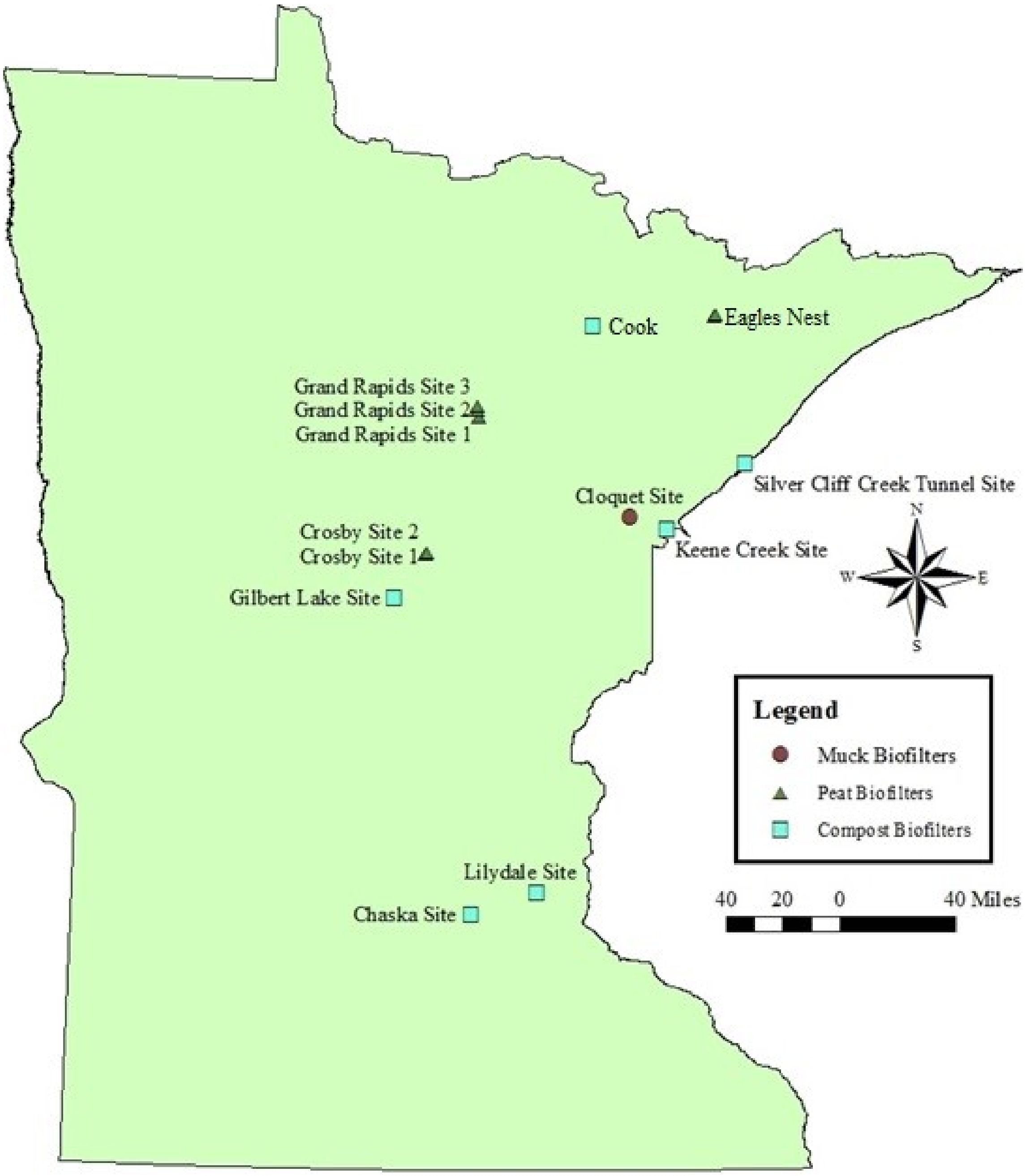


Figure 3.1 Map of biofilters included in this project.

Figure 3.2. Aerial view of the biofilter located in Chaska, Minnesota.

Figure 3.3. Ground view of the Chaska biofilter.

Figure 3.4. Characteristic soil profile from the Chaska biofilter.

3.2 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.

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.

3.3 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.

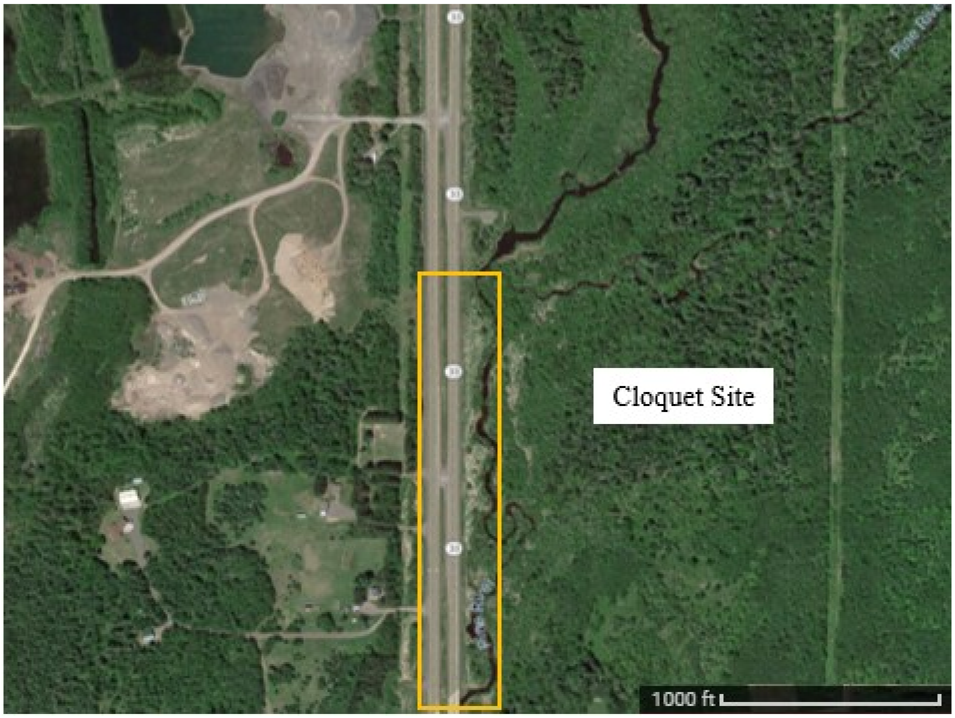


Figure 3.5. Aerial view of the biofilter located north of the city of Cloquet, Minnesota.

Figure 3.6. Ground view of the Cloquet biofilter.

Figure 3.7. Characteristic soil profile from the Cloquet biofilter.

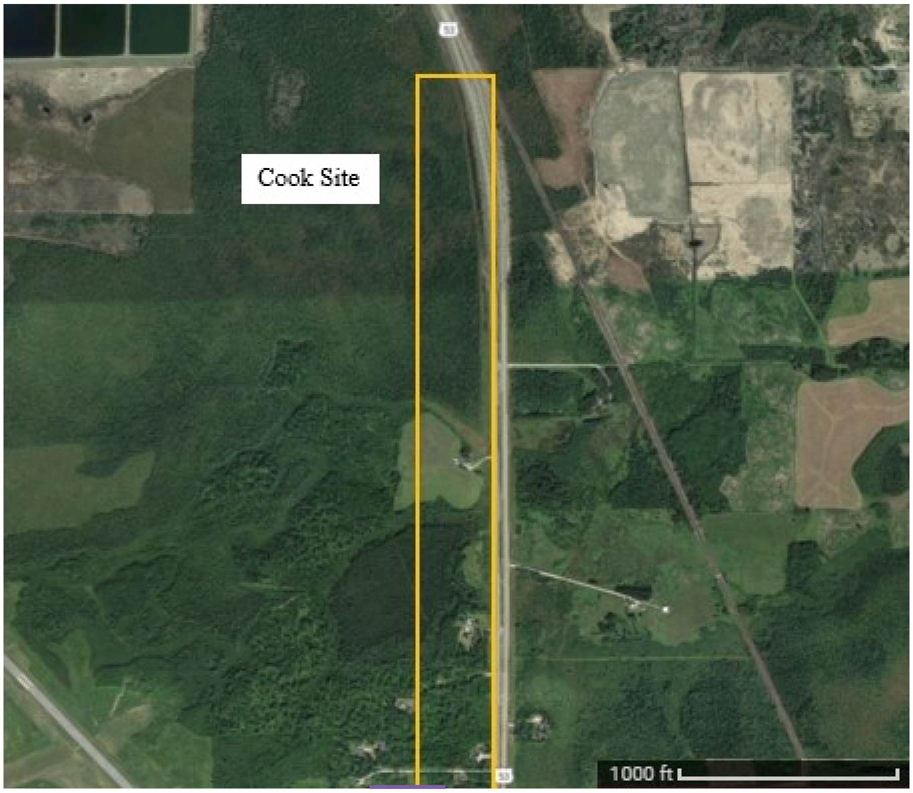


Figure 3.8. Aerial view of the biofilter located south of the city of Cook, Minnesota.

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 3.9. Ground view of the Cook biofilter.

Figure 3.10. Characteristic soil profile from the Cook biofilter.

3.4 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.

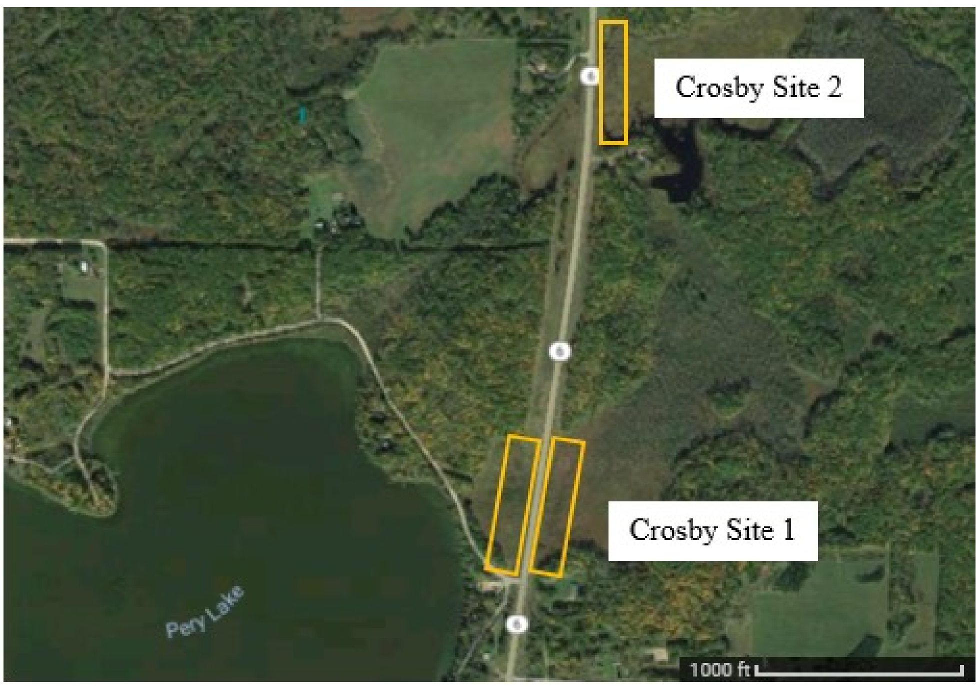


Figure 3.11. Aerial view of biofilters located near the city of Crosby, Minnesota.

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

Figure 3.13. Characteristic soil profile from the Crosby biofilters.

3.5 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.

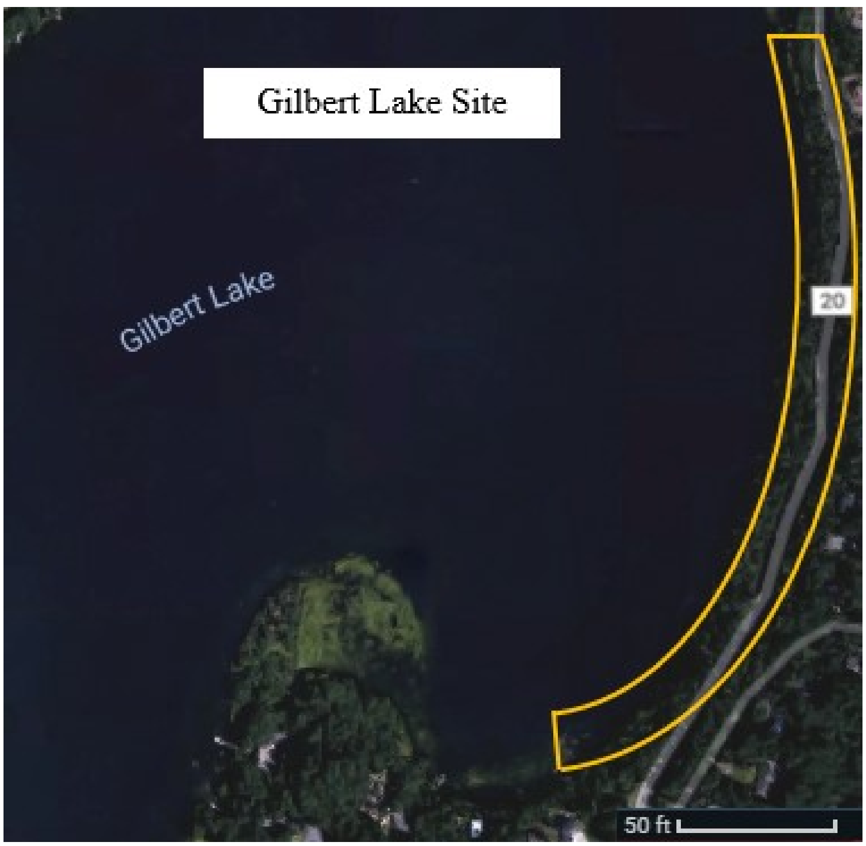


Figure 3.14. Aerial view of the location of the Gilbert Lake site.

Figure 3.15. Ground view of the Gilbert Lake site.

Figure 3.16. Characteristic soil profile from the Gilbert Lake biofilter.

3.6 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 3.17. 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 3.18. (a) Grand Rapids Site 1. (b) Grand Rapids Site 2. (c) Grand Rapids Site 3.

Figure 3.19. Characteristic soil profile from the Grand Rapids biofilters.

3.7 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 37. Compost, from an unknown source, was indicated as the media amendment used at the site. The biofilter was constructed in 2008.

Figure 3.20. 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 38. 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 39.

Figure 3.21. Ground view of the Lilydale biofilter.

Figure 3.22. Characteristic soil profile from the Lilydale biofilter.

3.8 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 40. 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.

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 41. 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 42.

Figure 3.23. Aerial view of the Silver Cliff Creek biofilter.

Figure 3.24. Biofilter along trail (left) and at the south trail access point (right) at the Silver Creek Cliff Tunnel.

Figure 3.25. Characteristic soil profile from the Silver Creek Cliff biofilter.

3.9 WEST DULUTH SITE

A biofilter was constructed in the city of Duluth, along Cody Street. Figure 43 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 3.26. 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 44, with a moderate slope. The media sampled at the site was found to be sandy with some larger sized aggregate as shown in Figure 45.

Figure 3.27. Ground view of the biofilter located over Keene Creek in Duluth, Minnesota.

Figure 3.28. Characteristic soil profile from the Keene Creek biofilter.

CHAPTER 4: CHARACTERIZATION AND EVALUATION OF MEDIA

This research included the characterization and performance monitoring of a newly constructed peat amended biofilter. 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 project realigned and updated a 5.7 mile stretch of Highway 1/169 west of McComber, Minnesota shown in Figure 46. Peat was considered readily available at the site, as wetlands and bogs are common to this region.

Figure 4.1 Location of the Eagles Nest Lake Area project in northern Minnesota.

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. 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 47. The media was evaluated for its ability to sustain vegetation, infiltrate water, and remove pollutants. The results of testing were then compared to current MnDOT media amendment standards and previous characterization of biofilter amendments from Johnson et al. (2017).

4.1 CURRENT SPECIFICATIONS

Grade 2 Compost is designated by MnDOT in the Standard Specifications for Construction (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 4. To improve the infiltration characteristics of compost MnDOT requires compost to be mixed with sand for filter topsoil applications. Current mixtures recommendations range from 40% to 60% compost with 60% to 40% sand.

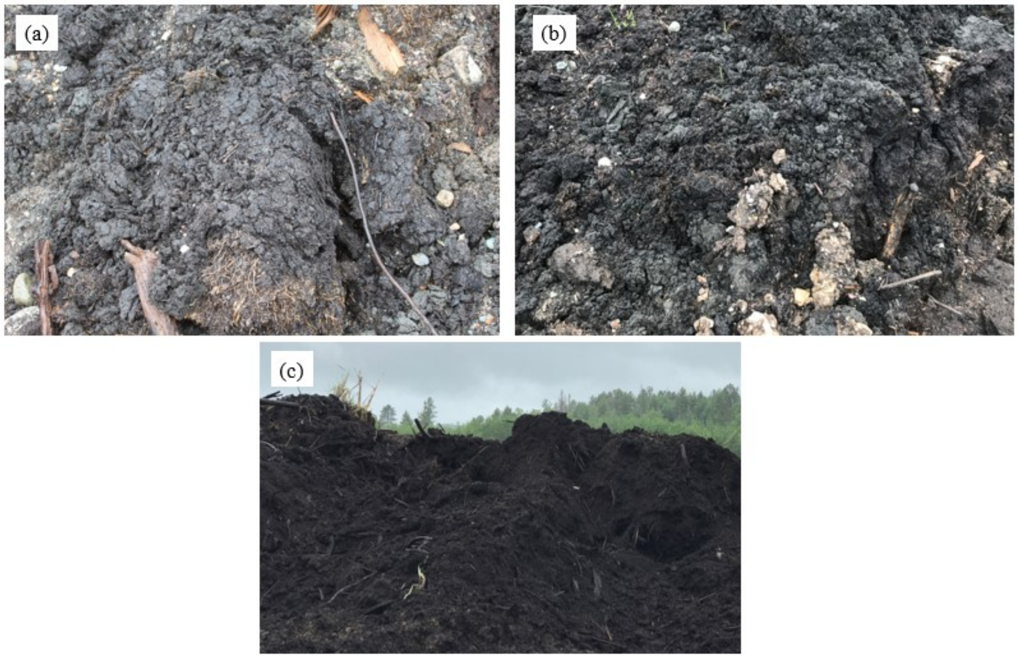


Figure 4.2. (a) Site 1 peat sample. (b) Site 2 peat sample. (c) Site 3 peat sample.

Table 4. 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.	

4.3 MEDIA CHARACTERIZATION

4.3.1 Biological

To determine substrate plant growth suitability samples were analyzed by the University of Minnesota Soils Analytical Laboratory. The substrates were tested according to professional turf management procedures as this most closely approximated the type of growing environment where the substrates would eventually be used. The tests determined macro and micro nutrients, organic matter (O.M), pH, and soluble salts (E.C.). The results are presented in Table 5.

The Site 1 sample is relatively low in organic matter and nitrate nitrogen (NO_3-N). It has an optimum pH in the neutral to slightly acidic range. The sample is low in phosphorus (P) and potassium (K), with sufficient sulfate (SO_4-S).

The Site 2 sample has higher organic matter and NO_3-N. The pH is lower and could benefit from some lime additions. The Soil Test Report recommendation calls for 140 lbs/1,000 sq.ft. The sample is low in P and K, with sufficient SO_4-S.

The Site 3 sample has the highest organic matter of the three samples and NO_3-N equal to the Site 2 sample. It has an optimum pH in the slightly acidic range. The sample is also low in P and K, with sufficient SO_4-S.

Soluble salt levels for all substrates were satisfactory. All substrates would benefit from additional N, P, and K fertilization. The Soil Test Report recommendation calls for 1 lb/1,000 sq.ft. of nitrogen, 5 lbs/1,000 sq.ft. of phosphate and 6 lbs/1,000 sq.ft. of potash fertilizer. It is important to note that these recommendations are for professional turf management. Native plant species seeded on bioslopes may have lower fertility requirements.

Table 5. Nutrient analyses for soil samples collected from the Eagles Nest construction site.

Parameter	Site 1	Site 2	Site 3
Soil Texture	Medium	Coarse	Coarse
O.M. (%)	6.8	24.8	43.1
E.C. (mmhos/cm)	2.3	2.4	0.6
pH	6.8	5.2	5.6
NO_3-N (ppm)	22.2	60	60
Bray 1 P (ppm)	2	4	1
K (ppm)	28	10	13
SO_4-S (ppm)	40+	40+	40+
Zn (ppm)	7.1	5.4	3.6
Fe (ppm)	205.6	451.8	386
Mn (ppm)	6.2	17.8	13.2
Cu (ppm)	6.6	4.5	3.4
B (ppm)	0.2	1	0.6
Ca (ppm)	3447	2950	2877
Mg (ppm)	75	100	101

4.3.2 Civil Engineering

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 6.

Table 6. 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%, 6.8	75%, 5.2	57%, 5.6
Absorbency	66%	73%	186 %

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 48-50 represent the results of compaction testing conducted with a summary of the optimum moisture contents and dry densities shown in Table 7. See Appendix 1 for raw data from compaction testing.

The results of compaction testing were used to determine a relative compaction 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).

Table 7. Results of compaction testing.

Peat Sample	Maximum Dry Density (kN/m^3)	Optimum Moisture Content (%)
Site 1	11.6	39%
Site 2	9.6	55%
Site 3	2.8	235%

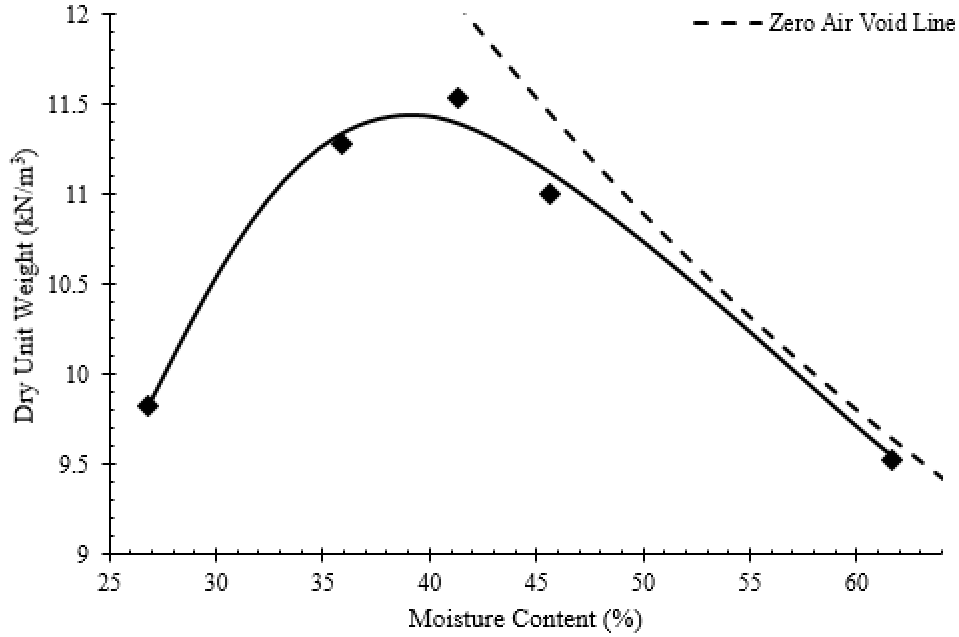


Figure 4.3. Compaction testing results for Site 1.

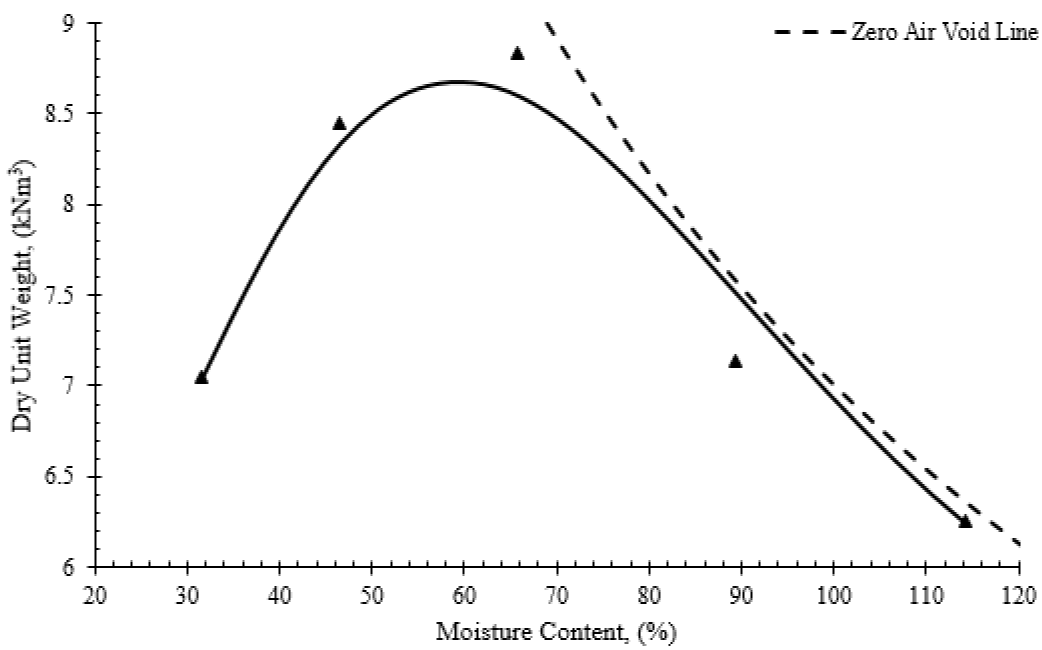


Figure 4.4. Compaction testing results for Site 2.

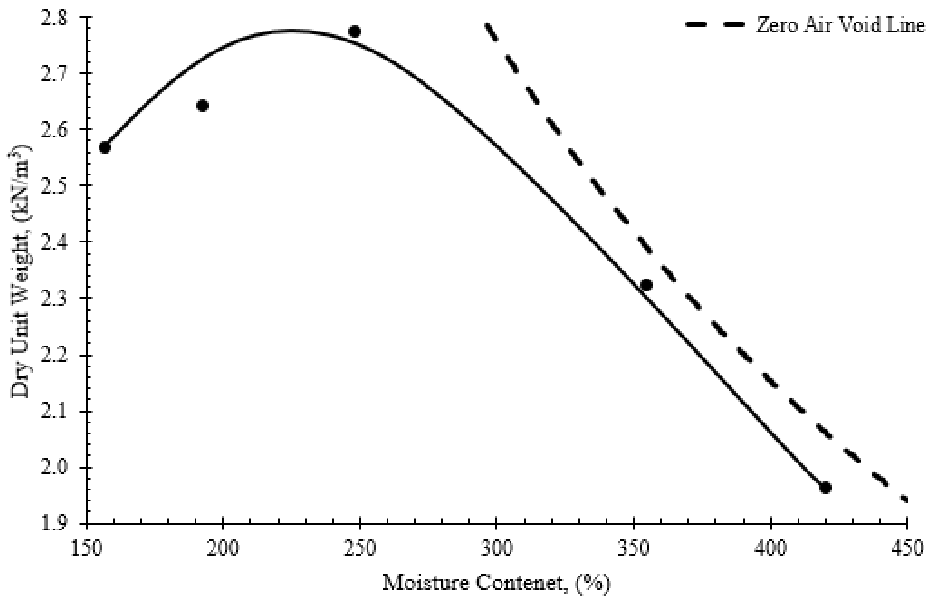


Figure 4.5. Compaction testing results for Site 3.

The results of hydraulic conductivity testing are summarized in Table 8. 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 (Johnson et al. 2017) but were still comparable to MnDOT grade compost.

Table 8. 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	$1.7*10^{-5}$

4.3.3 Environmental Engineering

Chemical properties of materials used in stormwater treatment determine if one material can remove pollutants or release chemicals into receiving water body. To examine the environmental properties of the selected materials, laboratory batch experiments were used to test the changes of primary cations and anions after treated with synthesized stormwater by studied materials. Three soil samples collected from Eagles Nest construction field were used in this batch test. Lab synthesized stormwater solution was prepared by dissolving $NaNO_3$,

$NaH_2PO_4 \cdot H_2O$, $CuCl_2 \cdot 2H_2O$, $Pb(NO_3)_2$ and $Zn(NO_3)_2 \cdot 6H_2O$ into deionized water to gain pollutant concentrations of the highest levels observed in Minnesota state. The initial concentrations of the synthesized stormwater are 0.826 mg/L for copper, 0.5 mg/L for lead, 1.153 mg/L for zinc, 8.37 mg/L nitrate and 4.68 mg/L phosphate.

Batch experiments were performed in 250 ml bottles by mixing 250 ml laboratory-synthesized solution and 2.5 g filtration material which was dried at 105 ^oC for 24 hours immediately before use. The mixture was shaken at 100 rpm for 24 hours and vacuum filtered through 0.45 µm membrane. The supernatant was stored in 4 ^oC cooling room for nitrate and phosphate measurement by ionic chromatography (IC) or acidified by concentrated nitrate (trace metal grade) for metal measurement by Atomic Absorption Spectrometry (AAS). For each solution and filtration material mixture, three replicates were run at same time.

The batch test results of current materials were compared with the results of compost and salvage peat which were used in Phase I project (Figure 50). Compost was selected as the infiltration materials by MN stormwater manual, while salvage peat was identified to have higher pollutant removal efficiencies and lower phosphate release in contrast to compost.

Organic contents of the soils from the three stockpiles (Site 1, Site 2 and Site 3) in Eagles Nest field varied largely from 11% to 68%. The organic matter contents highly affected the removal efficiencies of copper and zinc with positive relationships but didn't impact lead retention as almost all lead was retained in all of the three soil sites probably due to precipitation reaction. Overall, more than 85% of the metals were removed by these soil materials. In contrast, higher organic content can lead to the release of more nitrate. In comparison to compost and salvage peat, the metal removal efficiencies of the soil materials in Eagles Nest field are close to peat and higher than compost. In addition, small amounts of phosphate (15-22%) can be removed by current soil materials. In summary, the soil materials in Eagles Nest construction field performed well in adsorbing metals and released small amount of nitrogen which may be uptaken by plants.

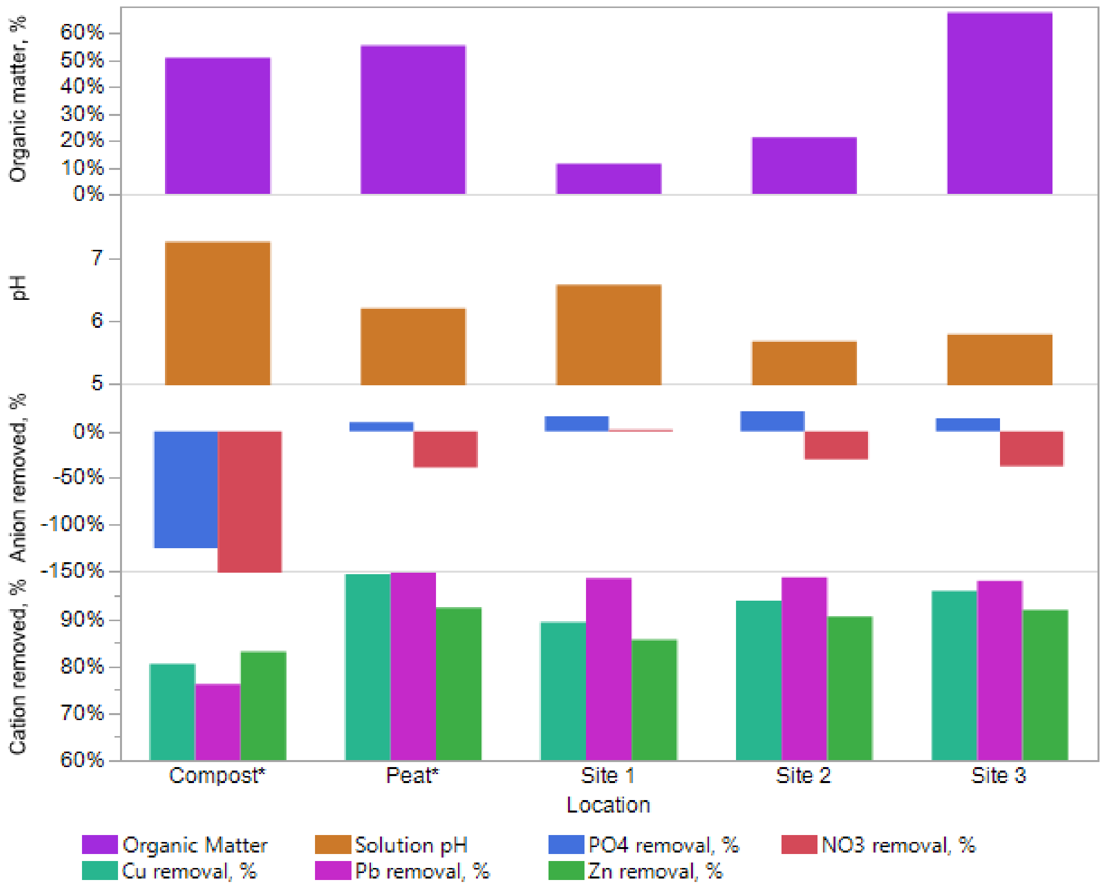


Figure 4.6. The chemical properties of soil samples collected from three sites in Eagles Nest Construction field, and the compost and salvage peat used in Phase I project.

CHAPTER 5: MEDIA CHARACTERIZATION

Each biofilter identified for this study was visited and tested for *in-situ* relative density and hydraulic conductivity. A record of native plant life was also made. Samples were taken from field sites and then tested using the laboratory program developed by Johnson et al. (2017). Laboratory testing included soil classification, hydraulic conductivity, and batch tests. The results of field and laboratory testing are compared in this report to evaluate the ability of laboratory testing to predict field performance of biofilter media.

5.1 MEDIA CHARACTERIZATION

5.1.1 Biological

To determine substrate plant growth suitability samples were analyzed by the University of Minnesota Soils Analytical Laboratory. The substrates were tested according to professional turf management procedures as this most closely approximated the type of growing environment where the substrates would eventually be used. The tests determined macro and micro nutrients, organic matter (O.M), pH, and soluble salts (E.C.). The results are presented in Table 9.

The following describes the soil characteristics for each site based on recommendations provided by the U of M Soils Analytical Laboratory. Summarizing their guidelines:

Organic matter: low (0-3%), medium (3.1-4.5%), high (4.6-19%), and organic soil (>19.1%)

Soluble salts (E.C.): < 3.0 mmhos/cm is satisfactory

pH: 6-7 is optimum

Nitrate nitrogen (NO_3-N): normal background is 5-10 ppm

Phosphorus (P): < 10 ppm is low

Potassium (K): < 50 is low

Sulfate (SO_4-S): < 5 is low

Table 9. Soil characterization of soil samples collected from existed stormwater biofilters.

Parameter	Chaska	Cloquet	Cook	Crosby 1	Crosby 2	Eagles Nest Slope	Eagles Nest Trench	Gilbert Lake	Grand Rapids 1	Grand Rapids 2	Grand Rapids 3	Keene Creek	Lilydale	Silver Creek
Soil Texture	Coarse	Coarse	Coarse	Medium	Coarse	Coarse	Coarse	Coarse	Coarse	Coarse	Coarse	Coarse	Medium	Medium
O.M. (%)	3.1	3	21.4	4.2	3.4	1.4	1.4	1.9	1	1.3	1.9	1.8	4.5	5.7
E.C. (mmhos/cm)	0.3	0.3	0.5	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.1
pH	7.6	5.9	7.6	6.2	6.5	7.4	7.5	7.6	7.1	6.8	6.8	7.6	7.8	6.5
NO_3-N (ppm)	4.2	20.8	30.9	12.1	2.9	1.6	2.2	2.5	1.1	0.7	1.3	57.6	18.4	11.8
Bray 1 P (ppm)	11	5	1	5	4	38	38	15	12	17	13	3	4	4
K (ppm)	128	57	45	57	26	55	46	31	21	34	53	52	84	132
SO_4-S (ppm)	8	14	9	8	8	9	7	6	4	3	4	7	8	9
Zn (ppm)	2.5	3	0.9	1.3	1.8	2.1	2.2	2.2	0.8	1.6	1.7	1.9	6.7	1
Fe (ppm)	41.8	242.7	87.2	262.5	188	34.6	32.9	32.9	50.5	100.2	108.5	39.5	70.8	110.7
Mn (ppm)	9.2	33.7	6.1	9.7	4.4	7.6	7	6.3	9.6	14	17	6.8	12.1	7.5
Cu (ppm)	0.9	6.3	1.1	3.5	1.2	0.8	0.7	0.5	0.7	1.2	0.9	4	1.3	6.2
B (ppm)	0.3	0.2	0.2	0.2	0.1	0.3	0.3	0.2	0.1	0.1	0.1	0.2	0.4	0.3
Ca (ppm)	3058	902	4355	962	977	836	1007	1158	434	153	407	1447	3643	1601
Mg (ppm)	227	160	450	136	141	85	99	127	38	20	46	86	104	209

All site samples have satisfactory soluble salt levels but have potential problems or deficiencies for soils at each site.

- The Chaska Site sample has medium organic matter content, higher than optimum pH, and low NO_3-N levels.
- The Cloquet Site sample has low organic matter content, lower than optimum pH, and low P.
- The Cook Site sample has organic matter levels high enough to classify it as an “organic soil”, higher than optimum pH, and low P and K.
- The Crosby 1 Site sample has medium organic matter content and low P.
- The Crosby 2 Site sample has medium organic matter content, and low NO_3-N, P, and K.
- The Eagles Nest Slope Site sample has low organic matter, higher than optimum pH, and low NO_3-N.
- The Eagles Nest Trench Site sample has low organic matter, higher than optimum pH, and low NO_3-N and K.
- The Gilbert Lake Site sample has low organic matter, higher than optimum pH, and low NO_3-N and K.
- The Grand Rapids 1 Site sample has low organic matter, higher than optimum pH, and low NO_3-N, K and SO_4-S.
- The Grand Rapids 2 Site sample has low organic matter, and low NO_3-N, K and SO_4-S.
- The Grand Rapids 3 Site sample has low organic matter, and low NO_3-N and SO_4-S.
- The Keene Creek Site sample has low organic matter content, higher than optimum pH, and low P.
- The Lilydale Site sample has medium organic matter content, higher than optimum pH, and low P.
- The Silver Creek Site sample has high organic matter content and low P.

During field soil collection, the vegetation covers of each site were surveyed and summarized as follows.

Chaska Plant List

Genus/species	Common Name
Lotus corniculatus	Birdsfoot Trefoil
Trifolium repens	White Clover
Taraxacum officinale	Dandelion
Bromus inermis	Smooth Bromegrass
Cirsium discolor	Field Thistle
Phalaris arundinacea	Reed Canary Grass

Figure 5.1 Chaska site.

Cloquet Plant List

Genus/species	Common Name
Phalaris arundinacea	Reed Canary Grass
Cirsium discolor	Field Thistle

Figure 5.2. Cloquet site.

Crosby 1 Plant List

Genus/species	Common Name
Andropogon gerardii	Big Bluestem
Solidago	Goldenrod
Phalaris arundinacea	Reed Canary Grass
Carex	Sedge
Typha	Cattail

Figure 5.3. Crosby Site 1.

Crosby 2 Plant List

Genus/species	Common Name
Bromus inurmis	Smooth Brome
Solidago	Goldenrod
Cirsium discolor	Field Thistle
Phalaris arundinacea	Reed Canary Grass
Andropogon gerardii	Big Bluestem
Carex	Sedge
Typha	Cattail

Figure 5.4. Crosby Site 2.

Eagles Nest Plant List

Genus/species	Common Name
Chenopodium gigantia	Lambsquarters
Medichen sativa	Alfalfa
Trifolium repens	Common Clover
Bromus inurmis	Smooth Brome Grass
Phalaris arundinacea	Reed Canary Grass
Avena sativa	Oats

Figure 5.5. Eagles Nest site.

Gilbert Lake Plant List

Genus/species	Common Name
Rubus strigosus	Raspberry
Linaria vulgaris	Toadflax
Vitis riparia	Wild Grape
Bromus inurmis	Smooth Brome
Parthenocissus quinquefolia	Virginia Creeper
Solidago	Goldenrod
Elymus repens	Quackgrass
Melilotus alba	Sweetclover
Cirsium discolor	Field Thistle
Equisetum arvense	Field Horsetail

Figure 5.6. Gilbert Lake site.

Grand Rapids 1 Plant List

<u>Genus/species</u>	<u>Common Name</u>
Symphyotrichum lanceolatus	Panicled Aster
Andropogon gerardii	Big Bluestem
Tanacetum vulgare	Common Tansy
Agrostis gigantea	Redtop
Cirsium discolor	Field Thistle
Ambrosia artemisiifolia	Common Ragweed
Equisetum arvense	Field Horsetail
Lotus corniculatus	Birdsfoot Trefoil
Typha	Cattail
Carex	Sedge

Figure 5.7. Grand Rapids Site 1.

Grand Rapids 2 Plant List

<u>Genus/species</u>	<u>Common Name</u>
Tanacetum vulgare	Common Tansy
Cirsium discolor	Field Thistle
Ambrosia artemisiifolia	Common Ragweed
Equisetum arvense	Field Horsetail
Phalaris arundinacea	Reed Canary Grass

Figure 5.8. Grand Rapids Site 2.

Grand Rapids 3 Plant List

Genus/species	Common Name
Tanacetum vulgare	Common Tansy
Cirsium discolor	Field Thistle
Ambrosia artemisiifolia	Common Ragweed
Equisetum arvense	Field Horsetail
Phalaris arundinacea	Reed Canary Grass
Typha	Cattail

Figure 5.9. Grand Rapids Site 3.

West Duluth Plant List

Genus/species	Common Name
Grindelia squarrosa	Gumweed
Bromus enermus	Smooth Brome
Medichen sativa	Alfalfa
Tanacetum vulgare	Common Tansy
Phalaris arundinacea	Reed Canary Grass

Figure 5.10. West Duluth site.

Lilydale Plant List

Genus/species	Common Name
Rhus glabra	Smooth Sumac
Rhamnus cathartica	Buckthorn
Fraxinus pennsylvanica	Green Ash
Solidago	Goldenrod
Setaria pumila	Yellow Foxtail
Phalaris arundinacea	Reed Canary Grass
Melilotus alba	Sweetclover

Figure 5.12 Lilydale site.

Silver Creek Plant List

Genus/species	Common Name
Phalaris arundinacea	Reed Canary Grass
Tanacetum vulgare	Common Tansy
Cirsium discolor	Field Thistle
Achillea millefolium	Common Yarrow
Agrostis gigantea	Red Top
Lupinus polyphyllus	Large-leaved Lupine
Ratibida pinnata	Yellow Coneflower
Andropogon gerardii	Big Bluestem
Hypericum perforatum	Common St. Johnswort
Lotus corniculatus	Birdsfoot Trefoil

Figure 5.11 Silver Creek site.

5.1.2 Civil Engineering

5.1.2.1 *In Situ* Testing

The dry unit of the media was determined for each site to aide in reproducing field conditions during laboratory hydraulic conductivity testing. The sand cone method was followed according to ASTM D1556 (2015) to determine the relative density and the unit weight of the media at each site. The results are presented in Table 10.

The saturated hydraulic conductivity at each site was considered to be the primary factor influencing the water transport capabilities of the site. The Modified Philip-Dunne (MPD) infiltrometer was used to test the hydraulic conductivity for each site following the guidelines given by Ahmed and Gulliver (2012). Each site was tested at four different locations and an average saturated hydraulic conductivity was found for each biofilter, see Table 11.

The value of saturated hydraulic conductivity of sandy soils were consistent with the laboratory values found by Johnson et al. (2017), 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 10. 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	89.9	16.85
Cloquet	1.59	99.3	3.67
Cook	1.55	96.8	2.55
Crosby Site 1	1.32	82.4	20.42
Crosby Site 2	1.15	71.8	5.06
Eagles Nest Trench	1.27	79.3	16.85
Eagles Nest Slope	1.36	84.9	19.75
Grand Rapids Site 1	1.23	76.8	4.31
Grand Rapids Site 2	1.55	96.8	0.85
Grand Rapids Site 3	1.40	87.4	5.40
Gilbert Lake	1.08	67.4	9.74
Lilydale	1.05	65.6	20.47
Silver Creek	1.74	108.6	5.89
West Duluth	1.29	80.5	10.35

Table 11. 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	$1.45*10^{-2}$
Eagles Nest Slope	$1.25*10^{-2}$
Eagles Nest Trench	$1.21*10^{-2}$
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	$2.76*10^{-2}$
Lilydale	$2.05*10^{-3}$
Silver Creek Cliff	$1.30*10^{-1}$
West Duluth	$1.31*10^{-3}$

5.1.2.2 Laboratory Testing

The Unified Soil Classification System (USCS), following ASTM D2487, was used to formally identify the biofilter media samples. This was done to aide in comparing the various samples to each other as well as current MnDOT media specifications. This method requires soil sieving which was done according to ASTM C136. Several of the samples contained a high fine content that required the determination of the Atterberg limits (ASTM, 2010) to properly classify the media. Additionally, the media sampled from just south of the city of Cook contained high levels of organic material. This soil was classified using ASTM D4427 which required additional testing that ultimately classified the media as sapric, high ash, basic, and slightly absorbent peat. Additional soil classification results are presented in Table 12.

Laboratory hydraulic conductivity testing was conducted following the falling head test method described by Germaine and Germaine (2009). The moisture content and dry unit weight of each media sample was used to replicate the *in-situ* conditions during laboratory testing. Each sample was run through three test cycles and an average saturated hydraulic conductivity was found. The results of laboratory hydraulic conductivity testing are presented in Table 13.

Table 12. 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)
Eagles Nest Slope	Poorly Graded Sand (SP)
Eagles Nest Trench	Poorly Graded Sand (SP)
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)
Lilydale	Poorly Graded Sand (SP)
Silver Creek	Well Graded Sand (SP)
West Duluth	Well Graded Sand (SW)

5.1.2.3 Comparison of *In Situ* and Laboratory Results

The laboratory characterization methods were developed as a potential predictive tool for evaluating the performance of biofilters (Johnson et al. 2017). As presented in Figure 63, 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.

5.1.2.4 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 during 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, as shown in Figure 64. This comparison does not lead to a significant relationship between the age of a biofilter impacting performance.

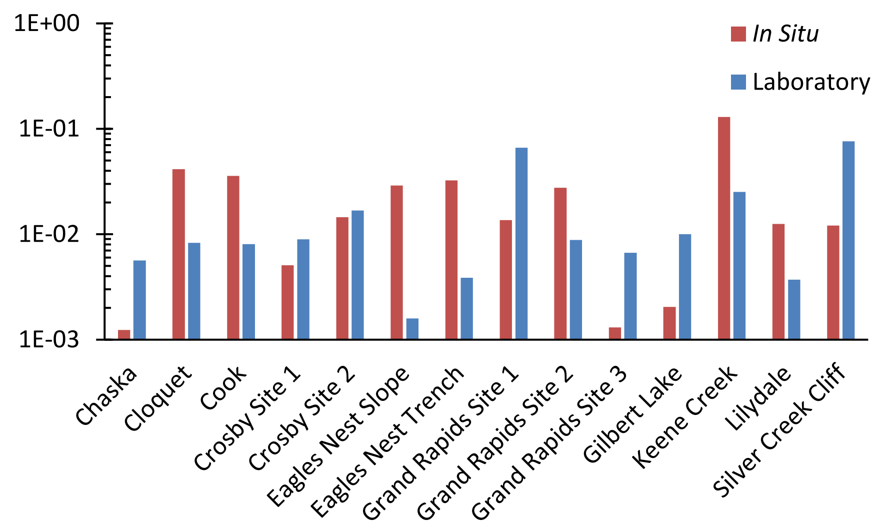


Figure 5.13. Comparison of *in situ* and laboratory hydraulic conductivity testing.

Table 13. 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	$1.68*10^{-2}$
Eagles Nest Slope	$1.59*10^{-3}$
Eagles Nest Trench	$3.86*10^{-3}$
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	$1.00*10^{-2}$
Lilydale	$3.70*10^{-3}$
Silver Creek Cliff	$7.62*10^{-2}$
West Duluth	$2.53*10^{-2}$

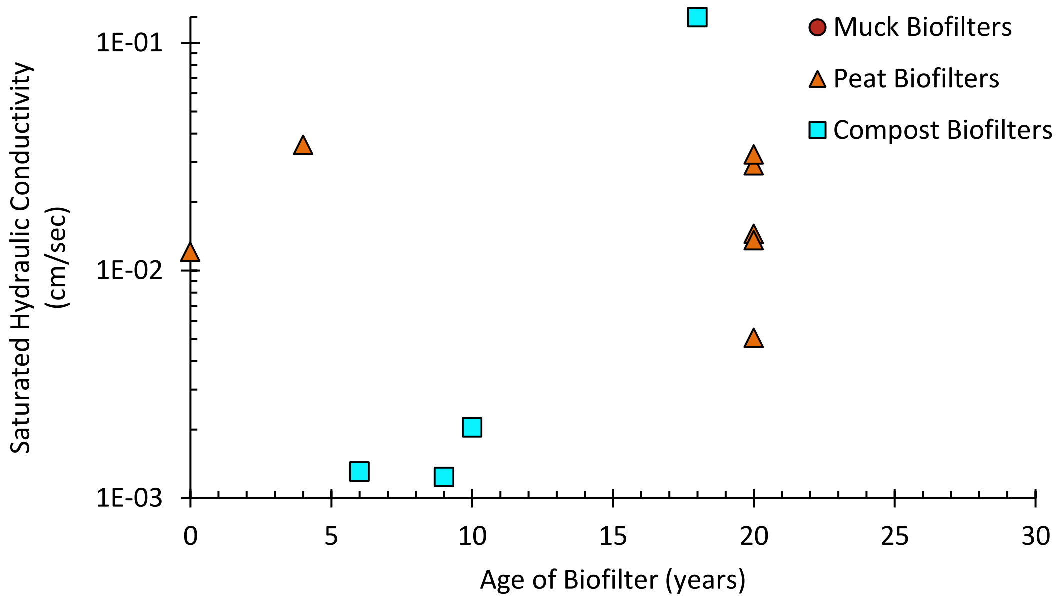


Figure 5.14. The saturated hydraulic conductivity versus the age of the various biofilters

5.1.3 Environmental Engineering

Metals (copper, lead and zinc) will be retained in soils by adsorption or precipitation, but nutrients (nitrate and phosphate) could be leached due to the decomposition of organic matters. The chemical removal/leaching capacities were tested by 24-hour batch tests by mixing soil samples with lab synthesized stormwater, which was prepared by dissolving $NaNO_3$, $NaH_2PO_4 \cdot H_2O$, $CuCl_2 \cdot 2H_2O$, $Pb(NO_3)_2$ and $Zn(NO_3)_2 \cdot 6H_2O$ into deionized water to gain pollutant concentrations of the highest levels observed in Minnesota state. The initial concentrations of the synthesized stormwater are 0.458 mg/L for copper, 0.342 mg/L for lead, 0.643 mg/L for zinc, 8.19 mg/L nitrate and 4.82 mg/L phosphate.

24-hour batch experiments were performed using the procedures described in the report of Task 3. The concentration changes of metals and nutrients before and after the experiments were recorded to examine the chemical removal capacities of each soil.

Overall more than 90% of lead were retained in soil (Figure 65) with all 14 types of soils because a lead hydroxide phase above pH 5.5 limited the immobility of lead. Other two metals of copper and zinc can be retained in soil, varied from around 30% to 90%, except that soils from one of Crosby sites and Gilbert lake site have negative removal capacities. For same soil, the retention amounts of copper and zinc are close, implying the similar soil adsorption affinities for these two metals. Nutrients of nitrate and phosphate were slightly leaching from the soil at a range of -10 – 10%.

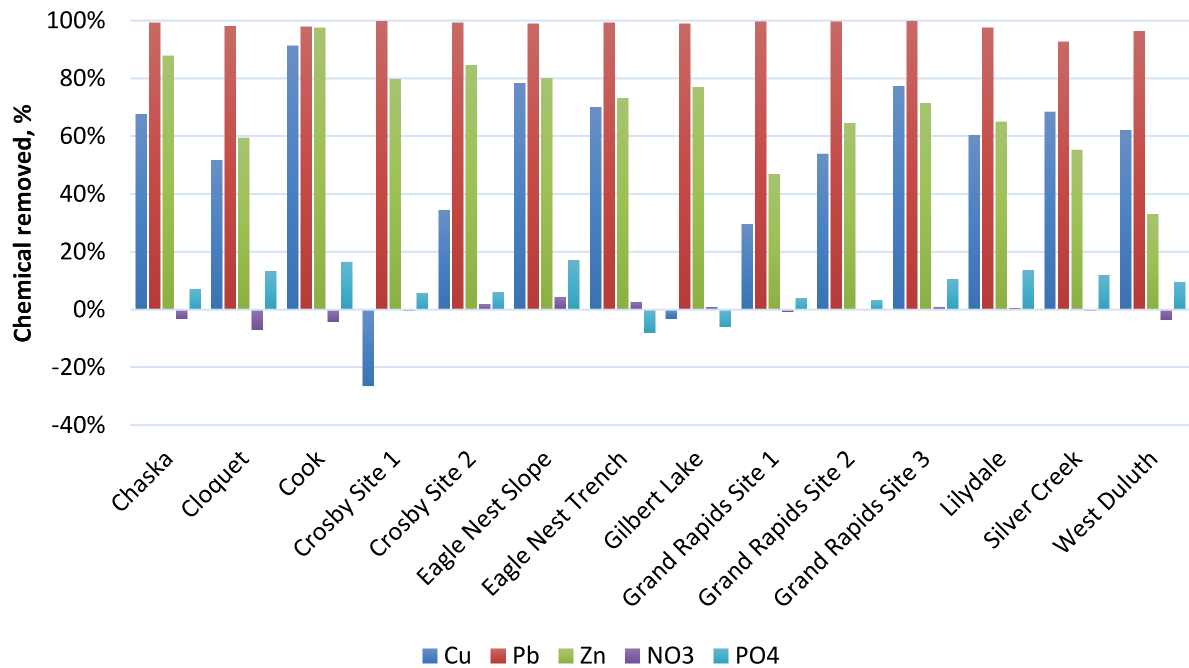
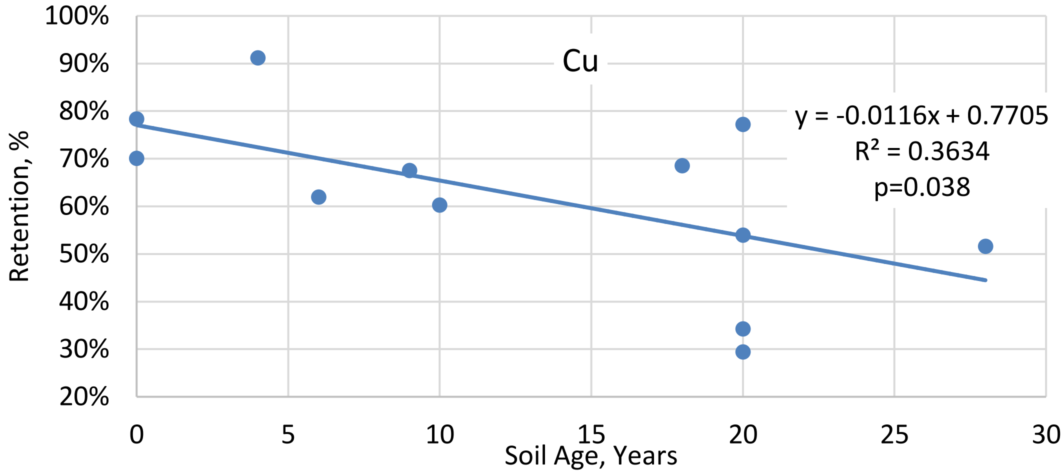
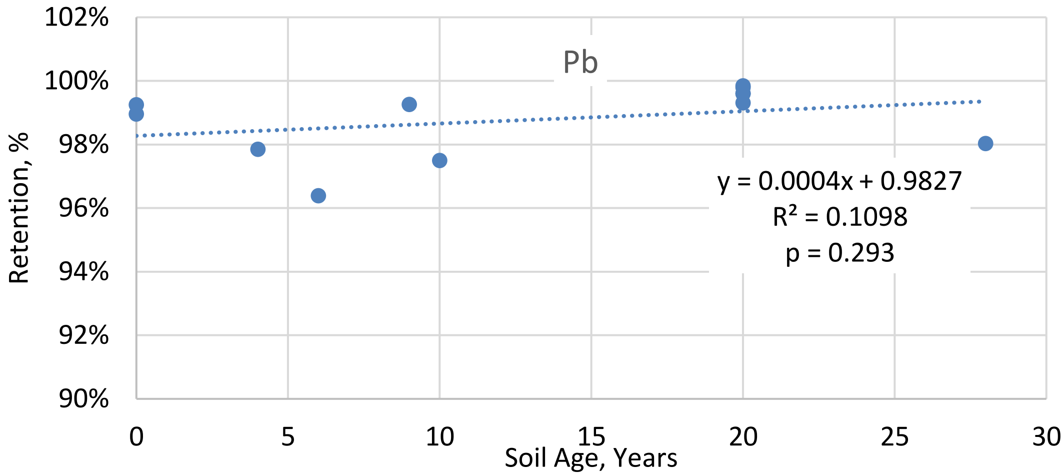


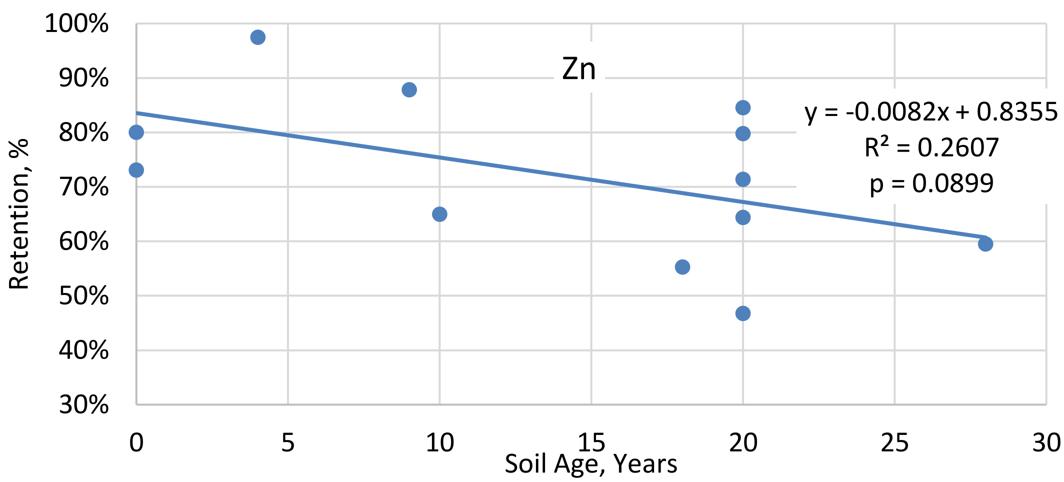
Figure 5.15. The adsorption/leaching of metals (Cu, Pb and Zn) and nutrients (NO_3 and PO_4) by soils, which were collected from existing stormwater treatment biofilters. The initial solution was synthesized in laboratory to simulate Minnesota stormwater.

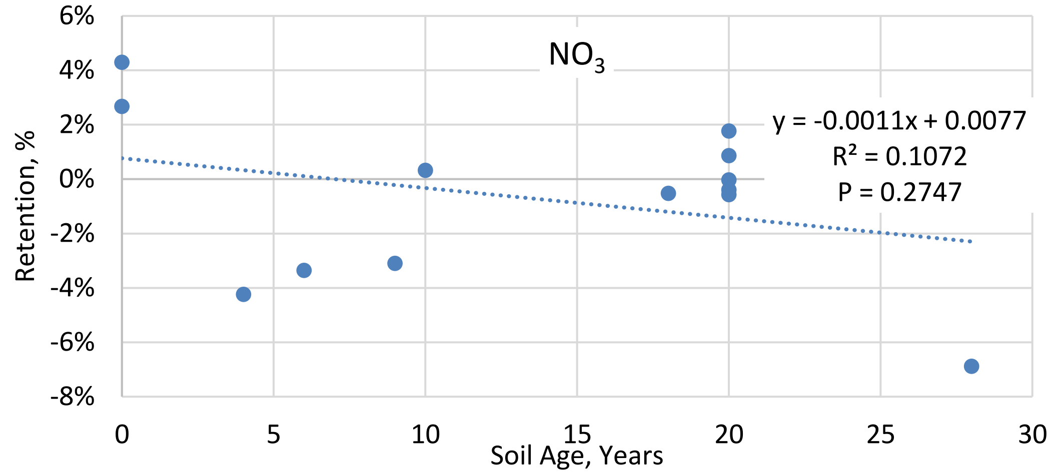
At the current 14 soil sampling locations, two sites use compost, eight sites are filled with peat, and the remaining four sites are lack of soil material information, so the specific materials used are unclear (Table 3). At the 10 sampling points of known soil materials, the retention/leaching ratios of metals and nutrients by soils did not find significant difference between compost and peat. This may also be because we don't have many compost sampling locations (only two sites). Since there is no significant difference between the two soil materials, the data from all sampling points were combined to determine the impact of the soil age on the environmental performance of the soil. This relationship was evaluated by single linear regression model.

The linear fitting models show that the retention amount of Cu, Zn and PO_4 are negatively and significantly correlated with the soil age (Figure 66). In other words, the soil retention capacities of copper, zinc and phosphate are reducing along the soil ages. Based on current trend, we predict that compost or peat may lose their retention capacities after the soil has been used for approximately 66 years for copper, 102 years for zinc and 7 years for phosphate. There is no clear trend for the soil retention capacities for lead and nitrate. The soil maintained relatively constant and high (>95%) retention capacities for lead and keeps leaching nitrate at small amount (around 4%).


Cu
Retention, %
100%
90%
80%
70%
60%
50%
40%
30%
20%
0
5
10
15
20
25
30
Soil Age, Years
y = -0.0116x + 0.7705
R² = 0.3634
p=0.038


Pb
Retention, %
102%
100%
98%
96%
94%
92%
90%
0
5
10
15
20
25
30
Soil Age, Years
y = 0.0004x + 0.9827
R² = 0.1098
p = 0.293


Zn
Retention, %
100%
90%
80%
70%
60%
50%
40%
30%
0
5
10
15
20
25
30
Soil Age, Years
y = -0.0082x + 0.8355
R² = 0.2607
p = 0.0899



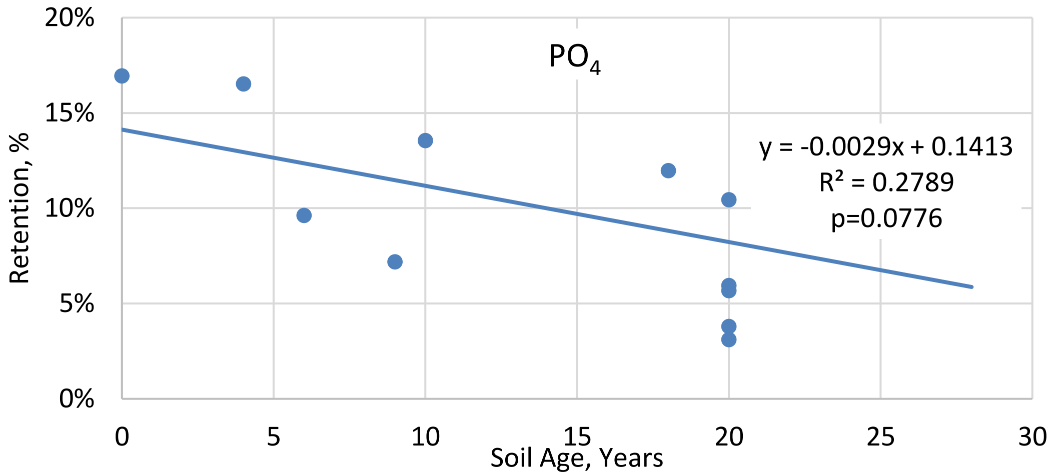


Figure 5.16. The linear fit between the percent of chemical retained and soil age. The significant ($p<0.1$) fit is shown in a solid line and the dashed line represents the insignificant fit.

CHAPTER 6: MONITORING OF ALTERNATIVE BIOFILTER SYSTEMS

During previous work completed for MnDOT, a pilot test program was initiated to compare the infiltration and water treatment of compost amended soils with peat amended soils. A vegetated slope adjoining a parking lot at the Natural Resource Research Institute (NRRI) (shown in Figure 67) was selected for instrumentation and water collection. Amended soil sections were contained in three-foot-square plots where native soil was mixed with the respective media amendment at a ratio of 1:1 by volume. Three of these plots were prepared with compost and three with peat for the amendment.

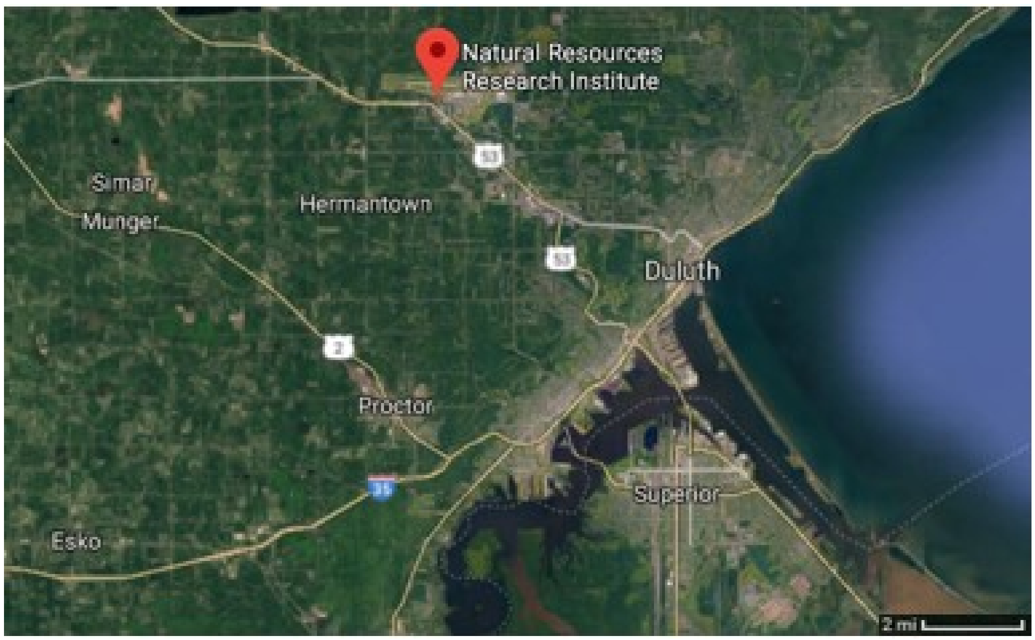


Figure 6.1 The location of the NRRI pilot test plot.

The Eagles Nest site contained biofilter amendments throughout the 5.7 miles of new road construction. Typical construction of the biofiltration system implemented at the site included a peat amended bioslope which flowed into a bioswale. Peat, shown in Figure 68, 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 69, 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 70, 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 6.2. Typical sample of peat used at the Eagles Nest Project site.

Figure 6.3. Bioswale construction at midpoint of hillside.

Figure 6.4. Permeable membrane sleeve and geomembrane placed at site to protect underdrain from clogging.

6.1 CIVIL ENGINEERING

6.1.1 NRRI

A sloped section, adjacent to a parking lot, shown in Figure 71, 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 72. An under drain was also placed at the bottom of each bed to promote drainage and to allow for sample collection.

Following construction, the site was instrumented with monitoring equipment. A data acquisition unit, shown in Figure 73, was installed to regularly sample soil moisture, rainfall, and ambient temperature. A single soil moisture probe, pictured in Figure 74, was placed centrally in each of the six media beds. The rain gauge, shown in Figure 75, and temperature probe, shown in Figure 76, 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 77, was used to ensure a consistent power for the data acquisition unit.

Figure 6.5. Field pilot test plot at NRRI.

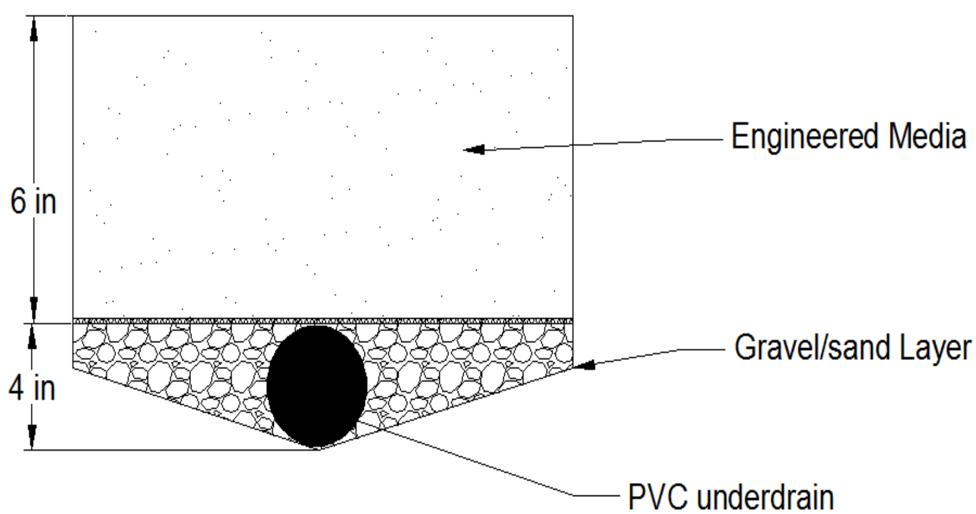


Figure 6.6. Cross section of media bed design (adapted from Johnson et. al, 2017).

Figure 6.7. Data acquisition unit used to record soil moisture, rainfall and temperature during monitoring.

Figure 6.8. Typical soil moisture probe used for monitoring.

Figure 6.9. Rain gauge monitoring unit.

Figure 6.10. Temperature probe with solar shield.

Figure 6.11. Solar panel used to sustain long term monitoring.

This instrumentation scheme allowed for correlations between rainfall data and changes in soil moisture content as shown in Figure 78. 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.

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 79 and 80 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 time when the third probe was broken.

Soil moisture data was also analyzed using weight volume relationships to determine the amount of rainfall captured at each site. This work was aided by previous characterization of the media amendments and native NRRI soils performed by Johnson et al. (2017).

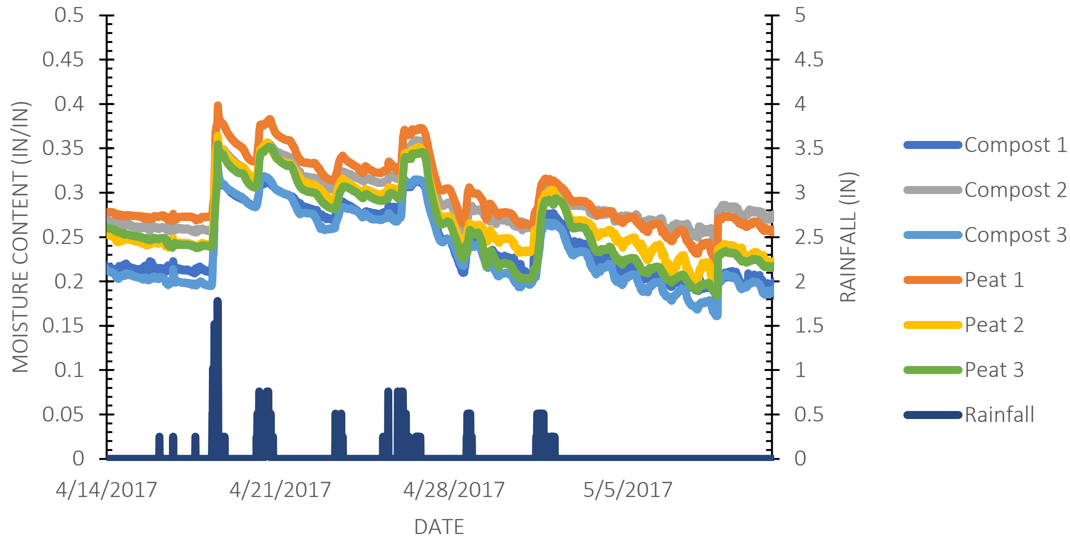


Figure 6.12. Soil moisture and rainfall event data for the NRRI test plot during the spring of 2017.

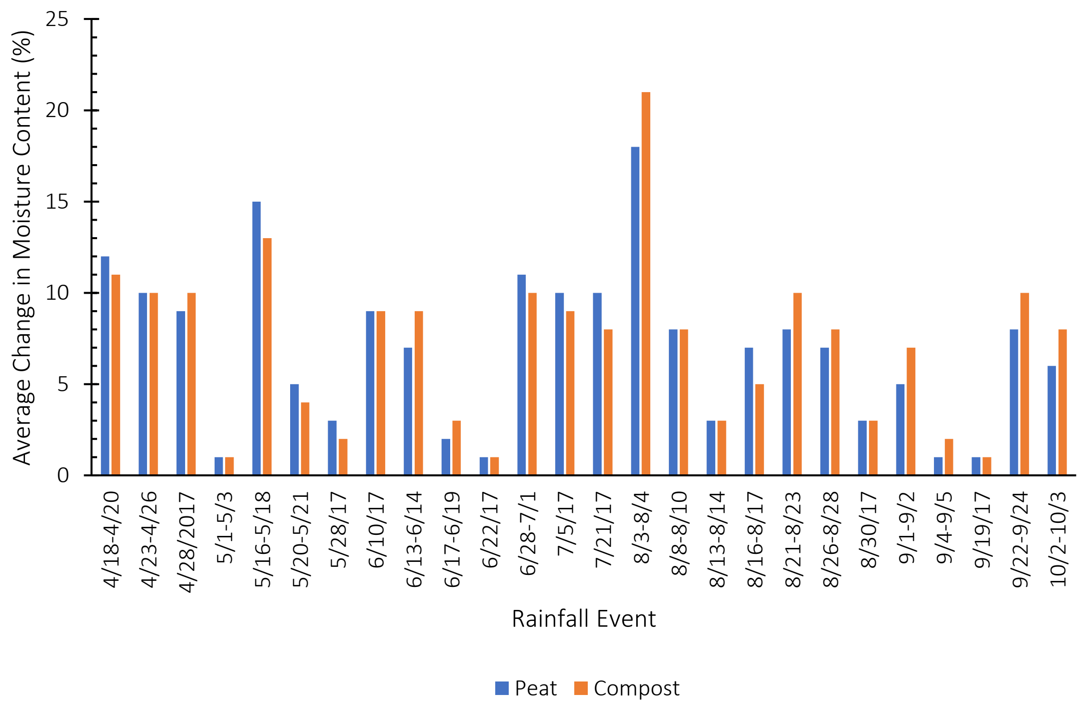


Figure 6.13. Comparison of water absorption for the NRRI pilot plot for 2017.

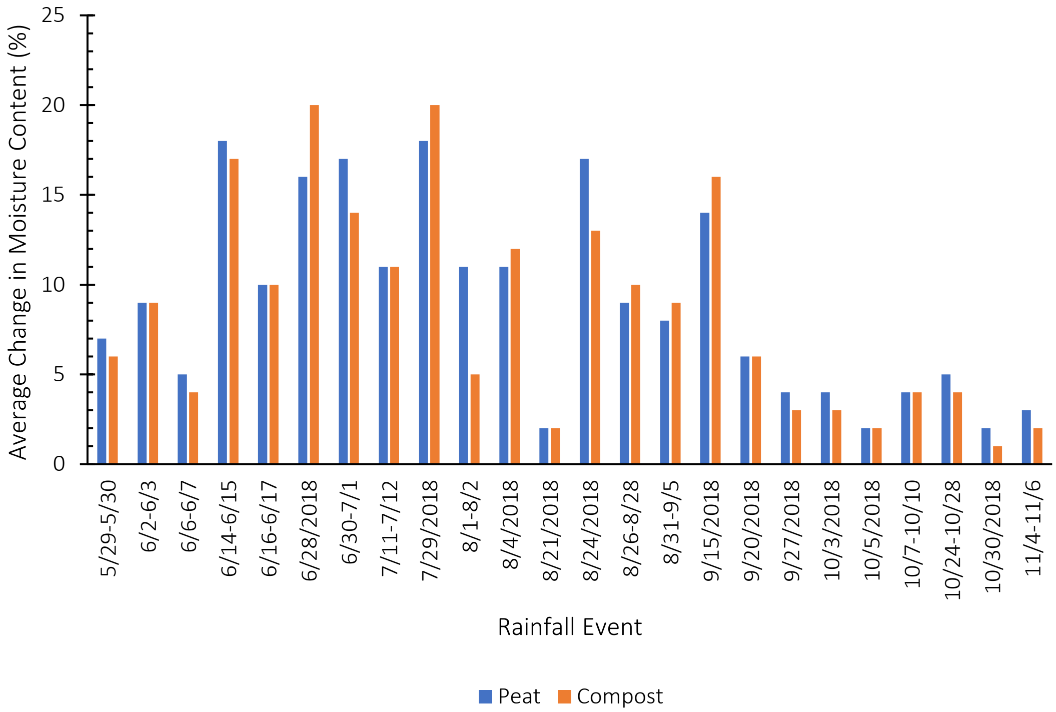


Figure 6.14. Comparison of water absorption for the NRRI pilot plot for 2018.

Figure 81 shows rainfall event totals as compared with water captured by the biofilters. The data indicates a near one to one relationship during smaller rainfall events where the biofilters were able to efficiently infiltrate rainfall. The data becomes less grouped as rainfall intensity increases. The higher 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 performed had comparable results in this comparison with no clear over or under performer.

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 82. 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.

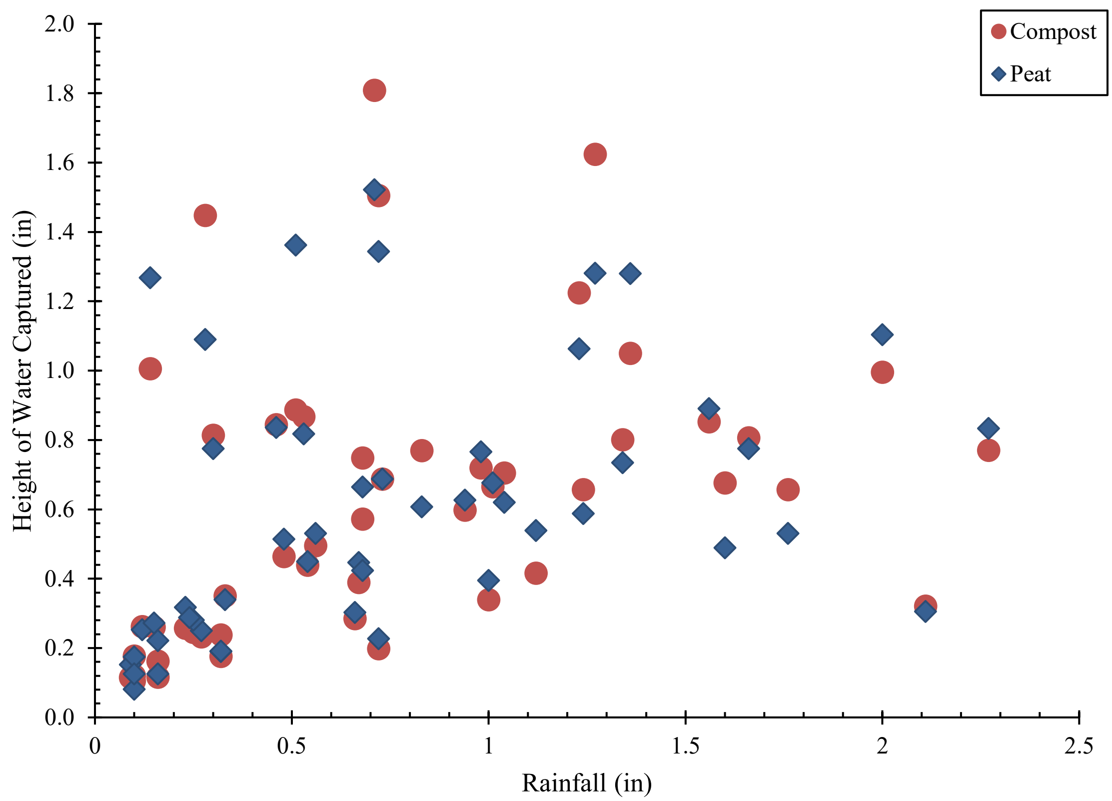


Figure 6.15. Comparison of rainfall total with water captured by peat and compost amended biofilters.

Prolonged storm events also appeared to have an impact on the infiltration capabilities of the biofilters. Figure 83 shows the amount of water caught by each biofilter compared with the duration of storm events. Figure 84 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 once again the most likely reasons for this behavior.

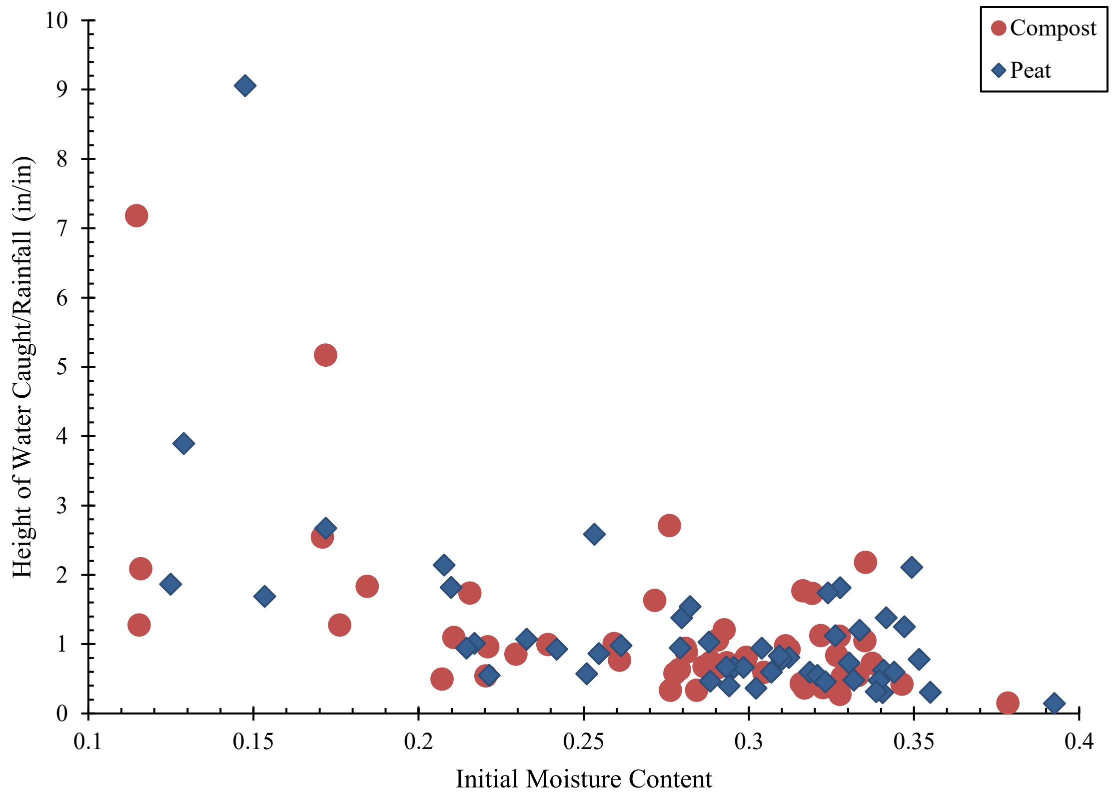


Figure 6.16. Initial soil moisture content compared to normalized rainfall and infiltration data.

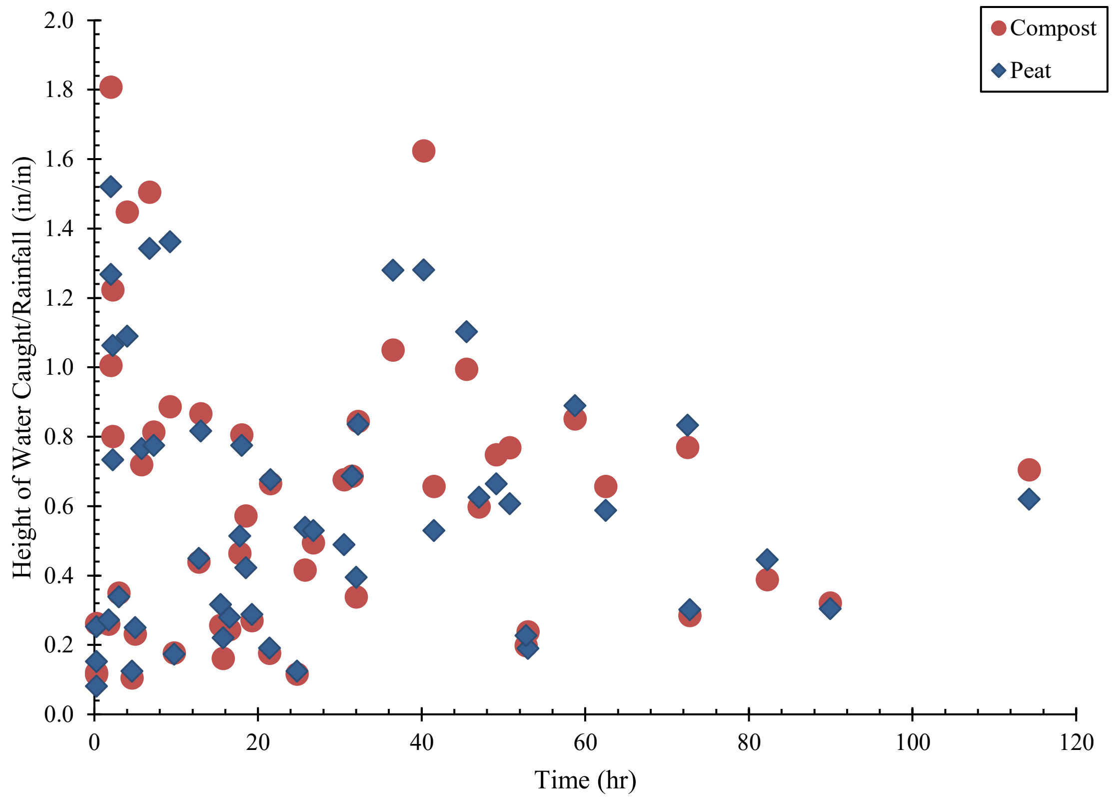


Figure 6.17. Infiltration compared to rainfall event duration.

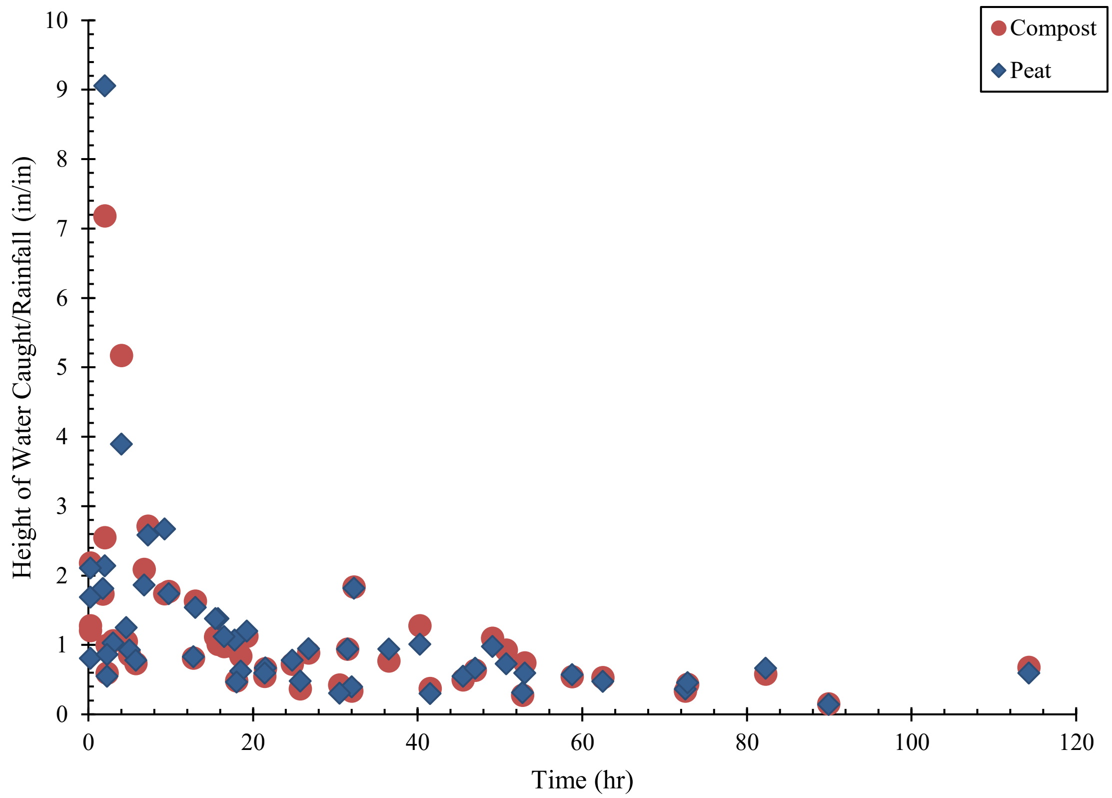


Figure 6.18. Normalized rainfall and infiltration data compared with rainfall event duration.

6.1.2 Eagles Nest

Instrumentation was installed at the Eagles Nest in August of 2018. 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 85. 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.

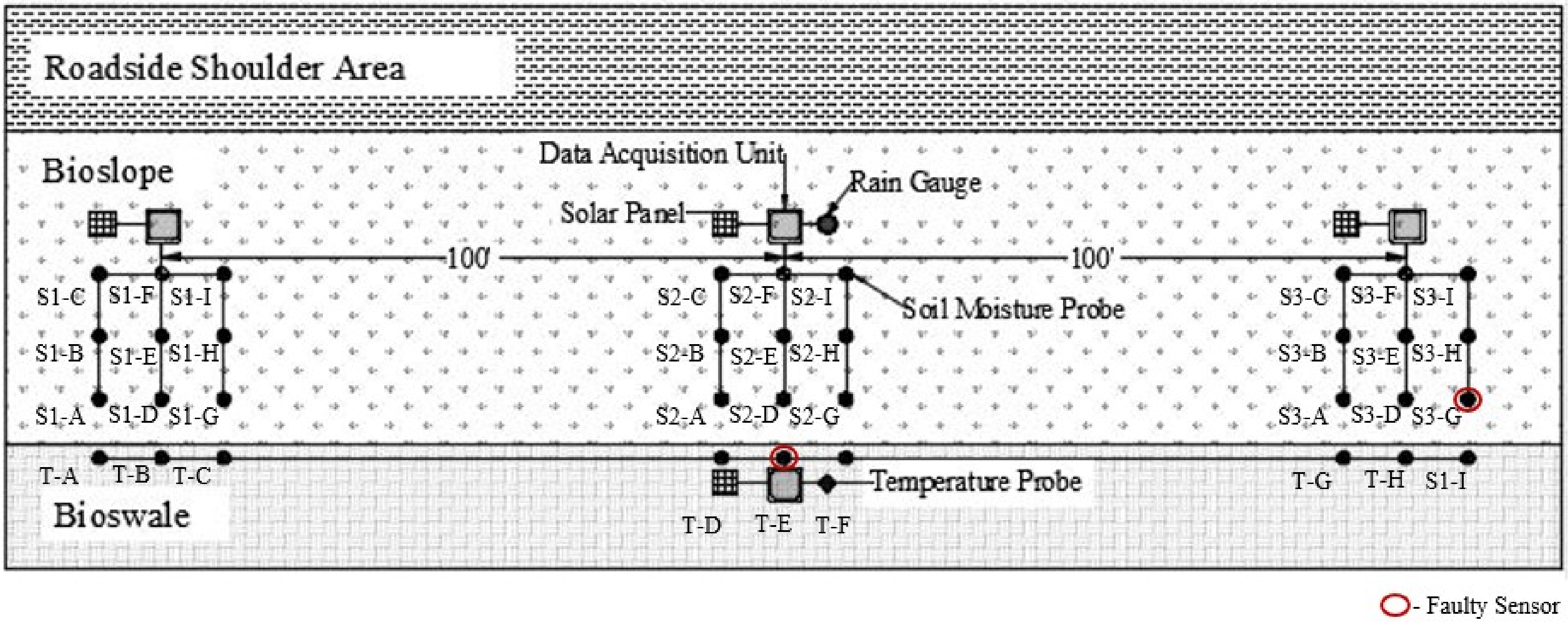


Figure 6.19. Biofiltration system monitoring schematic.

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. These sensors have been excluded from the following 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 86 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.

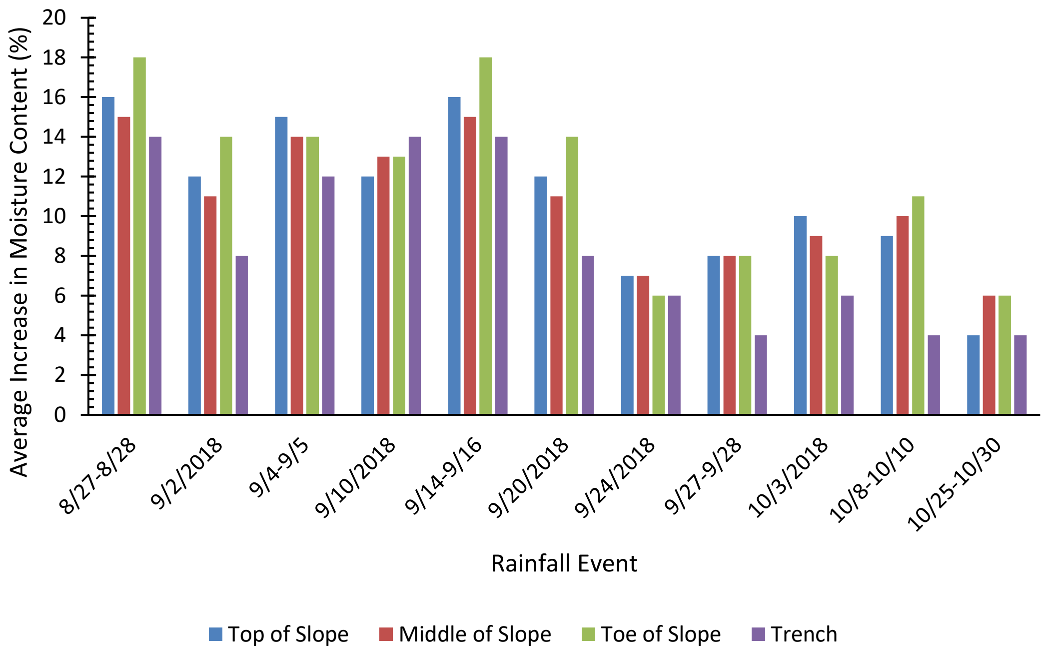


Figure 6.20. Comparison of water absorption over the course of the slope for the Eagles Nest biofiltration system.

Physical properties of the media were used along with weight volume relationships to evaluate the infiltration capabilities of the site. A global average of the soil moisture probes placed in the slope were used to verify the capability of the media to catch the first inch of rainfall at the Eagles Nest site. Figure 87 shows results consistent with the pilot plot with variable infiltration but in lower values of rainfall a nearly one to one relationship with higher intensity storms having less water caught. This one to one relationship shows the ability for the biofilter to infiltrate the first inch of rainfall during storm events.

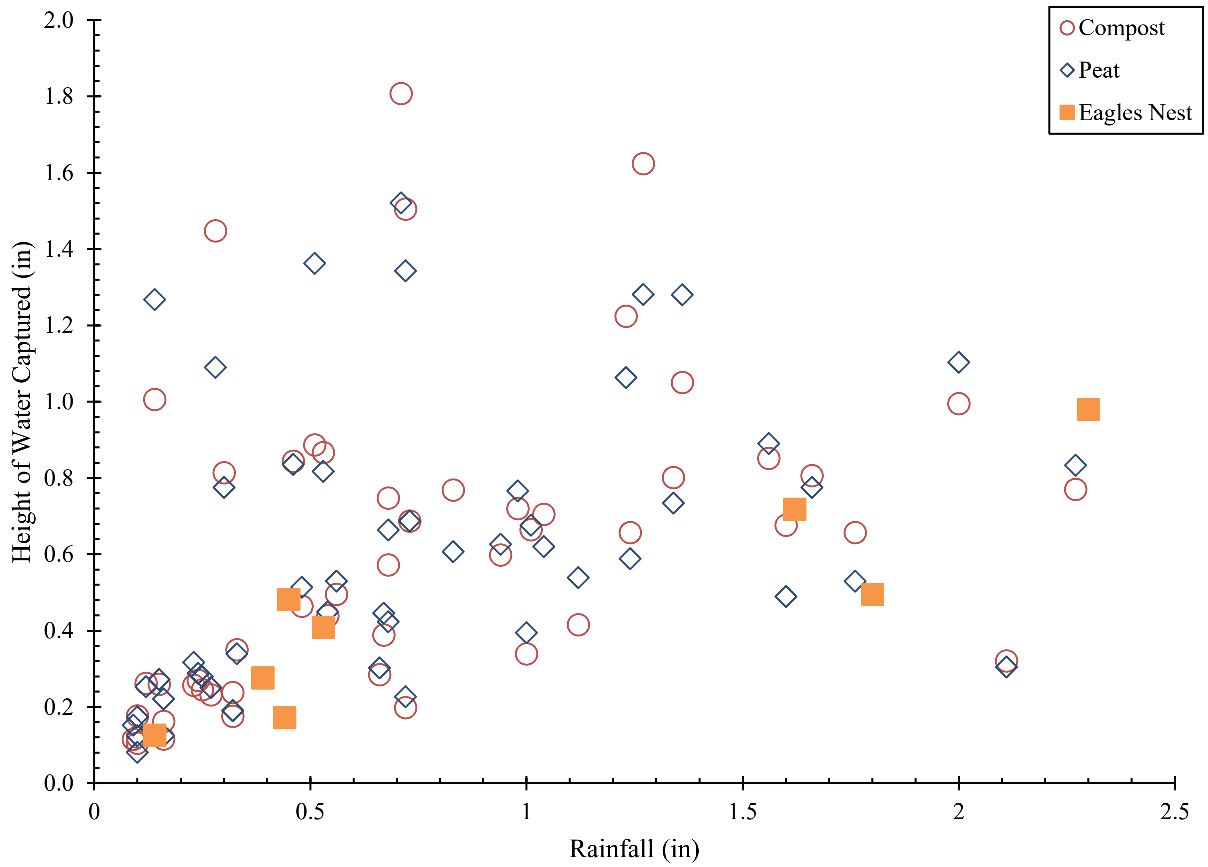


Figure 6.21. Comparison of water absorption against rainfall events.

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 88 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.

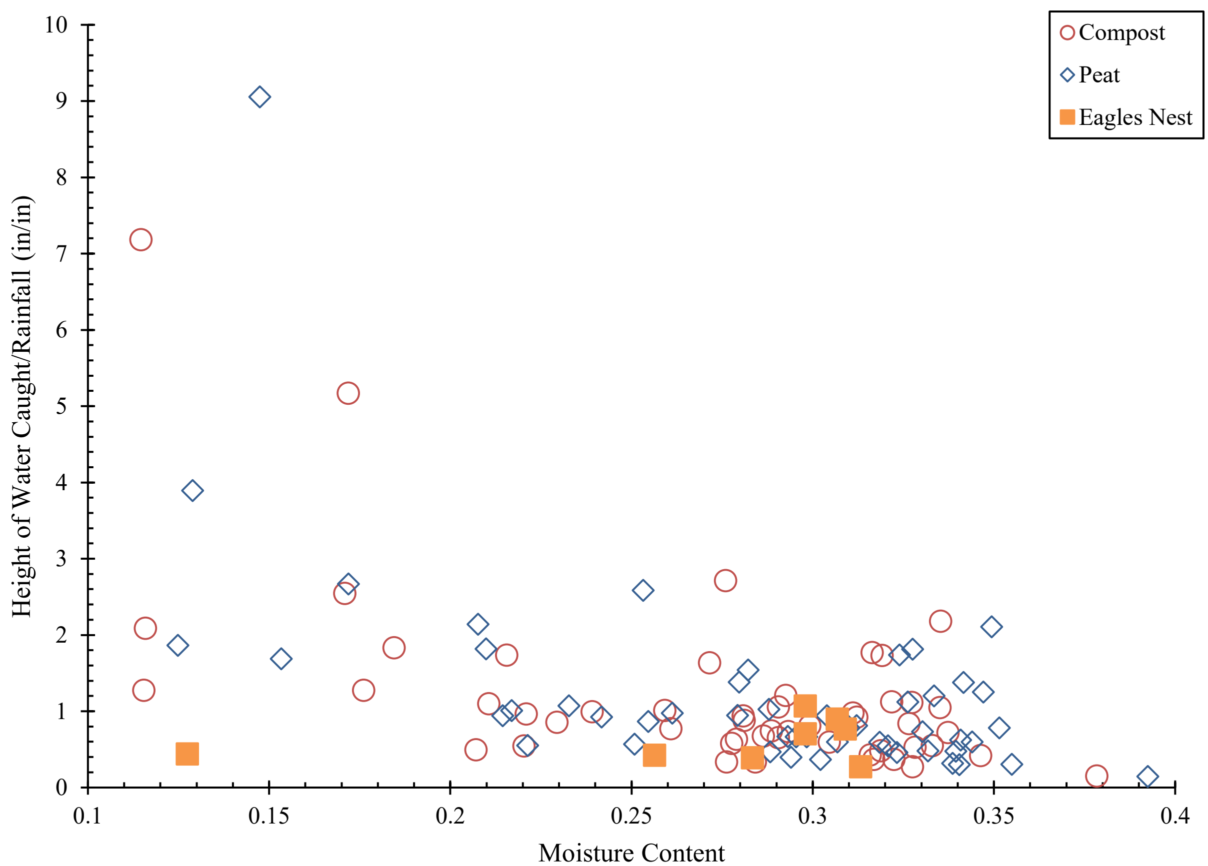


Figure 6.22. Comparison of normalized rainfall event data against initial moisture content.

The duration of rainfall events did appear to have a similar behavior at the Eagles Nest site as at the pilot plot. Figure 89 shows scattered data during short duration storms with values that tend towards approximately 0.9 inch of rainfall caught for longer duration storms. More data is needed to accurately assess the behavior for longer duration storms.

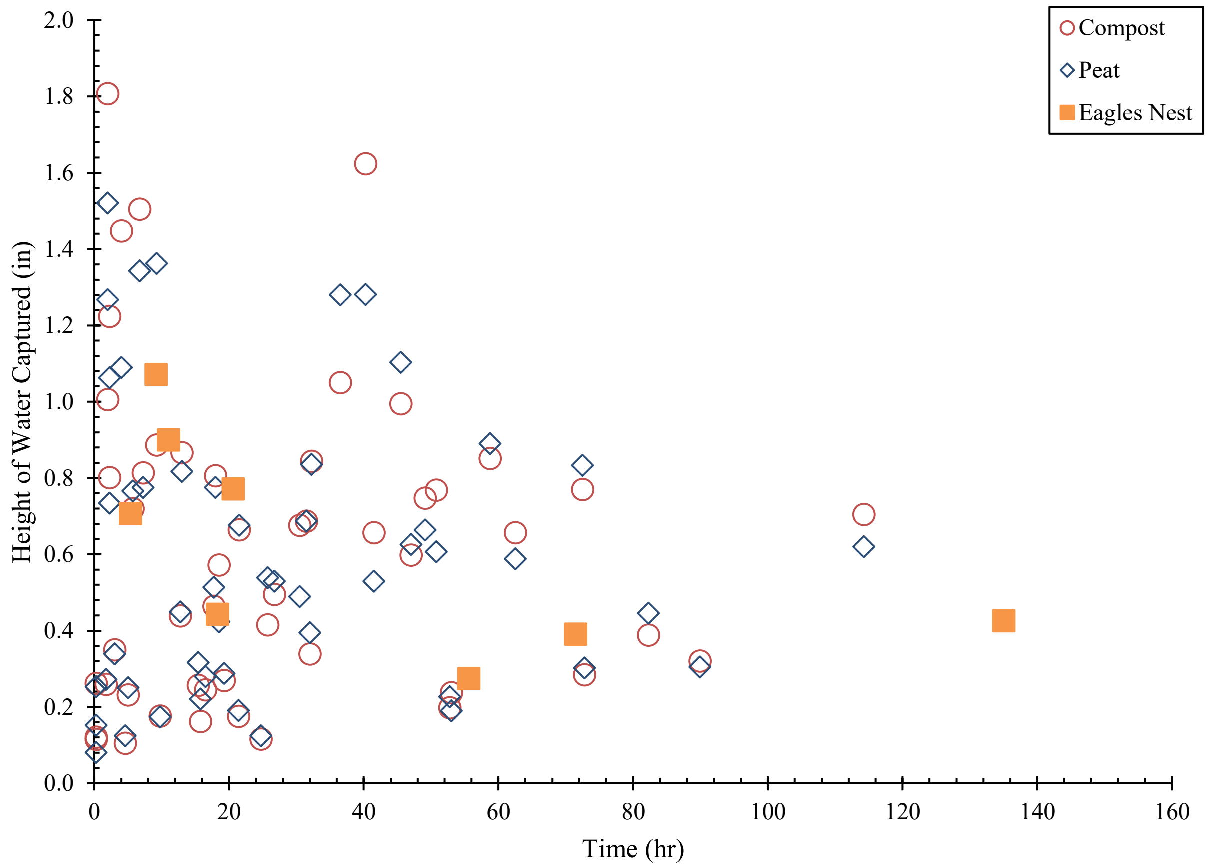


Figure 6.23. Comparison of water captured against rainfall event duration.

A normalization of the water caught with rainfall height against storm duration gives varied results. Figure 90 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 the data collected at the NRRI site, the Eagles Nest data would point towards higher initial moisture content conditions that were still capable of efficiently infiltrating rainfall.

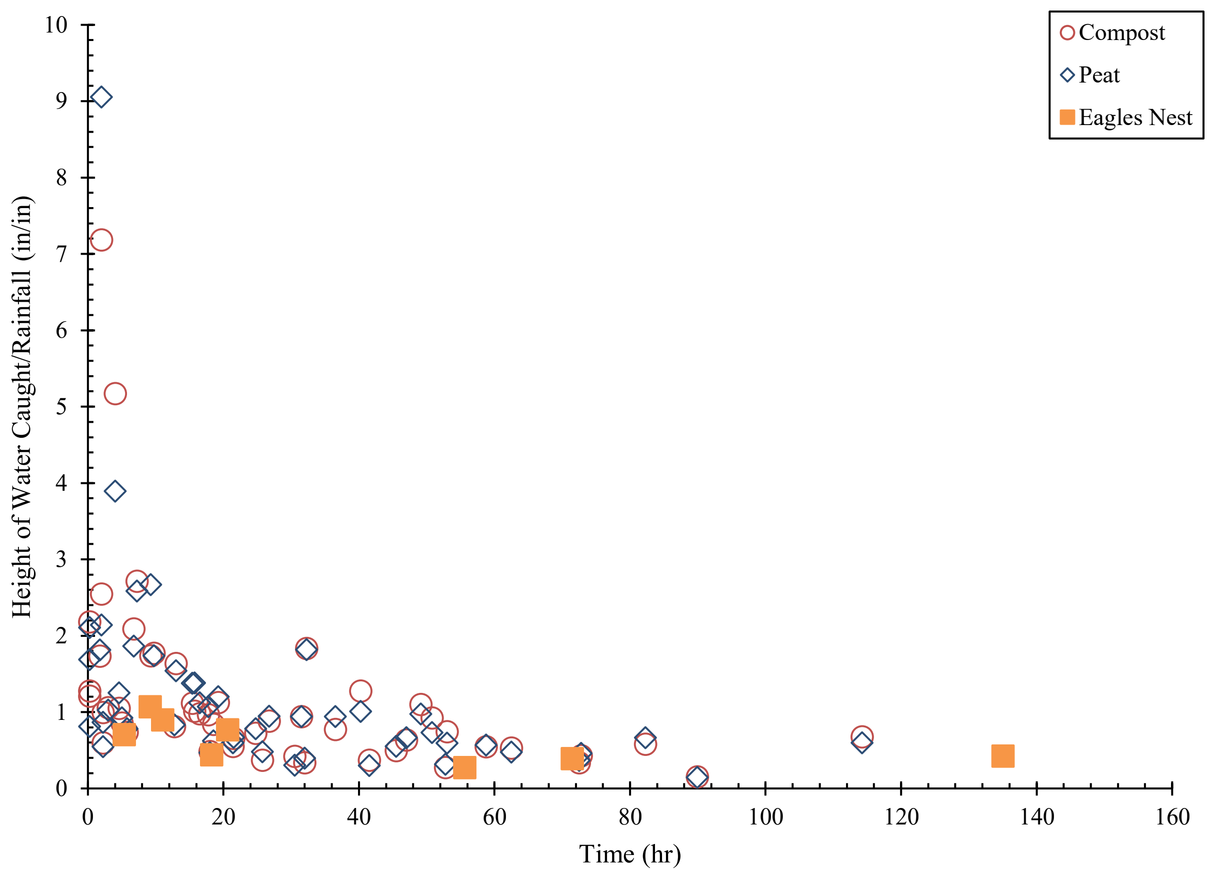


Figure 6.24. Normalized rainfall event data compared with event duration.

6.2 ENVIRONMENTAL ENGINEERING

6.2.1 NRRI

In phase I of this project, one field demonstration plot was constructed in September 2016. Since then, the continuous monitoring of water quality was performed. From April 18, 2017 till October 30, 2018, samples were collected in total 35 rain events (Figure 91). In most sampling days, the daily precipitation amounts were above 0.4 inch.

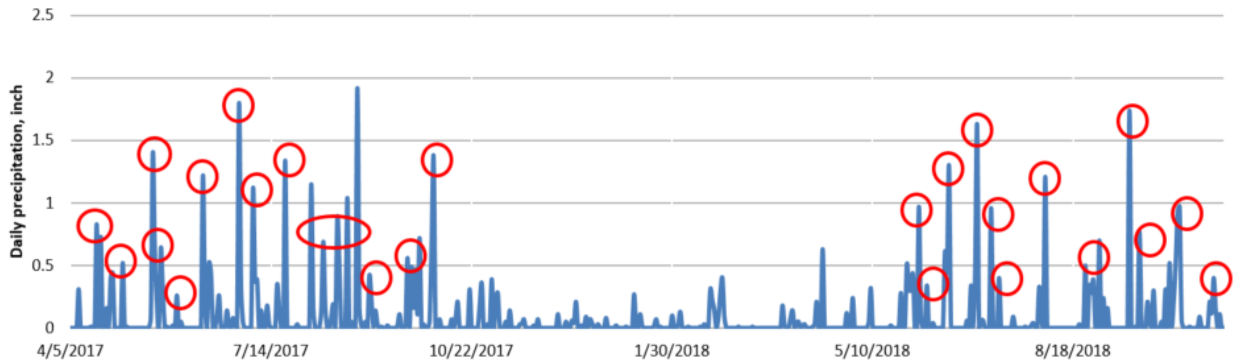


Figure 6.25. The daily precipitation recorded by Duluth airport weather station. Red circles are days when leachate samples were collected from the demonstration plots.

The leachate samples were filtrated by 0.45 µm membrane, and analyzed for pH by pH probe, metals (Cu, Pb, Zn) by graphite atomic absorption spectroscopy, and phosphate by colorimetric method.

The two-year monitoring gives us good data to check the water quality changes among materials and along the time (Figure 92). Overall, for most of the chemicals studied, we did not find significant temporal changes except the concentration of lead. The lead concentration in the leachate water sample contained 2-10 µg/L in 2017 but became undetectable in 2018.

Comparing among different soil materials and sampling locations, we found that the water quality demonstrated significant difference among materials/locations. The biggest difference between compost and peat is PO4 leaching, which has concentrations at the range of 1,000-5,000 µg/L for the compost sites, and generally below 100 µg/L for the peat sites. Because the phosphate content in rainwater is less than 10µg/L, this result tells us that both compost and peat are leaching phosphate, but the leaching amount from compost is much larger than peat. In addition, the pHs in compost leachates are also around 0.3 higher than the pH of the peat leachate, but both of their pHs are neutral, between 7 and 7.5. For copper and zinc, the difference among compost and peat leachates was small, and the concentrations were 20-80 µg/L for copper and 50-150 µg/L for zinc.

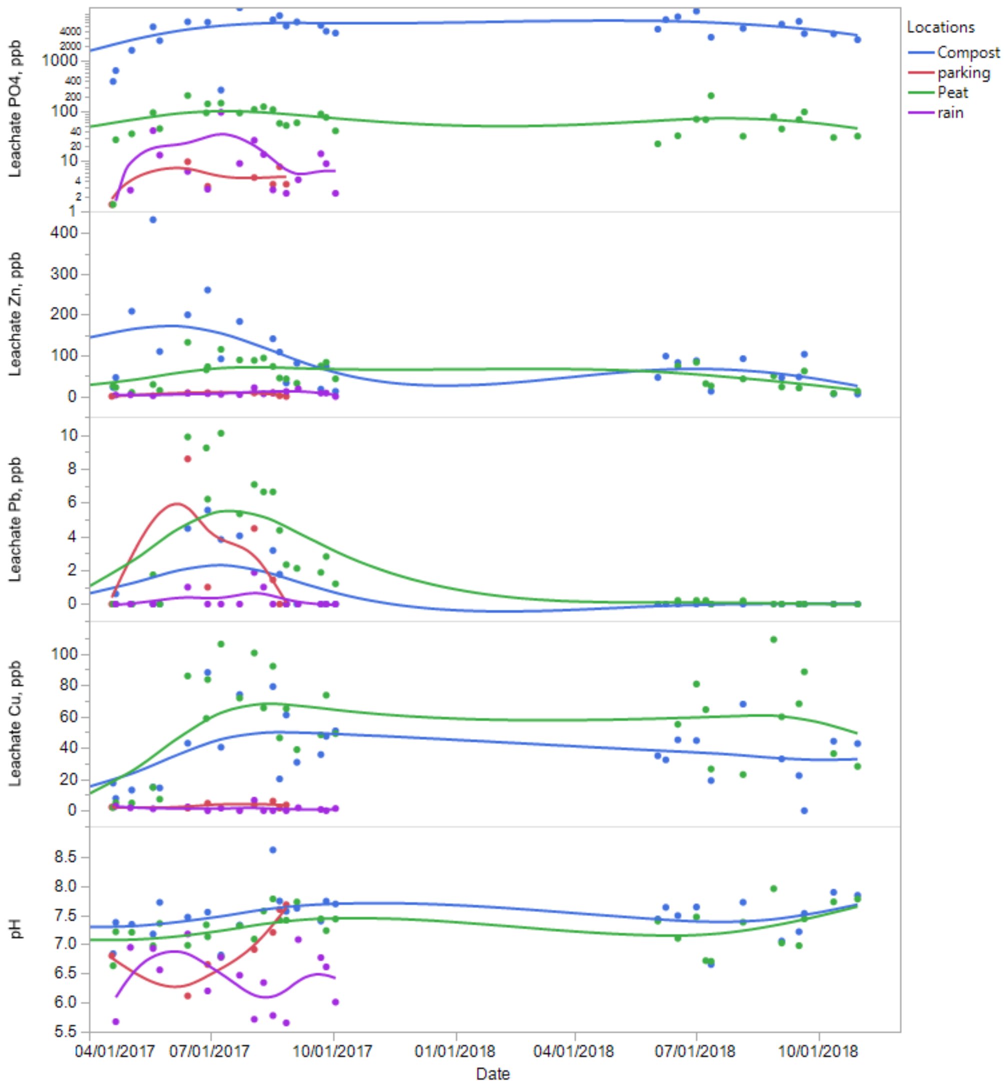


Figure 6.26. The mean chemical concentrations of soil leachates collected from three compost sites, three peat sites, one parking lot surface site and one rain site. The sites were newly constructed in September 2016 and located in the parking lot at NRRI.

6.2.2 Eagles Nest

In the Eagles Nest roadside, the slope surface was filled with peat for 4-6 inches and the trench was filled with the mixture of peat, compost, and sand. In order to monitor the water quality of leachates, two sample collection bottles were connected with perforated pipes under the trench on Aug. 23, 2018, and six lysimeters were installed on the slope at the intervals of 5 meters on Oct. 11, 2018 (Figure 93). Due to the short survey time before the coming of snow season, only four samples were collected from these equipment, and one sample collected on Oct. 29 was not sufficient enough for all parameter measurement.

Figure 6.27. Leachate collection from Eagles Nest trench (left) and lysimeters installed in Eagles Nest slope (right).

The water quality from both trench sites was relatively stable at neutral pH, and small amount leaching of copper, zinc and phosphate (Table 14). However, the water quality for leachate from slope varied significantly form one day to another day. This variation indicates the multiple lysimeters and long-term monitoring are necessary to record further changes.

Table 14. The water quality collected from slope and from the trench in Eagles Nest roadside. The sample collected on Oct. 29 was not sufficient enough to do all parameter analysis.

Date	Location	pH	Cu, µg/L	Pb, µg/L	Zn, µg/L	PO_4, µg/L
10/12/2018	Trench, south	7.7	7.9	<1	5.5	104
10/12/2018	Trench, north	7.7	14.4	<1	<1	219
10/15/2018	Slope	9.4	10.7	<1	6.2	170
10/29/2018	Slope	8.2				730

CHAPTER 7: CONCLUSIONS AND RECOMENDATIONS

7.1BIOLOGY CONCLUSIONS

Biofilter soil sample analyses revealed nutrient and organic matter deficiencies for most sites. This could be remedied by proper soil design and nutrient sampling after construction and prior to planting. If needed, additional fertilizer or organic matter could be added at this time. Biofilter sites were also dominated by weedy plant species. To avoid this, sites should be seeded with mixes containing a good annual cover crop and locally adapted native species. Rapid establishment of these desirable species will help reduce weedy infestations.

7.2 CIVIL ENGINEERING CONCLUSIONS

In comparing the results of *in situ* and laboratory testing, there was not a clear trend for laboratory methods either overpredicting 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.

7.3 ENVIRONMENTAL ENGINEERING CONCLUSIONS

The performance of soil capacities in treating pollutants of metals and phosphate was observed through lab batch tests and through the monitoring of an experimental field site for a two-year period. The experimental observations indicate that peat is a good alternative to compost for stormwater biofilter applications. Peat has similar retention capacities as compost in removing metals and peat leached significantly less phosphate than compost. Both compost and peat did not show significant capacities in removing nitrate.

The pollutant removal capacities of compost and peat are decreasing along soil age, such as 66 years for copper retention and 102 years for zinc retention. Once the soil loses its containment treatment capacities, the soil disposal will be another issue for stormwater treatment BMP.

7.4 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 NRRI 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 A. MEDIA CLASSIFICATION DATA

Table A-15. Moisture and organic matter for soil samples.

Site	Moisture		Organic Matter Content	
	Mean	Standard Deviation	Mean	Standard Deviation
Chaska	13.6%	0.42%	4.6%	0.08%
Cloquet	14.2%	0.76%	3.8%	0.39%
Compost	49.7%	0.32%	43.2%	0.43%
Cook	52.2%	3.26%	28.6%	3.51%
Crosby site 1	15.3%	1.10%	5.3%	0.19%
Crosby site 2	4.6%	0.01%	3.0%	0.02%
Eagle Nest Site 1	39.2%	3.52%	11.5%	2.02%
Eagle Nest Site 2	49.5%	3.54%	21.4%	2.66%
Eagle Nest Site 3	78.2%	2.02%	67.8%	8.11%
Eagle Nest Slope	13.5%	0.29%	11.1%	0.09%
Eagle Nest Trench	2.9%	0.12%	1.9%	0.46%
Gilbert Lake	5.7%	0.14%	2.9%	0.11%
Grand Rapids Site 1	3.9%	0.11%	1.7%	0.47%
Grand Rapids Site 2	1.9%	0.12%	2.0%	0.02%
Grand Rapids Site 3	3.0%	0.19%	2.6%	0.31%
Lilydale	17.4%	0.63%	6.0%	0.29%
Silver Creek	19.7%	0.70%	6.8%	0.11%
West Duluth	11.0%	0.11%	2.8%	0.33%

Table A-16. Raw data from compaction testing of Eagles Nest Site 1 media, where a specific gravity of 2.5 was assumed as a reasonable value for constructing the zero air void line.

Test No.	Dry Unit Weight (kN/m³)	Moisture Content (%)
1	9.83	26.8
2	11.28	35.9
3	11.54	41.3
4	11.01	45.6
5	9.52	61.7

Table 17. Raw data from compaction testing of Eagles Nest Site 2 media, where a specific gravity of 2.5 was assumed as a reasonable value for constructing the zero air void line.

Test No.	Dry Unit Weight (kN/m³)	Moisture Content (%)
1	7.0.5	31.5
2	8.45	46.6
3	8.84	65.9
4	7.14	89.3
5	6.25	114.3

Table 18. Raw data from compaction testing of Eagles Nest Site 2 media, where a specific gravity of 1.8 was assumed as a reasonable value for constructing the zero air void line.

Test No.	Dry Unit Weight (kN/m³)	Moisture Content (%)
1	2.57	157.0
2	2.64	192.8
3	2.77	248.4
4	2.33	354.7
5	1.96	420.3

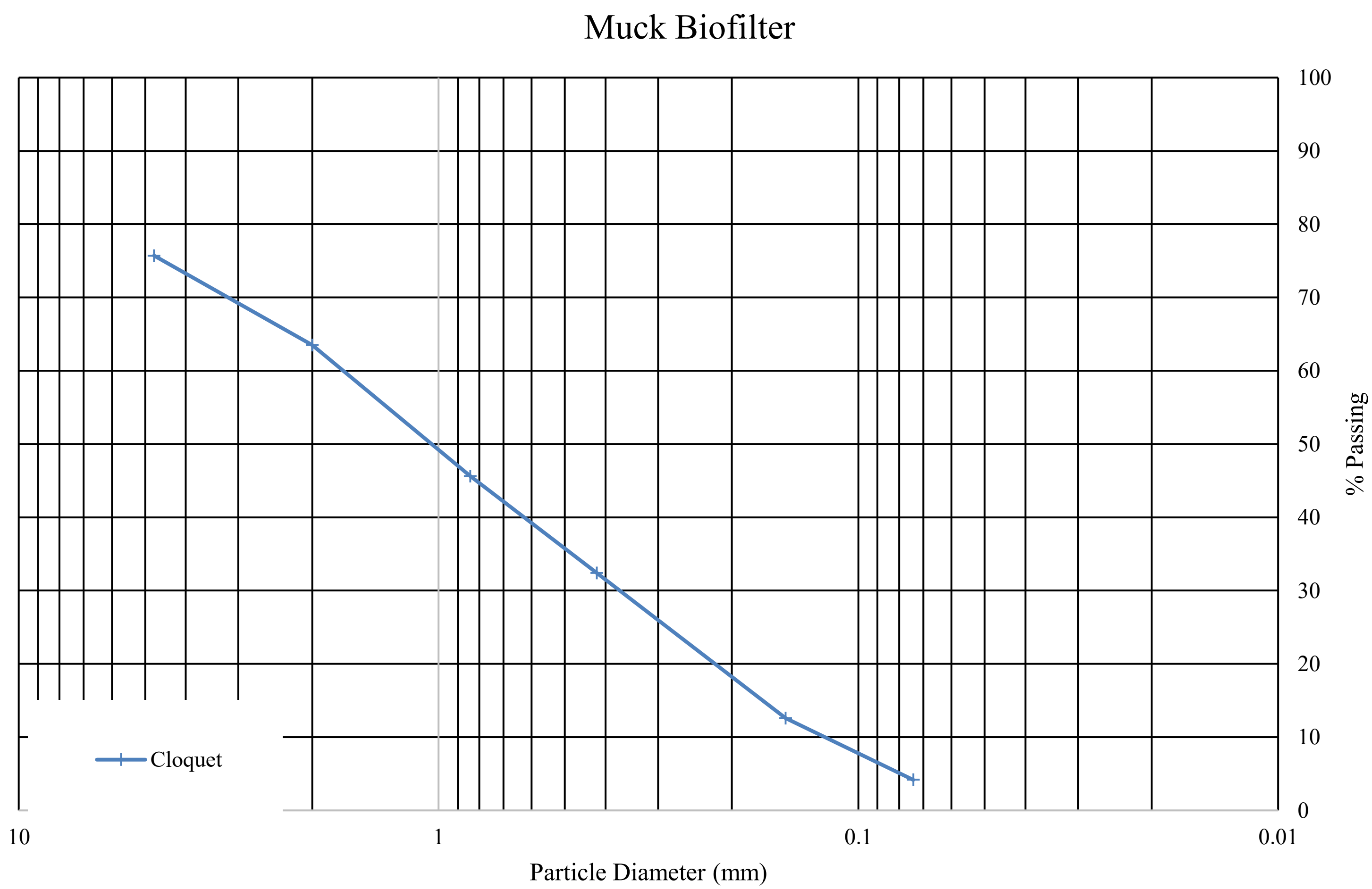


Figure A. 1 Soil gradation for the muck amended biofilter.

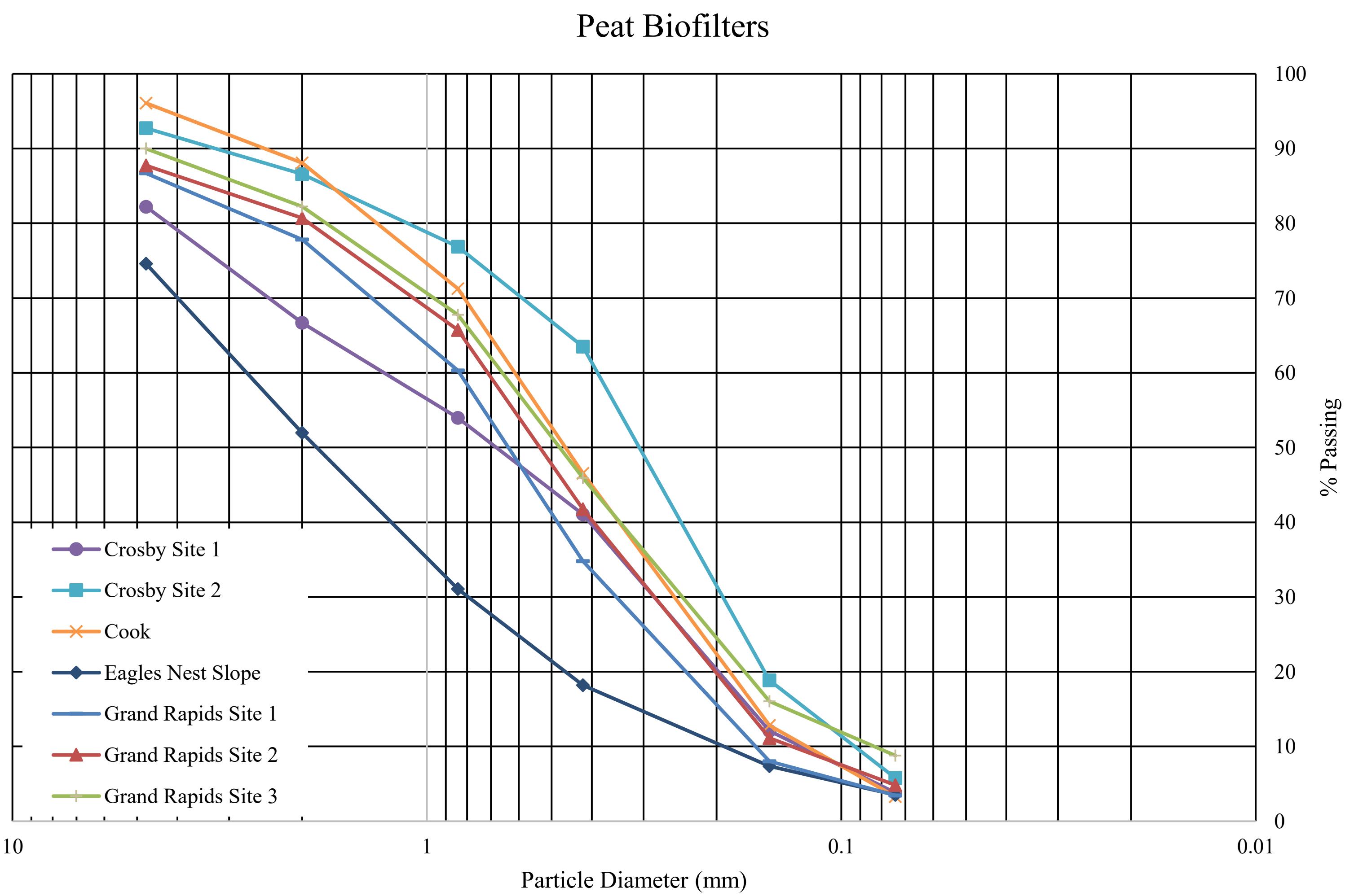
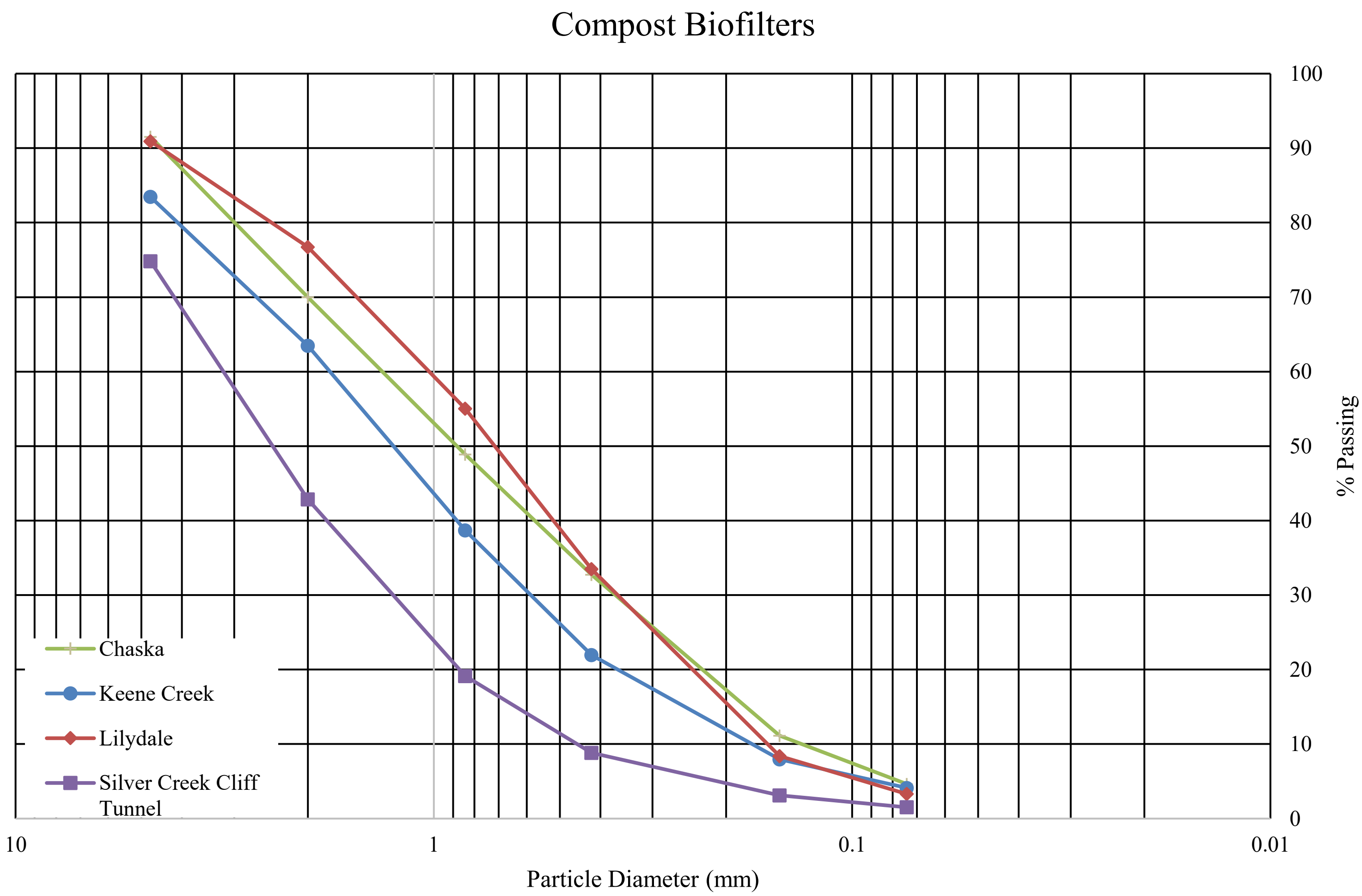


Figure A. 2 Soil gradation for the peat amended biofilters.



Compost Biofilters
100
90
80
70
60
50
40
30
20
10
0
% Passing
10
1
0.1
0.01
Particle Diameter (mm)
Chaska
Keene Creek
Lilydale
Silver Creek Cliff Tunnel