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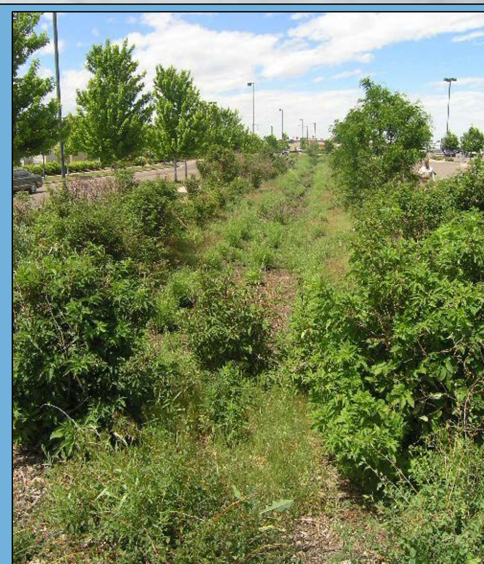

Engineered Bioretention Media Literature Review

Mile High Flood District

May 29, 2020
Denver, Colorado

ENGINEERED BIORETENTION MEDIA LITERATURE REVIEW

Prepared for

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May 29th, 2020

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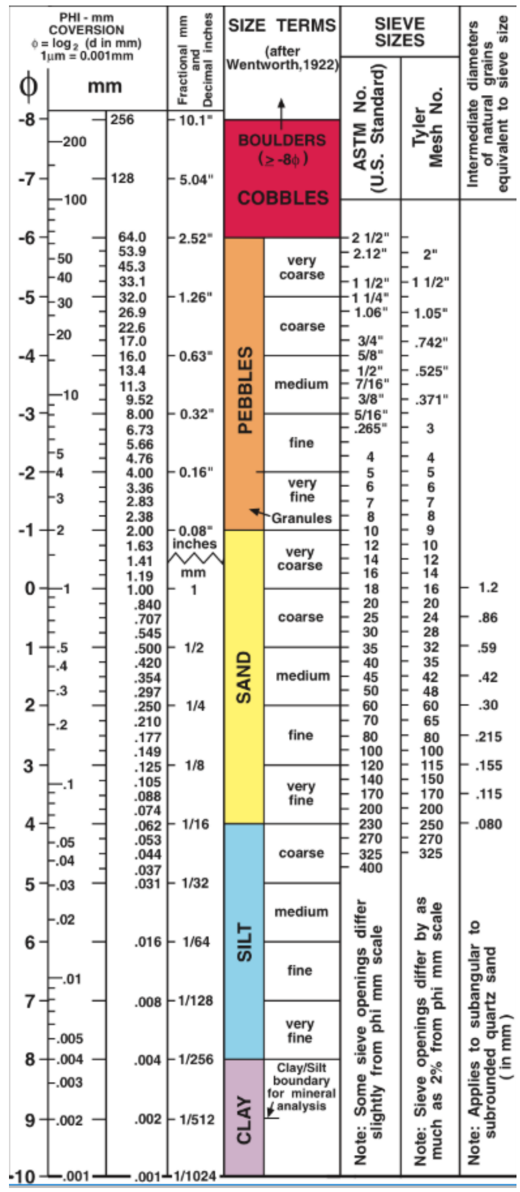
Acronyms and Abbreviations

BAV	Bioretention Abstraction Volume
BSM	Bioretention Soil Media
BMP	Best Management Practice (refers to stormwater treatment infrastructure)
CCD	City and County of Denver
EPA	US Environmental Protection Agency
IWS	Internal Water Storage
MHFD	Mile High Flood District
OM	Organic Matter
SZ	Saturated Zone
TN	Total Nitrogen
TP	Total Phosphorus
UDFCD	Urban Drainage and Flood Control District
WTR	Water Treatment Residual
WQCV	Water Quality Capture Volume

Introduction

Bioretention basins (also sometimes referred to as rain gardens or porous landscape detention areas) have been utilized by local governments and developers for decades in the Denver Metropolitan region to satisfy water quality requirements. The Mile High Flood District (MHFD) is updating its guidance regarding engineered media for bioretention basins, focusing on media that will improve basin function with respect to pollutant treatment performance and vegetation health. In an effort to support recommendations for the update, MHFD, in collaboration with the Urban Water Research Institute, is conducting a regional study of bioretention basins to better understand optimal design considerations to enhance vegetation growth, increase treatment performance, and minimize required maintenance.



To support decision-making efforts regarding updates to this guidance, Geosyntec has conducted a literature review, focusing on the optimization of media components and characteristics as they relate to treatment effectiveness and the health of vegetation in bioretention basins. The literature review considers media specifications such as the addition of finer particles (e.g., between 4–125 µm; categorized as very fine sand and silt) with the intent to enhance water retention and support vegetative growth during drier seasons. Therefore, we investigated media composition, loading rate, and pretreatment features that attempt to achieve multi-objective outcomes that may lead to better system performance.

Objectives

Performance objectives will influence the selection of bioretention parameters and should guide system design. Potential objectives could include specific treatment performance criteria, such as removal of nitrogen, phosphorus, metals, or other pollutants; runoff volume and/or peak flow controls to mimic pre-development hydrology; or promotion of vegetative growth to improve aesthetics and public acceptance. Specification of design parameters, including media, target hydraulic conductivity, organic matter content, vegetation type, and more, will therefore vary based on specific system needs.

This literature review attempts to highlight tradeoffs for the ranges of possible specification of a variety of design parameters. For example, a sandy media will promote more rapid hydraulic conductivity, but may not support long term water holding capacity which can impact vegetative health. Conversely, increasing finer particles in media gradation will increase water retention to better support vegetation, but will slow dewatering and lower system infiltration rates which can lead to reduced volumetric performance and a decreased ability to handle back to back precipitation events. Specification selection within this range will depend on the desired performance objectives.

When considering guidance documents for media specifications, keeping system objectives as design priorities during media selection will yield more favorable results (and performance) for individual bioretention systems (Hunt et al. 2012).

1. Media

1.1 Gradation

Media gradation, usually referenced in terms of particle size distribution or soil texture class, is often cited as one of the most important factors in bioretention performance.

1.1.1 Current Guidance

Current MHFD guidance recommends the sand component of the growing media to be graded according to the specifications shown in Table 1:

Table 1: Current Particle Size Distribution of Bioretention Media Specified by MHFD

Particle Type	Particle Diameter (mm)	Distribution
Sand	0.5 – 2.00	80% - 90%
Silt	0.002 – 0.5	3% - 17%
Clay	< 0.002	3% - 17%

As shown in Figure 1 below, this specification, while typical of many jurisdictional guidance documents, is generally limited compared to other specified bioretention media.

The City and County of Denver (CCD) specifies a similar media mix that is 80-90% sand, 3-14% silt, and 3-14% clay.

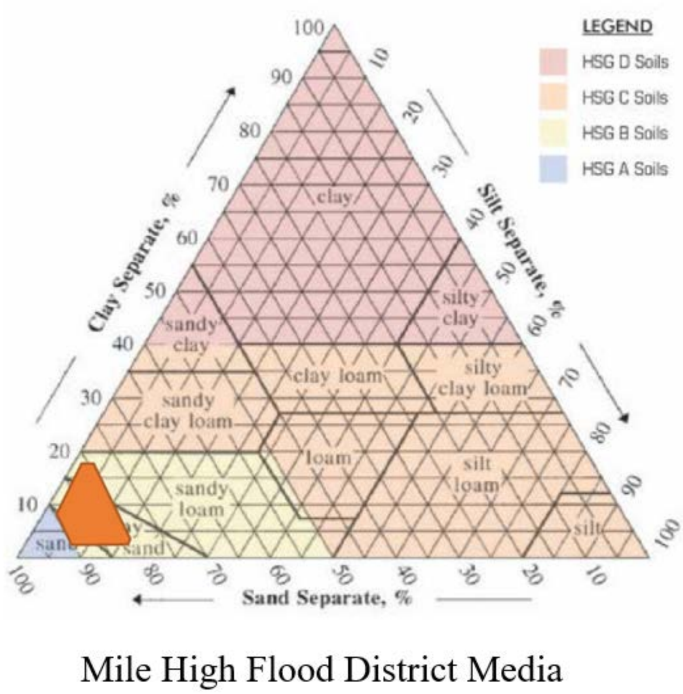


Figure 1: MHFD media specifications are sandy and have a limited range when compared to other media specifications (MHFD, 2020).

1.1.2 Literature Review General Findings

Increasing the percentage of finer particles (i.e. silt and clay) in bioretention media specifications would likely have many effects on system characteristics and performance. These are explained in detail, then summarized in Table 2 below.

First, increasing finer particles lowers infiltration rates (Lucas and Greenway, 2011). Figure 2 below shows how hydraulic conductivity (blue data points) generally decreases as the percentage of clay in the media mix increases (Saxton, 2019). A lower hydraulic conductivity media may increase the required system size (e.g., footprint) in order to comply with drawdown requirements (see section 1.5 for further discussion on loading rates and system sizing).

Increasing finer particles in bioretention media may also result in increased clogging (Le Coustumer, 2012), as a result of slower filtration rate. Both physical straining and settling can occur within finer grained media. This is discussed in more detail in Section 1.4.

It is generally agreed that increasing finer particles in the soil media can promote better treatment performance, especially with respect to nutrients. One reason for this is that finer media lowers hydraulic conductivity, which can provide more retention time for plant uptake of nutrients and in some cases create a residence time sufficient to allow denitrification to occur (Lucas and Greenway, 2011). Additionally, Glaister et al. (2014) found that the use of Skye sand filter medium (which has a higher clay content than loamy sand) increased removal of total nitrogen (TN) and ammonium. The authors proposed that this was due to greater adsorption capacity because of the smaller clay particles and affinity for ionized ammonia.

Additionally, increasing finer particles in the media specification increases field capacity, the amount of soil moisture or water content held in the soil after excess water has drained away, which can better support vegetative growth (Saxton, 2019). Figure 2 below shows how field capacity (orange data points) generally increases as the percentage of clay in the media increases. In the figure, circular data points represent sand media, triangle data points represent loamy sand media, and X data points represent sandy loam media. Plant growth, along with increased retention times, can promote plant uptake of nutrients and increases evapotranspiration, which reduces the amount of effluent and achieves a better overall system performance (Hess et al. 2015).

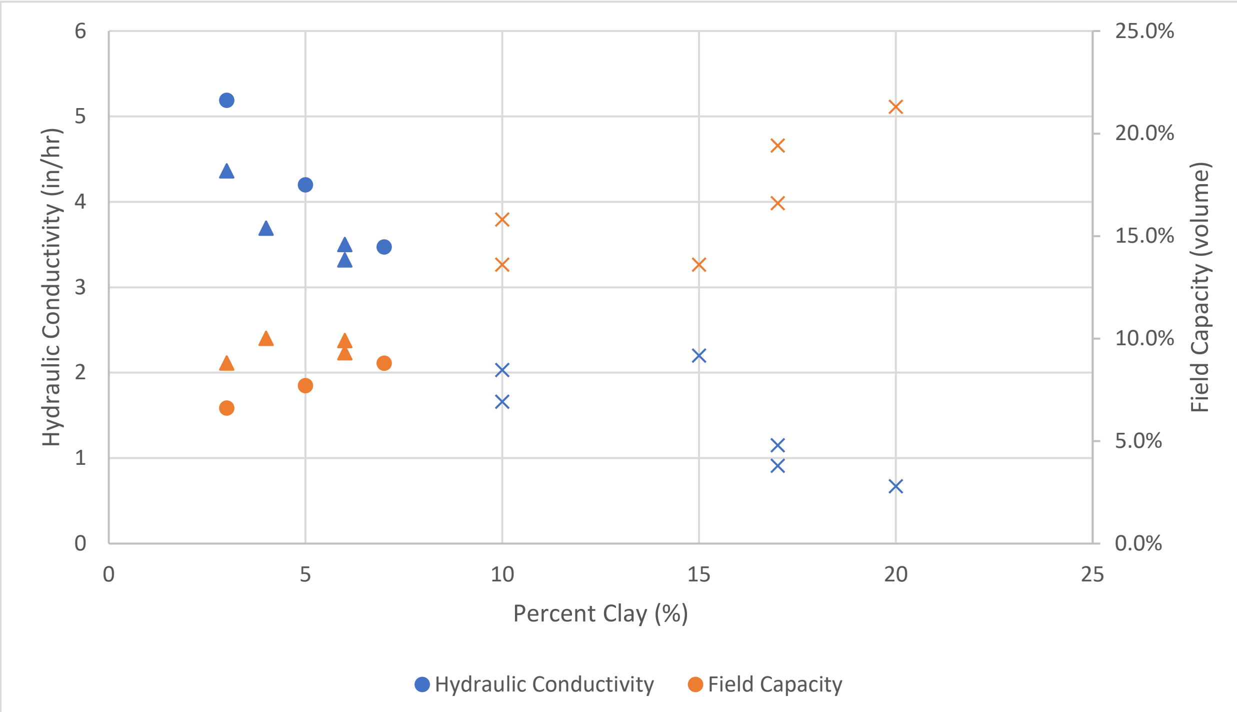


Figure 2: Hydraulic conductivity tends to decrease with increasing clay particles in media specification, while field capacity tends to increase. Soil texture classes are represented by circles (Sand), triangles (Loamy Sand) and X's (Sandy Loam).

Table 2: System Characteristics and Performance with Finer Particles in Bioretention Media.

Impacts of Increasing Finer particles in Bioretention Media Specifications	
Advantages	*Disadvantages*
Better treatment performance, especially with respect to nutrients.	Increases basin size necessary for treatment.
Increases field capacity, which supports vegetative growth.	Increases frequency of clogging, which may require more maintenance.
Promotes evapotranspiration.	

The literature review produced a range of recommended finer particulate fractions for bioretention media. Carpenter and Hallam (2010) cite clay content as the most varied recommendation in soil media mixes from a review of 27 US bioretention guidance documents. Their review found jurisdictions that did not specify clay content, others that specified ranges of less than 5% clay, and still others that specified ranges of up to 10%-25% clay.

Hunt et al. (2012) recommends a finer particles fraction between 8% and 12% in order to slow hydraulic conductivity to their recommended 1-2 in/hr in order to promote the design objective of nutrient removal. The New Jersey Department of Environmental Protection recommends finer particles fractions of no more than 2%-5% to maintain higher infiltration rates which prioritizes the design objective of more rapid stormwater treatment and faster drawdown times (2009). Henderson et al. (2007) recommends fine sand or sandy loam media due to their minimal leaching tendencies and ability to support plant growth.

1.2 Organic Matter Content

Organic matter (OM), has been shown to be an important factor in treatment performance and vegetation growth by impacting field capacity, hydraulic conductivity, and nutrient leaching. While high OM content can be beneficial for plant growth, in excess for what is needed by the plants, it can lead to nutrient leaching.

1.2.1 Current Guidance

MHFD and CCD specify that the bioretention soil must contain less than 1.5% OM (as determined by chemical attribute and nutrient analysis). Three to five percent by weight of shredded mulch is added to the soil to provide organic content.

1.2.2 Literature Review General Findings

Vegetative Health

Increased OM in the growing media is generally related to healthier vegetation. OM increases field capacity (moisture content) of the growing media, giving plants a healthier supply of water (Carpenter and Hallam, 2010). Figure 3 below from the Carpenter and Hallam study shows that field capacity (as measured by percentage of weight retained as water) decreases as OM content decreases. Note that the compositions of topsoil and compost were not defined in this study.

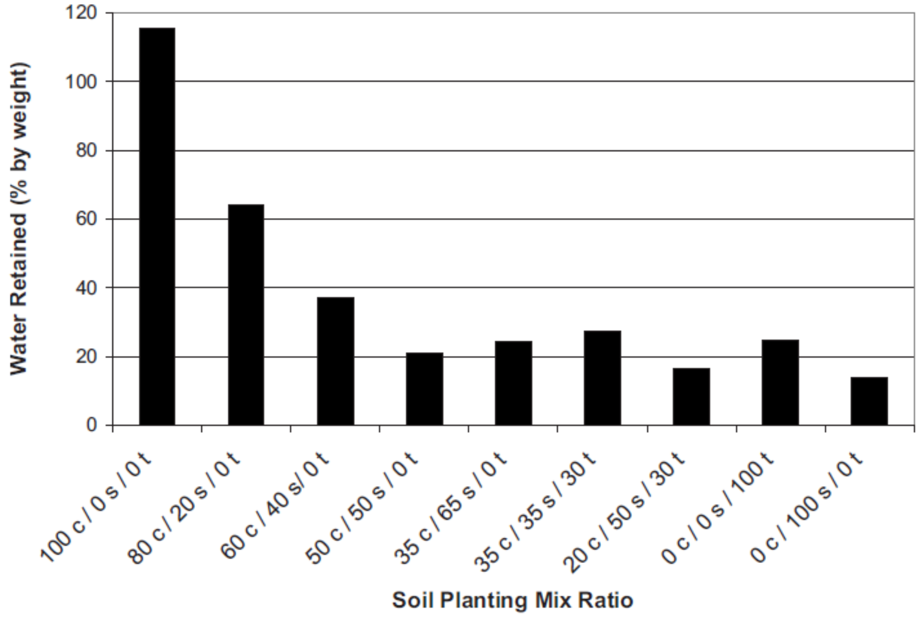


Figure 3. Field capacity of various bioretention media mixes. The mixes are characterized by percent compost / percent sand / percent topsoil. For example, 35 c / 35 s / 30 t contains 35% compost, 35% sand, and 30% topsoil (Carpenter and Hallam, 2010).

Hydraulic Conductivity

Le Coustumer et al. (2012) showed that added OM in media mixes (in the form of 10% mulch by volume with 10% mushroom compost by volume) may help maintain hydraulic conductivity, which prevents clogging. The mechanisms by which this occurs were not discussed. In their 60-week study, columns containing different media mixes were dosed with semi-synthetic stormwater having TSS concentrations of about 121 mg/L, made using natural sediment. It was found that columns with sandy loam media (no added OM) had a much lower hydraulic conductivity than those with 20% added OM (wood chips and mushroom compost) by volume at the end of 60 weeks. Columns with sandy loam media (no added OM) had an initial hydraulic conductivity of 9.9 in/hr, which reduced to 2.0 in/hr after 60 weeks (an 80% reduction). Columns with the added OM had initial hydraulic conductivity rates of 18.6 in/hr, which reduced to 6.8 in/hr after 60 weeks (a 63% reduction). Additionally, OM can support vegetative growth, which can improve media composition and increase hydraulic conductivity through rooting structures as discussed in Section 2.1.1.

Treatment Performance

Some organic carbon (as opposed to OM, which includes other organic elements such as oxygen, nitrogen, phosphorus, etc.) is necessary for bacteria to proceed with nitrifying / denitrifying processes which facilitate nitrogen removal from stormwater. However, high organic matter content in bioretention media can leach nutrients and hinder system performance.

Le Coustumer et al. (2012) found in a study of columns packed with different bioretention media mixes that sandy loam without added sources of OM performed better for nitrogen removal than columns with added OM (in the form of ten percent by volume wood chips and ten percent by volume mushroom compost). Several others (Hunt et al. 2012, Bratieres et al. 2008) warn of nutrient leaching using media with high OM content.

Sources of OM

Hunt et al. (2012) suggests that the amount of organic carbon needed for bacterial processes is no more than five percent of the total weight or ten percent of the total volume of media because stormwater concentrations of nitrogen are generally low.

Many OM additives have been studied with respect to their treatment performances in bioretention systems. They are summarized in Table 3 below.

Table 3: Sources of OM in Media Additives

Additive	Advantages	Disadvantages	Source	Amount Recommended
Compost	Can increase moisture content in growing media, supporting plant growth	Can induce nutrient leaching Highly variable mixtures	Herrera Environmental (2015); Colorado Stormwater Center	5% - 20% by volume; <10% of media by volume
Shredded Newspaper	Release relatively low amounts of carbon		Rippy (2015)	
Shredded Mulch*	Effective treatment of heavy metals	Should be site-tested for leaching	Colorado Stormwater Center	< 10% of media by volume
Biosolids	Supports plant growth	Should be assessed for leaching	Brown et al. (2016)	
Wood Chips	Release relatively low amounts of carbon	May float, clogging overflow drain	Rippy (2015)	
Sulfur-limestone	Release relatively low amounts of carbon		Rippy (2015)	
Coconut husk	Can improve soil structure, reduction of heavy metals	Should be assessed for leaching	Colorado Stormwater Center	
Coconut Husk and Sphagnum Peat	High water holding capacity; low nutrient content	May lower media pH	Herrera Environmental (2015)	5% - 20% by volume
Wood ash and Biochar	Promotes biological activity to promote uptake		Herrera Environmental (2015)	5% - 20% by volume
Iron-infused Wood Chips	High potential for lead and phosphorus adsorption	Needs more testing	Herrera Environmental (2015)	5% - 20% by volume

*For information mulch quality variability and quality control measures, see Section 3.2.2 on mulch tendency to leach nutrients.

A study by Brown et. al (2016) investigated the effects of several compost mixtures on plant growth and found that a mixture of yard / food compost or yard / biosolids best supported plant growth compared to other OM sources such as manure / sawdust. Note that the compositions of yard waste, food waste, and biosolids were not provided and should be used cautiously. Recognizing that many desirable and undesirable components may be included within these waste streams, caution should be exercised in using these materials.

1.3 Homogeny

1.3.1 Current Guidance

Current MHFD guidance implies a uniformity in its media specifications, but some studies have shown that heterogenous media, for example, layering media with different properties, may be beneficial for system performance.

1.3.2 Literature Review General Findings

Hsieh et al. (2007, 2007b) studied the effects of layered media, with 12 inches of high hydraulic conductivity media (sand) overlaying 22 inches of low hydraulic conductivity media (sandy loam) using column testing. It was shown that this configuration was more effective at total phosphorus removal than columns with low hydraulic conductivity media overlaying media with high hydraulic conductivity. When a layer of fine sand was added at the bottom to prevent leaching and particle movement, the layered media was able to remove 67% to greater than 98% of total phosphorus, and effluent concentrations ranged from 1.2 mg/L to less than 0.55 mg/L (2007). This configuration improved ammonium removal (up to 59%) but increased nitrate export (56%). The authors noted that nitrate export may have been exacerbated in this study by the use of high-nitrate mulch, and that mass-balance calculations showed that the low hydraulic conductivity media underlaying the high hydraulic conductivity media may promote a nitrification-denitrification process which could enhance nitrate treatment performance (2007b).

Dell and Brim (2017) note in their literature review that a layered media approach may be appropriate if compost is to be added in the rooting depth to support vegetative growth. They suggest that a lower layer without compost may be beneficial in preventing phosphorus leaching. Similarly, Houdeshel et al. (2012) suggest a two-layered media which has a 19-inch topsoil layer to support vegetation over a 24-inch porous media layer, which would serve as system storage.

Guo et al. (2009, 2010) designed a two-layer bioretention media that considered both detention flow hydrology and seepage hydraulics. They recommended a sand-mix over a granite gravel layer, the thickness of which was found to be related to the drain time and infiltration rate. This layout created an accelerated hydraulic gradient, which pulled water through the sand layer.

Fassman-Beck et al. (2015) note that a layered media approach may use less media than a homogenized media mix, especially if organic matter is added, to achieve hydrologic control objectives. The addition of OM is generally related to field capacity (see section 1.2.2), which, although beneficial to vegetative growth in the upper media, occupies storage volume between storms in the bioretention system, lowering what is known as the bioretention abstraction volume (BAV), a storage characteristic by which bioretention systems can completely capture smaller storms. Systems with media with high field capacity and shallow media depths have lower BAV.

If hydrologic mitigation targets are an objective, a layered media approach by which added OM is limited only to the rooting depth for vegetation support, and freely draining media is added below may decrease the overall system volume necessary to achieve a high BAV.

1.4 Hydraulic Conductivity

1.4.1 Current Guidance

MHFD does not specify a hydraulic conductivity for their media mix. CCD specifies that the initial infiltration rate of the media must be equal to two times the infiltration rate needed to drain the water quality control volume (WQCV) in 24 hours (i.e. a safety factor of 2). This depends on the size of the proposed basin and the water quality volume.

1.4.2 Literature Review General Findings

Media specifications directly impact hydraulic conductivity rates, which affect treatment performance and system size. It is important to note that infiltration rates cannot be fully known solely based on the properties of the bioretention media mix. Other factors like vegetation growth, and subsequently root density and depth, maintenance, and compaction also influence the effective infiltration rates experienced by bioretention systems (Carpenter and Hallam, 2010).

Because increasing finer particles in the media will also decrease hydraulic conductivity, readers may refer to Section 1.1.2 on gradation to understand the impacts of hydraulic conductivity on bioretention system performance.

Systems using outlet controls may achieve a lower effective hydraulic conductivity while using a higher conductivity media (Lucas and Greenway, 2011). This practice will achieve the benefits of a lower-conductivity media but can reduce the likelihood of clogging with time.

Le Coustumer (2012) showed in his experiments that hydraulic conductivity decreased by an average factor of 3.6 over a 72-week period in a variety of media mixes, plant types, basin sizes, and loading rates. There was evidence that the hydraulic conductivity attenuation had reached an asymptote and would not experience significant further decline. This suggests that a safety factor of three or four may be appropriate for conservative guidance (i.e. the initial infiltration rate of the media must be equal to three or four times the infiltration rate needed to drain the WQCV in 24 hours).

It should be noted that media specifications, especially particle size distributions, are not necessarily good predictors of hydraulic conductivities that will be observed in the field. Fassman-Beck et al. (2015) noted that sands shown in their lab experiment to have appropriate particle size distributions according to guidance did not achieve recommended hydraulic conductivities. This suggests that hydraulic conductivity testing may be necessary for each type of media selected, regardless of particle size distribution.

1.5 Loading Rate

1.5.1 Current Guidance

Neither the MHFD nor the CCD have specified loading rates. MHFD guidance suggests a minimum surface area of the system that is defined by the equation below, where A_f is the surface area of the filter (ft^2), A is the area tributary to the system (ft^2), and I is the imperviousness of the tributary area as a percent expressed as a decimal:

$$A_f = 0.02AI$$

1.5.2 Literature Review General Findings

Lower loading rates can extend the life of a system before clogging occurs, which will reduce the amount of maintenance needed (Le Coustumer, 2012). Biofilter size (represented as the percent of the catchment area) in this study ranged from 0.7% to 4% of the catchment area. Larger system sizes had higher initial infiltration rates as well as lower attenuation throughout the 60-week study. Figure 4 below shows initial and final hydraulic conductivities for two systems representing 0.7% and 4% by area of the total catchment area. The 4% area system had an attenuation rate of 65% over the 35-week study, while the 0.7% area system had an attenuation rate of over 98%.

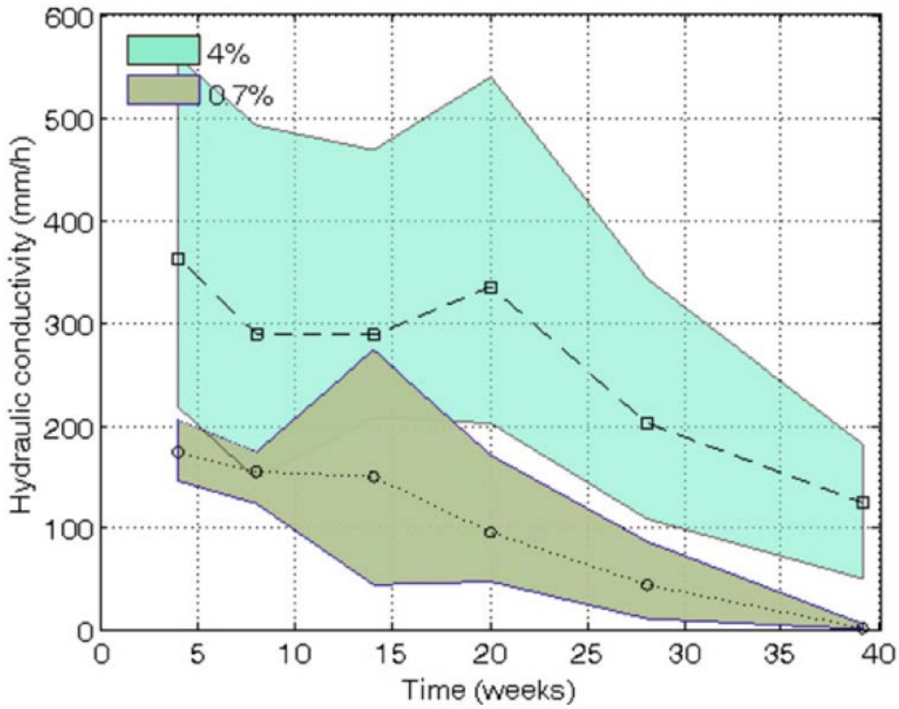


Figure 4: Hydraulic conductivity attenuation for biofilters designed at 4% and 0.7% of their catchment size. The mean is represented by the dotted line and the 95% confidence interval is shaded.

Mays and Hunt (2005) showed that there is a consistent relationship between flow velocity (dependent on loading ratios) and head loss in the bioretention system. They showed that under constant flow conditions, head loss can be predicted using a modified O'Melia and Ali model or a cake filtration model. This would help predict maintenance intervals for scraping the surface of the bioretention media.

1.6 Depth

Filter media depth can impact system performance for removal of a variety of contaminants.

1.6.1 Current Guidance

MHFD and CCD recommend a minimum of 18 inches of media for vegetated systems; CCD recommends a minimum of 36 inches of media if trees will be planted.

1.6.2 Literature Review General Findings

Brown and Hunt (2011) note that increasing media depths may improve system performance in unlined systems by decreasing effluent volumes through increased lateral exfiltration. This is due to a greater surface area with native soils to allow for infiltration/exfiltration

Increased filter depth has also been shown to increase performance for phosphate (Davis et al., 2001, Hatt et al., 2007). Nitrogen removal generally depends on a large media depth in order to create anoxic conditions necessary for denitrification to occur or an internal water storage (IWS) zone. Greater media depth also improves system performance for the removal of dissolved metals due to increased number of sorption sites in the media. This extends the life of the media until metal breakthrough is seen (Hunt et al. 2012).

Hunt et al. (2012) notes that particulate phosphorus is usually filtered at the system's surface with suspended solids, necessitating only a shallow layer of media. However, for total phosphorus reduction (including phosphates), Hunt et al. suggests two feet of media. They suggest three feet of media for TN removal, and two feet of media for bacterial removal.

2. Vegetation

Vegetation is recommended in most sources of literature reviewed, but guidance is widely varied with respect to its treatment capabilities, species recommendations, maintenance, and enhancement of other functional characteristics and conditions.

2.1 System Performance

System performance of vegetated bioretention basins has been reviewed extensively. Several factors, including rooting type, rooting depth, climate tolerances, and density have been shown to affect system performance.

Overall Performance

Many studies have shown that vegetation is necessary for nutrient removal, especially certain forms of nitrogen (NOx and ammonia) and phosphate (Lucas and Greenway, 2008). Vegetation did not impact total phosphorus removal because that is primarily related to surface filtration of suspended solids (Lucas and Greenway, 2011). Henderson et al. (2007) showed that significantly more nitrate leached from non-vegetated loamy sand media than from vegetated media.

Rippy (2015) noted that vegetation can improve soil conditions for rhizosphere bacteria, which help treat many nutrients. Roots release oxygen, amino acids, and sugar that can stimulate metabolic processes thereby enhancing microbial processing and treatment.

Multiple studies have shown that vegetation improves soil structure which can help basin media maintain hydraulic conductivity and prevent clogging (Lucas and Greenway, 2011). This is achieved through the creation of macropores as a result of root growth and decay (Hatt et al. 2008).

In a study by Culbertson and Hutchinson (2004), it was shown that planting vegetation (in this case, switchgrass) in a bare soil increased infiltration rates from 0.2 in/hr to 50.4 in/hr. Glaister et al. (2014) also notes that vegetation can prevent cracking due to drying in the media, which reduces the possibility of the creation of preferential flow pathways. Guo et al. (2010) showed that vegetation in bioretention basins can extend their life by 3 – 6 years compared to non-vegetated basins with sand/peat and sand/compost media.

Perhaps the most effective treatment from vegetation is associated with its ability to reduce the effluent volume (and therefore loads) through uptake and evapotranspiration. Brown et al. (2016) notes that treatments with the highest plant growth (e.g., density and biomass) had the lowest effluent volumes due to transpiration demand. Evapotranspiration also plays a key role in restoring media storage capability between storms (Skorobogatov, 2020).

2.1.1 Rooting Type

Figure 5 below shows the root densities for two different plant species at different media depths, exemplifying the variety of root structures that can be found between plant species (Le Coustumer et al., 2012). Bratieres et al. (2008) showed that a dense rooting structures (associated with *Carex*) with very fine roots were effective at TN removal by providing more surface area per volume for plant uptake. It also allows the plant to access more soil area for nutrient uptake. Bratieres et el. also noted one plant species in which fungi growing in the roots of the plant were able to increase plant uptake of soil-derived nutrients, probably for similar reasons as *Carex*. In their laboratory study, TN removal increased from -29% removal (leaching) to 46% removal over a period of six months. Hunt et al. (2012) notes in their recommendations that larger root masses appear to be more effective for nitrate removal.

Le Coustumer et al. (2012) showed that dense rooting structures can negatively impact hydraulic conductivity, as shown in Figure 6 below. Hydraulic conductivity at the end of the study for columns planted with *Carex* was not significantly different from columns without vegetation. One plant which improved hydraulic conductivity, Melaleuca, had a thicker rooting structure and therefore improved media hydraulic conductivity, likely through the creation of macropores. However, the possibilities of short circuiting with thicker root systems that can develop larger macropore flow can cause infiltrating runoff to preferentially bypass the bulk of the soil matrix. This should be avoided or closely monitored.

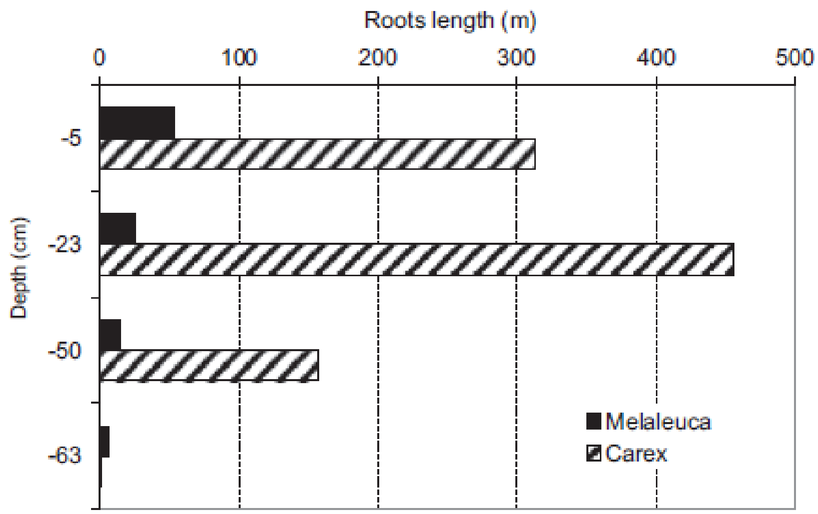


Figure 5: Root densities at different depths of two plant species grown in bioretention media (Le Coustumer, 2012).

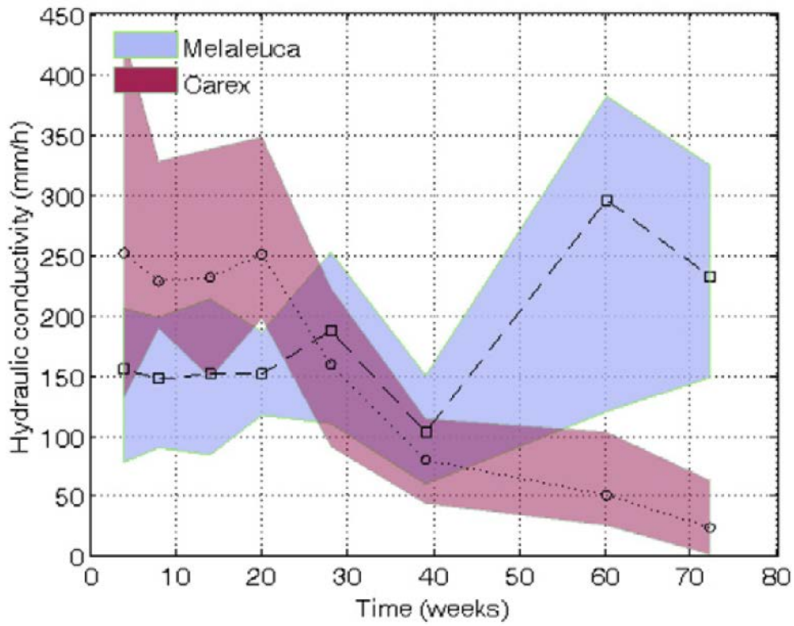


Figure 6: Change in hydraulic conductivity over time for systems planted with two different plants. The mean is shown by the dotted line, and the 95% confidence intervals are shaded (Le Coustumer, 2012).

2.1.2 Rooting Depth

Deep-rooted vegetation will provide better maintenance of high infiltration rates than shallow-rooted vegetation (Lucas and Greenway, 2011).

Rippy (2015) suggests that plants can also alter rates of nitrification/denitrification. Some evidence shows that shrubs with higher rooting depths have higher nitrogen removal than sedges with shallower rooting depths. Read et al. (2009) similarly cites rooting depth as an important factor for nutrient removal.

Rooting depth may depend on vegetation species, but also on the amount of available moisture in the media. The root zone extends deeper in the soil profile when moisture is limited; as such it should not be treated as a static parameter in basin design (Skorobogatov, 2020).

2.1.3 Vegetation Density

Hunt et al. (2012) notes that the desirability of a densely vegetated bioretention basin for temperature control, evapotranspiration, and aesthetics contrasts with media surface sun exposure to improve pathogen die-off if bacteria control is an objective. They recommend prioritizing these objectives in order to facilitate an appropriate design with respect to vegetation density.

2.2 Basin Resilience

Colorado bioretention basins are routinely subjected to prolonged dry periods, which can impact system performance. Vegetation has been shown to increase the resiliency of such bioretention basins although choosing the vegetation that is most adapted to these conditions can be challenging.

2.2.1 Treatment Performance

Treatment performance has much to do with maintaining appropriate hydraulic conductivity, as discussed in Section 2.2.1 above. The following studies further comment on system performance with respect to vegetation.

In a study by Glaister et al. (2014), the use of vegetation and internal water storage (IWS, see Section 4 below) maintained consistent treatment performance for nutrients (nitrogen, phosphorus) between wetting and drying periods in their study. Vegetated basins even without IWS were able to sustain ammonia removal through the wet and dry periods. The drying period was four months long (December through March) and antecedent dry periods varied from six to 18 days.

Hatt et al. (2007b) showed that vegetated biofilters had consistently high metal removal which was not affected by wetting and drying.

2.3 Vegetation Health

Fassman-Beck et al. (2015) list the three critical functions bioretention media provide for plant growth: water storage for dry periods, adequate rooting depth (based on media depth), and buffer against fertility and chemistry changes. Media specifications to meet these functions will vary based on the vegetation selected. Water storage is affected by soil media gradation and organic matter content, as discussed in sections 1.1 and 1.2. Media pore size, related to gradation and organic matter, influences the percentage of water that is available to plants (Skorobogatov, 2020). Rooting depth is discussed in section 2.1.2.

2.3.1 Climate Considerations

Careful consideration must be given to plant species that have favorable characteristics for water quality performance, but that can also withstand the unique features of Colorado climate. This includes tolerance of extended dry periods, cold weather or freezing conditions, and road deicers.

Shrestha et al. (2018) emphasizes the need for plant species that mature quickly (to increase resilience before their first winter) and have high salt tolerances. Denich et al. (2013) showed that most plant species, though tolerant of salt, showed loss of vigor in the early spring, but generally recovered throughout the summer.

2.3.2 Irrigation

Irrigation systems may sometimes be necessary for vegetative growth and to maintain plant health. Planting with native and drought-tolerant species will reduce the need for irrigation, but it may still be necessary. Where needed, herbaceous species should be irrigated at least once every 14 days (EPA, 2012).

The EPA recommends grouping plants in bioretention systems by type and water needs to more efficiently administer irrigation water (2010). One study suggests that overhead rotary irrigation systems may be more efficient than drip irrigation at evenly distributing irrigation water due to the high hydraulic conductivity of many basin media mixes. In drip irrigation, water does not flow over the media, so moisture is largely retained only in cones around the emission sites in drip irrigation systems (EPA, 2012).

3. Surface Treatment and Alternative Media Additions

Bioretention basins are often seeded to promote vegetation growth to enhance treatment and improve aesthetics. However, there are other cover components such as rock and mulch. This section will discuss advantages and disadvantages of alternative surface treatments and their impacts on hydraulic loading and maintenance requirements

3.1 Current Guidance

MHFD discourages the use of rock mulch because it is difficult to maintain and limits infiltration. The use of wood mulch is cautioned as it floats and could potentially clog the overflow.

3.2 Surface Treatment

3.2.1 Literature Review General Findings

Hunt et al. (2012) notes that a mulch layer may be helpful in the removal of hydrocarbons, and Hsieh et al. (2007) notes that mulch with a large pore size was effective in preventing surface clogging from TSS. Syring et al. (2009) studied the effectiveness of mulch in the removal of heavy metals. They found that wood chips may be effective for short term interception of heavy metals in roadway runoff, but that it does not provide permanent removal as metals are subsequently flushed away. Metal removal was slightly better if the wood chips were pre-saturated.

Rock can be used as a surface treatment to increase albedo and reduce surface evaporation (Orr, 2013).

The EPA guidance for green infrastructure in arid and semi-arid regions (2010) suggests the use of mulch to increase water retention and suppress weeds, benefitting vegetation growth. It warns, however, that some desert trees and shrubs do not tolerate mulch contact with their trunks, so careful selection of plant species is important when considering mulch use.

3.2.2 Mulch Quality Control

Mulch quality varies primarily in its nutrient leaching characteristics (which also affects mulch as an OM additive in filter media, see Section 1.2.2) and its tendency to float. In order to prevent leaching, the North Carolina Stormwater Design Manual (NCDEQ, 2018) recommends that the mulch should be free of soil, roots, and any material that is not bole or branch wood or bark. Hills (2019) states that mulches containing grass clippings, pine needles, straw, sawdust, leaf litter, turf, coir and compost should be avoided to prevent leaching. A leachate analysis could be used to confirm that the mulch would not contribute to nutrient leaching. Mulch may be sourced as single-, double-, or triple-shredded, which affects its floatability and hydraulic conductivity. Hills (2019) says that single-shredded mulch or mulch nuggets may be prone to floating, while triple-shredded mulch may contain too many fines and restrict flow through the system. NC Stormwater Manual (2018) recommends triple-shredded mulch. A float qualification test can be used to determine if floating will be problematic; place mulch in a clear contain filled with water and stir. Wait approximately 24 hours to ensure that most of the mulch has settled (Hills, 2019). Finally, mulch may be sourced that is certified by the Mulch and Soil Council, which ensures the product label is accurate and that the product claims are verified.

3.3 Alternative Media Additives

3.3.1 Literature Review General Findings

The Colorado Stormwater Center (2017) reviewed alternative media additives to inform improvement specification of the city of Fort Collins' bioretention media mix. The four categories reviewed included "natural" additives, water treatment residuals (WTR), biochar, and industrial byproducts.

Natural additives included compost, biosolids, shredded mulch, shredded newspaper, and coconut fibers and were generally discussed in Section 1.2.

WTRs are byproducts from drinking water treatment processes and contain precipitated aluminum and/or iron oxyhydroxides which have a strong affinity for anionic species such as dissolved phosphorus. WTRs have been shown to prevent phosphorus leaching, with various removal levels dependent on the amount of WTR added and its absorptive capacity. Removal ranges in the studies reviewed by the Colorado Stormwater Center ranged from 10% to 99%. WTRs also provide treatment for other constituents such as nitrogen and some heavy metals. Caution should be exercised when using WTRs to monitor for heavy metal export from the WTR. Herrera Environmental Consultants (2015) notes that they are prone to copper exportation. They can also limit the amount of phosphorus available to support vegetative growth, so application should be limited to less than 0.35 to 0.53 oz WTR/lb of soil (Colorado Stormwater Center, 2017).

Biochar (pyrolyzed organic matter) from wood chips can potentially increase removal of several pollutants, such as phosphorus, nitrogen, some heavy metals, and bacteria, but performance is variable, and research is ongoing (Colorado Stormwater Center, 2017). Herrera Environmental Consultants (2015) notes that biochar can have variable hydraulic conductivities, so properly testing is important before biochar is specified.

Industrial byproducts included blast/oxygen furnace slag (steel production), cement dust (cement production), fly ash (coal combustion), and ochre (mining). All were shown to facilitate high removal rates of phosphorus (83%-98% removal in the studies reviewed), but more testing is needed in order to ensure that no other chemicals may leach from these additives. Herrera Environmental Consultants (2015) notes that furnace slag and fly ash may decrease infiltration capacity and warns of the potential for metal leaching.

4. Internal Water Storage

Studies have shown that the inclusion of internal water storage (IWS) (sometimes called a saturated zone) can improve treatment performance and basin resiliency during prolonged dry periods. IWS also affects hydraulic conductivity, water volume reduction, treatment performance, and required system volumes.

Creating an IWS in a bioretention basin can be achieved by raising the underdrain outlet when used, as shown in Figure 7 from Rippy (2015) below.

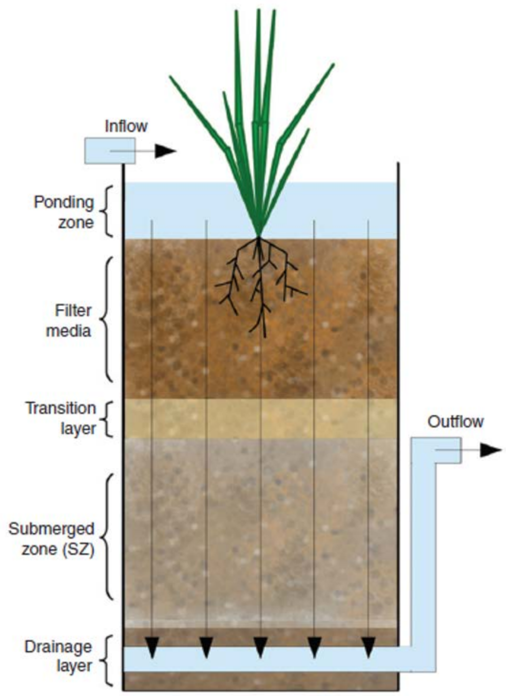


Figure 7: Simple schematic of a bioretention basin with a raised outflow which creates an IWS (labeled here as Submerged zone, SZ) (Rippy, 2015).

4.1 Basin Resilience and Vegetation Health

An IWS zone can help to mitigate the extremes of wetting and drying seasons bioretention basins in certain climates. Primarily, IWS provides a permanent (or semi-permanent) supply of water to support vegetation health during drier periods. Rippy (2015) suggests that the incorporation of an IWS can reduce plant stress and root damage during dry spells. An IWS zone can also help maintain soil moisture content, during prolonged dry periods (over two weeks) in systems which can better support vegetation.

4.2 Treatment Performance

Increased basin resiliency translates into more consistent treatment performance in vegetated bioretention basins with an IWS zone. Glaister et al. (2014) reports that treatment performance for nitrogen and phosphorus remained relatively steady throughout drying and wetting periods in bioretention basins with IWS and vegetation, regardless of media type.

4.2.1 Volume Reduction

The inclusion of IWS may improve drawdown rates and overall water volume reduction through increased lateral exfiltration capacity during dry periods. In a study of bioretention basins built with IWS on Class D (poorly draining) soils, Winston et al. (2016) showed that drawdown rates were significantly higher than field measurements of hydraulic conductivity. See Table 4 below.

These systems had runoff volume reductions of 36% to 59%. There were no basins without IWS or well-drained underlying soils observed for comparison.

Table 4: During and Post-Construction Hydraulic Conductivity for Three Bioretention Sites.

Site	Hydraulic Conductivity (mm/h) (measured during construction)	Observed Drawdown Rate (mm/h)
1	0.5 – 0.75	4.3 ± 4.3
2	0.5	1.7 ± 1.2
3	05 – 2.0	2.0 ± 3.5

4.2.2 Nitrogen

IWS can improve system performance for TN removal in two ways. First, it can increase water detention times which would provide further opportunity for vegetative uptake of nitrate. Second, it can provide an anoxic zone to promote denitrification. Glaister et al. (2014) did not achieve an anoxic zone in their IWS which would promote denitrification but hypothesized that it was possible to have pockets of anaerobic conditions that exist within an IWS to provide some denitrification benefits. They also note that incorporating an IWS can reduce the hydraulic head in a system, slowing infiltration rates. As discussed in Section 1.4, lower infiltration rates may improve nutrient treatment performance.

4.2.3 Phosphorus

Much like nitrogen, IWS can improve system treatment of phosphorus by increasing water detention time and allowing plants more opportunity for uptake, especially in the phosphate form. IWS also slows filtration velocities, which may minimize P leaching to effluent (Glaister, 2014). However, care must be taken to design an IWS with adequate spacing between the top of the saturated zone and the top of the bioretention media. Hunt et al. (2012) recommends at least 1.5 to two feet of separation between IWS and top of media to prevent P from leaching, as finer particles such as clay can leach phosphorus during anaerobic conditions.

5. Pretreatment

Many guidance documents suggest, but do not require, a pretreatment system before a bioretention system. Pretreatment, usually by sedimentation through a forebay, has several benefits including extending the life of the media filter and shifting maintenance requirements away from the media filter, which can be costly. Pitt and Clark (2010) state that media clogging by sediments generally occurs before chemical retention capacity is met in most media mixtures.

There are several benefits to delaying or avoiding maintenance to the filter media by use of a forebay. Pitt and Clark (2010) note that scraping the media surface was only temporarily and partially effective at restoring loading rates to the system, unless the surface media was sand. They noted that after two or three scrapings, maintenance was ineffective. This suggests that avoiding maintenance of the filter media may best prolong its useful life.

One drawback of pretreatment is that it requires a larger system footprint than a bioretention system alone. In site-constrained systems, a surface mulch layer may preclude the use of pretreatment as it can easily and cheaply be replaced periodically (Davis et al. 2009). Additionally, distributed water input with a velocity stilling zone (as opposed to concentrated inflow points) to the system can preclude the use of pretreatment. This may be achieved through a zone with shallow slopes (<0.5%) (Davis et al. 2009). While not the focus of their study, Shrestha et al. (2020) observationally saw success with a rock-lined inflow swale (its dimensions were not described) in slowing inflow to settle a portion of coarse sediments and particulates.

6. Climate Considerations

Climate conditions in Colorado, as previously mentioned, include long dry periods, cold and freezing conditions, and the application of road salts in the winter for deicing purposes, which all affect the performance of bioretention basins. Climate effects on vegetation are discussed in Section 2.3.

6.1 Deicers

Several studies indicate that the use of road salts may decrease hydraulic conductivity in bioretention media. Kakuturu et al. (2015b) observed in column tests with clayey silty sand media that infiltration rates decreased by about 19.1 percent with the application of deicing salts. When compost was added to the media (15 percent by mass), the rate decreased by 93.7 percent. It was hypothesized that salt had a greater effect on the column with compost because the sodium ions displaced other cations in the compost (Kakuturu, 2015a). Counterintuitively, the media pore size of the media enlarged. The decrease in hydraulic conductivity was attributed to blocking of pore throats by biofilms promoted by the salts (2015a, b). Finally, it was shown that the concentration of salt in the applied water, not the cumulative salt loading, determined the reduction in hydraulic conductivity. They hypothesized that this was due to the lack of complete sodium adsorption by the water (2015b). LeFevre et al. (2015) note that the loss of base cations from media due to their displacement by sodium ions can reduce forces that bind soil aggregates together, resulting in clogging of small pores. This results in reduced overall permeability.

Denich et al. (2013) found that road deicers comprised of 95% sand and 5% salt had little effect on hydraulic conductivity rates, as they were always offset by an increase in hydraulic conductivity due to media expansion from freezing. Figure 8 below shows infiltration rates in media basins before and after dosing with 2-years' equivalent winter runoff loading. Basins 1 – 5 did not receive loading with deicer, and Basin 7 received runoff loading equivalent to 15 years of deicer. In all cases, the infiltration rate increased, although to a lesser extent when deicer was added.

Studies of the effects of road salts on pollutant treatment are mixed. Denich et al. (2013) notes that the exposure of the bioretention soils to de-icing materials did not alter the media's ability to remove contaminants, nor was there evidence of increased heavy metal mobility. Kakuturu et al. (2015a) notes that the presence of salt can exacerbate leaching of organic matter, nutrients and zinc. Similarly, Pitt and Clark (2010) and LeFevre et al. (2015) cite that high salinity can strip accumulated heavy metals from sorption sites due to competition for sorption sites and impact long-term media structure.

Several studies note that bioretention basins, and other types of BMPs, are not effective at the treatment of road salts. The Colorado Stormwater Center (2020) shows in their study on roadway deicers that between 2012 and 2017, baseline chloride levels in the study stream increased, indicating that though there may be some temporary environmental storage of chlorides, they ultimately leach over time. Denich et al. (2013) notes that salts are generally held within the media for the season, and then flushed in the spring with the first infiltrations. It is therefore important to limit the amount of deicer used around bioretention basins. They also suggest underdrain controls that may restrict infiltration when media may contain high levels of salts and then be capped after flushing of salts in the spring.

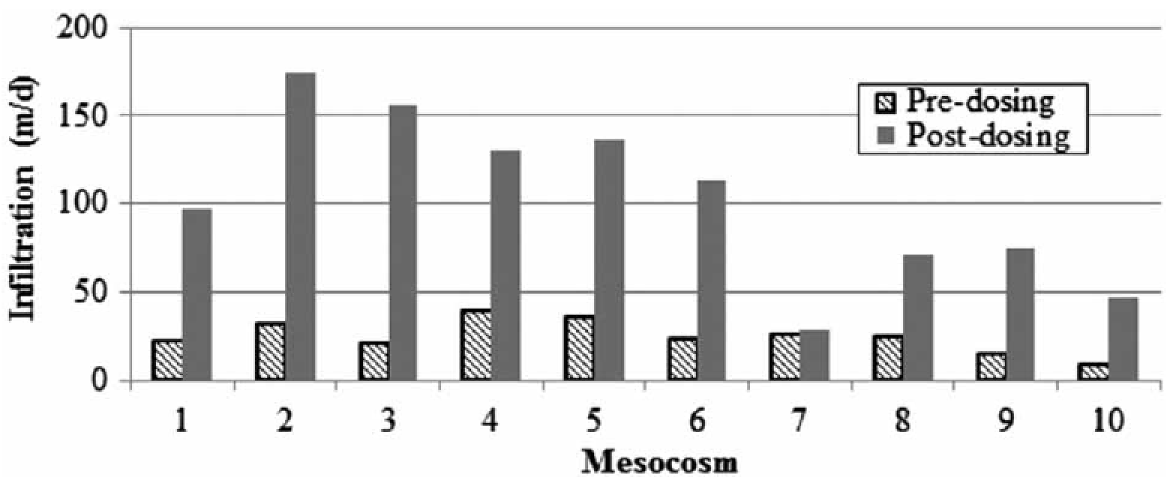


Figure 8: Infiltration rate comparison before and after the application of winter runoff. Mesocosms 1-5 were not loaded with deicer; mesocosm 7 was dosed with 15 years' load of deicer; the rest were dosed with 2 years' load of deicer.

7. Application to Colorado

Recognizing the unique environmental conditions presented by Colorado's climate, this section discusses reference sources local to Colorado, as well as literature cited from other locations and suggests how the results may be applicable or adapted to Colorado.

A number of publications are referenced that come from Colorado or focus on xeric and/or semi-arid climates. These include:

Publication	Location
EPA	Semi-arid Regions of the US
Dell and Brim (2017)	Colorado Stormwater Center/ City of Fort Collins
Guo et al. (2009)	University of Colorado
Guo et al. (2010)	University of Colorado
American Society of Landscape Architects (2020) *	Varying locations, Colorado
Colorado Stormwater Center (2020)	Colorado State University

*The American Society of Landscape Architects has published a list of stormwater case studies by state, which provides fact sheets on stormwater projects throughout Colorado, including their goals, achievements, site constraints, costs, cost-benefit analyses, and more.

Several other publications cited come from the Melbourne area of Australia. It is assumed that the climate of this region is sufficiently similar to that of Denver to consider results of these bioretention facilities informative. Other publications include only laboratory data, which is generally immune to the impacts of climate. Studies were limited to those containing reasonably locally available resources.

Publication	Location
Glaister et al. 2014	Australia
Lucas and Greenway, 2011	Brisbane, Australia
Le Coustumer et al. 2012	Melbourne, Australia
Bratieres et al. 2008	Victoria, Australia
Hatt et al. 2008	Laboratory study
Shrestha et al. 2018	Burlington, VT
Hsieh et al. 2007, 2007b	Laboratory study, materials from Prince George's County, MD
Winston et al. 2016	Northeast OH
Syring et al. 2009	Laboratory study
Brown and Hunt 2011	Nashville, NC
Davis et al. 2009	Desktop Analysis
Henderson et al. 2007	Laboratory study
Carpenter and Hallam 2010	Desktop analysis, laboratory study, and southeast MI
Hunt et al. 2012	Desktop Analysis
LeFevre et al. 2015	Desktop Analysis
Mays and Hunt 2005	Laboratory study

Reddi et al. 2005	Laboratory study
Brown et al. 2016	Laboratory study
Rippy 2015	Laboratory study
Denich et al. 2013	Guelph, Canada
Fassman- Beck et al. 2015	Laboratory study
Hess et al. 2015	Laboratory study
Kakuturu et al. 2015, 2015b	Laboratory study
Skorobogatov et al. 2020	Desktop Analysis

References

Bratieres, K., Fletcher, T.D., Deletic, A., and Zinger, Y. 2008. Nutrient and sediment removal by stormwater biofilters: A large-scale design optimization study. *Water Research* **42** (2008) 3930-3940.

Brown, S., Corfman, A., Mendrey, K., Kurtz, K., and Grothkopp, F. 2016. Stormwater Bioretention Systems: Testing the Phosphorus Saturation Index and Compost Feedstocks as Predictive Tools for System Performance. *J. Environ. Qual.* **45** (2016) 98-106.

Brown, R.A., and Hunt, W.F. 2011. Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells. *Journal of Irrigation Drain Engineering* **137(3)** (2011). 132-143. DOI 10.1061/(ASCE)IR.1943-4774.0000167.

Carpenter, D.D., and L. Hallam. 2010. Influence of planting soil mix characteristics on bioretention cell design and performance. *J. Hydrol. Eng*. **15** (2010) 404–416.

Colorado Stormwater Center. 2020. Research. http://stormwatercenter.colostate.edu/research/

Culbertson, T. A., and Hutchinson, S. L. 2004. Assessing Bioretention Cell Function in a Midwest Continental Climate. Presented at the 2004 ASABE Annual International Meeting, Ottawa, Ontario, Canada, Aug. 1–4; American Society of Agricultural and Biological Engineers: St. Joseph, Michigan.

Davis, A.P., Hunt, W.F., Traver, R.G., and Clar, M. 2009. Bioretention Technology: Overview of Current Practice and Future Needs. *Journal of Environmental Engineering.* **135(3)** (2009). 109-117. DOI: 10.1061/(ASCE)0733-9372(2009)135:3(109).

Dell, T., and Brim, J. 2017. Bioretention Media Mixtures- A Literature Review. City of Fort Collins.

Denich, C., Bradford, A., and Drake, J. 2013. Bioretention: Assessing effects of winter salt and aggregate application on plant health, media clogging and effluent quality. *Water Quality Research Journal of Canada* **48** (2013). 387.

Fassman-Beck, E. Want, S., Simcock, R., and Liu, R. 2015. Assessing the Effects of Bioretention's Engineered Media Composition and Compaction on Hydraulic Conductivity and Water Holding Capacity. *Journal of Sustainable Water in the Built Environment* **1 (4)** (2015). https://doi.org/10.1061/JSWBAY.0000799

Glaister, B., Fletcher, T., Cook, P.L.M., and Hatt, B. Co-optimization of phosphorus and nitrogen removal in stormwater biofilters: the role of filter media, vegetation and saturated zone. *Water Science & Technology* **69.9** (2014) 1961-1969.

Guo, J.C.Y., Ramaswami, A., and Kocman, S.M. 2009. Design of Two-Layered Porous Landscaping Detention Basin. *Journal of Environmental Engineering* **135 (12)** (2009).

Guo, J.C.Y., Ramaswami, A., and Kocman, S.M. 2010. Sustainable Design of Urban Porous Landscape Detention Basin. Urban Drainage and Flood Control District and Urban Watersheds Research Institute.

Henderson, C., Greenway, M., and Phillips, I. 2014. Sorption behaviour of nutrients in loamy-sand bioretention media subject to different conditions (vegetation, enrichment and incubation time). ResearchGate. https://www.researchgate.net/publication/29466967.

Herrera Environmental Consultants, Inc. 2015. Analysis of Bioretention Soil Media for Improved Nitrogen, Phosphorus, and Copper Retention. Kitsap County, Washington.

Hess, A., DelVecchio, T., Welker, A., Wadzuk, B. 2015. An Experimental Program to Evaluate Soil Mixes for Rain Gardens. *World Environmental and Water Resources Congress* (2015). https://doi.org/10.1061/9780784479162.021

Hills, M. 2019. Selecting the Right Mulch for your Biofiltration Practice. Contech Engineered Solutions. September 26, 2019. https://www.conteches.com/stormwater-article/article/180/selecting-the-right-mulch-for-your-biofiltration-practice

Hsieh, C., Davis, A.P., Needelman, B.A. 2007. Bioretention Column Studies of Phosphorus Removal from Urban Stormwater Runoff. *Water Environment Research*. **79** (2007) 177-185.

Hsieh, C., Davis, A.P., Needelman, B.A. 2007b. Nitrogen Removal from Urban Stormwater Runoff Through Layered Bioretention Columns. *Water Environment Research* **79** (2007). 2404-2412.

Houdeshel, C.D., Pomeroy, C.A., and Hultine, K.R. 2012. Bioretention Design for Xeric Climates Based on Ecological Principles. Journal of the American Water Resources Association **48 (6)** (2012). 1178-1190. https://doi.org/10.1111/j.1752-1688.2012.00678.x|

Hunt, W.F., Davis, A.P., and Traver, R.G. 2012. Meeting Hydrologic and Water Quality Goals through Targeted Bioretention Design. *J. Envrion. Eng.* **138(6)** (2012) 698-707.

Kakuturu, S.P., Clark, S.E. 2015. Clogging Mechanism of Stormwater Filter Media by NaCl as a Deicing Salt. *Environmental Engineering Science* **32 (2)** (2015). http://doi.org/10.1089/ees.2014.0337

Le Coustumer, S., Fletcher, T.D., Deletic, A., Barraud, S., and Poelsma, P. 2012. The influence of design parameters on clogging of stormwater biofilters: A large-scale column study. *Water Research* **46** (2012) 6743-6752.

LeFevre, G.H., Paus, K.H., Natarajan, P., Gulliver, J.S., Novak, P.J., and Hozalski, R.M. 2014. Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells. *J. Environ. Eng.* **141(1)** (2015) 04014050.

Liu, J., and Davis, A.P. 2013. Phosphorus Speciation and Treatment Using Enhanced Phosphorus Removal Bioretention. *Environ. Sci. Technol.* **48** (2014) 607-614.

Lucas, W.C. and Greenway, M. 2011. Hydraulic Response and Nitrogen Retention in Bioretention Mesocosms with Regulated Outlets: Part I- Hydraulic Response. *Water Environ. Res.* **83** (2011) 692-702.

Mays, D.C., and Hunt, J.R. 2005. Hydrodynamic Aspects of Particle Clogging in Porous Media. *Environ. Sci. Technol.* **39** (2005) 577-584.

Mile High Flood District. 2020. Soil Texture Chart Showing Mile High Flood District Media Specifications. Personal communication, Holly Piza. 2020.

North Carolina Department of Environmental Quality (NDEQ). 2018. Stormwater Design Manual.

Orr, A. 2013. Transpiration performance in bioretention systems designed for semiarid climates. University of Utah.

Read, J., Fletcher, T.D., Wevill, T., and Deletic, A. 2009. Plant traits that enhance pollutant removal from stormwater in biofiltration systems. *Int. J. Phytoremediat*. **12** (2009) 34–53.

Reddi, L.N., Xiao, M., Hajra, M.G., and Lee, I.M. 2005. Physical clogging of soil filters under constant flow rate versus constant head. *Can. Geotech. J.* **42** (2005) 804-811.

Rippy, M.A. 2015. Meeting the criteria: linking biofilter design to fecal indicator bacteria removal. *WIREs Water* **2** (2015). 577-592.

Saxton, K. 2019. Soil-Plant-Atmosphere-Water Field & Pond Hydrology. Soil Water Characteristics- Equations. US Department of Agriculture.

Shrestha, P., Hurley, S.E., and Wemple, B.C. 2018. Effects of different soil media, vegetation, and hydrologic treatments on nutrient and sediment removal in roadside bioretention systems. *Ecological Engineering* **112** (2018). 116–131.

Skorobogatov, A., He, J., Chu, A., Valeo, C., van Duin, B. 2020. The impact of media, plants and their interactions on bioretention performance: A review. *Science of the Total Environment* **715** (2020).

Syring, S.M., Krishnamurthy, R., MacKay, A.A. 2009. Attenuation of Roadway-Derived Heavy Metals by Wood Chips. *Journal of Environmental Engineering* **135 (9)** (2009). 747-757.

USEPA. 2010. Green Infrastructure in Arid and Semi-Arid Climates. EPA-833-B-10-002. https://www3.epa.gov/npdes/pubs/arid_climates_casestudy.pdf

USEPA. 2012. Evaluation of Green Roof Plants and Materials for Semi-Arid Climates. EPA/600/R-12/592.
https://nepis.epa.gov/Exe/ZyPDF.cgi/P100FS5E.PDF?Dockey=P100FS5E.PDF

Winston, R.J., Dorsey, J.D., Hunt, W.F. Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio. 2016. *Science of the Total Environment* **553** (2016). 83–95.