BIORETENTION SYSTEM DESIGN SPECIFICATIONS & “PERFORMANCE ENHANCING DEVICES”

Abstract

This paper was prepared to provide technical support for Chesapeake Bay managers and stormwater professionals implementing performance enhancing devices (PEDs) for bioretention stormwater management practices.

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Purpose & Background

This paper was prepared to provide technical support for Chesapeake Bay managers and stormwater professionals implementing performance enhancing devices (PEDs) for the bioretention stormwater best management practice (BMP). The recommendations in this document relate to the development of specifications for enhanced bioretention designs and media mixes. The intent of such PEDs is to sequester higher levels of nitrogen and/or phosphorus than those currently specified in the Bay states.

This paper supplements the final report entitled, "Performance Enhancing Devices for Stormwater Best Management Practices" (Hirschman et al., 2017). The aforementioned final report summarizes the technical findings of primarily laboratory studies of PEDs specific to media amendments, the usage of an internal water storage zone in the underdrain system, and the maximization of plant uptake. This paper adds the context of evolving state design standards, fundamentals of nutrient adsorption in soils, and field studies of PEDs. Its goal is to further inform the development of bioretention designs for specific pollutants of concern.

Improving existing bioretention specifications requires an understanding of the following:

1. The starting point and the current state of bioretention design specifications in several states and the notable differences between them;
2. PED materials used by researchers and specification considerations; and
3. Potential consequences of using specific PEDs.
4. The chemical behavior of pollutants in soil and their utilization by vegetation.

Current Bioretention Specifications

Many states offer design guidelines or establish design standards for structural post-construction stormwater BMPs. Consequently, bioretention media mixes and design specifications established by state permitting agencies can vary substantially; these differences are possibly due to age of the specification. Additionally, regionally different soils, adaptable plant species, geography, and pollutant stressors (or stormwater criteria of concern) produce variations among states and local jurisdictions. For example, a state with coastal plain and mountain geographies will follow different criteria for their respective regions.

Further, differences in bioretention specifications across states include varying interpretations of literature studies and engineering judgement to accommodate local conditions. The assumptions that the states use to develop the specifications vary as do the processes that result in their development.

In a review of bioretention design guidelines for California (Los Angeles region), Georgia, Michigan, Minnesota, North Carolina, Virginia, and Washington, D.C., there are notable differences, which will be discussed in this review. Also included in this review are some of the most recent and advanced design specifications located outside the Chesapeake Bay region.

As noted in Hirschman et al. (2017), there are four "eras" of bioretention design thus far, which are reflected in variations of bioretention criteria among states. For context, the state regulations with their respective eras are shown in Table 1 below.

Table 1. The four bioretention design eras indicating advancing knowledge and resulting performance

Design Era	State Bioretention Guideline Reviewed
Era 1 Initial Practice Development (1990's)	
Era 2 Mainstreaming Bioretention (2000 - ~2007)	GA 2001
Era 3 Design to Increase Runoff Reduction (2007 – Present)	CA, DC-2013, GA-2016, MI, MN, VA, NC 2017
Era 4 Design to Enhance Nutrient Removal	NC, MN

The oldest requirements reviewed for comparison were those from Georgia in 2001, reflecting design conditions from 17 years ago. The most recent requirements were for North Carolina and were finalized in mid-2017. The following sections compare, analyze, and summarize state requirements. Keep in mind that the specifications reflect the state of the knowledge at the date of origination.

1) Bioretention physical design specifications differ among states

Bioretention design specifications differ among the state manuals with ranges summarized in Table 2 and with details shown in Table 3 below.

Table 2. Bioretention design ranges for all states reviewed

Physical design characteristics	
maximum ponding level	Ranges from 12” to 24”.
peak ponding level	Ranges from 6” to 24”.
peak outlet level	Where specified it is 18”.
underdrain design	Ranges from 6” to 18”.
media depth	Ranges from 18” to no greater than 6’.
mulch layer depth	Ranges from 2-4”.
minimum design flow	Requirements range from 5”/hr drainage rate to long term permeability of 1-2”/hr.
minimum infiltration rate	Ranges from 1”/hr to 5”/hr
Media mix physical characteristics	
sand	Ranges from 30-50% to 80-90%
fines	Ranges from unspecified to <20%
clay	Ranges from unspecified to <20%
organic matter	Ranges from 30-50% to 80-90%
Media chemical characteristics	
pH	Ranges from 5.5-6.5 to 6.0-8.5
available phosphorus;	Generally low available phosphorus*
cation exchange capacity;	Not all states specify but those that do specify >5 meq
soluble salts; and	Not all states specify but those that do specify <500 meq
in several, compost criteria	One older spec requires compost, but newest spec removes compost
Water quality treatment characteristic	
internal water storage (IWS) level – minimum depth below surface	One older spec is silent on IWS, but newest spec provides detail and modeling tool for design level
* test for available phosphorus determined by state agriculture agencies, but generally stated a P-index of <30.	

Table 3. Pertinent state specific bioretention design requirements **in chronological order. Note: There are two Georgia criteria representing old (2001) and new (2016)**

Criteria	GA 2001	MI 2008	Los Angeles 2012	MN 2013	DC 2013	VA 2013 Level 2 Design	GA 2016	NC 2017
Maximum ponding level	6"	18"	18"	18"	24"	6 to 12”	12"	24"
Peak ponding level	6”	18”		18" HSG A & B	6 to 12"	6”	9"	18"
Peak outlet level			18"		18" + 3 to 6" freeboard		18"	18”
Underdrain	8” gravel layer	18" cover over perforated pipe	as necessary for adequate temporary storage	where used, 4” pipe on bottom and 3” stone above	≤12" gravel layer	provide 12” #57 stone sump	8" gravel layer	4” pipe on bottom and 3” #57 stone above
Internal Water Storage level (IWS) - minimum below media surface	not included	not included	infiltrate media volume in 48 hrs and complete volume in 96 hrs	can use IWS for nitrogen but with minimum depth of 3’)	infiltrate within 72 hrs at 1/2 measured infiltration rate	IWS of 12" or depth of sump	IWS through upturned underdrain must be 12-18" below bottom of planted area	IWS at a minimum of 18" below planting surface
Media Depth	≥ 48”	18-48"	2-3' as minimum	2-4’	≥18" standard; ≥24" enhanced <6' max	3-4’	≥ 18"	>24" w/o IWS; >36" w/ trees; 30" w/ IWS
Mulch Layer	2-4"	2-3”	1-2”	3-4”	2-3”	2-3"	3-4"	2-4"
Minimum onsite soils infiltration rate	≥ 0.5"/hr	drain within 24-48 hrs	> 0.3”/hr	must fully drain in 48 hrs	≥ 0.5"/hr	≥ 0.5"/hr	≥ 0.5"/hr	≥ 2"/hr
Media Mix	sandy loam, loamy sand or loam texture w/ <25% clay	20-30% topsoil	all sands complying with ASTM C33 comply	sandy loam, loamy sand or loam texture w/ <5% clay	ASTM C33 contains fines	loamy coarse sand	20-30% topsoil	homogenous engineered media blend
Sand	12-18"	30-50%; ASTM C33	60-80% fine sand	70-85% construction sand (depending on desired result)	80-90%; 75% coarse or very coarse	75% coarse or very coarse	35-60%	75-88%
Fines	not addressed	not addressed	< 5% passing #200 mesh; 10-20%	ASTM C33 complies	10-20%	>10% ≤20% silt + clay	Not addressed	8-15% (passing #200 sieve) 12-15% for TN as target; <8% for P as target
Clay	10-20%	<10%	media should be free from clay	<5% clay	<10%	<10%	<15%	included in fines
Organic Matter	1.5-3%	5-10%	20-40% compost	3-30%	3-5%	3-5%	10-25%	5-10%
pH	5.5-6.5	5.5-6.5		6.0-8.5			6-8	
Media Phosphorus				< 30 mg/kg Mehlich III*	5-15 mg/kg Mehlich-I; 18-40 Mehlich-III	5-15 mg/kg Mehlich-I; 18-40 Mehlich-III	P-index < 30	P-index < 30 up to 50 from the State Ag Lab
CEC					≥5 meq/100g	>5 meq/100g	>10 meq/100g	
Compost criteria		20-40%	C:N** 15:1 – 25:1 OM 35-75%***	C:N 6:1 – 20:1 OM ≥30%	C:N 25:1 OM 35-65%	C:N 25:1 OM >35%	Not addressed	****

* to receive P credit for water captured by underdrain the P content must be less than 30 mg/kg per Mehlich III (or equivalent) ** Carbon:Nitrogen ***OM – organic matter

**** addition of compost will likely export nutrients

Pretreatment

Bioretention specifications describe physical design characteristics that include provisions for pretreatment and non-erosive inlet flow. They are generally meant to manage silt deposition, media clogging, or erosion, and they do not vary significantly. Specifications do, however, vary in the allowable maximum ponding level. Washington, D.C. and North Carolina allow up to 24" of ponding, while earlier state requirements allow only 6" of ponding. Greater ponding depths assist with flood capacity and are acceptable if bioretention cells drain as designed. Greater ponding depths require greater consideration of public safety, fencing requirements, aesthetics, and erosion and scour of side slopes (DOEE, 2013).

Media Depth

In the earlier periods of bioretention application, allowable media depth was driven more by the unit's stormwater detention capacity, depth to groundwater, and site infiltration rate. The most recent specifications recognize and address depth of media to target specific pollutants, but they use varying design assumptions. For example, Washington, D.C. criteria target total suspended solids (TSS), and assume the 18" media depth can achieve sufficient TSS removal. In contrast, North Carolina's requirement to address TSS is with 30" or 24'' media depth for cells with and without internal water storage, respectively (NCDEQ, 2017). Georgia's 2016 Design Manual assumes that bioretention will be able to remove sufficient TSS if cells are sized for 1.2" target rainfall, and it assumes a minimum media depth of 18" (ARC, 2016).

Media Drainage

Hydraulic conductivity of the media is discussed in Hirschman et al. (2017), and it is considered in terms of design flow in hours to drain, as in California and Washington, D.C. This is important to prevent ponding or standing water that impacts plant viability, since most plants "don't like wet feet," and stormwater capacity is necessary to be prepared for subsequent storm events. North Carolina addresses ponding with a construction practice specification that prohibits mechanical compaction of media and recommends minimal contact once the media is in place (NCDEQ, 2017).

Site Infiltration Rate

Infiltration rate is meant to describe the permeability of a bioretention cell's underlying undisturbed soil. Among the states, there are a variety of terms for this—from "site permeability" to "field verified infiltration rate"—but they convey the same meaning.[1] Prior to design, the underlying undisturbed soil should be field tested for infiltration following a standard test method. If a minimum infiltration rate is not met, then bioretention underdrain(s) will be required. Minimum acceptable site infiltration rates for bioretention without underdrains vary among the states, but a field verified infiltration rate of ≥ 0.5"/hr is typical. During North Carolina's stakeholder process, compaction of underlying soils during facility construction was noted, which led to the following Minimum Design Criteria: *an underdrain with internal water storage shall be installed unless a soils report is provided showing that the in-situ soil infiltration rate is two inches per hour or greater prior to initial placement of the media* (NCDEQ, 2017).

[1] Calculation of hydraulic conductivity is sometimes required as it is a more representative soil characteristic and a better predictor of long term function.

2) Bioretention media mix specifications differ among states based on operational experience and targeted pollutants or elements of concern

Media Mix Specifications

Media mix is not only the substrate for bioretention plantings, but it also provides for capture of stormwater pollutants. Older media requirements allow more topsoil and a lower sand content, which is likely to improve plant viability. However, recent criteria recognize that, as a substrate, the media must not pond water for very long and should not be prone to clogging. This is reflected in a general requirement that the entire cell should drain in ≤ 48 hours. Consequently, coarse sand with low fines and clay content is becoming increasingly specified across the country. Older requirements, such as those in Michigan and California, encourage up to 40% organic matter content, which is intended to increase media water retention. However, high organic matter content through the addition of compost has been generally noted to potentially contribute phosphorus during drainage events (Logsdon & Sauer, 2016; Mullane et al., 2015; Paus et al., 2014).

North Carolina media mix requirements, with the intent to reduce bed compaction and clogging, specify a maximum of 8–10% clay and fines in the media mix (NCDEQ, 2017). Further, Minnesota and Washington, D.C. media size specifications demonstrate a move toward greater coarse sand content and reduced clay and fines by limiting clay to 5% and 10%, respectively. It is important to recognize, however, that cation exchange capacity (CEC) of clay is an important measure of a soil's capacity to retain and supply plants with nutrient cations (Sonon et al., 2014). The importance and a more detailed outline of CEC is discussed in a later section titled "Cation Exchange Capacity and Media pH."

Media Soil tests and P-Index

Bioretention media is also a source of nutrients necessary for the health and viability of vegetation. Soil science shows that healthy plant growth is dependent on soil pH, soil texture, organic matter, and plant-available nutrients, and of course, weather. For bioretention media criteria, it is important to remember that not all labs use the same chemical extractant to determine nutrient values, hence soil test results will differ between labs using the same soil sample. This in itself is not troubling if the soil test lab has research data that calibrates their recommendation with crop response in the field. Unfortunately, the correlation between different chemical extracts and a soil test value is poor (Klausner, S.D., and S.W. Reid. 1996).

Similarly, the P-Index is a measure that guides agricultural nutrient management planning to prevent excess phosphorus loss by leaching or runoff. The P-Index used in bioretention specifications serves the same purpose. Washington, D.C. and Virginia requirements indicate this as P-Index by the Mehlich III extraction procedure. North Carolina guidance on phosphorus in nutrient management planning derives their phosphorus loss index as a function of the soil test P-Index (Mehlich III), erosion, soluble-P runoff, leaching loss, and applied phosphorus loss (Osmond et al., 2014). The mixing of terms and differing nutrient extractants between states' agriculture and bioretention media guidelines can be confusing since both deal with lab results for a specified soil. It is also important to know the distinction between soil test P-Index and plant available P.

The Virginia design specification for bioretention mix states that the filter media should contain sufficient plant-available phosphorus to support initial plant establishment and plant growth, but it should not serve as a significant source for long-term leaching (VADCR, 2013). North Carolina specifies that media mix plant-available phosphorus must be less than 30 P-index for sensitive waters and less than 50 elsewhere (NCDEQ, 2017).

Plant-available phosphorus in media is determined using a soil extraction procedure, such as Mehlich I, Bray, Olsen, or Mehlich III (Sawyer & Mallarino, 1999). When writing a P-Index specification, it is imperative to use a soil test method derived for the soils of the state. For example, Minnesota stipulates that the Bray test not be used in calcareous soils or where soil pH is greater than 7.3 (MPCA, 2017). North Carolina, Virginia and Washington, D.C. recognize the Mehlich III test for the P-Index. The Mehlich III test method leads to a different interpretation of soil's phosphorus requirement than in a state that recognizes, for example, the Bray method. Therefore, it is important to be aware that a P-Index reported in one state may not be the same in the next.

Recent state specifications also recognize that media size distribution and constituents can either enhance adsorption and precipitation of phosphorus or favor leaching. Minnesota describes six media compositions in their 2014 Manual that vary in type and coarseness of sand and inorganic content. Each are expected to manage phosphorus to various degrees. The allowable phosphorus as determined by the soil P-index differs among the media mixes. Where phosphorus is targeted, the P-Index and organic matter is low. Minnesota's bioretention mixes that contain 15–30% organic matter from compost is assumed to leach phosphorus (MPCA, 2017). As previously mentioned, North Carolina allows a higher P-Index where nutrient leaching is not a great concern, and provides flexibility in the type of compost in the mixture (NCDEQ, 2017).

Cation Exchange Capacity and Media pH

Cation exchange capacity (CEC) is a direct measure of a soil's capacity to exchange cations (Ca, K, Mg, etc.) between the soil and soil solution. It is used as a comparative measure of a soil's ability to retain nutrients for plant use. This property is determined extraction and analysis of cations from a soil sample through the Mehlich I or other soil extraction procedure. The associated CECs for sandy soil, clay, and organic matter range from 1–5 meq/100 g, > 30 meq/100 g, and from 200–400 meq/100 g, respectively (Sonon et al., 2014). A CEC < 5 meq/100 g is considered low, meaning that soil amendments are needed to increase it to ≥ 5 meq/100 g (MPCA, 2017). Organic matter content will raise the CEC and can adsorb some phosphorus (Sonan et al., 2014). Additionally, the CEC will attract pollutants such as heavy metals (Cd, Pb, Ni, As, etc.) and help reduce their leaching (S. Klausen, personal communication, April 3, 2018).

Soil pH is also important to the retention of phosphorus in the media. At a low pH, phosphorus is retained by the soil's aluminum, iron, manganese, and others. However, at a very low soil pH, the aluminum becomes toxic to plants. At a high pH, the phosphorus is retained as calcium and magnesium phosphate (Ketterings et al., 2003). When a soil's pH is > 7 and when CEC is high (> 10 meq/100 g), the soil has a greater buffer capacity. This is reflected in the liming requirement in soils tests, and means that pH will not fluctuate rapidly. Consequently, and similar to agricultural recommendations, media pH is an important bioretention maintenance factor where nutrient retention is a concern. Regular soils tests to determine nutrient, organic matter, and liming application levels used by farmers, can also be useful for bioretention maintenance.

Organic Matter

As noted above, mix specifications typically include organic matter and allowable compost. Earlier specifications encouraged greater organic matter content. California encourages compost as the organic matter input for up to 40% of the media mixture (CA RWCB, 2012). More recently, concern over nutrient leaching from organic matter limits the use of compost, and lower limits on compost are specified. Minnesota notes that nutrient leaching from organic matter has the potential to contribute more nutrients to the discharge than the original inlet stormwater. For this reason, its bioretention guidance recommends peat or some other low-P or slow release material as the source of organic matter instead of compost (MPCA, 2017).

3) Performance Enhancing Designs and Precautions

As presented in Hirschman et al. (2017), "Performance Enhancing Designs" are the fourth era in the evolution of bioretention designs. Minnesota and North Carolina are two states that recently incorporated and provided criteria for performance enhancing designs in their stormwater design manuals. Each state has nutrient-sensitive waterways for which the intent is to support bioretention designs that address urban nutrient runoff. Minnesota cites additives to bioretention media mixes that will assist with phosphorus sequestration, while North Carolina provides a design tool for internal water storage to enhance denitrification. Derived from the Minnesota and North Carolina specifications and Hirschman et al. (2017), Table 4 summarizes performance enhancing designs in their current uses.

Table 4. Comparing Performance Enhancing Devices (PEDs) for various nutrient reduction goals

Goal	PED	What We Know	Greatest Advantage	Challenge to Use	References
TN	Internal Water Storage (IWS)	In broad use in NC; specified with IWS elevation of 18" below media surface (or lower) to avoid roots; can be modeled with tile drain model. Detention time drives denitrification.	Provides mechanism for denitrification to occur in bottom reservoir; found in current MN and NC state regulations.	Cells rely on sufficient drainage which can be a challenge in flat terrain or high groundwater.	MPCA, 2017. NCDEQ, 2017.
TSS TP	Use qualified media: high sand, low fines, low organic matter; <5% compost by weight; test media for soil-P (Mehlich III), pH, and cation exchange capacity.	Soil P should be low (< 30 Mehlich III) for discharge to nutrient sensitive waters.	Soil pH should be optimized for plant phosphorus uptake; soil P and CEC will identify potential to release P in discharge.	Regular soil tests are needed as a maintenance practice; interpret soils results for bioretention, not for plant production.	NCDEQ, 2017 Sonon, 2014
TP PO_4	Media Amendment: Aluminum-Ferric water treatment residuals (WTR)	WTR are a waste requiring land disposal. They have high moisture and present some handling challenges. In use, fixated phosphorus is bioavailable. Relative proportion of iron and aluminum will vary among suppliers.	At normal soil pH they retain phosphorus. Material is readily available water treatment plant waste.	Residual moisture affects handling and mixing with media. Limited field data on life in bioretention cells.	Davis, 2016
TP PO_4	Media Amendment: Iron filings layered in media	Retains phosphorus in wide pH range below 7	Handling is not difficult. Can be a part of retrofit and applied in layers.	In a sand filter application, as the practice aged it showed a drop-off in phosphorus retention. A difficult maintenance task to break up iron rust that formed in sheets within the sand filter. Question on filings' availability.	Erickson et al., 2015
TP PO_4	Media Amendment: Acid Mine Drainage (AMD) treatment residue	In some areas of the US it is readily available. No reports of field testing in bioretention	In other waste treatment applications, AMD is effective in capture of dissolved phosphorus.	Question concerning life in the media and maintenance requirements.	Penn et.al., 2007
TP PO_4	Media Amendment: Biochar	Relative ease of handling as it is a dry product	Retains o-phosphorus	Cost, since it is a heat- derived material. Question whether its performance deteriorates over time due to loss of active adsorption sites.	Beneski, 2013

The current era of bioretention system development includes efforts to improve pollutant and nutrient sequestration in the bioretention media. Analytical chemistry and water treatment references discuss the chemistry of pH-based precipitation, metal hydroxide formation, and coagulation of phosphorus with metal salts, which have been in use for many years. Further, sorption of pollutants by active carbon has long been used for purification of waters and wastewaters (Weber, 1972). Expanding that knowledge to the field of stormwater management, researchers use batch and column studies in the laboratory to derive the life of such media additives and constraints on their successful uses. This research results in estimates of the kinetics of chemical and physical reactions, dosage response dynamics, and application rates. Additionally, the results help to optimize such operating parameters as pH, temperature, alkalinity, contact time or flow rate, and chemical impurities.

Field studies can use the results of these batch and column studies for their models, which allows them to develop field scales where additives are applied to otherwise standard systems. The testing of scaled-up systems using synthetic and real-world stormwater is used to project the systems' responses in other locations or situations. At this time, as reported in Hirschman et al. (2017), field studies are fairly rare, as are sufficient operating conditions to describe PED specifications. Yet, available bench-scale and field studies further advance the understanding of PEDs. As such, Tables 5, 6, and 7 below summarize bench-scale column studies and field studies to identify operating parameters, which will ultimately be useful in developing specifications for a variety of PEDs.

Hirschman et al. (2017) reviews papers covering research on media additives that have promise for nutrient removal in stormwater treatment. Some of the media additives included are biochar from poultry waste and wood to address forms of nitrogen and phosphorus, water treatment residuals from aluminum and ferric chloride treatment to address phosphorus, and iron from filings, slag, steel wool and acid mine drainage sludge to address phosphorus. The papers included many column studies and several field studies of additives either sandwiched between columns of sand or mixed in with the sand. Each pursued a better definition of the additive properties, their best method of application, and their residual lives.

As with most research, it takes many studies to derive a conclusion and design specification, and the study of nutrient sequestration in bioretention media is no exception. From the research thus far, there are components of a bioretention specification that start to emerge. None by themselves are specification-ready, but together they contribute to a better composite. The tables below outline those components, each attributed to their respective papers.

Table 5. Biochar PEDs studies

		Biochar - Poultry Litter (PL) in a column study (Beneski 2013)	Biochar - Wood Based (WB) in a column study (Beneski 2013)	Biochar - Wood Based (WB) in a column study (Reddy 2014)
System Design	**Pretreatment**	Not applicable to this study	Not applicable to this study	Wash biochar to remove fines that may impact removal efficiencies by releasing pollutants back into the solution.
	Media Size	Testing was on 0.85-1.0 mm and <0.85 mm diameter particle sizes mixed with 20/30 (mid-range sand of ASTM C33 standard) sand in columns.	Testing was on 0.85-1.0 mm and <0.85 mm diameter particle sizes mixed with 20/30 (mid-range sand of ASTM C33 standard) sand in columns.	Biochar screened in No.10 (2 mm) sieve was used.
	Media composition	Testing involved 10% biochar; 90% sand by volume	10% biochar; 90% sand by volume	Tests done on a biochar bed sandwiched with pea gravel.
	Media Drainage & Specification	Not applicable to this study	Not applicable to this study	Not applicable to this study
	Underdrain	Not applicable to this study	Not applicable to this study	Not applicable to this study
Reported Results	**Source Material Considerations**	Biochar produced at 500°C is more effective at NH_4^+ removal than that produced at 400°C. PL biochar contains higher levels of most Mehlich III extractable than WD.	Biochar produced at 500°C is more effective at NH_4^+ removal than that produced at 400°C.	Recommends further research to optimize contaminant removal by investigating different types of biochar and/or filter media (e.g. zeolite, others)
	Results on Targeted Pollutant	PL leached NH_4^+; biochar active sites hold and successfully remove NH_4^+.	Column experiments showed <0.85 mm particle size from 500°C WD biochar increased NH_4 adsorption	Biochar is not prone to releasing phosphate.
	% Removals	Removal of NH_4^+ reported as decreasing over volume treated; fine biochar leached more NH_4^+. NO_3 removal negligible.	WD biochar removed >10X the NH_4^+ removal per gram than PL biochar. NO_3 removal negligible.	86% NO_3; 47% TP
	Other Results / Observations	PL biochar increases pH; cites literature that states NH_4^+ is plant available. A range of particle sizes is desirable.	WB biochar slightly decreases pH.	Reported removal of 18% Cd, 19% Cr,65% Cu,75% Pb, 17% Ni, and 24% Zn from synthetic stormwater.
	Recommendations	Biochar is recommended where excess NH_4^+ is to be controlled, but smaller particle size should be avoided. It is not effective at removal of nitrate.	Biochar is recommended where excess NH_4^+ is to be controlled, but would not be effective at removal of nitrate.	Biochar is a promising alternative absorbent to reclaim phosphorus from stormwater or reduce phosphate leaching. And it offers high NO_3 removal.

Table 6. Water treatment residual PEDs studies

		Water Treatment Residuals - Aluminum, Ferric Water Treatment Residual (WRT) in a field study (Liu & Davis 2013 and (Li, 2007)	Water Treatment Residuals - Aluminum Water Treatment Residual (WRT) in a field study (Roseen & Stone 2013)
System Design	**Pretreatment**	Not reported	Not reported
	Media Size	Earlier study of cells classified soils as USDA sandy soils; d_{50} = 570 µm and Uniformity Coefficient (d_{60}/d_{10}) of 3.2	Described as coarse sand
	Media composition	80% sand pH 7.3 13% silt O.M. 5.7% 7% clay 5% WTR by mass sandy loam	50% sand; 10% compost; 20% wood chips; 10% loam; 10% WTR (dry mass of <1%)
	Media Drainage & Specification	Enhanced bioretention cell (underdrained); media depth 0.5-0.8m	Cells were designed for a maximum ponding depth of 4 inches with an overflow.
	Underdrain	6” perforated underdrain to discharge manhole	Used internal water storage; outlet above permanently saturated 6" pea gravel layer
Reported Results	**Source Material Considerations**	Media with high phosphorus content causes total phosphorus (TP) export	WTR with <5% solids cannot be practically added to bioretention soil mix due to issues with clumping during mixing.
	Results on Targeted Pollutant	WTR retrofit of existing bioretention cell significantly reduced effluent TP concentration.	Effluent water quality generally improved over influent as the result of treatment by the bioretention cell.
	% Removals	84% TP; 60% diss. P based on event mean concentrations	36% TN; 55% TP, and 20% ortho-P based on event mean concentrations
	Other Results / Observations	High flow media can be modified with WTR and alum to provide high runoff infiltration and improved P removal.	Use of a backhoe to mix filter media is common but insufficient for WRT. The adsorption process is based on the availability of solid aluminum (hydr)oxide sites as well as other available cation sites to which dissolved phosphorus may adsorb. Very high water content provides fewer sorption sites for removing phosphorus than do other sorbent materials with higher solids content at the same volume ratio. The sum of cation equivalents present may be used as an indicator of phosphorus sorption capacity.
	Recommendations	WTR appears to be an available option to address P removal from urban stormwater	Limit sand content to 50-60% for plant survivability.

Table 7. Iron-based PEDs Studies

		Ferric as acid mine drainage (AMD) sludge in a column study (Sibrell & Tucker 2012)	Iron as filings within a sand filter field study (Erickson et al. 2010 and 2015)	Trapping Phosphorus in Runoff (Iron slag) field study (Penn 2012)
System Design	Pretreatment	Pretreat to remove fines from media; Sludge dried at 105˚C overnight	Solids settling in adjacent detention pond. Stormwater enters sand filter alongside pond.	Evenly distributed flow through perforated inlet pipe below media surface.
	Media Size	Air-dried sludge crushed to achieve particle size 0.3-4.0 mm.	Construction sand (ASTM C33) and fine particle size iron filings (0.15-4.75 mm)	Slag sieved to 6.35-11 mm.
	Media composition	Iron rich, AMD sludge	Mix of iron filings and sand; 7-10.7% iron. The later study used 5% iron filings by weight.	Slag is the only media described. Test was on a bed of slag in a constructed sluice.
	Media Drainage & Specification	Not applicable to this study	Designed for system to be aerobic with positive underdrain flow to outlet.	Dye test used to confirm modeled flow and contaminant transport.
	Underdrain	Not applicable to this study	Perforated pipe drain tile in bottom of sand filter	Drain pipe outlet at bottom of solid bottom structure.
Reported Results	Source Material Considerations	This was a wastewater treatment study. Sludge pellets require a pretreatment wash before use.	Studies completed on sand filters with layered iron filings in the beds.	Steel slag came from steel mill waste.
	Results on Targeted Pollutant	96% removal of P from influent over 46 days of continuous operation	Earlier installation retained 71% of phosphate.	Flow through equations overestimated the P removal. The variability likely due to variability in slag properties.
	% Removals	P sorption capacity was about 10,000 mg/kg for 1 mg/l P solution	26% phosphate by mass determined in later study	28% TP; 25% dissolved P
	Other Results / Observations	Smallest particle (0.28-0.9 mm) size gave the most rapid uptake of P and least resistance to mass transfer.	Prolonged inundation where anaerobic conditions could develop and drive the iron to the ferrous state was associated with iron clumping. Clumped iron caused ponding.	P removal improved with smaller particle size fraction. Smaller particle size will affect hydraulic conductivity.
	Recommendations	Intermittent flow enhances P removal.	Visual inspection to note a drop in hydraulic performance. Phosphate removal should be used to schedule maintenance.	75% of all P delivery occurred during six largest rainfall events. Size P removal structures for peak rainfall events.

Conclusions & Recommendations

In order to sustain high levels of runoff and pollutant reduction over the long haul, multiple bioretention functions must be balanced when creating and installing bioretention media mixes. Underlying the concern with nutrients, there can be complications between providing a substrate for healthy plant growth and providing a media that scavenges nutrients from stormwater. Readily available nutrient sequestration components can impact plant growth or create an imbalance of beneficial and harmful soil minerals. Another consideration is that pH of media may change as vegetation decomposes over time, which could trigger the leaching of metals from the soil and amendments if the media is too acidic.

As in good agronomic practice, bioretention systems should rely on soil test recommendations as a guide for initial bioretention mix, rates of application, and the status of soil pH, phosphorus, cation exchange capacity (CEC), and organic matter. Media size attributes are necessary criteria for the proper hydrologic function of bioretention cells. Maintaining sufficient soil pH, phosphorus, and effluent pH are also useful maintenance measures in cases where discharge goes to nutrient-sensitive waters. In states that have experience with agricultural application of water treatment residuals or acid mine waste, guidance for their use may be applicable to bioretention media application. Where nutrient-sensitive receiving waters are involved, a bioretention cell's soil phosphorus should be maintained at a low level; water treatment residuals can assist with that process. Internal water storage, following North Carolina guidance, is especially promising for achieving hard-to-get total nitrogen reductions.

The primary benefit of performance enhancing devices (PEDs) in bioretention cells is their ability to target specific nutrients and pollutants. PEDs provide better pollutant reduction performance over traditional bioretention configurations and media mixes. Each type of PED performs differently and targets different nutrients and pollutants. Therefore, additional considerations need to be made during the design process to ensure that the processes by which the PEDs reduce nutrients are maximized, and to ensure the risk of potential contamination is reduced. The origin of the PED material varies and can significantly impact performance. As an example, AMD sludge material from coal mines are preferred over sludge from metal mines due to concentrations of cadmium, arsenic, copper, and zinc (Sibrell, 2006). In another example of the use of industrial byproducts, bottom ash from a coal-fired power plant provided greater P sorption compared to basic slag; however, it is not recommended due to alkaline pH and dissolution of harmful constituents (McDowell et al., 2007).

Pretreatment

Many PEDs are byproducts of other industries (drinking water treatment residuals, wood products residuals, agricultural residuals, etc.) and show promise for processing stormwater nutrients. Researchers have found that the nutrient and hydrologic benefits of these byproducts can vary widely based on production conditions. Therefore, PEDs need specific treatments to ensure that they function as intended in the bioretention. These production treatments include sieving to achieve a specific particle size distribution, drying, pyrolysis, and neutralization. These treatments impact the ability to mix the material into the soil media, the drainage rate of the soil media, the materials' ability to adsorb or process nutrients, and the resilience of the material to weathering. Failure to pretreat the PED material properly can dramatically impact the performance and lifespan of the PED-amended stormwater facility.

PED Media Composition

Researchers have incorporated PED materials into filter media in a variety of ways and at a variety of rates. A media mix that has too much PED material (iron, aluminum, carbon, etc.) can leach out nutrients or other potential contaminants, and it could clog or produce unacceptable drainage rates. A media mix that has too little PED material will not produce the expected nutrient and pollution reduction results, and it may reduce the effectiveness period of the material. Additionally, how the media and the PED material are installed can impact the performance of the practices; some researchers incorporate the PED material into the top few inches of soil, some incorporate the mix through the media, and others layer the media and the PED material (iron filings).

PED Media Drainage

Incorporating PEDs into filter media can impact the overall drainage rate of the practice, and it can push the media to drain faster or slower than its non-PED-amended counterpart. PED media that drains too quickly will not provide optimal contact time, which is deleterious since the ability of the PED material to reduce nutrients is often tied to contact time. In some instances, dissolved phosphorus removal rates with water treatment residuals were > 60% under low flow conditions and < 25% under high flow conditions (Penn et al., 2012). However, PED media that drains too slowly can increase the number of bypass events, resulting in less overall storm volume treatment. As such, the use of flow splitters could help ensure high treatment rates for the "first flush" of storm events.

PED Selection

As described in Penn et al. (2007), there is a process for evaluating and selecting PED amendments. The first step is determining if the PED material is available, followed by determining the cost of the material and—often more significant—the cost to transport the material to the project location. Subsequently, Penn et al. (2007) recommends evaluating potential contaminants from the specific source of the PED material and evaluating the performance characteristics of the PED. Lastly, the physical properties of the PED material—like particle size, CEC, and hydraulic conductivity—need to be evaluated. This evaluation process will help determine if the use of PED materials is appropriate and cost effective, and whether additional pretreatment actions (drying, sieving, neutralizing, etc.) need to occur to reduce the potential for contamination (pH, soluble metals, etc.), ensuring optimum performance. The selection and use of PED amendments in filter media is, at this stage, a process and not a prescription; however, the information needed to test, treat, and apply these amendments is becoming increasingly available and accessible. As a result, PED amendments are expected to be used more frequently and refined as additional field applications occur and results are made public.

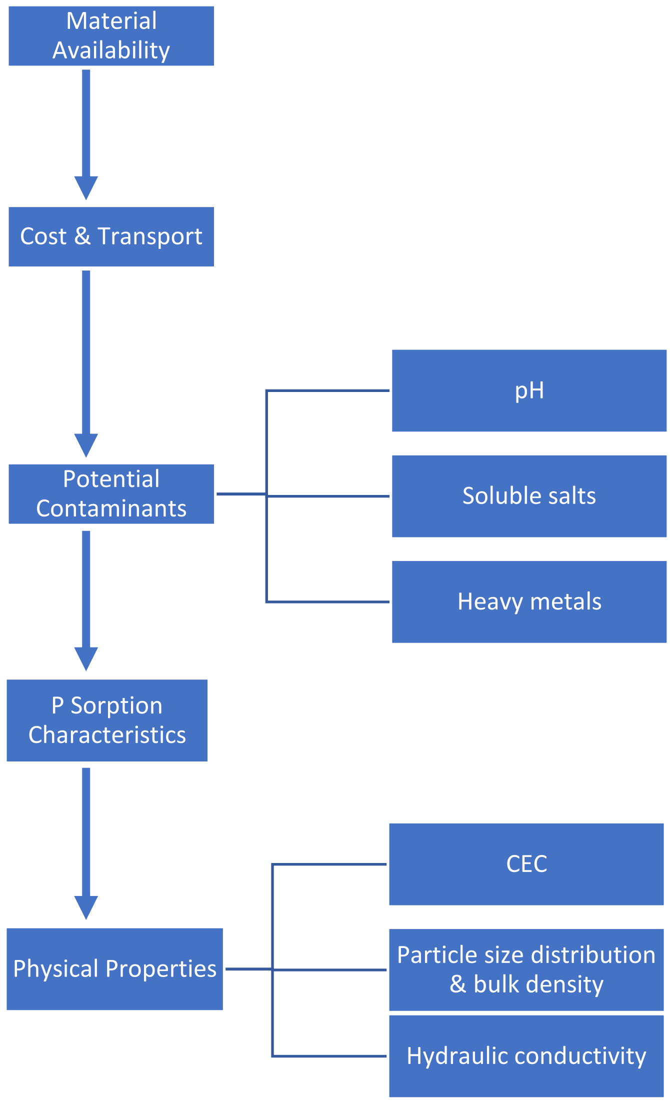

Figure 1. Overall process for screening materials for potential use as a performance enhancing amendment. Adapted from Penn et al. (2007).

Despite being in the 4th era of bioretention design, the number of scientific studies demonstrating enhanced nutrient sequestration in bioretention media are limited and do not cover the full range of geographic and climatic conditions. The development of specifications for BMPs have long recognized this limitation, allowing for expert judgement and operational experience in tailoring the study results to local conditions. This summary intended to capture the state of the science and its applicability in developing state standards for PEDs in bioretention design in a clearly adaptive management process.

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