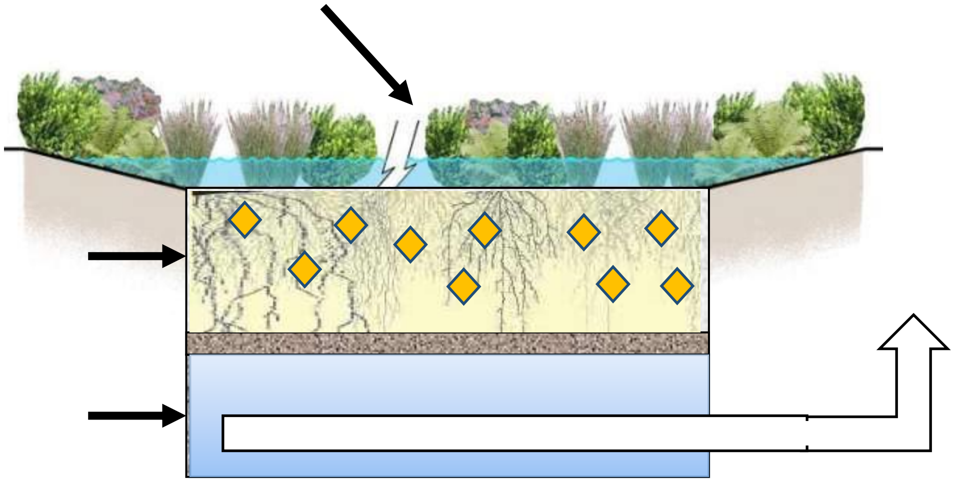
FINAL REPORT

Performance Enhancing Devices for Stormwater Best Management Practices



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Date:

April 24, 2017

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Foreword

This research synthesis was prepared to provide technical support for Bay managers and stormwater professionals to decide whether nutrient removal credits should be offered for bioretention, sand filter and other LID practices that rely on one or more performance enhancing devices or PEDs. The recommendations from this synthesis will be considered by the Urban Stormwater Work Group (USWG) as part of its BMP crediting review process. Since baseline removal rates have already been derived for bioretention, sand filters and other LID practices by a prior expert panel (SSPS EP, 2013), the incremental increase in removal rates associated with PEDs can be credited using the work group's new fast track urban BMP decision process (Schueler, 2016).

Acknowledgments

Support for this report was provided by a National Fish and Wildlife Foundation Innovative Nutrient and Sediment Removal (INSR) Grant (#44992) to the Center for Watershed Protection entitled "Performance Enhancing Devices for Urban BMPs." In addition, the authors gratefully acknowledge the comments and perspectives provided by Drs. Allen Davis (University of Maryland), Neely Law (Center for Watershed Protection) and Ryan Winston (Ohio State University) on earlier versions of this report. Thanks are also extended to David Wood and Cecilia Lane for organizing two Bay-wide webcasts to discuss new PED research and crediting options that were broadcast in late 2016.

Acronym List

AMD	Acid Mine Drainage
BMP	Best Management Practices
CBP	Chesapeake Bay Program
EMC	Event Mean Concentration
IWS	Internal Water Storage
LID	Low Impact Development
MS4	Municipal Separate Storm Sewer System
NO3	Nitrate-Nitrogen
PED	Performance Enhancing Device
RR	Runoff Reduction
ST	Stormwater Treatment
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
USWG	Urban Stormwater Work Group
WTR	Water Treatment Residuals

Section 1. Purpose of Report

This report focuses on the capability of performance enhancing devices (PEDs) to increase nitrogen and phosphorus removal in bioretention, sand filters and other low impact development (LID) practices. Common PED strategies include adding media amendments, incorporating an internal water storage (IWS) zone in the underdrain system and maximizing plant uptake. This report summarizes the findings of an extensive literature review and recommends options for potentially crediting PEDs by adapting existing Chesapeake Bay nutrient reduction protocols.

Section 2. Brief History of Bioretention Design

Stormwater management in the Chesapeake Bay watershed has evolved over the course of several decades as communities have shifted to LID practices and refined their design standards. Communities have also strengthened their plan review, inspection, maintenance and BMP verification processes.

PEDs can only be understood in the context of existing urban BMP designs which continue to evolve. No practice epitomizes this more than bioretention. Over the last three decades, bioretention design criteria have been continually adjusted to specify different soil media, underdrain configurations, plant communities, and sizing and geometry considerations. Table 1 summarizes how bioretention design has evolved through its first three generations, as well as a new fourth generation that uses PEDs.

Table 1. The 4 Bioretention Design Eras

Design Era	Design Characteristics
Era 1 Initial Practice Development (1990's)	• Prince Georges County MD design standards defined the initial practice • Media had high organic matter content (e.g., 20-40%) • Most were freely-drained with underdrain at the bottom of the practice
Era 2 Mainstreaming Bioretention (2000 - ~2007)	• Practice included in most state and local design manuals • Improved design specs to respond to design, installation, and maintenance issues • Shift to media with much higher sand content and less organic matter
Era 3 Design to Increase Runoff Reduction (2007 – Present)	• Bioretention gains popularity and lessons learned with implementation • Runoff reduction recognized as essential part of bioretention [1] • Pollutant removal performance defined by Chesapeake Bay expert panels [2]
Era 4 Design to Enhance Nutrient Removal	• Still in the research and demonstration phase • Enhanced design specs are needed to support a shift to PED • Some PED delivery issues still need to be solved

[1] CWP and CSN (2008) [2] SSPS EP (2013) and SR EP (2013)

Table 2 shows how each design era has influenced the projected nutrient removal rate for bioretention. This report evaluates whether a fourth design generation is warranted to incorporate new PED technology.

Table 2: Nutrient Removal Rates Associated with Each Bioretention Design Era

Design Era	General Nutrient Removal Rates [1]
ERA 1 1990s	• TP: 25% removal, with leaching of dissolved phosphorus • TN: 55% removal, but negligible or negative capture of dissolved nitrogen
ERA 2 2000 -- 2007	• TP: 45-75%, but very high variability, including some negative removal rates [2] • TN: 25-70%, less scatter in the data
ERA 3 2007 – present	• TP: Typically 55-70% for rainfall depths of 0.5 – 1.0", but even higher for practices that achieve high runoff reduction [3] • TN: Typically 45-60% for similar rainfall depths
ERA 4 2017 and beyond	• Possibility of higher or more reliable nutrient removal rates due to PEDs...which is the subject of this technical report

[1] Based on BMP monitoring and engineering models

[2] CWP, 2007

[3] VA DEQ 2011 and SSPS EP, 2013

Total phosphorus and nitrogen removal rates have increased steadily as designers progressed from one bioretention design era to the next (Table 2). Much of the removal has been due to the effective capture of particulate forms of phosphorus and nitrogen. By contrast, removal of dissolved nutrients has not always been very high or reliable. While dissolved nutrients comprise a modest fraction of the total urban nutrient load, they are more bio-available in downstream receiving waters. Researchers have been exploring new techniques to reliably remove both particulate and dissolved nutrients.

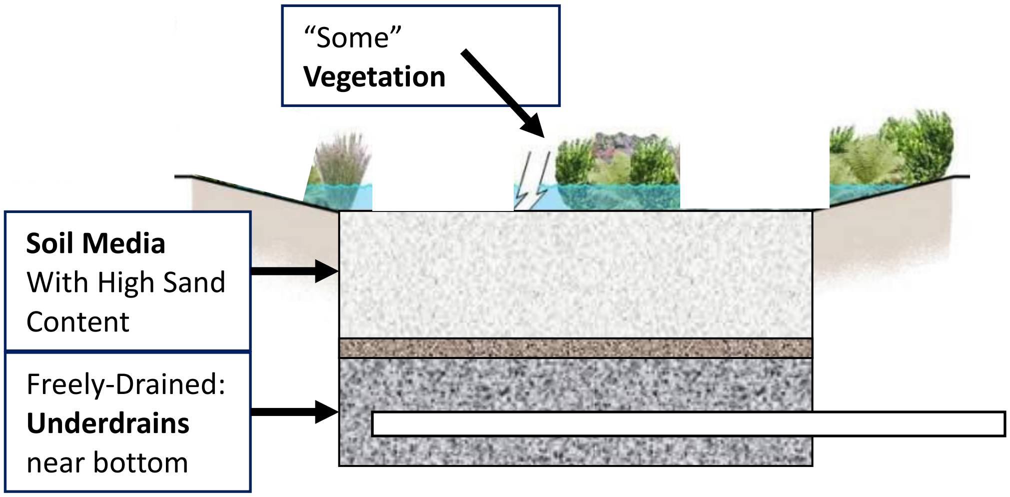


Figure 1: Current Bay Bioretention Design Standard

Section 3. Scope of the Literature Review

The literature review included 138 research papers, journal articles, technical reports, doctoral or masters theses and conference presentations. The following characterizes the scope of the PED research reviewed:

- 77 studies addressed phosphorus or nitrogen removal. Of these, 58 studies focused on urban stormwater or BMPs, while the remainder addressed agricultural drainage ditches, wastewater, or acid mine drainage.

- About half of the nutrient studies were conducted in the laboratory using batch, test column, or mesocosm experiments. About a third of the research studies relied on field monitoring techniques.

- The major focus of the stormwater studies was bioretention (37 studies), with a handful of studies on sand filters, agricultural ditch filters, grass swales, green roofs, or other LID practices.

- PED research has proliferated in recent years with more than 75% of all studies published since 2010. The research has been conducted in a wide variety of geographic locations both in the U.S. and across the world.

Table 3 analyzes the number of stormwater research studies for the various PED categories. In general, there were a moderate to high number of research studies in most PED categories, although there were fewer field studies than lab studies.

Field monitoring data is often preferred since it is more representative of real world conditions that help define the expected performance of PED applications across the Bay watershed. In particular, field studies often provide insights about mass load reductions as well as changes in the event mean concentration (EMC). Mass load and runoff reduction metrics tend to very important in defining overall pollutant removal performance.

Table 3. Qualitative Assessment of PED Stormwater Research Studies

PED Category	Total Studies	Field Studies	Lab Studies
Water Treatment Residuals (WTR)	H	L	M
Iron/Steel Wool	H	L	M
Biochar/Activated Carbon	M	L	H
Internal Water Storage (IWS)	H	M	M
Vegetation	M	L	M

H = High = 10 studies or more
M = Medium = 5 to 9 studies
L = Low = Less than 5 studies

Section 4. Understanding Pollutant Removal Dynamics

Several researchers have explored unit processes that enhance pollutant removal in stormwater BMPs. Designers and installers that optimize these unit processes should be able to improve overall pollutant removal performance. Some of the key literature reviews on unit processes include Davis et al (2010), Liu and Davis (2014), Clark and Pitt (2012), Grebel et al (2013) and Collins et al (2010).

The following section provides some context on important unit processes involved in pollutant removal within LID practices (loosely based on Davis et al 2010):

- *Sedimentation and Filtration for Particulate Matter:* The capture of sediment and attached pollutants through settling or physical filtering through media.

- *Adsorption: This process allows certain molecules t*o bond to the surface area of a material or mineral. Much research has explored the sorption capacity of various minerals to adsorb dissolved phosphorus.

- *Microbial Activity:* The metabolic processes of certain microbes transform or biodegrade pollutants from one phase to another. For example, microbes can transform nitrate into nitrogen gas through denitrification, given a suitable carbon source and the presence of hypoxic or anoxic conditions.

- *Phytobiology:* Plants can play several functions in pollutant removal – physically slowing and filtering incoming flows, reducing runoff volumes through transpiration, and taking up nutrients and incorporating them into above-ground or below-ground biomass.

Section 5. Current Assessment of PEDs for LID Practices

Current bioretention designs in the Bay watershed rely on a media with a very high sand content (up to 85% in some cases). Many designs are “freely-drained” systems with an underdrain near the bottom of a gravel layer (Figure 1). Bioretention field research suggest that these current designs are effective in removing sediments, metals, and particulate nutrients, but can leach dissolved nutrients under typical conditions.

Export of dissolved nutrients can occur when the media has too much organic content, influent stormwater concentrations are low, or short residence times prevent uptake of dissolved nutrients (Winston et al 2015; Roseen and Stone 2013; Liu and Davis, 2014; Culver 2015; Line and Hunt 2009, 2012; Hunt et al 2012; Collins et al 2010). The findings from field research are also corroborated by test column and mesocosm experiments that show the potential for nutrient leaching under certain conditions (Morgan 2011, Glaister et al 2012, Read et al 2008).

PEDs fall into three basic categories, as described below and shown in Figure 2:

1. Media Amendments: Various media amendments have been proposed to improve the adsorption capacity for dissolved phosphorus, as well as metals, hydrocarbons and other pollutants. Common media amendments include residuals with high aluminum or iron content and biochar or activated carbon. Factors thought to influence adsorption capacity include the incoming nutrient concentration, contact time, the weight, volume or pH of the amendment, the surface area of reactive particles and the ability of the amendment to maintain its adsorptive capacity over time.

2. Internal Water Storage: Most current bioretention designs create an aerobic environment for chemical and microbial reactions. Some of these reactions can produce dissolved oxidized forms such as nitrate that are susceptible to leaching. Several studies have investigated whether an intentional low-oxygen water layer within LID practices could create anaerobic conditions. The most common underdrain configuration creates an internal water storage or IWS zone. This low-oxygen zone can increase annual runoff reduction rates, promote denitrification and immobilize other pollutants.

3. Vegetation: Plants can act as a sink for both P and N. Several studies have investigated the role of plants in removing nutrients, including which species and landscape features optimize plant uptake, reduce runoff volumes and maintain media permeability. Other studies have looked at whether periodic harvesting is needed to remove sequestered nutrients or maintain practice performance.

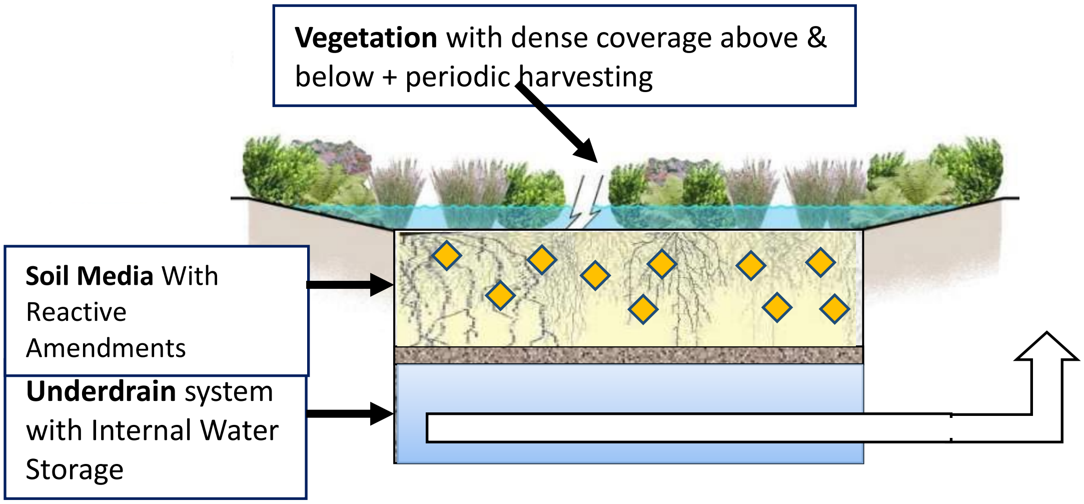


Figure 2: Three Categories of PED in a LID Practice

The next three sections explore each of these PED categories in more detail emphasizing the most recent research findings.

Section 6. Filter Media Amendments

A long list of media amendments have been proposed to boost pollutant removal in LID practices -- including many natural materials and industrial byproducts. Researchers have tested these amendments to determine their sorption capacity, longevity, commercial availability and ease of incorporation into the media. Most of the research has focused on media amendments that maximize sorption of dissolved phosphorus.

Law et al (2014) presents an overview of the two broad categories of media amendments that can boost dissolved phosphorus removal, as follows:

- *Metal Cations:* The most common amendments include calcium and magnesium (Ca/Mg) and aluminum and iron (Al/Fe). The first group removes phosphorus via precipitation while the second group relies on phosphorus adsorption (which is generally a much faster reaction). The amendments may be naturally-occurring (e.g., limestone, gypsum) or be derived from industrial and process waste materials (such as water treatment residuals, fly ash, steel slag, acid mine drainage residuals and zeolite).

- *Carbon sources*: These amendments contain carbon and have a high surface area for chemical reactions. The two main carbon sources are biochar and activated carbon.

Several papers reviewed other amendments that potentially could increase nutrient removal in urban, agricultural or roadside ditch settings (Prabhukumar 2013, Ballantine and Tanner 2010). Some of the amendments investigated include compost, sand, metal-coated sand, calcareous sand, limestone, peat, mulch, sawdust, tire chips, soybean hulls, crab shells, shell sand, pumice soil, tephra and mushroom mycelium. In most cases, however, there was insufficient monitoring data to adequately evaluate these proposed media amendments.

Key Factors to Consider When Choosing Media Amendments

Four key factors should be kept in mind when choosing media amendments to retrofit existing LID practices. A good amendment should be:

1. Readily-obtainable within the Chesapeake Bay watershed, especially amendments that convert an existing waste product into a new beneficial use (and poses little or no risk that any pollutants will leach and harm downstream aquatic life).

2. Easily adapted for existing bioretention construction techniques, especially when it comes to how the amendment will be mixed or incorporated into the standard bioretention media recipe.

3. Long-lasting so that the amendment does not need to be frequently replaced or recharged to maintain its water quality function (i.e., the media will last for at least 5 years or longer).

4. Capable of providing a measurable boost in nutrient removal that is supported by stormwater research conducted in both the field and lab.

Based on these factors, several media amendments appear to be good candidates to enhance the performance of existing bioretention areas, sand filters and other LID practices in the Chesapeake Bay watershed (see Tables 4 and 5). Several researchers are also exploring whether these amendments can be combined to optimize nutrient removal (Chiu et al 2015, Prabhukumar 2013 and Liu and Sample 2014).

Table 4. Summary of Most Feasible Media Amendments

Iron or Aluminum Amendments (Fe/Al)	Iron (filings), steel wool, slag, water treatment residuals (WTRs), acid mine drainage (AMD) residuals, fly ash Target pollutant: Dissolved P
Carbon [1]	Biochar, wood chips and activated carbon [1] Need to carefully choose very refractory carbon sources to prevent nutrient leaching [2] Target pollutants: • Total P • Some potential for N reduction, as the carbon and anaerobic conditions can promote denitrification at the bottom of the practice or within the IWS zones.

[1] The use of compost and other labile forms of organic matter in bioretention media has been conclusively linked to nutrient leaching and should be expressly avoided in higher concentrations within the media (see Morgan 2011, Winston et al 2015 and Culver 2015)

[2] Even more refractory carbon sources are very dependent on their carbon feedstock to ensure performance

Iron/Aluminum Amendments

Water Treatment Residuals

Liu and Davis (2013) installed a retrofit at an existing bioretention area on the University of Maryland campus with water treatment residuals (WTR) that contained both Al and Fe, and compared removal rates before and after the retrofit. The retrofit was simple -- a WTR amendment was incorporated into the top media layer at 5% of the media mass. Monitoring indicated that TP removal increased from 55% to 84% after the WTR retrofit. More importantly, the WTR retrofit achieved 60% dissolved phosphorus removal without compromising the filtration properties of the bioretention media.

Roseen and Stone (2013) compared a standard bioretention area with a bioretention retrofit that incorporated 10% WTR (by volume) into the media at the University of New Hampshire. Monitoring showed that the standard bioretention area leached phosphorus to some degree, whereas the WTR retrofit reduced the TP and DP concentrations by 55% and 20%, respectively. The authors contended that the WTR retrofit could have been even more effective if the WTR was mixed more evenly into the media and BMP short-circuiting problems were corrected.

Several test-column and mesocosm experiments confirm that WTR media amendments can enhance both total and dissolved phosphorus removal. For instance, Liu et al (2014) reported on mesocosm experiments that showed a WTR media mix out-performed other types of media amendments, removing as much as 95% of TP in stormwater influent. These mesocosms were tested at Virginia Tech's research facility in Virginia Beach.

Lucas and Greenway (2011a) also conducted bioretention mesocosm experiments and reported 99% dissolved P removal at the highest levels of WTR incorporation, and projected that the sorption capacity of WTR amendments should last as long as the bioretention practice itself. Other test column experiments also confirm this trend with reported phosphorus mass removals of 89% (O'Neill and Davis 2012) and EMC reductions of 84% (Novak 2013).

Iron Filings and Steel Wool

The University of Minnesota tested whether iron filings or steel wool could be an effective amendment for sand filters for treating soluble nutrients. The retrofit, known as a Minnesota sand filter, relied on iron media amendments around the perimeter of a wet detention pond. The retrofit improved dissolved P removal, which ranged from 29 to 91%, with the lower removal rates associated with very low dissolved P inflow concentrations (Erickson et al 2012). Erickson and his colleagues recommend a media amendment containing 5% iron by weight.

Similar dissolved P removal rates were reported for other Minnesota field studies, including a permeable weir wall in a wet pond and a Minnesota Sand Filter (Erickson et al 2011, Erickson and Gulliver 2010). Erickson also concluded that iron amendments may need to be replaced more frequently when hydraulic loading rates are high (e.g., when the surface area of the practice is small in relation to the size of the drainage area).

Penn et al (2012) reported that their iron media amendment formulation had a relatively short sorption capacity (about 17 months) and was better at removing phosphorus when retention times were longer. Drizo et al (2002) reported that the P adsorption capacity of steel slag was rejuvenated when allowed to "rest" between storm events which increased the effective lifespan of the slag. Obviously, extending the effective lifespan of media amendments is critical when it comes to operating PED retrofits since it is not practical to frequently replace them.

Laboratory tests generally confirm the field results, with relatively high removal of dissolved P when iron amendments were added compared to very low removal for test columns composed of 100% sand (Erickson et al 2012). The same researchers looked at the performance of limestone and calcareous sand amendments and found they were prone to clogging (in contrast to iron amendments, which did not experience clogging --

Erickson et al 2007). Other researchers have also concluded that iron-based amendments are superior to calcium amendment when it comes to P adsorption (Lyngsie et al 2013, Bryant et al 2012).

Acid Mine Drainage (AMD) Residuals

Much of the research on AMD residuals has focused on non-stormwater applications, such as treating agriculture runoff and wastewater discharges. AMD residuals contain iron and aluminum oxides, and are generally considered a waste product in coal-producing areas of the Appalachians. Sibrell and colleagues report dissolved P removals that ranged from 50 to 96% in various BMPs that used AMD residual amendments (Sibrell and Tucker 2012, Sibrell et al 2009, Sibrell et al 2006). The authors also contend that the use of AMD residuals does not pose a risk for leaching aluminum or other trace metals to downstream waters.

Table 5. Summary of Media Amendment Field Research

Bioretention and Stormwater Filters		
Source	Material	P Removal
Roseen & Stone 2013	WTR [1]	20 – 55% [2]
Liu and Davis, 2013	WTR	60 – 84% [2]
Ahmed *et al*. 2014	Iron filings	65%
Erickson *et al*.2012	Iron filings	29-91% [3]
Erickson and Gulliver 2010	Iron filings	72-90% [3]
Erickson *et al*. 2011	Steel wool	80-90% [3]
Penn *et al*. 2012	Steel slag	25%
Agricultural Applications		
McDowell *et al*.2008	Steel slag, fly ash	56-73% [4]
McDowell and Nash 2012	Fly ash & slag	50%
Shilton *et al*.2005	Steel slag	77%
Bird 2009	Steel slag	79%

[1] WTR = water treatment residuals

[2] Ranges of values indicate removal rates for Total P (upper end of range) and Dissolved P (lower end of range).

[3] Removal rates for Dissolved P (concentration reductions).

[4] Ranges of values indicate concentration removal rates (upper end of range) and mass load removal rates (lower end of range)

For lab research results, see Appendix A.

Carbon-Based Amendments

Biochar

Biochar is produced by the pyrolysis of biomass (i.e., combustion at extreme heat with no oxygen) such as wood chips, poultry litter, switchgrass, and waste wood products (Law 2014). In most applications, biochar is used as a soil amendment to boost soil water and nutrient retention (Reddy et al 2014). Other researchers have investigated whether biochar can sequester nutrients and metals since it produces a large porous surface area for pollutant adsorption and microbial processing. Depending on its parent feedstock, biochar is not expected to have the same nutrient leaching potential as other, more raw forms of carbon, such as peat or compost.

For now, most of our understanding about biochar amendments is based on lab studies. For example, Reddy et al (2014) conducted column studies using biochar derived from waste wood pellets that showed 47% removal of dissolved P and 86% of dissolved N. Beneski (2013) also operated test columns and found that wood-derived biochar with smaller particle sizes out-performed biochar derived from poultry litter. Overall, Beneski found that biochar removed ammonia (but not nitrate) and altered the pH of the water in the test column. Biochar also increased media water retention capability compared to a uniform sand, giving more water contact time for pollutant removal processes (Tian et al 2014).

Until recently, there has been little or no field monitoring data to evaluate the potential impact of biochar retrofits in existing stormwater practices, such as bioretention. Three research projects are now underway to test biochar retrofits in Virginia (Chiu et al 2015) Delaware (Imhoff, in press) and Maryland (Seipp, in press).

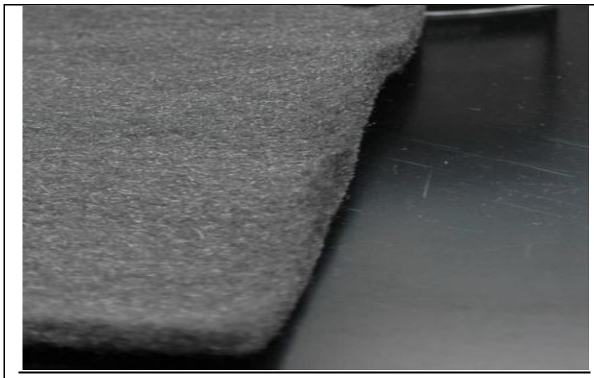
Activated Carbon and Other Carbon Sources

Lab studies have also investigated the capability of other sources of carbon to treat stormwater runoff and agricultural ditch water. Schang et al (2011) investigated the use of zinc-coated granular activated carbon amendments for pre-treatment at a rainwater harvesting system, and reported that the activated carbon amendment enhanced TP removal by 25% but also leached zinc in the filter outflow. Another study reported that an amendment consisting of granular activated carbon and zeolite could remove about 60% of total nitrogen in a permeable pavement system (Al-Anbari 2008).

Clark and Pitt (2012) caution that media amendments containing compost or peat should be situated in an aerobic environment so they do not become saturated between storm events.

Calcium-Based Amendments

Not much stormwater research has focused on calcium-based media amendments. The chief concern is that calcium amendments may lead to clogging and lower retention times. This problem has been observed on agricultural filters that used gypsum or limestone amendments (Bryant et al 2012). Some agriculture research indicates that calcium amendments could help precipitate phosphorus (especially at lower pH levels); others concluded that iron-based amendments were superior when it comes to phosphorus adsorption (Penn et al 2011; Lyngsie et al 2013). Given the concerns about clogging and the limited urban data on phosphorus removal, calcium-based amendments are not likely to be a useful PED retrofit.



(a) Steel Wool

(b) Iron Filings and Concrete Sand

(c)Water Treatment Residuals

(d) Biochar

Figure 3: Some Promising Media Filter Amendments

Potential Risks Associated With Media Amendments

Effect on Flow Rate Through the Practice

There is a dynamic balance between having adequate retention time within the media (so that pollutant removal processes can be effective) and not clogging the media or slowing flow rates so that stormwater bypasses the practice with little treatment. As noted in the preceding section, calcium amendments appear to pose a strong risk for clogging or reduced hydraulic conductivity through the filter media. Other materials show more promise. For example, Erickson et al (2012) reported that an iron-based media amendment did not affect hydraulic conductivity. Liu and Davis (2013) found similar results for WTR media amendments. Roseen and Stone (2013) did report some problems with WTR amendments that were initially too wet and caused clumping within the filter media.

More testing is needed to see how the hydraulic conductivity of media amendments hold up over time under real world conditions. Field research should also focus on the best ways to install and maintain media amendments at both new stormwater practices and retrofits.

Potential Media Leaching Risk for Metals or Nutrients

Some researcher are concerned that aluminum oxides found in WTR amendments could potentially dissolve and release Al into the environment (Buda et al 2012 and Penn et al 2011). However, the risk is probably quite small since leaching only occurs in a low pH environment (< 5) -- and both stormwater runoff and WTR amendments tend to be only slightly acidic (Roseen and Stone 2013).

While the risk of metal leaching appears to be low, more definitive testing should be undertaken for any media amendments that are ultimately recommended for PED credits. Test column data may also be needed to craft better material specifications for stormwater BMP and retrofit applications.

The risk of nutrient leaching appears to much higher in communities that still specify organic-rich media recipes for their bioretention areas and filters. Numerous field and lab studies have documented the risk of N and P leaching from filter media with a high organic content, especially peat and compost (Morgan 2011, Winston et al 2015, Culver 2015). Fortunately, most of the Bay states have adopted media specifications that limit the organic or compost content to no more than 3 to 5% of the media (by volume). Other parts of the country still specify a compost content as high as 30% (Morgan 2011).

Effect of Media Amendments on BMP Construction Costs

At this point, it is not known precisely how much it costs to find, transport, mix and install media amendments, compared to standard LID construction costs. Erickson et al (2007) suggests that iron media amendments might increase material costs by 3 to 5% and also marginally increase total construction costs. Some amendments may be more costly to procure, while other amendments might be cheaper if they are considered a waste product that would otherwise need to be disposed by a more costly method.

The initial cost to shift to PED media amendments could be high until the private or public sector establishes standard procedures on how to procure, mix and install them. In general, construction costs tend to increase when BMP design and maintenance criteria become more complex and prescriptive.

Section 7. Internal Water Storage and Enhanced Runoff Reduction

Many researchers have investigated how BMP underdrains can be reconfigured to enhance runoff reduction and nutrient removal. Most have focused on internal water storage (IWS) zones, which refers to the creation of a very slow-draining or saturated zone within the underdrains of bioretention areas, dry swales, permeable pavement or similar practices. The saturated IWS zone becomes a low-oxygen environment near the bottom of the practice and is typically formed by an “upturned elbow” or weir wall in the manhole structure that discharges underdrain flow (see Figure 4)

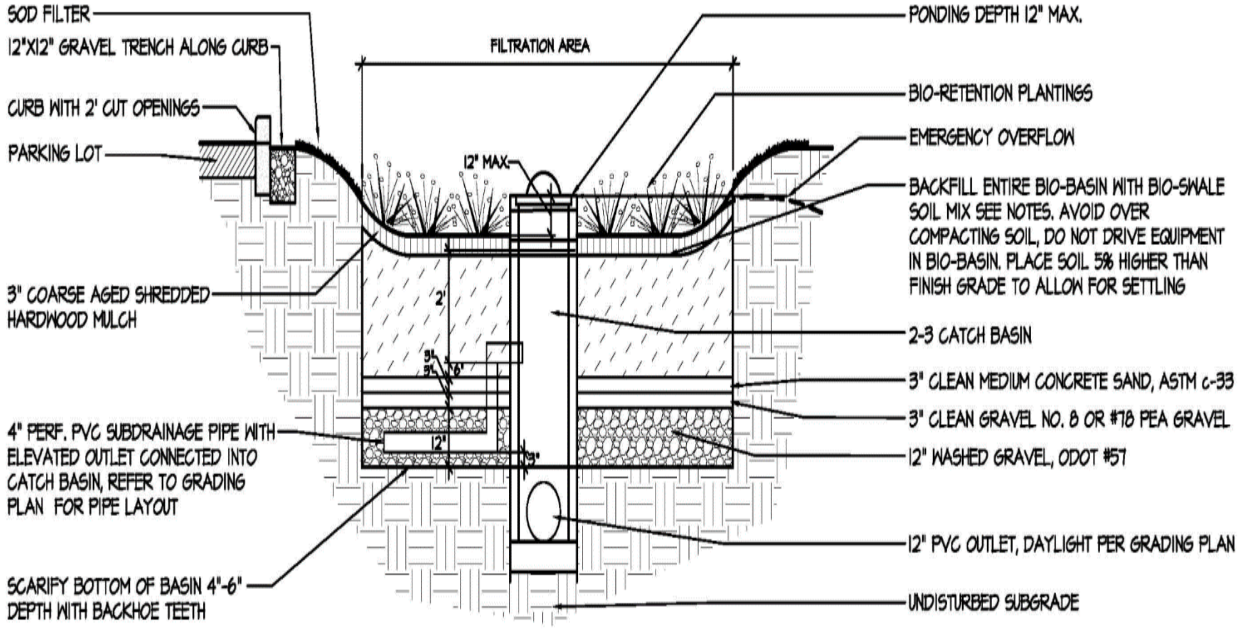


Figure 4: Internal Water Storage Created by an Upturned Elbow on Underdrain Pipe
Courtesy Ryan Winston, Ohio State

The value of IWS is reinforced by several bioretention monitoring studies (Table 6). For example, Gilchrest et al (2013) reported that un-vegetated rain gardens with IWS achieved a 75% mass reduction of dissolved N compared to just 7% for rain gardens that did not have IWS. Roseen and Stone (2013) monitored bioretention practices with and without IWS at the University of New Hampshire. Bioretention areas without IWS actually released higher concentrations, compared to inflow, of dissolved and total N. By contrast, bioretention areas with IWS reduced dissolved N concentrations by more than 60%.

Brown and Hunt (2011) also reported very high levels of runoff reduction associated with bioretention areas equipped with IWS in North Carolina. Bioretention areas with IWS reduced annual runoff volume by 75 to 87%, chiefly as a result of additional exfiltration and transpiration that occurred during their longer hydraulic retention times (up to 7 days). The finding was reinforced by Winston et al (2015) who sampled bioretention areas with IWS zones installed in Ohio -- and found that IWS did not produce any measurable outflow in 40 out of 50 storm events sampled.

The longer retention time achieved by IWS enables other runoff and pollutant reduction mechanisms to operate over a longer time frame. Several test column and mesocosm experiments have demonstrated the value of IWS in improving N removal (Table B.2 in Appendix B). Most these experiments tested different combinations of IWS, media amendments, carbon sources and plant density.

For example, Zinger et al (2012) conducted a mesocosm study where a simulated bioretention area was retrofit with an IWS. While the IWS mesocosm retrofit produced high dissolved N removal, total phosphorus removal declined from about 75-90% to around 50-60% at the end of the experiment. Glaister et al (2012) also reported declining TP removal in test columns that simulated IWS zones. They attributed the decline to washout or leaching of organic matter from the IWS layer. By contrast, Zhang et al (2011) found that IWS improved phosphorus removal by increasing the amount plant uptake over the growing season.

Table 6. Summary of Internal Water Storage Field Research

Source	P Removal	N Removal
Roseen & Stone 2013; Stone 2006	20-55% [1]	36-60% [1]
DeBusk & Wynn 2011	99% [2]	99% [2]
Brown & Hunt 2011	--	>50%
Gilchrist *et al.* 2013	--	75% [2]
Passeport *et al.* 2009	58-78% [1]	47-88% [2]
Winston *et al.* 2015	Negative removals due to organic content in media	

[1] Range of values show removals for Total P or N and Dissolved P or N.

[2] Mass load reduction with a majority of reduction attributable to runoff reduction processes

For lab research results, see Appendix B

More research is needed to determine the potential nutrient leaching risk when an IWS intersects with a filter media layer. The key design question is whether the IWS should be confined just to the underdrain layer or can extend upward into the media layer. More testing is needed, but it may be wise to consider some IWS depth restrictions. Davis et al (2009) provide some strategies to customize IWS to optimize phosphorus and nitrogen removal based on the depth of the IWS zone.

Several researchers also contend that the IWS zone may not always produce truly anaerobic conditions across the range of wet and dry cycles in an LID practice. The high dissolved N removal associated with IWS zones may have less to do with denitrification than processes such as runoff reduction and microbial activity (Winston et al 2015, Glaister et al 2012, Caruso 2014).

Virginia was the first Bay state to adopt the runoff reduction method (CWP and CSN, 2008) to document compliance with their new stormwater performance standards. Most Bay states have since adopted some form of the runoff reduction method into their new BMP standards. More recently, the Chesapeake Bay Program recognized the importance of runoff reduction by adopting specific performance curves to define the pollutant removal achieved by individual retrofits and new stormwater practices. The curves indicate higher sediment and nutrient removal for runoff reduction practices compared to traditional stormwater treatment practices, based on the consensus achieved by two different CBP expert panels (SSPS EP 2013,SR EP, 2013).

Recent bioretention research has reinforced the importance of runoff reduction in determining the overall nutrient removal provided by an LID practice. For instance, DeBusk (2011) reported that almost all of the high nutrient reductions observed in her study could be attributed to runoff reduction. Winston et al (2015) and Culver (2015) also concluded that runoff reduction was responsible for the bulk of the pollutant removal measured in the bioretention areas they monitored in the field.

Brown et al (2011) also measured a 69% reduction in annual runoff volume for a bioretention area located in a relatively poor setting for infiltration in the North Carolina coastal plain. Other researchers have concluded that infiltration and transpiration were important runoff reduction mechanisms that improved the performance of grass swales (Stagge et al 2012, Ahmed et al 2014) and green roofs (Lang 2010).

Section 8. Managing Plants to Optimize Nutrient Removal

One of the more intriguing research findings is the critical role that plants play in improving runoff reduction, pollutant removal and practice longevity. While stormwater engineers generally understand the importance of vegetation in LID performance, researchers have isolated several vegetative processes and landscaping strategies that might potentially improve performance. Most of the plant research so far has relied on experimental mesocosms and test columns. Table 7 summarizes some of the key findings on the role of that vegetation plays in pollutant removal.

Table 7. Lab Research on Vegetation for Bioretention

Source	Vegetation	P Removal	N Removal
Henderson 2008	Various species	85-94% (31-90% for non-vegetated)	63-77% (negative to 25% for non-vegetated)
Caruso 2014	Big bluestem, switchgrass and other native grasses	86-92%	72-85%
Zhang *et al.*2011	Plants native to Australia	28-71%	59-83%
Lucas and Greenway 2008	Plants native to Australia	67-92% (39-56% for non-vegetated)	51-76% (max 18% for non-vegetated
Lucas and Greenway 2011b	Native grasses and shrubs from Australia, w/IWS	N/A	53-94% (negative to 50% with no IWS)
Barrett *et al.*2013	Buffalograss, Big Muhly (native to TX)	77-94%	59-79% (negative for non-vegetated)
Bratieres *et al.*2008	*Carex appressa* and *Melaleuca ericfolia*	85%	up to 70%

Much of the bioretention plant research has been conducted in Australia (Lucas and Greenway 2011a, 2011b, 2008). Lucas and Greenway (2008) compared nutrient uptake in vegetated and barren bioretention mesocosms. The vegetated mesocosms consistently retained more nutrients than the barren mesocosms -- 92% compared to 56% for TP and 76% compared to 18% for TN. Other researchers have observed that vegetated mesocosms perform better than barren mesocosms when it comes to runoff and pollutant reduction (Henderson 2008 and Barrett et al 2012). Zhang (2011) found that plant uptake in a bioretention area accounted for 59-83% of N input and 28-71% of P input over a 20 month period.

The presence of plants enhances other nutrient removal mechanisms in LID practices. The below ground microbial community associated with plant roots plays a key role in immobilizing dissolved nutrients during the wet and dry cycles encountered in stormwater practices (Lucas and Greenway 2011a, Glaister et al 2012,Hunt et al 2012, Davis et al 2010, Clark and Pitt 2012, and Collins et al 2010). As plants mature, their root systems maintain or even increase the hydraulic conductivity of the media and the practice as a whole.

The type of vegetation planted appears to very important in performance, and some plant species appear to perform better than others (Bratieres et al 2008, Read et al 2008). Caruso (2014) suggests that plants with a deep, thick, and dense root system enhance dissolved nutrient removal. Deep-rooted prairie plant species such as big bluestem, Joe Pye weed and switchgrass performed very well in recent experiments (Caruso,2014 and Davis, 2014).

The other key question that researchers are exploring is whether bioretention vegetation should be harvested periodically either to remove sequestered nutrients or to refresh plant uptake. Lucas and Greenway (2011b) observed marked seasonal differences in nutrient uptake, with much more nitrogen retained during the growing season. Clark and Pitt (2012) caution that harvesting plant biomass during the growing season could reduce plant uptake. Harvesting during the non-growing season could remove excess nutrients from bioretention areas and keep the plant community in a vigorous growth mode.

Most BMP specifications in the Bay watershed require that some kind of vegetative cover be established. However, our ability to establish and maintain the desired BMP plant community is uneven (Hirschman et al 2009, CWP 2014). More prescriptive landscaping targets may be needed to define the minimum required cover of annual and perennial species to create dense below and above ground biomass (in combination with more widely-spaced tree species, where needed). This planting approach may conflict with the traditional tree-shrub-perennial planting template for bioretention that requires extensive (and expensive) mulching.

10. Recommended Options for PED Crediting Protocols

Key Findings from the Review

Based on the PED research review, five key conclusions can be drawn on how to improve the performance of LID practices:

- **Runoff Reduction** is the most important function influencing the hydrologic and water quality performance of LID practices. Any design feature that improves runoff reduction should be considered, including internal water storage layers and increased runoff storage in the bowl.

- **Media Amendments** can boost nutrient removal rates, especially for dissolved phosphorus. Current research suggests that iron, aluminum or carbon-based media amendments are the best candidates for LID retrofits. More detailed Bay-wide retrofit guidance is needed on mixture rates (e.g., 5-10% by weight), depth of incorporation into the media and other installation issues.

- **Internal Water Storage (IWS)** is an effective strategy to increase runoff reduction rates and lengthen hydraulic retention time in LID practices. IWS may also be an effective strategy to remove dissolved N and, to a lesser degree, dissolved P. The removal mechanisms involved are still being explored, but appear to be microbial activity and denitrification.

- **Plant selection** and management plays an important role in the function of bioretention and other LID practices, although the science has yet to precisely quantify the impact of plants and their root networks on overall performance. More specific landscaping guidance is needed to maximize the benefit of plants in bioretention. A shift may be warranted to a landscaping template that utilizes a meadow cover consisting of deep-rooted annual and perennial plant species that can be periodically harvested and removed from the system.
- **Good installation and maintenance** continue to be critical factors governing LID performance in the real world. Any system developed to credit PEDs should also include reduction "discounts" that reflect the loss of water quality function due to poor construction, inconsistent blending of amendments, or lack of maintenance.

Context for Crediting Nutrient Reductions for PEDs

The science clearly supports the notion that all three categories of PEDs can improve nutrient and runoff reduction within LID practices, although we do not have enough monitoring data or engineering models to precisely isolate how much each category contributes to total removal. Therefore, it makes sense to combine all three PED categories into an integrated design that receives a single nutrient reduction credit. Most of the PED research has been undertaken on bioretention areas and sand filters, but the credit should apply to any LID practice that has filtering media and an underdrain configuration. Thus, the PED crediting approach should also apply to dry swales and some permeable pavement applications (but not green roofs).

Initially, the PED credit would apply only to retrofits of existing stormwater practices in the Bay watershed. More detailed guidance on PED retrofits will need to be crafted by a team of stormwater designers, regulators and plan reviewers before the credit can be implemented.

Eventually the PED credit could be extended to new LID practices installed on new or redevelopment projects, but this would require the state stormwater agencies to approve detailed PED specifications to supplement their existing stormwater design manuals. Appendix C contains a compilation of recommendations to improve LID design criteria and media recipes.

It is recommended that the PED credit be based on the existing CBP framework for crediting urban pollutant removal, using the performance adjustor curves for TP, TN, and TSS developed by prior expert panels (SSPS EP 2013 SR EP, 2013). The curves are used to estimate pollutant removal for individual BMPs based on the amount of runoff captured and the treatment method used. The BMP treatment methods can involve either stormwater treatment or runoff reduction.

- Stormwater Treatment (ST) practices treat runoff as it passes through the BMP using filtering, settling and other removal mechanisms, but do not reduce the total volume of stormwater runoff.

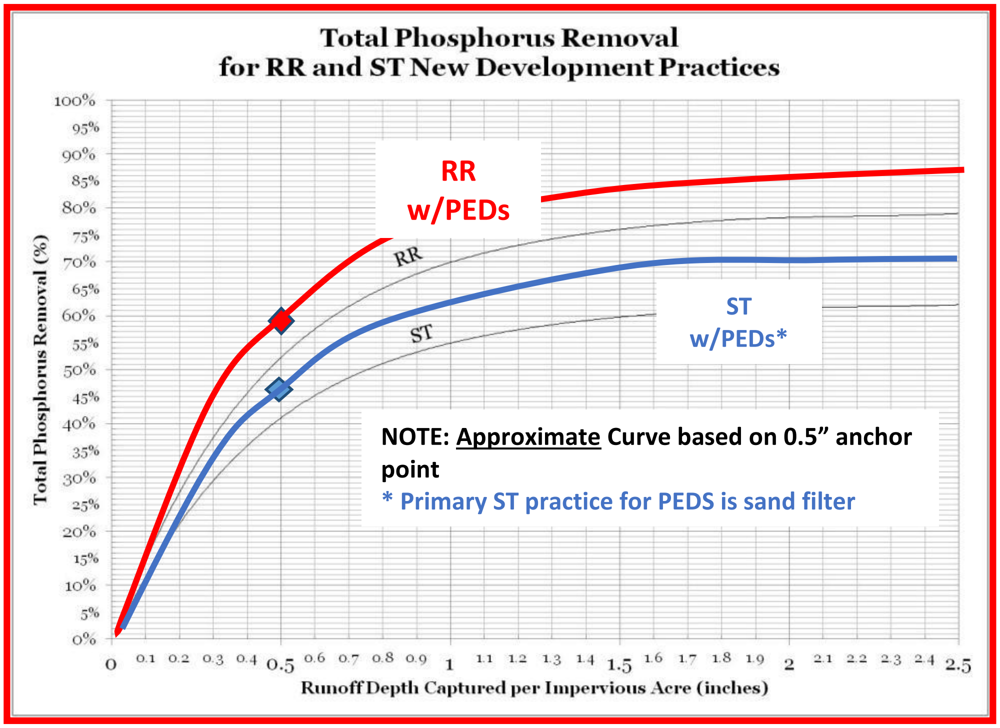
- Runoff Reduction (RR) practices not only treat runoff but actually reduce the volume of stormwater runoff leaving the practice through mechanisms such as infiltration, evapo-transpiration, extended filtration, canopy interception and rainfall harvesting. As a result, RR practices achieve a higher pollutant removal rate than ST practices.

Recommended PED Crediting Protocols

The recommended approach is to:

- Add PED enhancement to the existing adjustor curves for phosphorus removal for ST and RR practices, as shown in Figure 5. The PED curve is roughly 10% higher than the standard curve, which is a conservative estimate based on the research available.

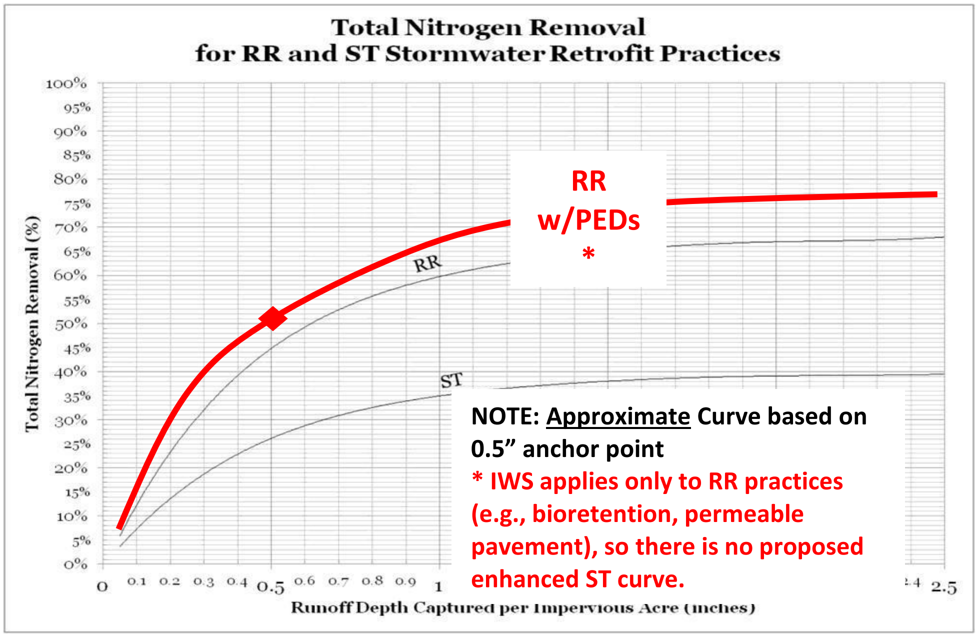
- Add PED enhancement to the existing adjustor curve for nitrogen removal for RR practices, as shown in Figure 6. The new curve is also 10% higher than the standard curve, which is consistent with the research available.



NOTE: <u>Approximate</u> Curve based on 0.5” anchor point

* Primary ST practice for PEDS is sand filter

Figure 5: Proposed Enhanced PED Adjustor Curves for Phosphorus



NOTE: <u>Approximate</u> Curve based on 0.5” anchor point

* IWS applies only to RR practices (e.g., bioretention, permeable pavement), so there is no proposed enhanced ST curve.

Figure 6 Proposed Adjustor Curve for Nitrogen

Implementing the PED Credit

Additional work needs to get done over the next year to develop the detailed PED retrofit design guidance needed to actually implement the proposed credit. It is recommended that the USWG form a small technical team composed of researchers, practitioners and regulators to craft the design guidance. CSN staff can facilitate the team and help it work through key implementation issues. In addition, the Center for Watershed Protection and other researchers expect to release more research findings and design guidance in the next several months.

The USWG is encouraged to scope out the charge for the effort which could include some of the following implementation issues.

- PED media testing procedures
- Certification of PED media sources and consistency
- Standard PED media specification and recommended recipe (e.g., iron/aluminum-based and/or biochar)
- Proper drying and mixing of the PED amendments
- PED retrofit construction methods and maintenance issues.
- Appropriate landscaping template(s) and plant species
- Minimum requirements to establish and maintain vegetation
- Detailed design guidelines for IWS including IWS depth, whether it can intersect the media layer and need for any carbon amendment to promote denitrification
- Visual indicators to downgrade performance of LID practices due to practice failure
- Other key PED delivery issues, as identified by the USWG

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Appendix A. Summary Tables for Media Amendments Research

Table A.1 summarizes the results of field research on various media amendments, and Table A.2 includes a similar overview for laboratory studies. Each table divides the studies into stormwater applications, such as bioretention and sand filters, and non-stormwater studies, such as agricultural drainage ditches or wastewater.

Table A.1. Media Amendment Research -- FIELD

Source	Material	P Removal	N Removal	Notes
Bioretention				
Source	Material	P Removal	N Removal	Notes
Roseen and Stone 2013; Stone 2006	WTR	Dissolved P: 20% conc. TP: 55% conc.	Dissolved N: 60% conc. TN: 36% conc.	Dissolved P effluent conc. < 0.02
Liu and Davis, 2013	WTR	Dissolved P: 8% conc.; 60% mass TP: 63% conc.; 84% mass		Also reported 95.6% volume reduction, accounting for much of the pollutant removal
Filters & Other Stormwater Practices				
Source	Material	P Removal	N Removal	Notes
Ahmed *et al.* 2014	Iron filings	Dissolved P: 65% conc.		Grass swale check dam filter
Erickson *et al.* 2012	Iron filings	Dissolved P: 29-91% conc.; 85-90% for most rainfall events based on model		Minnesota Sand Filter trench along wet pond
Erickson and Gulliver 2010	Iron filings	Dissolved P: 72-90% conc. & mass		Minnesota Sand Filter
Erickson *et al.* 2011	Steel wool	Dissolved P: 80-90% conc. & mass		Sand filter pond trench and weir wall
Penn *et al.* 2012	Steel slag	Dissolved P: 25% conc.		Filter in suburban watershed
Non-Stormwater (e.g., Agricultural) Applications				
McDowell *et al.* 2008	Steel slag, fly ash	Dissolved P: 73% conc.; 60% mass TP: 70% conc.; 56% mass		Applied to ag tile drains
McDowell and Nash 2012	Fly ash & slag	Dissolved P: 50% mass, average based on literature review		
Shilton *et al.* 2005	Steel slag	TP: 77% conc.		P sorption declined after 5 years
Bird 2009	Steel slag	Dissolved P: 79% conc.		Filters for dairy waste; filters in series increased removal from 45% to 79%
Bryant *et al.* 2012	flue gas desulferization gypsum	Dissolved P: 73% conc.; 65% mass		Drainage ditch filter; actual mass load reduction

Table A.1. Media Amendment Research -- FIELD				
				closer to 22% when by-pass flow considered due to decrease in hydraulic conductivity
Penn *et al.* 2007	AMD	Dissolved P: 99% mass		Ag drainage ditch

Table A.2. Media Amendment Research -- LAB				
Bioretention and Stormwater Filters				
Source	Material	P Removal	N Removal	Notes
Roseen and Stone 2013; Stone 2006	WTR	Dissolved P: >50% conc. TP: 86-99% conc.		At least 10% WTR by volume
Liu *et al.* 2014	WTR, Compost	TP: 95% conc.		Mesocosms
Lucas and Greenway 2011(a)	WTR, clay soil	Dissolved P: 76-99% conc.		Mesocosms; highest removals for restricted outlet and highest concentration of WTRs. Vegetation also important for removal. P adsorption “resets” after resting time.
O'Neill and Davis2012	WTR, bark mulch	Dissolved P: 88.5% mass		Column study
Novak 2013	WTR	TP: 84% conc.		Column study
Beneski 2013	Biochar		Ammonia: 50% conc.	Column study; removal predicted based on lab results
Tian *et al.* 2014	Biochar		Ammonia: 37-74% conc.	Biochar also increased water retention
Reddy *et al.* 2014	Biochar	Dissolved P: 47% conc.	Dissolved N: 86% conc.	Column study
Al-Anbari 2008	GAC, zeolite	TP: 20-60% conc.	TN: 20-60% conc.	Column study
Schang *et al.* 2011	Zinc-coated GAC	TP: 80-90% conc.	TN: 75-85% conc.	
Kim *et al.* 2003	Various carbon sources		Dissolved N: 30-100% conc.	Columns also used IWS
Glaister *et al.* 2012	Iron sand	Dissolved P: 95% conc.	Dissolved N: 35-77% conc.	Columns also used IWS; exported TP
Erickson *et al.* 2012	Iron filings	Dissolved P: 88% conc.		
Prabhukumar 2013	Iron sand, calcite, zeolite	TP: 99% mass	Dissolved N: 88-95% mass	Column results for mixed media filter using listed

Table A.2. Media Amendment Research -- LAB				
				materials
Erickson *et al.* 2007	Steel wool, calcareous sand, limestone	Dissolved P: 34-81% retention		Column study
Ahmed *et al.* 2014	Iron filings	Dissolved P: 51-93% conc.		Column study for application to grass swale check dam filter
Non-Stormwater (e.g., Agricultural) Applications				
Source	Material	P Removal	N Removal	Notes
Lyngsie *et al.* 2013	Iron, limestone, shell-sand	Dissolved P: 90% retention		Batch study. Best P retention with iron-based and smaller particle sizes. Iron performed better than Calcium-based materials.
King *et al.* 2010	Activated carbon, zeolite, activated Al	Dissolved P: 51.6% mass	Dissolved N: 4.7% mass	Column study for ag tile drain filter. Best removal at low flow rates.
Penn *et al.* 2011	AMD, WTR, fly ash	Dissolved P: 64-90% conc.		Column study. See Law (2014) for EMC efficiencies for various materials
Sibrell *et al.* 2006	AMD	Dissolved P: 50-70% conc.		Column study. Aquaculture effluents.
Sibrell et al. 2009	AMD	Dissolved P: 60-90% conc.		Column study. Agricultural wastewater.
Sibrell and Tucker 2012	AMD	Dissolved P: 96% conc.		Column study. Fixed filter beds for wastewater.
Ballantine and Tanner 2010	Limestone, slag, tree bark	Dissolved P: 49-99% conc.		Based on lit review; filters for ag constructed wetlands. Best filters use limestone, slag, seashells, shell-sand, tree bark.
Allred 2010	Iron, fly ash, zeolite	Dissolved P: 66-99% conc.	Dissolved N: 95% conc.	Batch study. Ag drainage water

Appendix B. Summary Tables for Internal Water Storage (IWS) Research:

Table B.1 summarizes the results of IWS field research, and Table B.2 includes a similar overview for laboratory studies. All of this IWS research was conducted for bioretention practices.

Table B.1. IWS Research -- FIELD

Source	P Removal	N Removal	Notes
Roseen & Stone 2013; Stone 2006	Dissolved P: 20% conc. TP: 55% conc.	Dissolved N: 60% conc. TN: 36% conc.	Dissolved P effluent conc. < 0.02
DeBusk and Wynn 2011	TP: 99% mass	TN: 99% mass	Almost all reduction from volume reduction
Brown & Hunt 2011		Dissolved N: >50% conc. TN: >50% conc.	75-87% or runoff reduced through evapotranspiration and exfiltration
Gilchrist *et al.* 2013		Dissolved N: 75% mass	Compared to 7% removal without IWS
Passeport *et al.* 2009	Dissolved P: 74-78% conc. TP: 58-63 % conc.	TN: 47-88% mass	No difference in P loads, partially due to low influent concentrations.
Winston *et al.* 2015	Dissolved P: -120% conc. TP: -47% conc.; 11% mass	Dissolved N: -223 conc. TN: -144 conc.; -40% mass	60% volume reduction. Organic content in media suspected for negative removals. Only 7 events had outflow to sample.

Table B.2. IWS -- LAB

Source	P Removal	N Removal	Notes
Roseen and Stone 2013; Stone 2006	Dissolved P: >50% conc. TP: 86-99% conc.		
Caruso 2014	TP: 50-90% conc. for IWS & vegetated; 47-67% for no IWS	Dissolved N: 43-92% conc. for IWS & vegetated; -17 – 81% conc. for no IWS	Column study. Best performance with combination of IWS and well-vegetated.
Lucas and Greenway 2011b		Dissolved N: 68-94% retention, compared to -17 – 25% for no IWS. TN: 53-78% retention, compared to 27-50% for no IWS.	Mesocosms. Higher removal rates for low flow rates compared to high. Vegetation plays large role in N retention.
Zhang *et al.* 2011	TP: Accumulation in plants	TN: Accumulation in plants increased	Column study tested different combinations of plants, IWS,

Table B.2. IWS -- LAB

Source	P Removal	N Removal	Notes
	increased from 28% to >70% with IWS	from 59% to 83% with IWS	and carbon
Zinger *et al.* 2013	IWS increased Dissolved N removal 1.8 to 3.7X from no IWS, but also decreased P removal from 75-90% to 50-60% conc.		Mesocosms; retrofit with IWS after monitoring no IWS
Glaister *et al.* 2012	Dissolved P: 95% conc. TP: < 50% with some washout of fines	Dissolved N: 70-77% conc.; no IWS leached N	Authors speculate that Dissolved N removal more a function of vegetation than IWS

Appendix C
Design Recommendations for the Next Generation of Bioretention

Several researchers have outlined design criteria and media specifications to improve the performance of bioretention and other LID practices. Table D-1 provides a quick overview of these design recommendations. State stormwater agencies and practitioners may want to consult these sources as they update standards and specifications for the next generation of LID practices in their stormwater design manuals.

Table D-1. Compilation of Bioretention Design and Media Recommendations

Author	Design Objectives and Recommendations
Hunt, Davis, and Traver (2012)	For Bioretention: meet multiple criteria for hydrology (e.g., replicate pre-development hydrology, prevent stream erosion) and water quality (nutrients, bacteria, metals, hydrocarbons, temperature) Recommendations • Bowl volume to meet design requirements; surface area to capture water quality volume • Media: P-sorptive material, fines between 8 to 12%, limited organic matter • IWS thickness to saturate bottom 2 feet of underdrain gravel + media • 4 foot media depth; 3-4 inch mulch layer • Infiltration rate: 1-2 inches/hour • Vegetate at moderate density (may be different for temperature control vs. pathogen removal)
Liu et al (2014)	Design Objective: “Ideal” Bioretention Media Recommendations • <10% fine-textured silt & clay sized particles • Source of Al for P adsorption (such as WTR of up to 12%) • 3-5% carbon source, such a low-P, stable compost with enough nutrients just to establish vegetation • Virginia Tech mix, created at Virginia Beach research facility: 3% WTR, 15% saprolite, 25% yard waste compost, 57% medium sand
Lucas and Greenway (2010)	Design Objective: P and N retention and retention time Recommendations • WTR media amendments • Dual stage outlet • Adaptive controls on underdrains to control retention time
Liu and Davis (2014)	Design Objective: Enhance removal of dissolved N Recommendations • Media with low organic matter content, particularly N • Harvest vegetation to remove N • IWS

Table D-1. Compilation of Bioretention Design and Media Recommendations	
	• Activated carbon or similar adsorbing dissolved N • WTR or P sorbing material mixed into top 40 cm of soil media for P
Roseen and Stone (2013)	Design Objective: Optimized nutrient removal <u>Recommendations</u> • "Processed" WTR (dried to increase solids content to 10-33%) tested to ensure minimal P saturation index and oxalate ratio (20-40, as per O'Neill and Davis, 2012, or substitute equivalent Mehlich 3 test) @ 10% by volume • Loam content: 10-20%, although more research needed to confirm • <10% compost by volume (tested for P saturation index and C:N ratio), or perhaps substitute wood chips • Volume of IWS > 10% of overall water quality storage (preferably 20-30%).
Erickson et al (2012)	Design Objective: Enhanced removal of dissolved P for sand filters <u>Recommendations</u> • 5% iron by weight mixed with sand • BMPs in series with different features and/or target pollutants