Technical Memorandum

Date: June 1, 2016

To: Tom Schueler, Chesapeake Stormwater Network

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Re: PEDs Supporting Technical Document

Performance Enhancing Devices for Stormwater Best Management Practices

Technical Support Document

1. Scope & Purpose

This technical support document is a companion to a separate *Recommendations Memorandum.* The support document provides a more detailed overview of "performance enhancing devices" (PEDs) for stormwater best management practices (BMPs). The *Recommendations Memorandum* is a concise summary of PEDs research as well as specific recommendations for crediting PEDs using existing Chesapeake Bay protocols.

The scope and purpose of the overall PEDs review includes:

1. Conduct a literature review of PEDs research. PEDs are intended to boost the pollutant removal capabilities of several BMPs. The paper focuses on the ability of PEDs to provide incremental removal of urban nutrients (phosphorus and nitrogen), compared to existing practice. Examples of PEDs include adding amendments to filter or bioretention soil media, providing an "internal water storage" zone, and enhancing the selection and management of vegetation.
2. Synthesize and evaluate the research in order to characterize different PEDs -- either as stand-along approaches or in combination – to assess influences on pollutant removal performance for nutrients.
3. Compare PEDs with existing performance crediting methods used at the Bay Program level.

This technical support document contains the following sections:

- Brief history of "generations" of bioretention design and performance
- Description and scope of the literature review
- Understanding treatment processes and pollutant removal dynamics
- Current practice and the call the better BMP performance
- Enhanced and reactive media amendments (sorptive minerals)
- BMP configuration: internal water storage & storage/sizing
- Vegetation

- Synthesizing PEDs research: lessons for BMP design
- Integrating research with existing pollutant removal protocols

2. Brief History of "Generations" of Bioretention Design & Performance

Stormwater management in the Bay Watershed and across the country has evolved over the course of several decades. Many innovations have occurred in the past 25 years. These include the rise of low-impact development (LID) and continued refinement of design standards as well as state and local programs for stormwater criteria, plan review, inspection, maintenance and tracking. Certainly both phases of the MS4 permit, coupled with the Chesapeake Bay TMDL, have launched stormwater into a new era of implementation and accountability.

No practice epitomizes changes in the stormwater arena as much as bioretention. Bioretention design has undergone continued adjustment in soil media, underdrain configuration, vegetation, sizing, materials, and pollutant removal performance. **Table 1** provides a very concise overview of how bioretention has evolved through three generations. The topic of this paper is whether a fourth generation can be ushered in with the addition of various PEDs.

Table 1. Concise overview of generations of bioretention design and performance

Generation of Bioretention Design	Characteristics	General Nutrient Removal Rates
1990s: Technology Development	• PG County design standards defined the practice • Media had relatively high organic matter (e.g., 20-40%) • Most were/are freely-drained with underdrain near the bottom of the practice, unless designed for infiltration	• Limited TP removal – around 25%, with leaching of dissolved P • Moderate TN removal: 55%, but negligible or negative capture of dissolved N
2000 -- 2007: Mainstreaming Bioretention	• Practice addressed in state-wide and local design manuals • Studies showed great variability in removal rates based on event-mean concentration (EMC) • Many design, installation, and maintenance issues	• TP: 45-75%, but very wide range of results, including negative removals • TN: 25-70%, less scatter in the data (CWP 2007)
2007 – Present: State stormwater specifications & Chesapeake Bay performance curves	• LID in general gaining popularity and lessons learned with implementation • Runoff reduction recognized as essential part of practice performance (CWP and CSN, 2008) • Performance defined by states and C.B. expert panels: performance curves from State Performance Standards & Retrofits (Schueler and Lane 2012a, 2012b)	• TP: Typically 55-70% for rainfall 0.5 – 1.0", but as high as 90% with high levels of runoff reduction • TN: Typically 45-60% for same rainfall depths (VA DEQ 2011; Schueler and Lane 2012a, 2012b)

One of the take-home points from **Table 1** is that bioretention – and several other stormwater BMPs – have done an admirable job of removing particulate forms of phosphorus (P) and nitrogen (N), and steady improvement has been made in pollutant removal performance. However, dissolved forms of both P and N have lagged behind in terms of effective removal mechanisms. This has been a concern, since dissolved nutrients can constitute a sizable fraction of total urban loads, and the dissolved forms may be more bioavailable in downstream receiving waters than the particulate-bound forms left behind in the BMPs. A strong focus of more recent research has been on how to effectively reduce the fuller spectrum of nutrients, including both particulate and dissolved forms.

3. Description & Scope of the Literature Review

The literature review included 138 research papers, journal articles, technical reports, and few powerpoint presentations. The following further characterizes the research:

- 77 studies addressed nutrients (phosphorus and nitrogen). Of these 58 had a focus on stormwater, with the others addressing agricultural drainage ditches, wastewater, or other non-stormwater topics. Other studies addressed hydrology, heavy metals, *E coli,* or other contaminants.
- Of the 77 nutrient-focused studies, 37 were conducted in a laboratory or research facility using batch, column, or mesocosm research; 23 were field studies; 6 included both laboratory and field, and 12 were general discussion papers or literature reviews.
- Of the stormwater studies, the overwhelming BMP of choice was bioretention (37 studies). Other practices included stormwater sand filters (4), agricultural or wastewater filters (19), grass swales (3), green roofs (1), or a variety of practices (13).
- One interesting phenomenon is the proliferation in research in recent years, with many university centers and departments focusing increasingly on stormwater topics. Of the nutrient studies, 23% were published between 2003 and 2009, and, remarkably, 77% since 2010.
- The authors are based in a variety of geographic locations, with the highest number being from Australia (12). Maryland had the next highest number (9), followed by MN (6), NC (5), New Zealand (5), with other representation from Bay states VA, WV, PA, and DE. Other locations include NH, GA, OR, IL, OK, MO, OH, VT, FL, CA, and TX, and also Canada, China, and Denmark.
- Most were journal articles, with good representation from the *Journal of Environmental Engineering, Water Research, Journal of Environmental Quality, Journal of Irrigation and Drainage Engineering, and Ecological Engineering.* Ten of the studies were doctoral or masters theses, and others were university stormwater center publications, symposium proceedings, and several PowerPoints.

As indicated above, the laboratory is the location of choice for this type of research, as it allows for control of many variables (media types, configurations, dosing rates, time sequence, wet/dry cycles, etc.), mostly using "synthetic stormwater" that simulates concentrations from the literature. Field studies tend to be much more expensive, time-intensive, suffer from the vagaries of weather and other conditions, and are most often preceded by laboratory studies to narrow the range of variables to investigate in the field. Field studies also tend to be conducted when BMPs are newly-installed, which may skew the data a bit towards immature vegetation and "unsettled" soil media conditions. Given all of this, the data derived from the field is certainly more representative of actual conditions, and thus expected performance of real-world applications across the Bay Watershed.

Importantly, the field studies are more likely to provide data on mass load reductions in addition to reductions in concentration (such as Event Mean Concentration, or EMC), typical of the laboratory. As will be highlighted later in this paper, mass load and "runoff reduction" processes are important metrics for overall pollutant removal performance.

Table 2 in the Recommendations Memorandum provides a quick analysis of relative data quality of studies in the literature review. It is evident that PEDs-focused work is gaining traction in the stormwater research world.

4. Understanding Treatment Processes and Pollutant Removal Dynamics

Several authors have contributed significantly to understanding how certain "unit processes" or functions of stormwater BMPs actually work to reduce pollutants. A better understanding of these actual processes, it is believed, will lead to better performance metrics, and therefore design and implementation. This body of work is actually quite lengthy, but the current literature review included examples from Davis et al (2010, 2009), Li and Davis (2014), Clark and Pitt (2012), Grebel et al 2013, and Collins et al (2010).

It is beyond the scope of this paper to provide a thorough review of this topic; the following is a brief summary based on Davis, Traver, and Hunt (2010), with some simplifications for the sake of brevity. The Clark and Pitt paper is a more technical and very thorough overview of this topic for those interested in more detail. The purpose of including this is to provide context for understanding the role of PEDs.

- Sedimentation and Filtration for Particulate Matter: capture of a various range of particle sizes through settling and physical filtering through a media, as well as pollutants that adsorb onto particles, such as metals, hydrophobic organics, and some phosphorus.
- Adsorption: This process allows certain molecules to bond to the surface area of a material or mineral. This sorption process has different strengths and lifespans. In both agriculture and stormwater, much research has been done on the sorption capacity of various minerals for dissolved phosphorus, as well as the role of other factors, such as pH.
- Microbiological Processes: The metabolic processes of certain organisms will transform certain pollutants from one phase to another, or biodegrade the pollutants. For example, microbiological processes in the presence or organic material can promote transformation of dissolved nitrogen (a bioavailable form of nitrogen) to nitrogen gas through denitrification, but only in a low-oxygen, or anoxic, environment. Other processes are effective in a more aerobic setting.
- Phytobiology: Vegetation can play several functions for flow and pollutant treatment – physically slowing incoming flow, reducing volume through evapotranspiration, and accumulating certain pollutants (including nutrients) into above-ground and underground biomass.
- Heat Transfer: It has long been acknowledged that some stormwater practices, such as wet ponds, can transfer heat load to downstream waters, affecting sensitive fisheries and other organisms. Some other BMPs, with subsurface storage layers and exfiltration into the surrounding soil, can mitigate heat in stormwater runoff and release cooler water.

One of the main themes from these analyses is the increased focus in the stormwater world on the ability of BMPs to capture and treat dissolved constituents, such as nitrate and orthophosphate. Much of a BMP's function to date, has been concerned with the first category above: sedimentation and filtration, and performance associated with particulate-bound pollutants. Many BMPs have an excellent track record with this, but dissolved pollutants have been more elusive, as explained below. The explanation of unit processes is certainly an asset for understanding how to build higher-performing BMPs.

A note on terminology is that there are various forms of P and N (particularly the latter). This paper will use the terms "dissolved P" and "dissolved N" to refer to the dissolved fractions collectively.

5. Current Practice & the Call for Better BMP Performance

Existing bioretention specifications for the Bay states rely largely on a high sand content media (up to 85% in some cases) and a "freely-drained" system (underdrain at or near the bottom of the gravel layer, unless it is an infiltration design with no underdrain). As noted above, many bioretention field studies indicate that, while this type of system is quite effective at removing TSS and particulate forms of P, the systems also tend to leach or create a net export of dissolved forms of N and P. The causes are variable, and include: addition of too much organic content to the media, low influent concentrations, short residence time of runoff in the practices, and inadequate uptake of NOx, among other causes (Winston et al 2015; Roseen and Stone 2013; Li and Davis, 2014; Culver 2015; Line and Hunt 2009, 2012; Hunt et al 2012; Collins et al 2010).

The findings of these field studies are corroborated by column and mesocosm studies that reveal leaching of dissolved nutrients (see, for example, Morgan 2011, Glaister et al 2012, Read et al 2008).

PEDs research can be categorized into three general categories:

1. <u>Reactive Media:</u> Various materials have been studied for their adsorption capacity for dissolved forms of N and P, as well as metals and other pollutants. Examples include aluminum/iron (Al/Fe) and Biochar. Factors thought to influence adsorption capacity include content of the materials by weight or volume in the media mix, contact time, sorptive capacity, surface area of the reactive particles, longevity or lifespan of sorption before materials become saturated or start leaching pollutants, and pH of the media.

2. <u>Anaerobic or Anoxic Reactions/Internal Water Storage:</u> With "freely-drained" underdrains, chemical reactions within the practice are largely taking place in an aerobic environment. Particularly for N, aerobic reactions can tend to leach dissolved forms, such as NO_x. Many studies have investigated the role of creating an intentional low-oxygen layer within the media and/or underdrain layer through various underdrain configurations, notably the creation of an "internal water storage" (IWS) zone. Low-oxygen reactions within the IWS can help promote denitrification and/or immobilization of pollutants through microbial processes, with the intended affect to reduce leaching of dissolved N and/or convert NOx to nitrogen gas.

   IWS is one example of the "configuration" of a BMP. Other research addressed the overall sizing and storage of practices, and how this influences pollutant removal performance.

3. Vegetation: Actively-growing vegetation can act as a “sink” for both P and N. A selected number of studies investigated the role of vegetation in removing certain pollutants, including the types and structure of vegetation and efficacy of periodic harvesting of vegetation to remove sequestered pollutants from the system.

The sections below address each of these three categories, summarizing key research findings. The body of research includes stormwater applications, such as optimizing bioretention soil media mixes for nutrient removal, as well as a longer history of research on agricultural and wastewater applications.

6. Enhanced & Reactive Media Amendments (Sorptive Minerals)

There is an impressively long list of materials used in various studies of amendments added to filter media to enhance pollutant removal. Studies have tested the sorption capacity, longevity, relative availability, and ease of mixing of many types of natural materials and industrial by-products. In terms of sorption, much of the focus has been on dissolved P.

Law et al (2014) provides a good overview of different types of “particulate-sorptive media (PSMs) for P removal, classified as:

- Metal cations: Those containing Ca/Mg and Al/Fe. The former removes P through precipitation and the latter through adsorption, which in general is a much faster reaction. The materials can be naturally-occurring (limestone, gypsum), industrial/process waste materials (water treatment residuals, fly ash, steel slag, acid mine drainage residuals), or industrial products (zeolite).
- Carbon sources: Materials containing carbon and a relatively high surface area for chemical reactions, including various types of Biochar and activated carbon.

Other authors also provide extensive literature reviews of available materials for removal of nutrients and other pollutants for stormwater and agricultural applications (Prabhukumar 2013, Ballantine and Tanner 2010). The wide array of materials reviewed include: compost, sand, metal-coated sand, calcareous sand, limestone, peat, zeolite, iron, slag, fly ash, alum, mulch, wood chips, sawdust, tire chips, soybean hulls, crab shells, shell sand, pumice soil, tephra, mushroom mycelium, and several commercially-available additives.

For eventual implementation within the Chesapeake Bay Watershed, it is more instructive to focus on material that are:

- Readily-obtainable within the Watershed, perhaps with the added social or sustainability benefit of diverting a waste material to beneficial use.
- Adaptable for field application of bioretention and other practices in terms of delivery, mixing with other media constituents (e.g., sand), and installation.
- Would generally not have to be replaced or “recharged” on a frequent basis (e.g., every 3-5 years), as this would prove difficult for practices such as bioretention.
- Supported by stormwater-focused research, particularly field studies.

In this regard, **Table 2** lists in general priority order materials that can enhance existing bioretention, sand filter, or other BMP soil media in the Chesapeake Bay Watershed. It is important to note that the materials listed in **Table 2** can be used in various combinations to optimize removal of both N and P, as being applied by several researchers (Chiu et al 2015, Prabhukumar 2013, Liu and Sample 2014, among others). Media additives are also being explored for other pollutants, such as heavy metals and *E. coli.*

Table 2. Media Amendment Materials, in Priority Order	
Iron/Aluminum (Fe/Al), with stronger emphasis on Fe	Iron (filings), steel wool, slag, water treatment residuals (WTRs), acid mine drainage (AMD) residuals, fly ash Primary target pollutant: dissolved P
Carbon	Biochar, wood chips, activated carbon, compost* Target pollutants: N and P, due to surface area, adsorption capacity, and carbon donor for denitrification (studies indicate this amendment is also used extensively for heavy metals mitigation). Can be used in combination with Fe/Al additives. *Note that use of compost has been linked with leaching of nutrients from stormwater systems (Morgan 2011, Winston et al 2015, Culver 2015, and others).

Iron/Aluminum

Water Treatment Residuals (WTR)

A study by Liu and Davis (2013) performed a retrofit of an existing bioretention practice on the University of MD campus, and compared pre-retrofit to post-retrofit monitoring results. The retrofit involved adding WTR (5% by mass) to the top soil media layers. TP reductions increased from 55% to 84% (with nearly 60% mass removal for dissolved P), and filtration performance was not reduced with addition of the WTR.

Roseen and Stone (2013) monitored conventional bioretention and one enhanced with 10% WTR by volume at the University of NH. While the conventional bioretention leached both dissolved P and TP, the WTR practice removed 55% of TP and 20% of dissolved P (by concentration). The authors contend that removal rates with WTR could have been higher if the WTR had a lower moisture content, had been better mixed into the media, and if various construction and short-circuiting issues had been corrected. The authors recommend freeze-thaw dewatering of the WTR to achieve a solids content of 30-40%, compared to simple air-drying, which produced a wetter mix and led to clumping when mixing into the media.

A series of laboratory column and mesocosm studies confirm that the addition of WTR enhances removal of dissolved P and TP. For instance, Liu et al (2014) showed that vegetated mesocosms with a media mix containing WTR out-performed other types of filter media, removing up to 95% of TP from the influent. This experiment was conducted at the Virginia Tech research facility in Virginia Beach. Lucas and Greenway (2011a) found up to 99% dissolved P removal with the higher levels of WTR in bioretention mesocosms, and that the sorption lifespan of the amendment could be expected to last as long as the bioretention practice itself. Laboratory column studies confirm this trend with P mass removals of 88.5% (O'Neill and Davis 2012) and EMC removals of 84% (Novak 2013).

Iron Filings, Steel Wool

The University of Minnesota has been a leader in testing the use of iron filing (ground cast iron) and steel wool as an amendment for sand filters (known as the Minnesota Sand Filter), and also in making a strong case for the importance of treating dissolved nutrients in stormwater practices. Field applications of this technology along the perimeter of a wet detention pond demonstrated removal of dissolved P of 29 to 91%, with the lower rates applying to low inflow concentrations (typical removals were in the 85-90% range) (Erickson et al 2012). The authors recommend a media mix containing 5% iron by weight.

Similar dissolved P capture rates were found in other Minnesota field studies, including a permeable weir wall in a wet pond and a Minnesota Sand Filter, with a modelled life cycle of 35 years (Erickson et al 2011, Erickson and Gulliver 2010). However, if the hydraulic loading rate is high (e.g., small practice surface area compared to the drainage area), the filter media may have to be replaced more frequently, such as every 3-5 years (Erickson et al 2012). Other authors found that a P removal structure could have a shorter lifespan (e.g., 17 months) and that they do a much better job of pollutant removal during low inflow events when retention time in the structure is higher (Penn et al 2012). Others found that the P adsorbing capacity of steel slag was rejuvenated if allowed to "rest" (no inflow), thus increasing the lifespan of the material (Drizo et al). Obviously, the lifespan of the material is of great importance for stormwater facilities, where it would be impractical to "recharge" the amendment on a frequent basis, and where inflows are episodic.

As with WTR, laboratory work helps to confirm the field results, with relatively high capture of dissolved P compared with negligible capture in a 100% sand column (Erickson et al 2012). These experiments also revealed that some materials – such as limestone and calcareous sand – are prone to clogging, but iron tends to maintain the hydrologic properties of the filter (Erickson et al 2007). Others also concluded that iron-based materials are superior to calcium for P adsorption (Lyngsie et al 2013, Bryant et al 2012, and others). Chie and colleagues are currently conducting field and laboratory studies of zero-valent iron and compost additives to bioretention media in Delaware and Virginia (in process), so more information is forthcoming.

Acid Mine Drainage (AMD) Residuals, Fly Ash, and Other Sources of Fe/Al

Much of the research on AMD has been for non-stormwater applications, such as treating discharges from agriculture and wastewater. AMD sludge contains a lot Fe and Al oxides, and is otherwise considered a waste product. Sibrell and colleagues have found dissolved P removals of 50 to 96% in various studies (Sibrell and Tucker 2012, Sibrell et al 2009, Sibrell et al 2006), arguing that this waste product from coal-producing areas of PA could be used for a variety of uses to remove P from wastewater. The authors also contend that the additives are unlikely to contribute contaminants (e.g., heavy metals) to the treated water.

Other studies have investigated the use of other materials, such as fly ash, largely for agricultural drainage ditch filters. However, these materials may not have a wide application for stormwater compared to the other materials listed above.

Carbon-Based

Biochar

Biochar is produced by "pyrolysizing" (combustion at extreme heat with no oxygen) various forms of biomass, including wood chips, chicken litter, switchgrass, and waste wood products (Law 2014). Usually, it is used as a soil amendment to boost productivity and nutrient retention (Reddy et al 2014). However, it is thought that biochar can sequester various pollutants (notably metals) because it provides a relatively large surface area and porous structure for biological activity and adsorption, and would not have the same nutrient leaching effect as other "raw" forms of carbon, such as compost.

While extensive work has been done with biochar related to its amendment and metals mitigation properties, field deployment and monitoring of biochar for specific stormwater purposes (e.g., mixed into bioretention soil media) has not been done to the same extent as some of the Fe amendments noted above. However, some work on this nature is underway in Virginia (Chie et al ongoing). Several laboratory studies geared towards stormwater applications have been conducted. A column study using biochar derived from gasification of waste wood pellets showed 47% removal of dissolved P and 86% of dissolved N (Reddy et al 2014). Beneski (2013) found that wood-derived biochar with smaller particle sizes out-performed biochar derived from poultry litter, and that biochar removed ammonia, but not dissolved N. Also, biochar can alter pH of the water, so the overall pH of the media needs to be evaluated. Biochar was also found to increase the water retention capabilities of media compared to a uniform sand, so water would have more contact time for pollutant removal processes (Tian et al 2014).

Activated Carbon and Other Sources of Carbon

Laboratory studies have also investigated other sources of carbon to treat stormwater as well as agricultural drainage ditch water. Schang investigated the use a zinc-coated granular activated carbon (GAC), intended as a filter that provides pre-treatment for a rainwater harvesting system. Removal of both TP was enhanced by 25%, but the filter also leached zinc (Schang et al 2011). Another study found that a mixture of GAC and zeolite could make an effective filter under a permeable pavement system, removing around 60% of TN (Al-Anbari 2008). Kim, Seagren and Davis (2000) found that columns containing newspaper and wood chips were the best carbon materials for TN removal. Clark and Pitt (2012) caution that media layers containing carbon materials (such as compost or peat) should be in an aerobic environment and not stay saturated between storm events.

Given the research, it is likely that biochar in particular will be investigated further, especially as a media additive used in combination with other amendments (e.g., iron) and/or configurations (e.g., internal water storage).

Calcium-Based

There has been little stormwater research conducted on Ca products as a soil amendment, and for good reason. The chief concern is that Ca products would lead to clogging and lower retention times. This is borne out by research on agricultural filters using materials such as gypsum and limestone (Bryant et al

2012). While some agriculture-related research indicated Ca/Mg material could be good P sorbing amendments (especially at lower pH levels), others found that Fe-based materials would be superior (Penn et al 2011; Lyngsie eta l 2013).

Based on the clogging concerns alone for stormwater applications, there is little chance that Ca-based amendments would be pursued for PEDs.

Risks Associated With Use of Sorptive Mineral Media Amendments

Effect on Flow Rate Through the Practice (Hydraulic Conductivity)

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 system or slowing the flow rates to the extent that more stormwater by-pass is occurring, and thus releasing untreated stormwater downstream. As noted above, Ca materials may be the largest concern for potential clogging or slowing the movement of water through the filter media. Other materials show more promise. Erickson et al (2012) found that a Fe/sand filter media did not affect hydraulic conductivity compared to just sand. Liu and Davis (2013) found similar results for WTR-amended bioretention media, although Roseen and Stone (2013) had some problems with WTR additives that were too wet and causes clumping within the media.

Actual field conditions and the characteristics of the various amendments will have a bearing on this important BMP function.

Potential Leaching of Metals or Nutrients From Amended Media

Some research mentions a concern for dissolving of aluminum oxides found in WTR, and thus release of toxic metals from the system. However, this dissolving would take place in a low pH environment (< 5), and WTR and other materials tends to be slightly acidic to slightly alkaline (Roseen and Stone 2013). Potential concerns with leaching metals is mentioned in other research related to agricultural applications (Buda et al 2012). General findings are that metals content in the available materials are low compared to EPA limits, but more research needs to be conducted on the bioavailability of any released metals (Penn et al 2011).

At this point, it appears that the risk of metals leaching is low, but this should certainly be confirmed for the actual materials used for stormwater applications, and specifications should be developed for materials selection and testing.

Leaching of nutrients is different story altogether, as many studies and field results indicate leaching of both N and P when the organic or compost content of filter media is too high (Morgan 2011, Winston et al 2015, Culver 2015). Fortunately, most of the Bay states have adopted updated soil media specifications that limit the organic or compost content (generally in the 3-5% range). Other parts of the country still specify a compost content of up to 30% (Morgan 2011).

Increase in Construction Costs

It would be highly speculative at this point to predict the impact on installation and materials costs for the marginal effort to purchase, transport, and mix the various amendments. Erickson et al (2007) notes a 3-5% increase in materials costs and a marginal effect on installation costs for iron-amended sand filter media. There will also be a difference for materials that must be purchased versus those that could be donated because they would have to be disposed of by other means. Costs for the initial years of adoption of this technology are likely to be higher than long-term costs, as the systems for procuring, transporting, and mixing these amendments become more established.

Another construction risk is incrementally increasing the complexity of design and installation. This has already been taking place in the stormwater world, as specifications become more detailed and the profession collectively learns from performance issues observed as a result of various design, installation, and maintenance issues. If the trend continues, the vendor community will be able to respond to demand for "pre-made" media mixes that include recommended amendments.

Appendix A contains summary tables for both field and laboratory research on PEDs media amendments, showing the types of amendments tested as well as P and N removal results.

7. BMP Configuration: Internal Water Storage (IWS), Storage/Sizing

Another major area of research focus has been on changes in BMP configuration to enhance removal of dissolved nutrients. A majority of the work has been focused on creating IWS zones within the practice. Some studies address the overall role of storage and sizing on BMP performance. Both of these topics are addressed below.

Internal Water Storage

IWS refers to the inclusion of a very slow-draining or saturated zone within the underdrain system of bioretention, permeable pavement, or other underdrained practices. This zone is created by an "upturned elbow" or weir wall in the manhole structure that receives underdrain flow.

IWS is referred to by various terms in the research, including "saturated zone" (SZ), "internal storage reservoir" (ISR), and other terms. For the purposes of this paper, IWS is used to refer to the general approach of having a low-oxygen environment, usually near the bottom of the practice.

Of particular interest is a number of bioretention field studies. Gilchrest et al (2013) measured a 75% mass load reduction of dissolved N in unvegetated rain gardens with IWS, compared to 7% for rain gardens without IWS. Roseen and Stone (2013) monitored bioretention practices with and without IWS (and WTR media amendment) at the University of New Hampshire. The practices without IWS released higher concentrations of both TN and dissolved N at the outlet (compared to inlet), but the IWS systems saw reductions of approximately 60% for dissolved N. Brown and Hunt (2011) found very high levels (75-87%) of runoff volume being removed through exfiltration and evapotranspiration in North Carolina IWS practices, and hydraulic retention times of up to 7 days. Winston et al (2015) found similar results in Ohio, with 40 out of 50 events producing no outflow to sample. It is evident from these studies that the higher retention time provided by an IWS system enhances other runoff reduction mechanisms.

A series of laboratory studies generally confirm the findings of field research that IWS enhances N removal (see **Table B.2** in Appendix B). Most the laboratory work involved various combinations of IWS, media types and amendments (e.g. WTR, carbon sources to promote denitrification), and vegetation (see **Section 8** below).

It is important to note that several authors indicated important potential trade-offs inherent with the use of IWS. For one, the IWS layer takes up storage that could otherwise be used to collect and treat additional runoff. Also, the IWS can intersect the filter media and put more organic matter into solution.

Collins et al (2010) and Lucas and Greenway (2011b) address the former point – that there may be inherent trade-offs between hydrologic (e.g., storage; minimizing runoff that by-passes the treatment altogether) and N removal goals, and that more work should be conducted to identify an optimal design.

On the latter point, Zinger et al (2012) conducted a study where mesocosms started out with no IWS, and then were retrofitted with IWS to monitor the differences. While the retrofitted IWS enhanced dissolved N removal by fairly large factors, TP removal decreased (starting at 75-90% and decreasing to 50-60%). Glaister et al (2012) also found reductions in TP removal performance with IWS. The authors attribute this decreased TP performance to washout of organic matter in the IWS layer. Zhang et al (2011) found differently – that the IWS increased P uptake by plants, reinforcing the importance of vegetation.

A related design consideration is whether the IWS should stay within the underdrain layer or extent into the filter media. Clark and Pitt (2012) contend that layers containing compost or peat should remain aerobic between storms to avoid leaching nutrients. This may imply that the IWS should not extend too far into the soil media layer, as some of the studies noted above detected a net increase in nutrient concentrations when the lower part of the media layer was saturated and the media contained compost or organic matter.

The possibility exists that various design options may lead to a P-focused system (perhaps a smaller IWS zone) or an N-focused system (full IWS), depending on the location and objectives for the practice (see Davis et al 2009 for a good overview).

A final point from the literature on IWS is worth noting. Several researchers contend that the IWS may not really produce truly anaerobic conditions across the range of wet and dry cycles, and that the dissolved N removal mechanism has less to do with denitrification (which requires anaerobic conditions and a carbon source) than with uptake by vegetation and microbial activity within the media (Winston et al 2015, Glaister et al 2012, Caruso 2014). Indeed, the IWS will not stay saturated in some instances, depending on infiltration and exfiltration rates, depth of the IWS, and other factors. This finding does not diminish the potential benefits of IWS, but stresses the importance of pairing IWS with good vegetation selection and management (see **Section X**).

<u>Storage & Sizing</u>

Virginia adopted the Runoff Reduction Method (CWP and CSN, 2008) as a state compliance system, and other Bay states have also adopted some form of runoff reduction metric into their BMP standards and specifications. An original tenet of the method is that, while pollutant removal performance based on "scrubbing" pollutants from runoff (reducing concentrations from inlet to outlet), is quite variable, the runoff reduction capabilities of various BMPs are both more predictable and practically associated with design choices, such as storage, media depth, and underdrain configuration. This led to the formulation of "Level 2" design standards that specifically address runoff reduction mechanisms (CSN, Bay-wide design specifications).

More recently, the role of runoff reduction was officially acknowledged in the Bay Program BMP performance crediting system, with the adoption of performance curves for retrofits and state stormwater standards (Schueler and Lane 2012a, 2012b). The performance curves were the result of two expert panels that conducted literature reviews that confirmed the veracity of the runoff reduction approach (see **Section 10**).

More recent research has helped stress the importance of runoff or volume reduction functions. Bioretention field studies, in particular, reveal the often overriding roll of runoff reduction in overall pollutant removal. For instance, DeBusk (2011) found that for a bioretention practice at Virginia Tech, almost all of the 99% reduction in TP and TN could be attributed to runoff/volume reduction (although part of the monitoring took place during relative drought conditions). Winston et al (2015) and Culver (2015) found that, even though some practices had concentration increases at the outlet (due, in part, to lower than expected inflow concentrations), runoff reduction led to overall mass reductions in most cases. Brown et al (2011) found 69% volume reduction for a conventionally-drained bioretention, even in a high-water table setting in North Carolina.

Other researchers found that infiltration and other runoff reduction mechanisms were also important factors for grass swales (Stagge et al 2012, Ahmed et al 2014) and, in some cases, green roofs (Lang 2010).

Hunt et al (2012) provides a good overview of how bioretention design can be targeted to achieve specific objectives, including hydrologic goals. Olszewski and Davis (2013) found that a bioretention facility in Maryland successfully dampened outflow rates compared to inflow, but that cell size would have to be increased to 4.5 to 8.3% of the drainage area to fully mimic forested stream hydrology.

A more recent innovation is the use of adaptive controls to optimize storage and hydrologic functions (Opti 2015). This relatively simple technology makes use of sensors and internet weather predictions to open or restrict outlet controls, such as pond outlet structures, bioretention underdrains, and rainwater harvesting system drains. This system does not change anything about design standards, but uses the technology to substantially increase runoff capture and residence time.

Despite any other configuration and media amendment, runoff reduction remains perhaps the most important BMP process and can account for a large fraction of overall removal for both particulate and dissolved constituents. It may be that enhanced sizing (as per Olszewski and Davis) or the Opti adaptive control system can further capitalize on this function.

Risks Associated With Configuration Changes

Aside from the storage trade-offs with IWS noted above, the chief risk of configuration changes would appear to be cost, especially for increasing the size and storage of BMPs. While increasing the size of a bioretention practice to 8.3% of the drainage area may enhance hydrologic performance, the direct and indirect costs (e.g., larger footprint on constrained sites) must be considered. The Bay Program performance curves show a flattening of the curve as the practice storage increases, suggesting that there is an optimum storage (at or near the curve's inflection point) to meet water quality goals.

There may be other risks that have to be fleshed out, such as using IWS in proximity to fill, road beds, etc., but these risks are inherent with existing designs, so additional guidance in specifications would likely suffice to address these issues.

Appendix B contains summary tables for field and laboratory research on IWS.

8. Vegetation

One of the most compelling findings from the research is the role of vegetation as a pollutant removal mechanism. While stormwater professionals can understand the importance of vegetation in a general sense, researchers have done a good job of articulating the processes and in some cases management strategies that allow vegetation to play this critical role. These studies have used mesocosms and large columns to test the performance of different types of vegetation, as well as the role of vegetation in combination with configuration changes (e.g., IWS) and media amendments (e.g., WTR).

Leading the charge is Lucas and Greenway, with several Australian studies (2011a, 2011b, 2008). For instance, the 2008 study compared uptake of TP and TN in vegetated vs. "barren" mesocosms. The vegetated mesocosms retained substantially more of both nutrients: 92% compared to 56% for TP and 76% compared to 18% for TN (for loam media and 50 weeks of loading). Others found similar gaps between vegetated and non-vegetated systems (Henderson 2008, Barrett et al 2012). Zhang (2011) found that uptake by vegetation accounted for 59-83% of N input and 28-71% of P input over a 20 month period, with more uptake during low pollutant loading conditions versus high. Henderson (2008) pegs much of this uptake occurring in above-ground biomass.

It is interesting to note that the presence of vegetation abets other nutrient processing mechanisms. In particular, vegetation adds microbial biomass that has a role in immobilizing dissolved nutrients, and this "microbial immobilization" may be contributing to high removal rates otherwise attributed to denitrification (especially during the wet/dry cycles typical of stormwater practices) (Lucas and Greenway 2011a, Glaister et al 2012; see also Hunt et al 2012, Davis et al 2010, Clark and Pitt 2012, and Collins et al 2010 for deeper explanations of pollutant removal processes). As vegetation matures, the root systems also contribute to hydraulic performance.

The type of vegetation is also important, and some vegetation types perform much better than others (Bratieres et al 2008, Read et al 2008). Caruso (2014) suggests that vegetation may be more important than IWS for removal of dissolved N, and that root thickness, density, and coverage are factors in how well vegetation performs for pollutant removal, with Big Bluestem and Switchgrass performing the best for a Georgia column experiment. Scharenbroch and colleagues (2016) found that trees in bioswales in an Illinois field study accounted for 46 to 72% of total water output (largely through transpiration), and that trees with higher stomatal conductance, leaf area, and mature size will contribute more to this hydrologic benefit.

Unfortunately, not much insight can be gained about which types of vegetation in the Chesapeake Bay Watershed may be preferable, as many studies took place in Australia or other parts of the U.S. However, Caruso's observations about vegetation that has thick and dense root structures would provide clues about vegetation characteristics, with plant types such as Carex, Swithgrass, Big Bluestem, and Joe Pye Weed (*Eupatorium dubium*) (as per Davis 2014) being good candidates (see also CWP 2014 for guidance on selecting vegetation for stormwater practices).

Finally, some researchers come to the logical conclusion that, in order to be effective, vegetation should be harvested periodically to remove nutrients from the system. Lucas and Greenway (2011b) note marked seasonal differences, with much more N retention during the summer. Clark and Pitt also caution about harvesting biomass during the growing season, as it may lead to reduced uptake. Harvesting would appear to both remove sequestered nutrients from the system as well as keep the plant community in a vigorously-growing condition. Harvesting may not be advisable for trees, but growth rate and mature size may be important factors for hydrologic performance (Scharenbroch et al 2016).

All existing BMP specifications in the Bay Watershed already require vegetation. However, the general track record of selecting and maintaining the proper vegetation is quite poor (Hirschman et al 2009, CWP 2014). The bottom line of this research is that the stormwater community should strive for higher levels of competence in this arena. Designers should move more towards good surface area coverage with a variety of herbaceous species that have dense below and above-ground biomass (perhaps in combination with more widely-spaced and appropriate tree species). This may be in contrast to the traditional tree/shrub/herbaceous approach, with large areas of mulch in between plantings. Also, periodic harvesting should take place, with removal of the material to proper composting facilities. Bush-hogging in the early spring (March) is a recommended approach (CWP 2014). In general, maintenance programs must acknowledge that vegetation management is about more than aesthetics, and designers must take long-term maintenance into account with planting plans.

Appendix C contains summary tables for laboratory research on the role of vegetation in pollutant removal. While there may be ongoing research in the field on this topic, the research to date has been with columns and mesocosms.

9. Synthesizing PEDs Research: Lessons for BMP Design

Several authors delve into the topic of how to optimize BMP design to address multiple pollutants, utilizing the various tools addressed in **Sections 6** through **8**. For the purposes of this white paper, these design recommendations are focused on optimizing for P and N, although some studies also address metals, *E. coli,* thermal impacts, and other pollutants. **Table 3** provides a quick overview of several of these design recommendations. The table notes the design objectives that are mentioned in each study, as these vary from study to study.

Table 3. Optimized Design Recommendations from Selected Authors	
Author(s)	Design Objectives & Recommendations
Hunt, Davis, and Traver (2012)	Design Objective(s) for Bioretention: meet multiple criteria for hydrology (e.g., replicate pre-development, 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 – 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 • Vegetation at moderate density (may be different for temperature control vs. pathogen removal) • Rake bottom of excavation and protect/stabilize perimeter * These authors advocate for more of a customized design approach based on specific objectives, but do provide the general recommendations note above.
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 • Authors note use of "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, such as one used at Science Museum of VA • Adaptive controls on underdrains to control retention time
Li 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 • Activated carbon or similar adsorbing dissolved N • WTR or P sorbing material mixed into top 40 cm of soil media for P (as per Davis 2014)

Table 3. Optimized Design Recommendations from Selected Authors	
Roseen and Stone (2013)	Design Objective: Optimized nutrient removal Recommendations • "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 • IWS: 22-30 foot subsurface flow path from inlet to outlet; 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 Recommendations • 5% iron by weight mixed with sand • BMPs in series with different features and/or target pollutants

Several over-arching conclusions can be drawn from the research and design recommendations noted above:

- **Runoff Reduction** likely remains the most important BMP function for overall performance, addressing hydrologic and water quality criteria, including nutrients. Performance measurements that account for storage (e.g., surface area ratio to drainage area, media depth, etc.) are sound and in many cases verified by research. Innovations in adaptive controls to optimize storage are also promising, with lessons to be learned from implementation (Opti 2015). In this context, other performance enhancing techniques should be built on the foundation of runoff reduction.
- **Soil Media Amendments (sorptive minerals, biochar, etc.)** do appear to boost nutrient removal, especially for dissolved P. While not uniform in findings, the research provides good guidance on the types (Fe is better than Ca) and mixture rates (5-10% by weight, or mixed into the top 16 inches of media as a retrofit). Some of these materials, such as WTR, may otherwise be waste products and may be readily available and affordable.
- **Internal Water Storage (IWS)** is a strategy that targets dissolved N, and appears to be effective by promoting microbial activity and/or denitrification. IWS can be paired with a carbon amendment, such as biochar, and appropriate vegetation selection and management in order to be an effective tool. In some cases, IWS may take up storage capacity within a BMP and lead to more runoff bypassing the BMP treatment, so treatment trains may be warranted. In general, IWS seems to be a sound practice in areas where N is the primary nutrient of concern.
- Behind Runoff Reduction, **Vegetation selection and long-term management** appears to be the most important, common, and readily implementable strategy for enhanced nutrient removal. Vegetation plays a role in the uptake of nutrients that may otherwise be leached from the system. Of course, most bioretention and related practices are currently vegetated, and existing design

specifications include vegetation. However, the "enhancement" in this category includes refining the list of categories, species, and structure (e.g., dense root system and above-ground biomass) and long-term management, such as annual or semi-annual harvesting and removal in the spring/fall.

- **Installation and maintenance issues** will certainly not go away with the addition of media enhancements. Issues that came up in the research were short-circuiting, sloped ponding surface, and poor vegetative growth. The Bay stormwater community generally acknowledges these issues, and is trying to address them through better training, inspection and verification programs. However, if new performance enhancement techniques are promoted that also add a bit more complexity and cost, it becomes even more imperative to minimize preventable performance "discounts" associated with design, installation, and maintenance.

10. Integrating the Research with Existing Pollutant Removal Crediting Protocols

The Bay Program and model have an existing framework for crediting urban pollutant removal performance. The expert panels for *State Stormwater Standards* and *Urban Retrofit Practices* (Schueler and Lane 2012a, 2012b) formulated performance curves for TP, TN, and TSS. The curves gage pollutant removal percentages in relation to the amount of runoff captured by a BMP. The method includes two types of curves:

- Stormwater Treatment (ST) practices that achieve concentration reductions through filtering, settling, and other mechanisms.
- A higher Runoff Reduction (RR) curve for practices that also accomplish runoff and volume reduction through media storage, infiltration, evapotranspiration, water reuse, and other mechanisms.

It is important to note that individual Bay states have their own BMP crediting systems that also address the role of runoff reduction.

Tables 4 through **6** provide a rough summary, using median values from the research included in this literature review, as well as the pollutant removal percentages one would currently obtain by using the performance curves. The three tables address: (1) Media Amendments, (2) Internal Water Storage, and (3) Vegetation.

The summaries provided in the tables should certainly not be considered exhaustive or definitive, as there are continued options to obtain more precise numbers from individual research studies. The pollutants in ***bold/italics*** in each table are considered the specific target pollutant for the respective PED, which is important when considering modifications to a certain performance curve (separate curves for TP, TN, and TSS).

See the separate *Recommendations Memorandum* for specific recommendations for crediting PEDs using the performance curves.

Table 4. Media Amendments			
Pollutant	Performance Curves (% Removal)[1]	PEDs Research: Field (Median % Removal)[2]	PEDs Research: Lab (Median % Removal)[2]
Phosphorus	*54 - 71*	*51 - 72* [3]	*82*
Nitrogen	46 - 60		77

[1] Range represents performance curve results for 0.5" to 1.0" runoff depth/impervious acre.
[2] Most studies reported a range of removals based on research variables; the medians reported here were calculated using two values for the bottom and top of the reported range instead of each individual value. This is the same for Tables 5 and 6 below.
[3] Value for dissolved P, as that was the main target pollutant of field research. Of the research studies that measured both dissolved P and TP, the TP removal rate was at least 40% higher than the dissolved P rate. Therefore, the 51 -- 72% values can be considered conservative if extrapolated to TP removal rates.

Table 5. IWS			
Pollutant	Performance Curves (% Removal)[1]	PEDs Research: Field (Median % Removal)	PEDs Research: Lab (Median % Removal)
Phosphorus	54 - 71	57	89
Nitrogen	*46 - 60*	*68* [2]	*75* [3]

[1] Range represents performance curve results for 0.5" to 1.0" runoff depth/impervious acre
[2] Mass load reduction, which account for runoff reduction as well as EMC reductions
[3] Value is for NOx and not TN

Table 6. Vegetation			
Pollutant	Performance Curves (% Removal)[1]	PEDs Research: Field (Median % Removal)	PEDs Research: Lab (Median % Removal)
Phosphorus	54 - 71		86
Nitrogen	46 - 60		70

[1] Range represents performance curve results for 0.5" to 1.0" runoff depth/impervious acre

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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				
Bioretention				
Source	Material	P Removal	N Removal	Notes
Roseen & 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		

Table A.1. Media Amendment Research -- FIELD				
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 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 & Stormwater Filters				
Source	Material	P Removal	N Removal	Notes
Roseen & 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 & 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 Davis 2012	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

Table A.2. Media Amendment Research -- LAB				
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 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

Table A.2. Media Amendment Research -- LAB				
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 & 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 & 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 & 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.

Table B.2. IWS -- LAB			
Source	P Removal	N Removal	Notes
Zhang *et al.* 2011	TP: Accumulation in plants increased from 28% to >70% with IWS	TN: Accumulation in plants increased from 59% to 83% with IWS	Column study tested different combinations of plants, 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. Summary Tables for Vegetation Research:

Table C.1 summarizes the results of research on the role of vegetation in bioretention and bioswales. All of this research was conducted under laboratory conditions using mesocosm and column studies.

Table C.1. Research on Vegetation -- LAB				
Source	Vegetation	P Removal	N Removal	Notes
Henderson 2008	Various	TP: 85-94% conc. (31-90% for non-vegetated)	TN: 63-77% conc. (-12 – 25% for non-vegetated)	Mesocosms. 71-78% of N stored in above-ground biomass.
Caruso 2014	Big Bluestem, Switchgrass & other GA native grasses	TP: 86-92% conc.	Dissolved N: 72-85% conc. TN: max of 18% with many columns leaching	Best results with increased root thickness and density (Big Bluestem & Switchgrass). Columns also contained IWS.
Zhang *et al.* 2011	Plants native to Western Australia	TP: 28-71% retention in plant biomass	TN: 59-83% retention in plant biomass; higher % with IWS.	Column study. Removal increased as plants matured. Removal also enhanced in vegetated columns with IWS + carbon.
Lucas & Greenway 2008	Native grasses & shrubs from Australia	TP: 67-92% retention, compared to 39-56% for non-vegetated	TN: 51-76% retention, compared to maximum of 18% for non-vegetated	Mesocosms. P retention quickly exhausted in non-vegetated mesocosms.
Lucas & Greenway 2011b	Native grasses & shrubs from Australia		Dissolved N: 68-94% retention, compared to -17 – 25% for no IWS. TN: 53-78% retention, compared to 27-50% for no IWS.	Mesocosms, also with IWS. Vegetation significant factor for N retention, with better removal with higher residence time. Paper also stressed need to harvest vegetation.
Barrett *et al.* 2013	Buffalograss, Big Muhly (native to TX)	TP: 77-94% conc.	TN: 59-79% conc.; non-vegetated exported dissolved N	Column to test City of Austin bioretention specs.
Bratieres *et al.* 2008	*Carex appressa &*	TP: 85% conc.	TN: up to 70% conc.	Column test. Optimal design

Table C.1. Research on Vegetation -- LAB				
Source	Vegetation	P Removal	N Removal	Notes
	Melaleuca ericfolia from Australia			should be 2% of CDA, sand loam, and appropriate vegetation.
Read *et al.* 2008	20 Australian species	From 2 to >150 fold change in removal for N and P species, depending on vegetation.		Mesocosm pots
Scharenbroch *et al.* 2016	7 tree species from the Midwest	Study focused on water cycle and transpiration rather than nutrient removal		Through transpiration, trees accounted for 46 – 72% of water output from bioswales