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Building the Next Generation of Smart BMPs: Media Enhancements for Phosphorus Removal

Law, N. L[a]*, R. D. Christianson[a], L. Fraley-McNeal[b] and G. Hoffman[a]
[a] Center for Watershed Protection, Inc., Ellicott City, MD
[b] Watershed Protection and Restoration Program, Anne Arundel County Government, MD
*Corresponding author, nll@cwp.org

Abstract

The science and practice of stormwater management to improve best management practices to protect and restore water resources is an ongoing field of study. Innovation to develop smart BMPs is an essential component of stormwater management given the high cost of retrofitting urban areas and required pollutant load reductions to meet TMDLs and other local program goals. The focus of this paper is a review of the use of media additives to enhance the phosphorus (P) removal from BMPs and to identify information needs to move this innovation from research to practical application. A review of different types of additives and their pollutant removal capabilities is described along with information needs to move this smart BMP from research into practice.

Introduction

The evolution of stormwater management over the decades suggests that we are getting smarter about controlling and treating pollutants associated with stormwater runoff. Our improved understanding of stormwater runoff—its quality, quantity and impacts—has informed the design of best management practices (BMPs) to better protect our water resources. We have improved greatly on the detention-era, regional scale BMPs designed to control peak discharges and reduce flooding risks of the 1970s. Our improved understanding has moved us into an era of distributed systems intending to manage stormwater close to its source with smaller-sized, on-site BMPs that includes volume control. The development and implementation of total maximum daily loads (TMDLs) continues to push the field of stormwater science to innovate and meet the targeted load reductions in a cost-effective manner. Recent estimates to implement the Chesapeake Bay TMDL comes with a very high price tag; Maryland alone is estimated to need more than $2.5 billion to meet 2017 midpoint assessment targets and more than $7.3 billion for the 2025 TMDL target.[1] Stormwater management options to meet these load reductions focus largely on retrofits where BMPs are implemented on existing development that is currently untreated by any BMP or inadequately treated by an existing BMP. As urban stormwater retrofits may incur an annualized cost between $4,000 to $10,000[2] per acre of impervious cover (King and Hagan 2011) to implement, innovative approaches to develop smarter BMPs with demonstrated load reduction capabilities are needed for urban load reductions that can meet TMDL and other local program goals.

We define the new generation of smart BMPs[3] as practices that incorporate design elements to exploit specific physical, chemical and/or biological processes to remove targeted pollutants from stormwater. Smart BMPs may also include technology to better control the volume and rate of stormwater runoff to maximize the treatment capacity of a BMP (Clark and Pitt 2012; Schueler 2012). Examples of smart BMPs highlighted by Schueler (2012) include: filter media and other design features that are directly related to enhanced nutrient reduction, the retention or release of stormwater volumes within a BMP based on real-time weather data, design features that capture nutrients in a confined area where they can be removed and possibly re-used, or self-inspection features that identify failures or maintenance needs. These smart BMPs that retrofit existing practices have the potential to avoid major, costly retrofits in areas without stormwater management, thereby also increasing cost-effectiveness.

The focus of this paper is a review of the use of media additives to enhance the phosphorus (P) removal from BMPs and to identify information needs to move this innovation from research to practical application. The appeal of media additives is their low cost, high availability, and low toxicity to soil and water resources.

Enhanced Media to Improve Nutrient Removal

Stormwater BMPs have varying degrees of documented nutrient removal capability, which depend on variables such as hydraulic loading rate (size), drainage area characteristics, and design elements, for example, to promote pollutant removal processes (i.e., sedimentation, plant uptake,

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[1] See Maryland Department of Environment 2012, Phase II WIP Implementation Plan, Appendix C, http://www.mde.state.md.us/programs/Water/TMDL/TMDLImplementation/Documents/FINAL_PhaseII_Report_Docs/Final_Documents_PhaseII/Appendix_C_PhIIWIP_Cost_Funding_Studies_101512.pdf).

[2] Initial survey, design, permitting, land and construction costs may average $108,000 (King and Hagan 2011).

[3] The use of the term smart BMPs is separate from the SMART tool developed by the University of Maryland Extension to track the implementation of smaller scale residential and private properties Best Management Practices. Information on the SMART tool can be found at http://extension.umd.edu/watershed/smart-tool.

denitrification). By including additives to the BMP soil media, these practices can be modified to achieve enhanced nutrient removal rates through the use of specific removal pathways. A majority of the published literature on enhanced media focuses on dissolved P removal, and as such, is the focus of this review. Nitrate and nitrite are more challenging to remove with soil additives as a result of their high solubility and are more effectively treated by design features that enhance soil microbial processes to facilitate denitrification, as well as plant uptake (Clark and Pitt 2012).

Stormwater runoff P is found in both the dissolved and particulate phase. Stormwater practices typically provide capture of particulate P by settling and/or filtration; however, few stormwater practices have a mechanism for capturing dissolved P over the life-cycle of the practice (Hunt et al. 2012). As the National Stormwater Quality Database finds that approximately 54% of the total P in stormwater is in the dissolved phase, this fraction may receive only minimal treatment by a BMP. According to Erickson et al. (2012), this untreated dissolved P can be more than 95% of total P depending on the storm event. Of particular concern are the surface water quality impacts of dissolved P because of its greater bioavailability than particulate P. Bioavailable P can result in eutrophication of freshwater lakes and rivers (Smith et al. 2006). The addition of P-sorbing media (PSM) enhancements to soils with high phosphorus concentrations has been shown to reduce water-soluble P and, therefore, reductions of dissolved P in runoff (Gallimore et al. 1999; Rhoton and Bigham 2005; Callahan et al. 2002). Further, Liu and Davis (2014) suggest that phosphorus enhancing media added to a BMP's soil mixture may improve the performance of the BMP by reducing the variability in phosphorus load reductions.

Media Enhancement Materials

The media enhancements are typically metal cations that react with dissolved P to create an insoluble compound that cannot physically move through the infiltration media. PSM enhancements come in the form of natural materials, by-products from industrial activities, or synthetic filtration products, all of which contain appreciable concentrations of aluminum (Al), iron (Fe), calcium (Ca) or magnesium (Mg). The solubility of these metal cations vary based on their chemical forms and environmental parameters, such as pH. Most PSM enhancements can be classified into two groups: Ca/Mg- and Al/Fe-based. The Ca/Mg-based enhancements remove P by precipitation reactions that occur at a much slower rate compared to adsorption reactions of P with Al/Fe oxides/hydroxides (Penn et al. 2007). The faster reaction rates of Al and Fe may favor these types of additives, compared to Ca/Mg additives.

Naturally Occurring Materials

Limestone, gypsum, hydrated lime and other Ca-based products are commonly used for increasing the pH of a solution. Limestone tends to be very stable and has relatively low solubility compared to other materials such as gypsum, which limits its reaction potential with P. Although gypsum has less influence on pH, it is much more soluble than limestone, allowing for greater reaction potential with P. The Ca in these products promotes the formation of insoluble Ca phosphates (Penn et al. 2007).

Waste Materials

Industrial by-products are often the substrate of choice for PSM enhancements because of their widespread availability and low cost compared with natural materials and synthetic filtration products (Buda et al. 2012; Ballantine and Tanner 2010). In many instances, this material can be obtained at no cost other than trucking the material to the desired location. However, the potential environmental impacts of heavy metals leaching into runoff needs to be understood and controlled for and is a part of the developing research for the media enhancements. Acid mine drainage (AMD) flocculant or industrial by-products, such as fly ash, slag from the steel industry, sludge from the paper industry, foundry sand from metal casting, waste products from bauxite processing, and drinking water treatment residuals (WTRs), are examples of PSM enhancements (Agyei et al. 2002; Torbert et al. 2005; Penn et al. 2007). In addition, certain industries produce by-products rich in gypsum from mining or production of drywall (Penn et al. 2007).

Other Materials

Biochar is another material being explored to reduce the impact of AMD (Oh and Yoon 2013) and nutrient leaching (Major et al. 2009). Biochar is pyrolysized (using extreme heat with no oxygen) biomass that results in an extremely porous material with high surface area for its volume. Materials often used for production include wood chips, chicken litter, and switchgrass, though any other biomass substances can be used. Biochar can aid in P removal because it provides a carbon source and high surface area for biological activity. Because of the large variety of parent materials, the resulting product can have significantly different physical properties, which could lead to significantly different P removal rates. This discrepancy illustrates the need to develop standards for biochar, specifically relating to P removal in BMPs. Research studies in Wisconsin and North Carolina are also investigating the use of commercially available mix of Al and Fe oxides. Finally, there are many specially designed sorbent materials with high surface area used in a more commercial setting for removal of hydrocarbons, esters, acids, pesticides, etc. (Yang et al. 2013). This type of stormwater media has not had an overwhelming number of field trials to demonstrate effectiveness; however, substantial use in commercial applications has helped drive standards and specifications for some of these materials.

Phosphorus Removal Potential

The majority of studies on the ability of PSM enhancements to reduce water-soluble P have been conducted in the laboratory, with fewer field-scale examples in urban BMPs. Although laboratory studies represent a first step in determining the suitability of media enhancements for field-scale experimentation, their results may be difficult to compare with long-term field studies (Westholm 2006) and may not effectively simulate the varying climatic and hydrologic conditions observed in a field situation (Buda et al. 2012). Further, the physical-chemical characteristics of the various types of PSM within the same category can also affect P adsorption and thus removal (Salame and Bandosz 2003; Li et al. 2002; King et al. 2010). However, initial studies of PSM show promise regarding its load-reducing capabilities for urban BMPs.

P removal by a BMP varies widely depending on the inflow P concentration, amount of PSM added, pH of runoff, flow rate, and contact time between the PSM and dissolved P. Erickson et al. (2012) found that only a few seconds are available for the reactions to occur during column experiments. The researchers found that 5% Fe-filing mixtures retained substantial phosphates compared to a 0.3% mixture. The reaction of the metal cations with dissolved P is also affected by the type of PSM and pH. In general, Al and Fe are effective at removing dissolved P when the pH is less than 7.5 (Rhoton and Bigham 2005); similarly, Ca and Mg additives more effectively react with P at pH levels between 6 and 7.5. Although the pH is an important factor in driving the reactions to precipitate P, acidic conditions or low pH levels may release metals from sediment and into solution (i.e., runoff) increasing the toxicity or harmful effects to surface waters. Further, Novotny (2003) lists a range of detrimental biological impacts that result from low pH levels. The National Stormwater Quality Database suggests that the pH of stormwater runoff is on average neutral, with a pH of 7.2.

Flow conditions may also affect performance; research by Penn et al. (2012) found removal of dissolved P to be greater than 60% at low flow rates compared to less than 25% removal at high flow rates. The higher flow rate likely affects the contact time between the PSM and the dissolved P in runoff, limiting the reactions to occur (O'Neill and Davis 2012a; Liu and Davis 2014). The high flows can also overwhelm the saturated hydraulic conductivity of the filtering media in the BMP, resulting in decreased retention times and reduced treatment efficiencies (Pionke et al. 2000). Additional research is needed to determine how BMPs with PSM respond to different storm events (Hunt et al. 2012) and where concentrated flow conditions exist (Buda et al. 2012).

Acid Mine Drainage Flocculant

AMD (Figure 1) flocs are one of the materials commonly studied for P removal application. AMD flocs contain many of the same compounds effective in P removal as the more commonly used materials of Fe and Al oxides and Ca compounds, such as limestone and gypsum. When AMD is neutralized with alkaline substances, a floc is formed, consisting mainly of base metal hydroxides, sulfate salts and unreacted alkaline material. The resulting floc may have a high Fe or Al content, or a mixture of the two, depending on the host rock composition (Adler and Sibrell 2003).

Figure 1. Acid mine drainage material collection.
Credit: U.S. Geological Survey, Department of the Interior/USGS, U.S. Geological Survey/photo by Philip Sibrell. (available at http://gallery.usgs.gov/photos/12_17_2012_d28Kb54AAu_12_17_2012_1)

Laboratory studies show a high P removal efficiency from the use of AMD flocs, ranging from 60–95% efficiency based on concentration (Adler and Sibrell 2003; Sibrell et al. 2009; Penn et al. 2011). A field-based study by Penn et al. (2007) for an agricultural drainage ditch filter amended with AMD floc resulted in a 99% P load reduction in the treated flow. However, that was only for one sampled storm event, and the ditch was only capable of treating 9% of the total flow. Adler and Sibrell (2003) found that at an amendment rate of 20g/kg soil, the AMD floc decreased water soluble P by more than 70%. A mixture of Fe and Al oxides in AMD sludge resulted in better P sorption than in sludges primarily containing either Fe or Al hydroxides alone (Sibrell et al. 2009).

Drinking Water Treatment Residuals

Drinking WTRs are by-products from the coagulation process in drinking water treatment that includes Al and Fe minerals with high P-sorption potential (Penn et al. 2007). Laboratory studies of WTRs show greater than 80% P removal efficiency based on concentration (Penn et al. 2011; O'Neill and Davis 2012b). In addition, a field analysis of an existing bioretention cell retrofit with WTR by Liu and Davis (2014) found an 84% P load reduction, compared to 55.1% load reduction before the retrofit and without WTR. Overall amendment with WTR decreased dissolved P mass by approximately 60%. O'Neill and Davis (2012b) suggest that amending the soil with WTR at a rate of 5% by mass and to a depth of at least 10 cm (3.9 inches) should be sufficient to adsorb influent stormwater P. Further work is needed to determine the capacity for P adsorption by varying the application rate of PSM and its incorporation into media at varying depths.

Figure 2. Drinking water treatment residuals. Credit: U.S. Department of Agriculture. Agriculture Research Service/photo by Peggy Greb. (available at http://www.ars.usda.gov/is/graphics/photos/jul04/k11257-1.htm)

Iron Filing Enhancements

Erickson et al. (2012) found that Fe filings added to a sand filter increased the removal of dissolved P such that effluent concentrations were significantly reduced compared to using sand alone as the media. A 5% mixture by weight reduced approximately 33% of the effluent samples to concentrations below 0.01 mg/L phosphate, concentrations considered oligotrophic. In these experiments, the 100% sand media did not effectively reduce any phosphate, whereas lower percentages of Fe filings by weight became saturated and could no longer retain phosphate. Field applications of sand filters enhanced with Fe filings showed removal efficiencies between 29% and 91%, where the performance of the enhanced sand filter increased with elevated influent phosphate concentration. Erickson et al. (2012) state that the expected removal of phosphates from Fe filing–enhanced sand filters would be between 85% and 90% for the majority of rainfall events.

Moving PSM Int Practice

According to CSN (2014), the top stormwater topic stormwater practitioners want to learn more about in the next year is smart BMPs. Laboratory and field-based studies provide promising results that demonstrate the improved performance of BMPs to further reduce P loadings in stormwater. Although PSM amendments will likely continue to remove P for the lifetime of the BMP (e.g. Lucas and Greenway 2011; O'Neill and Davis 2012b; Erickson et al. 2012), design specifications, material specifications, cost information and maintenance issues need to be addressed prior to their widespread application.

Similar to other material specifications for BMP designs, the use of PSM requires testing to ensure that the additive will perform as expected. This includes, for example, determining the PSM composition and physical-chemical properties that may affect its P sorption or capacity. Materials used for PSM, such as WTR or AMD flocculants, contain other materials that may pose a risk when added to BMPs (Ballantine and Tanner 2010). Other material considerations is the impact PSM may have on the infiltration capacity of volume-reduction BMPs. Clogging has been a reported issue using limestone or calcareous sand, resulting in hydraulic failure (Erickson et al. 2007), and also has been reported with Fe additives (as referenced by Minnesota Pollution Control Agency 2014). Hunt et al. (2012) recommend media infiltration rates for bioretention BMPs of 0.007 and 0.028 mm/s (1 to 4 inches per hour) to provide adequate hydraulic retention time for P sorption to occur. This typically results in a minimum bioretention media depth of 0.6 m (2 ft) and a depth of 0.9 m (3 ft) for good total P sequestration at those depths (Davis 2007; Hatt et al. 2009; Passeport et al. 2009). Liu and Davis (2014) found that a 5% (by mass) mixture of WTR with bioretention media did not negatively affect its infiltration. However, Erickson et al. (2012) found that a higher percent composition of Fe filing reduced the filtration rate of a sand filter, although this was not statistically tested. The hydraulic conductivity was similar for a range of Fe filings mixtures of 0% (all sand) to 5%.

Although lower infiltration rates would allow more complete reactions with P, current bioretention soil media specifications have relatively high infiltration rates as a result of heavy sand content. Materials used for PSM may allow for adequate P removal while meeting current soil specifications, thus maintaining high infiltration. Regardless, additional research is needed to determine the proper balance.

Another consideration of adding PSM to BMP designs is the unintended consequence of releasing previously sorbed metals in sediment within a BMP. For example, design features such as an internal water storage (IWS) layer that create anoxic conditions to promote denitrification may leach P under saturated, or anoxic, conditions. Jansson (1987) found that nitrate-reducing bacteria can increase the rate of dissolution of Fe-phosphate precipitates in stream sediment under anoxic conditions. Given the potential conflicting benefits of two separate design features, Hunt et al. (2012) recommend the location of an IWS below the P-sequestering portion of the media with a 0.45–0.6 m (1.5–2 ft) separation between the top of the IWS layer and the media surface. In addition, the impact of cations from the use of road salts in cold climates should also be considered when selecting additive materials. These cations can displace previously sorbed heavy metals, allowing them to exit the BMP and move downstream (Clark and Pitt 2012). As such, stormwater engineers are tasked with developing design specifications that clearly articulate the outcome of BMP enhancements such that one feature does not negate the benefits of another or ensure that features are not negatively affected by local environmental conditions.

Perhaps most importantly, there is a need for larger scale studies to test the pollutant removal numbers that have been reported to date and further refine and expand on the limited design guidance that currently exists. Although the Minnesota Pollution Control Agency is moving toward approval of Fe-enhanced filings for P removal, it seems likely that enhancing filter media with specific additives will become an essential contributor to pollutant removal for BMPs—whether these additives are P, as discussed here, or other pollutants, such as heavy metals, pH, bacteria or another pollutant specific to a given site.

In an effort to increase the performance of BMPs while using less space, researchers and practitioners have taken a hard look at the physical processes and constraints governing typical stormwater management. Opportunities for advancement are seemingly limitless as researchers and stormwater practitioners start to examine combinations of additives for specific pollutant reduction, specialized media to maintain high flow-through rates using less space, targeting BMPs to reduce pollution at/near the source, and real-time monitoring of water quantity/quality with an adaptive management approach. When we add in rainfall prediction and the use of advanced computing techniques at local or regional scales, we may be able to further reduce the size and increase the efficiency of BMPs. All of these possibilities may change what we call the next generation of smart BMPs in the future.

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