Improved Media and Plant Species for long term sustainability of Nutrient Retention in Bioretention Systems

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Advanced Bioretention Experiments:
Washington State University and the Science Museum of Virginia

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Abstract
This paper presents a brief background on nutrient removal performance of an improved bioretention system. An advanced media has been tested that greatly improves phosphorus (P) retention by bioretention facilities for many decades. The systems include an innovative outlet design that provides for extended detention of small events while passing large events through the media. The increased retention time significantly improves nitrogen (N) retention compared to free discharge facilities using sandy media.

An extensive study of these systems is presently under way at Washington State University (WSU) and the Science Museum of Virginia (SMV). The former comprises a comprehensive array of 1.5m diameter mesocosms, with four replicates for each of five media treatments. This large size allows for the interaction of plants and media to be observed. The SMV system comprises two field scale systems, one with advanced media, while the other has a compost sand based media. All systems incorporate the outlets.

Introduction
Excess nutrient loads from non-point source (NPS) runoff, whether urban or agricultural, are the most common and widespread stressors upon receiving water bodies. The deleterious effects of excess nutrients upon receiving waters has been documented in many studies. Correll (1998) noted that excess nitrogen is responsible for the eutrophication of estuaries and marine environments. As an example, elevated N inputs are implicated in the degradation of the Chesapeake Bay and the anoxic zone in the Gulf of Mexico. Excess phosphorus is responsible for the eutrophication of freshwater lakes (Vollenvieder, 1968; Correll, 1998). Runoff from even relatively small areas of directly connected impervious areas (DCIA) results in impairment of urban streams. Elevated levels of reactive P and algal biomass were associated with increased DCIA (Walsh et al, 2005).

As a result, measures to improve nutrient retention performance of better management practices (BMPs-and not necessarily best) are essential to improving the ecological well-being of our water resources. Of the suite of BMPs available, bioretention is considered among the more effective, largely because removal rates of total suspended sediments (TSS) and metals is very high (Davis et al, 2001). However, their nutrient retention performance has been more variable and less effective, particularly for N (Davis et al. 2006).

This paper briefly investigates the various biogeochemical mechanisms involved in nutrient retention, and how bioretention systems can be improved to maximize nutrient retention. A description is then provided of how these factors have been incorporated into the design of several different bioretention BMPs. An overview of the large mesocosm and field scale experimentation of these advanced bioretention systems in Washington and Virginia is also provided.
Nutrient Retention

Since particulate nutrients are easily filtered by bioretention systems, this paper focuses upon dissolved forms of N and P. These nutrients comprise several different species, each with differing implications for interception and impacts. Dissolved P is primarily found as ortho-phosphate (PO₄-P). This is the form of P that it is most readily taken up by plants and algae. Since it is highly reactive with soils, it is adsorbed within the soil profile. The resultant equilibrium concentration depends upon the cumulative P adsorbed in relation to the extent of available sorption sites. Dissolved organic P (DOP) comprises many different compounds, most of which have not been identified. Unlike PO₄-P, some of these compounds do not bind to soils.

Nitrogen oxides (NOₓ) comprise nitrate and nitrite, which is found in very low concentrations. Nitrate is the form of N preferably taken up by plants. It is very conservative in groundwater, so once infiltrated, it can pass into the receiving waters with minimal attenuation. NOₓ is generated by ammonium nitrification, a process that occurs readily in runoff so ammonium is often found at low concentrations. Ammonium is generated by the mineralization of organic nitrogen (ON), which occurs rapidly with readily degradable compounds such as urea. Other forms of ON are much less degradable.

Phosphorus Retention

Many studies suggest that bioretention systems retain the majority of applied P (Davis et al. 2006; Hsieh and Davis 2005; Bratieres et al., 2008). However, these studies represent relatively new systems that have only been exposed to short term P loads. On the other hand, P saturation in constructed wastewater wetlands is widely reported in the literature on P sorption (Johansson-Westholm 2006). Unvegetated (barren) column studies by Erickson et al. (2007) and Hsieh et al. (2007) also document that retention by sandy media such as that used in most bioretention treatments will be exhausted within a decade at typical bioretention loads. Even with vegetation present, Lucas and Greenway (2008) confirmed that sandy media will be exhausted within a decade of stormwater loading. A salient finding of this study was that plants substantially improved P retention, even though uptake was a minor proportion of the P retained.

Therefore, measures to improve media retention of P are necessary for long term P retention performance. A promising option is the use of water treatment residuals (WTRs). WTRs are the residues resulting from coagulating dissolved organic acids and mineral colloids with aluminium sulfate. Together with clay and organic matter from the raw source water, Al-WTRs comprise extensive amounts of aluminum hydroxides, of which a substantial proportion is in the most effective amorphous form.

To evaluate WTR amendments over the lifetime of a bioretention facility, Lucas and Greenway (2010a) recently published the results of a 18 month study of 240L mesocosms (three replicates for each treatment) filled with 60cm of WTR-amended media. The WTR30 treatment comprised a pure WTR amendment. The WTR-K treatment combined WTRs with Krasnozem soils, which also are very effective in retaining P. These systems had regulated outlets to extend retention time in the rapidly draining media. The WTR-Knr treatment was a free discharge WTR-K system with no outlet regulating device, used as the control.

To accelerate nutrient loads, these systems were dosed weekly with 55 cm of tertiary treated effluent at an average PO₄-P concentration of 2.8 mg-L⁻¹. At a hydraulic loading rate of 29 m-y⁻¹, this resulted in a P load of 1,190 kg-ha⁻¹ over the eighteen month duration of the study. Even taking into account high uptake rates, this is equivalent to over three decades of typical bioretention loads. Every six months, lower concentration synthetic stormwater runs of a similar intensity (60 cm over 90 minutes) were undertaken to examine trends in P retention as these loads accumulated. Refer to Lucas and Greenway (2010a) for more background and discussion of this experiment.
Cumulative PO$_4$-P retention over the entire experiment was 99%, with stormwater outflow concentrations remaining close to the detection limit of 0.004 mg-L$^{-1}$. Figure 1 compares the results from the first stormwater dosing at 26 weeks to the final dosing at 80 weeks. The percentages indicate the amount of retained PO$_4$-P and total dissolved P (TDP), respectively. Net inflow represents the amount of inflow remaining after projected plant uptake. This was based on observations of other treatments where P uptake was projected at 110 kg-ha$^{-1}$-yr$^{-1}$ (Greenway and Lucas, 2009). Recent analysis of the WTR-K treatment indicates that average P uptake was 118 kg-ha$^{-1}$-yr$^{-1}$ (Greenway and Lucas, 2010).

This high uptake value reflects regular harvesting of plants subjected to very high nutrient loads. Depending upon concentration, projected uptake represents 34% to 53% of the stormwater PO$_4$-P load, and a lower proportion of the TDP load. In all cases though, uptake is much less than observed reductions. PO$_4$-P retention by the WTR treatments was 89% to 93%. Surprisingly, retention became even better after another 54 weeks of PO$_4$-P loading. By this time, the outlet regulated treatments were 99% effective, while the free discharge system retained 94% of applied PO$_4$-P.

We hypothesize that rapid P retention is mediated primarily by microbial activities, as the WTR-Knr treatment with a media contact time of barely 15 minutes was often as effective as the outlet regulated system with a contact time at least 7 times longer. This short of an exposure is not long enough for even the most rapid (and most reversible) sorption processes to provide such high retention of PO$_4$-P. During inter-event periods, immobilized microbial P is then released back into the media where a cascade of sorption processes sequesters P irreversibly. As a result, it is the long-term sorption properties of media amendments that dominate the retention response. Due to rhizosphere microbial processing, retention of TDP was less, but still at least 92% in the outlet regulated systems. Most of the resultant dissolved organic P (DOP) compounds are much less bioavailable than PO$_4$-P.

The preceding indicates that Al-WTRs are excellent candidates for removal of P, as they perform well at neutral pH values, while offering very high infiltration rates. The infiltration rates observed in our study ranged from 37 to 115 cm-h$^{-1}$, which is why the retention time without the outlet was so short. Combined with sand, refractory organics and aged compost, this media can provide much better P retention performance than a pure sand/compost media often used. In this manner, improved hydraulic performance is combined with advanced P retention amendments to improve media properties.
Nitrogen Retention

Unlike P sorption by media amendments, N retention is largely mediated by biological processes. While uptake may be the most obvious process, net uptake declines when plants senesce, unless they are harvested regularly. Other biological transformations may also occur that promote denitrification, which is irreversible. Together, these processes can remove considerable amounts of N from urban runoff, even at dilute concentrations conveyed at high flows. Therefore, factors underlying N removal must be taken into account in order to design systems that improve N retention. This is of particular importance in the case of nitrogen oxides (NOx) which comprise nitrate for the most part.

N removal in barren columns has been universally reported as poor, with little retention of total N (TN), and export of NOx (Hsieh and Davis, 2005; Hsieh et al. 2007). In contrast, TN removal can be substantial (sometimes exceeding 75%) in corresponding vegetated treatments, (Henderson et al. 2007; Lucas and Greenway 2008; Bratières et al. 2008, Lucas and Greenway, 2010b). Since other studies also confirm that N removal is either minimal or absent in similar barren systems, this suggests that the factor most responsible for retention of N in bioretention systems is the presence of vegetation. This relationship is particularly evident in the case of NOx, as there is a clear trend toward export of NOx in barren systems (Henderson et al, 2007; Lucas and Greenway, 2008; Lucas and Greenway, 2010b).

As in the case of P retention, we projected uptake based on the observations of Greenway and Lucas (2009) where annual N uptake in similar treatments was observed at 400 kg-ha^-1 yr^-1. At this value, projected uptake was a relatively small proportion of NOx load, and even lower proportion of TN load, as shown in Figure 2. However, recent analysis of the WTR-K treatment showed that annual N uptake was actually 636 kg-ha^-1 yr^-1 (Greenway and Lucas, 2010). Given this value, projected uptake closely matched the N retention observed in these systems. This suggests a minimal amount of denitrification. With uptake projected to vary as a function of season, uptake corresponded with retention trends, as shown in Figure 2.

Once the plants had matured by September 2008, the outlet controlled WTR-K treatment performed significantly better than the corresponding free discharge WTR-Knr treatment. We hypothesize that this is due to the differences in retention time. The saturated hydraulic conductivity of the media used in the free discharge replicates ranged from 104 to 115 cm-h^-1, while the hydraulic conductivity of the media in the outlet regulated replicates ranged from 37 to 96 cm-h^-1. (Lucas and Greenway, 2010c).

Figure 2: Cumulative NOx (solid) and DN (hatched) inflow and outflow loads (kg-ha^-1). (a) Winter Season: March 2008 to August 2008, from 26-50 weeks, and (b) Summer Season: September 2008 to February, 2009, from 52-80 weeks. Net inflow represents the load projected to remain after plant uptake. Percentages represent removal for NOx and TN. (From Lucas and Greenway, 2010b).
A dual stage outlet was used to equalize the flow response between these replicates to eliminate variations in retention time from affecting N retention results. In brief, this outlet had a low flow orifice that controlled drainage to 8 cm h\(^{-1}\) when the system ponding ceased. Once ponding occurred due to high inflows, the upper outlet with a high capacity conveys rapid flows as a function of Darcy’s Law through the media. The upper outlet elevation was set to equalize the effective infiltration rates among the different replicates, being lowered for less rapid media so there is more effective head (Lucas and Greenway, 2010c). This outlet configuration extended retention time in the system from less than 19 minutes to more than 157 minutes, which is over an eightfold increase (Lucas and Greenway, 2010c). As a result, there is more time for nitrification-uptake/denitrification processes to occur, resulting in the improved retention performance displayed in Figure 2.

The outlets were elevated to provide an 18 cm deep internal saturated (IS) zone. Zinger et al (2007) showed that an internal saturated (IS) layer in vegetated columns can be very effective when it represents a considerable proportion of the inflow volume. Mesocosms with an IS layer approximately 70% of the applied volume were able to provide close to 100% NO\(_x\) removal from small volumes of synthetic stormwater. However, in our stormwater dosing experiments, the mesocosms where subjected to an intense event equal to 25 mm of rainfall in 90 minutes at a 25:1 source to treatment area capture ratio. This represents an event that occurs perhaps twice a year in Brisbane. As such, it reflects a considerably higher hydraulic load and intensity than reported in other experimental observations. At these rates, the IS layer represented only 15% of inflow volume. Figure 3 presents the results of the stormwater runs after 80 weeks of the experiment.

TN retention by the WTR-K treatment of 66% in the high concentration stormwater runs was over twice the 27% reduction in the unregulated WTR-Knr control. The 62% NO\(_x\) retention by the outlet controlled treatment was over three times the 19% retention obtained in the control. Both of these outlet regulated results were significantly better. In the low concentration runs, TN retention was only 35% due to outflows being limited to an irreducible concentration in the range of 0.25 mg L\(^{-1}\). However, the 76% NO\(_x\) retention by the outlet regulated configuration was significantly better than the 28% NO\(_x\) retention in the control.

Figure 3: Mean NO\(_x\) (solid) and DN (hatched) inflow and outflow concentrations (mg L\(^{-1}\)). (a) Four events with high stormwater concentrations, and (b) three events with relatively low stormwater concentrations. Net inflow represents the load projected to remain after plant uptake. Percentages represent removal for NO\(_x\) and TN. (From Lucas and Greenway, 2010b).
These results indicate that increased retention time can provide considerable N retention, even when subjected to very high flow rates. The innovative aspect of this outlet system is the provision of an upper outlet designed to convey high flows so overall responses are not constrained by the lower outlet. By setting its elevation so that even very large events still pass through the media, the entire volume of particulate pollutants and metals are treated, instead of being bypassed into the receiving waters. Its elevation is set highest when the media has the highest hydraulic conductivity. As the media accumulates sediments and becomes less permeable, the outlet is lowered to provide more head across the media. This results in flow responses similar to what was obtained when the media was originally installed. This provides a unique approach for adaptive management over time as the systems age.

Large Scale Experimental BMP Design

Washington State University

Based upon the preceding findings, several extensive experiments are presently under way in the USA to test these findings with much larger mesocosms and at the field scale. Washington State University (WSU) is constructing twenty 160 cm diameter mesocosms with five media types (four replicates each). In addition to the mesocosms, sixteen pilot scale (4.5 m square) rain garden facilities will be constructed to compare three different planting palettes to a barren control. Media depth is 60 cm in the mesocosms, and 45 cm in the rain gardens. This system is located at the Agricultural Extension Station in Puyallup, WA, USA.

The rain garden systems will utilize the standard Washington State 60% sand/40% compost (v/v) media. This translates to 90% sand/10% compost on a weight basis. In addition to the standard mix, the mesocosms will evaluate a variant in which some of the compost is replaced by coir peat to decrease leaching losses. Two other treatments will evaluate both of these mixes amended with 20% (v/v) WTRs to improve P retention. Subject to the findings from column studies, a final mix may evaluate biosolids mixed with biochar and WTRs. The mesocosms will utilize meadow grass/perennial vegetation.

In all, the 9 different treatments (four replicates each) will be monitored over a period of at least five years. The system is supplied with runoff from a 0.8 ha equipment maintenance facility. This assures a regular supply of suitably polluted runoff into the mixing and distribution tanks shown in Figure 4a. These tanks have ejectors to maintain well mixed conditions. Flows from the tanks then pass into the rain gardens and mesocosms by gravity. Flows are equally distributed to each replicate through arrays of V-notch weirs in each distribution tank.
In this manner, the system can allocate flows passively and the BMPs will function for pollutant removal even when experiments are not being conducted. After an initial two-year observation period of background runoff events, additional pollutants will be mixed into the runoff in the distribution tanks during events to observe responses to elevated pollutant levels. Eventually, the mesocosms will be saturated with P to accelerate aging of sorption capabilities. Likewise, an experiment will add TSS to the rain gardens to accelerate the onset of clogging responses. In this manner, the long term responses of these experimental treatments will be obtained.

All of these systems will utilize the version of the dual stage outlets shown in Figure 4b. Not only will these outlets improve retention time, they will also be used to equalize drainage responses in soils and media with differing infiltration rates. This is essential for eliminating the effect that differing retention times would have upon treatment N responses. Since the vegetation palette for the mesocosms will be identical, it is expected that N retention will be similar among treatments once the systems mature. By manipulation of outlets in selected treatments with similar N retention responses, the effect of altering retention times will become more apparent. To accomplish this, the outlets also have a bypass to permit observation of unregulated conditions found in most bioretention systems.

Flows from the mesocosms will be measured with tipping bucket flow meters, while flows from the rain gardens will be measured by trapezoidal flumes. Flows will be continuously monitored in all events to obtain annual hydrologic performance data. This level of accuracy for continuous flow measurement across so many treatments with so many replicates is unparalleled in BMP research. The system will be operational in

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Figure 4: a) Layout of WSU Bioretention Array, b) Plan and elevation view of typical outlet.
September 2010. Each of the 36 replicates will be sampled for all nutrient species over the two-year duration of the initial monitoring program. Under this protocol, the mass balance of cumulative inflow and outflow loads will be obtained.

Science Museum of Virginia: Bioretention

Another series of field scale experiments is underway at the Science Museum of Virginia (SMV), located in Richmond VA, USA. In this study, two full-scale bioretention systems are to be constructed, one using a WTR-amended media, which is to be compared to the other using the same compost/sand media as used for WSU. Each system comprises 93 m² of bioretention media 60 cm deep, underlain by 45 cm of stone within which the underdrains are placed. Located in very poorly infiltrating soils, they drain a source area of 2045 m², with a capture ratio of 22:1. Both systems will use a more elaborate version of the outlet, as displayed in Figure 5.

In this case, two underdrains are used. The lower underdrain is controlled by an adjustable orifice similar to the WSU system. The underdrain is supplied by a series of SmartDrains®, which are laminar flow sheets that do not clog due to roots or algae, even with clay soils. This prevents roots from entering the underdrain, which is intended to remain within an IS zone. The outlet is adjustable to set both IS elevation and extended detention outflow rates, which are set to provide the optimal balance between retention time and treatment volume. A very low flow “drain” outlet is used to equalize the effective infiltration rates between replicates. Closed in the system with the higher rate, it would be opened as needed in the system with the lower rate to provide equivalent drawdown times. In this manner, differences in retention times due to underlying soil properties can be minimized.

The upper underdrain is located at the top of the stone layer, which is typically above the IS elevation so potential for root penetration is minimized. This underdrain supplies the upper outlet comprising an adjustable Van Stone flange and a pipe/elbow assembly. By rotating the flange, the effective elevation of the aperture which determines head across the media is established. As in the case of the lower outlet, its elevation will be set according the saturated hydraulic conductivity of the media. In this manner, the differences in hydraulic properties between the two systems will be minimized, so the experimental comparisons will not be affected by retention time differences.
Inflows are to be measured by highly accurate HS flumes. Outflows will be measured by V-notch weirs placed inside the outlet boxes. A baffle plate is used to divert overflows from the grate from bypassing the weir. Pressure transducers in the surface, the underdrain and the outlet box will enable measurements of flows into and through the media. The knife valve is used for measurements of falling head hydraulic conductivity needed to determine infiltration rates. This is accomplished by shutting the lower outlet and knife valve before a small event so runoff can be ponded. The valve is then opened up and the decline in water elevation is recorded over time.

After the systems are fully established, the differences in N and P retention will be observed with typical runoff. As in the case of the WSU experiments, the WTR amended system will eventually be saturated with P to accelerate aging of sorption capabilities. TSS will also be added to accelerate the onset of clogging responses in both systems, so that the effect of outlet adjustments can be examined. These systems are to be constructed in the fall of 2010.

If highly permeable coastal plain soils had been present, it would be necessary to retain the runoff treated by flow through the media so it is not immediately infiltrated. This would be accomplished by lining the media and underdrain stone with an impermeable membrane so that flows can be captured and then controlled by the outlet. Treated runoff then infiltrates into an additional stone layer under the liner, with excess flows of treated runoff discharged through the pipe system. In this manner, treated runoff can be infiltrated and/or discharged at much lower N concentrations than with a typical free discharge system. In N sensitive watersheds, this concept would be essential to obtain adequate N retention.

Figure 5: a) Elevation of SMV bioretention outlet, b) Section through SMV bioretention outlet.
Science Museum of Virginia: Planter-Trenches

In addition to the bioretention systems, four innovative planter/trench systems for ultra-urban retrofits will also be installed. These are similar to the planter trench systems designed for Philadelphia Water Department (PWD) to reduce combined sewer overflows (CSOs) (Lucas, 2009). However, in this case, the systems are designed to be installed on streets with grades as high as 6%. This is accomplished by judicious selection of materials and disaggregated routing of flows through the various compartments of the system. These compartments and their linkages are displayed in Figure 6. As indicated by the surface discontinuities, its length is broken up to shorten it to fit on the page.

The planters are 120 cm wide by 420 cm long. Two of the four planters will use WTR amended media, while the other two planters will use the standard bioretention media. The planters are placed between two structural stone compartments. Each stone compartment is 6 m long and 1.8 m wide. Depth varies according to the grade of the sidewalk above. The structural stone is proprietary blend of coarse graded aggregate mixed with clay loam and a binding agent to prevent separation of the clay from the stone. As such, it not only provides structural load bearing capacity, it also permits plant roots to extend through the stone to obtain water and nutrients. This substantially increases both vigor and eventual size of the trees in the planters. It also provides approximately 30% storage within its voids.
Flows are collected off the street by means of a curb cut, from which they enter an inlet distribution box that also acts as a sump to collect debris and grit. After passing through a vertical screen of PermaPave™ to keep out floatables such as cigarette butts, flows enter the planter by means of a perforated pipe. The planter surface is located 15 cm below the street, so it receives runoff in all events, and most of the runoff in all but the more extreme events. In larger events, runoff also enters the distribution pipe into the upper stone through a standpipe 10 cm above the planter surface. Inflows are measured with trapezoidal flumes.

Flows from the planter and the upper stone compartments have to pass through the pea gravel to fill up the lower stone. These flows are routed according to Darcy's Law according to the relative head between the upper stone/planter and the lower stone. In this manner, the hydraulic gradient applied results in different peak storage elevations in what would ostensibly be considered a “level” storage compartment. These elevations are graphically displayed in Figure 6. In large events, this peak elevation can differ by over 40 cm.

Flows are conveyed from the lower stone to the upper outlet by a perforated pipe, while a smaller SmartDrain™ collection system is used to convey low flows to the lower extended detention outlet, similar to the method used in the bioretention systems. Note that this design does not contemplate adjustments in the upper outlet, since flows through the stone and pea gravel are so much faster than flow through the planter media so outlet elevations can remain as high as possible. Its elevation is set just high enough to prevent surcharging onto the surface to maximize storage. During experiments, its elevation will be manipulated to observe its effect upon performance as part of the experimental analysis of these systems. A V-notch weir is used to measure flows through both outlets, from which flows drop into a pipe that passes through the next planter downslope. This permits an additional grade drop for each planter trench system determined by overall system gradient. In this way, it is possible for the four different facilities in this experiment to be individually manipulated to provide a factorial analysis of the effect of both the media and the outlets. Pressure transducers in the inflow, stone and media will record the hydraulic gradient through the various compartments. As in the case of the bioretention systems, these hydraulic components will be continuously monitored throughout the experimental period.

Conclusions

Several innovative elements to improve the performance of urban retrofit BMPs have been presented in this analysis. The use of WTR media amendments will essentially eliminate P discharges from the system for its entire life cycle. The dual stage outlet offers the best retention time performance, while being able to treat high flows effectively. Therefore, it provides the most effective N removal possible during the entire life cycle of bioretention BMP facilities. As such, this provides an opportunity for N retention to be substantially improved over current free discharge technologies.

This also means that the system will be able to treat particulate bound pollutants and dissolved P that would otherwise bypass the system during large events. By providing for adaptive management of these facilities, much greater N retention can be obtained compared to typical designs, while still treating high flow volumes. The long term experiments under way at WSU and SMV will provide extensive data on how well these systems perform over time, and how the outlets can be adapted to changing media and site conditions to optimize hydraulic performance.

References


