Design Guidelines for Detention With Biofiltration

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Stormwater runoff contains a large number of contaminants, including nutrients (nitrogen and phosphorus), metals, oil and grease, organics, solids, and microorganisms (U.S. Environmental Protection Agency, 2005). Excessive nutrients discharged from urbanized areas can cause eutrophication in receiving water bodies (Figure 1a). Best management practices (BMPs) have been used as a measure to reduce nitrogen loadings to receiving water bodies. One type of BMP is low impact development (LID), which can incorporate innovative measures to restore system hydrologic function and reduce nitrogen loadings. Due to recent legislative initiatives, stakeholders have become increasingly more interested in the potential benefits that LID technologies provide.

One type of LID technology is bioretention (Figure 1b), also known as "raingardens," "bioinfiltration," or "bioswales" (Davis et al, 2006). The surface of bioretention systems may be planted with vegetation, such as wildflowers, sedges, rushes, ferns, shrubs and small trees, to provide a landscaped area. This enhances their aesthetic appeal to property owners and municipal and other agencies. Bioretention systems have the capability of reducing runoff volumes, attenuating peak flows, and removing solids, organics, fecal indicator organisms, metals, phosphorous, and various forms of nitrogen (Davis et al, 2006). As a unique advantage to other LID technologies, bioretention systems can be modified to include an internal water storage zone (IWSZ) containing an electron donor (e.g., wood chips or sulfur pellets), to remove nitrate (Kim et al, 2003; Ergas et al, 2010). A bioretention system that includes an IWSZ can be referred to as a detention with biofiltration system (Figure 2).

A number of nitrogen transformation processes occur in detention with biofiltration systems that include nitrification, denitrification, immobilization, mineralization, plant uptake (Lucas and Greenway, 2011b), adsorption, and filtration. In particular, denitrification is the only of the mentioned processes that can remove nitrogen from water and discharge it into the atmosphere as nitrogen gas. An extensive study was conducted to understand the factors controlling nitrate removal in IWSZs. This article presents the results and previous work by others that can be used to better understand how detention with biofiltration systems function and the design of these systems can be improved, and reports on the progress of a recent field demonstration.

Methods

Laboratory microcosm and column studies were conducted in the Environmental Engineering Laboratories at the University of South Florida (USF). Field studies that are currently being carried out at a field site in Tampa are described.

The source water that was used in the laboratory studies was surface water from a USF campus stormwater pond. The source water was spiked with 2 mg/L of potassium nitrate to mimic expected nitrified conditions as runoff enters the IWSZ. Batch experiments were conducted to evaluate nitrate removal performance using various media types, such as sand, pea gravel, eucalyptus wood chips (Figure 3a), tire chips, and mixtures of these materials under unsaturated, saturated, aerobic, and anaerobic conditions. The sand and gravel were obtained from Seffner Rock & Gravel, wood chips were obtained from Sarasota County staff, and tire chips were obtained from Liberty Tire Recycling. Column experiments (Figure 3b) were used to investigate nitrate removal performance using the gravel-and-wood-chip medium using varying IWSZ detention times of 0.25 to 9 hours; IWSZ depths of 1, 1.5, and 2 ft); and antecedent dry conditions (ADCs), which are the number of days between the previous and current storm event, from 0 to 30 days. More detailed methods and the majority of the results from the wood-containing media types can be found in Lynn et al (2014a and 2014b). The tire-containing media types were used as a side experiment to evaluate whether tire media

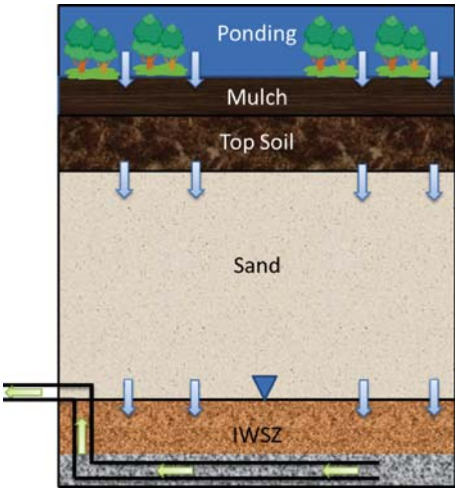

Figure 2. Cross-Sectional View of a Typical Detention With Biofiltration System

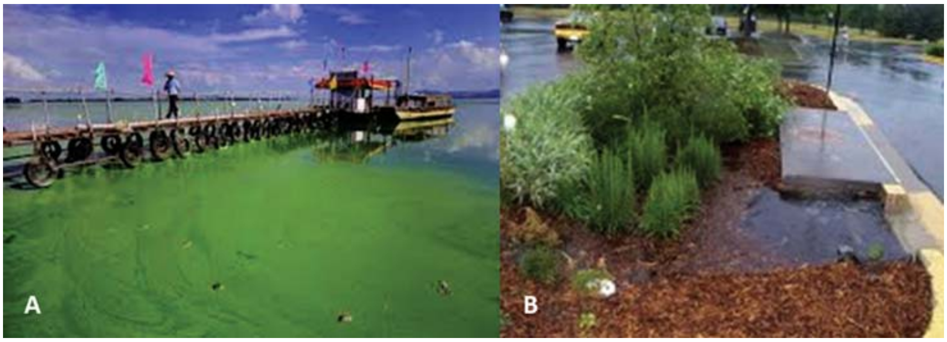

Figure 1. Water body Impaired by Eutrophication (A) and a Bioretention System (B)

could be used as an alternative electron-donor media to promote denitrification.

Laboratory Study Results

Concentrations of nitrate (as nitrogen) over time from the saturated batch experiments using the sand, gravel, and tire-containing media types are shown in Figure 4. The tire-containing media was the only medium that appreciably removed nitrate, with the tire-only media removing nitrate the fastest, followed by the gravel-and-tire and sand-and-tire media. Similar results were observed using the wood-containing media types (Lynn et al, 2014a). Additional investigations of nitrate adsorption and denitrification using tire-containing media can be found in Krayzelova et al. (2014).

Nitrate removal efficiency data from a 30-day ADC storm event are shown in Figure 5. The storm event was set up to mimic the falling head hydraulics over approximately 36 hours for a slug load storm event, which is typically used to satisfy water quality drawdown requirements. Nearly 100 percent of the nitrate was removed in all columns from the first sample taken (water that was detained in the IWSZ prior to the storm event). Nitrate removal efficiency in all columns decreased during the second sample taken; thereafter, nitrate removal efficiency increased as the detention time increased. Nitrate removal efficiency in the 1-ft cm column was consistently lower than the 2-ft column, even though these columns were operated with equal detention times.

Figure 3. Photograph of the Wood Chips Used for the Study (3a) and Experimental Setup Used for Column Study (3b)

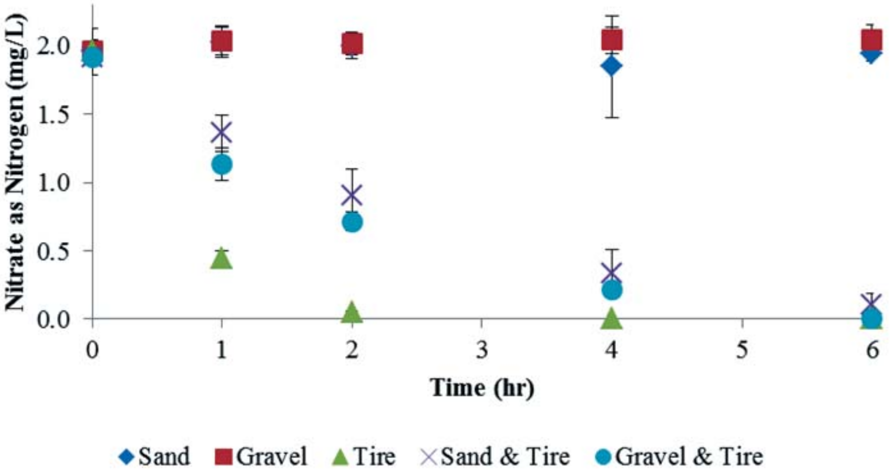

Figure 4. Nitrate as Nitrogen Concentration Data from the Sand, Gravel, and Tire-Containing Media Batch Experiments With Error Bars Representing Standard Deviation

Design Implications

The batch experiment results (Figure 4) provide insights on how nitrate is removed from IWSZs. The results clearly show that an electron donor media source (tire chips, in this case) needs to be included in IWSZ media to remove nitrate within a short period of time (6 hours). In addition, the carbon-containing media with the greatest surface area (sand-and-tire) removed nitrate at a slower rate than the other carbon-containing media. This is quite interesting since a higher-surface area medium is generally assumed to enhance removal. The use of a larger particle-size medium in IWSZs is therefore recommended since these materials also have higher hydraulic capacities. The results also indicate that tire chips can be used as an alternative electron donor to promote denitrification in the IWSZ. However, the gravel-and-wood media was selected for further evaluation due to the wide body of literature and the presumed greater societal acceptance to use wood instead of tires.

Data from the 30-day ADC storm event (Figure 5) provide clues on the dynamics of nitrate removal in IWSZs. As the initial runoff from a storm event enters the IWSZ, water previously detained in the IWSZ is discharged. The initially discharged water should be assumed to have a very low nitrate concentration, since this water was detained in the IWSZ for a long period of time. Nitrate removal efficiency will then decrease as water from the current storm event discharges from the IWSZ. When the water surface elevation in the system decreases towards the end of the storm, nitrate removal efficiency will increase because the system will be operating at higher detention times (Lynn et al, 2014). The depth of the IWSZ also plays a role in nitrate removal. Taller IWSZs were found to remove nitrate at a higher rate, even when the systems were operated at the same hydraulic detention time. This is attributed to greater dispersion in the shorter columns (Lynn et al, 2014b). Based on observation, effective IWSZs should be "generally" designed with a mean detention time of three hours and a length of at least 1.5 ft. The term "general" should be stressed since biological processes and their rates can change with respect to other environmental factors.

An important measure in designing an effective detention with biofiltration system is to ensure that organic media additives (wood chips, tire chips, etc.) are only included in a permanently submerged IWSZ. An impermeable liner should be designed to encapsulate this layer in conjunction with an under-drain layer. There are two reasons for this control measure: 1) unsaturated organic material will quickly degrade (Moorman et al, 2010) and

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decrease the longevity of the system; and 2) unsaturated organic material will export high concentrations of both nitrogen and phosphorus from the system (Lynn et al, 2014a).

The longevity of organic material largely depends on whether the material is placed in a saturated or unsaturated environment. Organic material that is placed in an unsaturated environment (such as mulch added to the surface) will rapidly degrade due to rapid decomposition from aerobic bacteria and fungi. In saturated environments, however, anaerobic bacteria excrete a "film" around organic substances, which slows organic carbon (in addition to nutrient) leaching into the pore water (Malherbe and Cloete, 2002). By including organic material in a permanently saturated environment, it is estimated that this material will supply organic carbon for at least 10 years (Lynn et al, 2014a).

Typical biofiltration systems include an organic mulch layer, which is placed just above the sand layer. The organic mulch layer can be used to retain oil and grease in runoff, improve moisture in plant root zones, and prevent the growth of weeds (Hunt et al, 2012). However, recent findings reveal that an organic mulch layer acts as a nutrient source, resulting in the export of high concentrations of total kjeldahl nitrogen (TKN), phosphate, and dissolved organic carbon (Lynn et al, 2014a). Furthermore, current operation and maintenance procedures suggest a frequent replacement of the organic mulch layer (Hunt et al, 2012). These measures would certainly increase nutrient loadings into the system and may eventually be discharged into receiving waters; therefore, it is recommended to replace the organic mulch layer with a nonorganic layer such as pea gravel or lava rock.

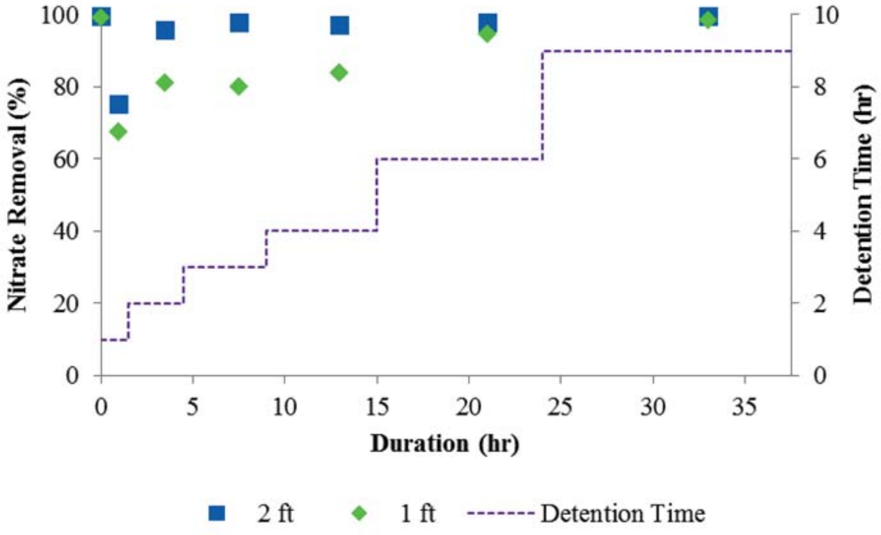

Figure 5. Nitrate Removal Efficiency Data From the 30-Day ADC Storm Event

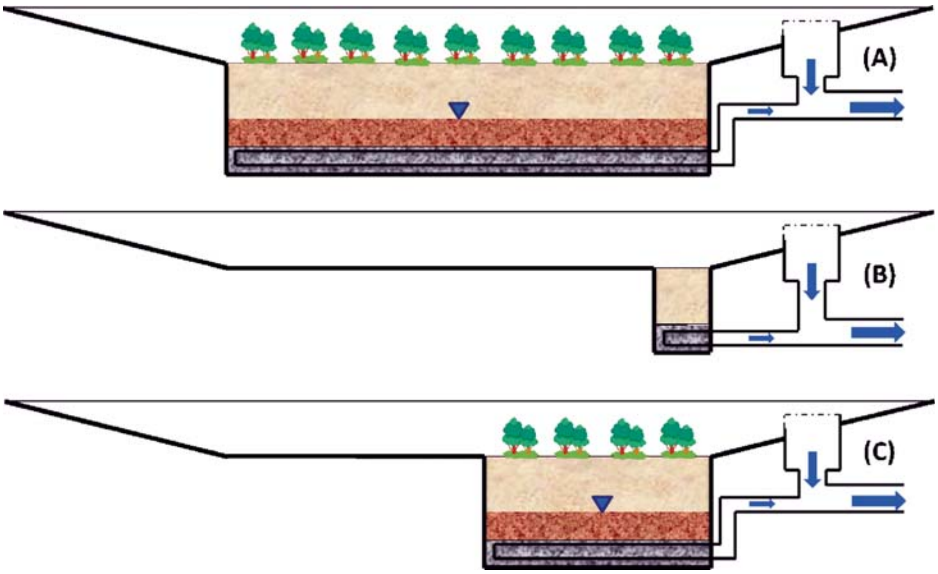

Figure 6. Structural Schematics of a Typical Detention With Biofiltration System (a), an Under-Drain Filtration System (b), and a More Suitable Detention With Biofiltration System for High-Rainfall Climates (c).

General Sizing

To ensure effective management, detention with biofiltration systems needs to be regulated under specific design criteria that is independent of other conventional stormwater system design requirements. For example, if detention with biofiltration systems is designed in accordance with criteria for underdrain or side-drain filtration systems, there will not be enough time to allow biological processes to substantially remove nitrogen. If these systems are designed in accordance with detention system regulations, the retention of water in the ponding layer could increase the mosquito-breeding potential. Therefore, specific design criteria for detention with biofiltration systems need to be developed.

A large portion of biofiltration development, research, and implementation has been conducted in the Northeast, Midwest, and Mid-Atlantic states. As a result, design guidelines for these systems are more conducive to regions that have poorly drained soils with relatively constant year-round precipitation. A schematic of a typical detention with biofiltration is shown in Figure 6a. This design includes planted engineered soils that encompass the entire bottom of the ponding area; however, in areas with high rainfall (e.g., Florida), stormwater management systems require a larger footprint. Detention with biofiltration designs in high-rainfall climates will require greater capital expenditures and operation and maintenance costs if typical designs are used.

Under-drain filtration systems (Figure 6b) have many similar physical characteristics as detention with biofiltration systems. Design guidelines for under-drain filtration systems require the treatment volume to be discharged from the ponding area within a maximum of one-and-a-half to three days. Engineers often design these systems to be as small as permitted by regulation. These guidelines and resulting design measures impact biological nutrient removal processes since the filtration cell is operated at a low detention time.

In high-rainfall climates, detention with biofiltration systems should be designed so that the cell footprint is smaller than the pond bottom area, but larger than the area required for conventional under-drain filtration systems, as shown in Figure 6c. Design requirements should include a range of drawdown times to ensure that the ponding area is large enough to prevent flooding and that a sufficient detention time is provided to allow biological processes to occur. Three design parameters that can be modified to meet this criteria include: 1) changing the cell footprint; 2) changing the type of filtration media used (hydraulic conductivity); and/or 3) including an orifice between the under-drain discharge pipe and the weir control structure. Lucas and Greenway (2011a) proposed a unique dual-stage orifice discharge system that could be beneficial under some circumstances.

Establishing Design Credits

Detention with biofiltration systems should be subject to similar treatment removal design methodologies as other stormwater systems. Dry retention treatment design methodology assumes 100 percent nutrient removal efficiency from any runoff that infiltrates into the ground (Harper and Baker, 2007). Similarly, 100 percent nutrient removal efficiency should be assumed for any runoff that is retained outside of the filtration cell in detention with biofiltration systems. Even though this assumption is not scientifically correct, it should be included for the designer to perform a more accurate comparative analysis when selecting the most appropriate treatment system.

The hydraulic characteristics of detention with biofiltration systems are different from other stormwater treatment systems. In particular, these systems will likely be designed to include a large amount of engineered soil. The drainable porosity volume in the unsaturated sand layer will provide a greater detention capacity than just the designed ponding treatment volume. For example, assuming 1) a system is designed to detain 1in. of runoff with a treatment depth of 12 in., 2) the filtration cell contains 2 ft of unsaturated engineered sand with a drainable porosity of 25 percent, and 3) the cell footprint is one-half the size of the ponding area. If the volume of the drainable porosity is included with the volume of the ponding area, then the system is actually designed to detain 1.25 in. of runoff.

Detention with biofiltration systems will also detain a significant volume of runoff in the saturated zones. Adding on to the example provided, assume that the depths of the IWSZ and under-drain layers are each 1ft and both of these layers have a drainable porosity of 0.4. The combined detention volume of runoff in these layers would then be 0.4 in., with a total system capacity of 1.65 in. of runoff. In addition, stormwater treatment regulations focus on treating runoff from small storm events. The majority of storm events will likely generate a volume of runoff that is less than the pore volume capacity of the IWSZ/under-drain layers. This means that most of the generated runoff will be detained during the storm event and during the ADC days after the storm event.

Detention with biofiltration systems should be provided additional water quality/quantity credit for the volume of runoff that can be detained in the sand and IWSZ/under-drain layers. However, two challenges will arise in establishing this credit: 1) regulators will need to adopt robust design guidelines to ensure that this credit does not create unintended consequences; and 2) design procedures may need to be established using existing stormwater modeling software or simple equations that ignore important variables (e.g., soil moisture content), which control system performance. A practical solution may be to assume that the ponding volume, sand pore volume, and IWSZ/under-drain pore volume function in whole as a detention basin where runoff "drops" into the entire system. In addition, the discharge hydraulics of the system could be modeled using Darcy's Law and continued to be modeled in this fashion, even when the water elevation is located within the sand layer.

Figure 7. Installation (left) and Installed Bioretention Cells (right) at the Spotford Center

Issues

Stormwater filtration systems must be carefully designed and maintained to prevent clogging, which can reduce flow through the treatment system, increase flooding potential, and increase maintenance costs. Plant roots in detention with biofiltration systems can reduce clogging by creating macropores in the sand layer (Hatt et al, 2009); however, this can also decrease total suspended solids removal. An additional measure could be to control the flow of the system with an orifice at the outlet of the discharge pipe, as described. If an orifice is used, the filtration rate will be lower than the hydraulic capacity of the filtration media, which can reduce clogging and improve total suspended solids removal.

There is a possibility that detention with biofiltration systems could impact receiving waters from indirect processes at the expense of removing nitrate from stormwater runoff. Before denitrification occurs, facultative anaerobic bacteria consume dissolved oxygen, reducing the dissolved oxygen concentrations in water discharged from the IWSZ. In addition, excess dissolved organic carbon produced from the wood chips may also be discharged (Lynn et al, 2014). This could prevent dissolved oxygen from reentering the discharged water, which may impair receiving surface waters. Additional research should be performed to investigate these potential issues.

The experimental study was focused on understanding the processes that control nitrate removal in the IWSZ of detention with biofiltration systems. However, it is also important to understand how other design elements (sand layer, plants, etc.) function independently and in combination with all other design elements to provide the most appropriate design recommendations. For instance, if ammonia is not completely nitrified in the sand layer before runoff enters the IWSZ, then the footprint of these systems may need to be increased to enhance total nitrogen removal.

The current knowledge in understanding all of the factors that control treatment processes in stormwater systems is limited. This prevents engineers from developing dynamic water quality models that can accurately predict water quality performance. A

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dynamic model is currently being developed for these systems that can be used to quantify nitrogen removal performance with existing stormwater modeling software.

Full-Scale Bioretention System Demonstration

The current research includes an evaluation of full-scale bioretention systems, with and without IWSZs containing an organic electron donor, under field conditions. These systems will be used to: 1) evaluate bioretention under southwest Florida conditions; 2) verify models of nitrogen removal performance that are currently under development; and 3) demonstrate the value of bioretention to community members, middle and high school students, and regulators. Students from the Corporation for the Development of Communities (CDC) Tampa Vocational Institute are assisting with this project to provide green-job training for disadvantaged youth.

Two bioretention cells (Figure 7) were constructed at CDC's Audrey Spotford Youth and Family Center in Tampa in November 2013, with the help of Ceres H_2O Technologies of Sarasota. The cells receive runoff from the Spotford Center parking lot and roof. The dimensions of the top of the ponding area are 11 ft x 16 ft. Cell A has an IWSZ containing a mixture of wood chips and pea gravel, similar to the medium described in the column experiments. Cell B is a conventional bioretention design without an IWSZ. Each cell was installed in a wooden frame lined with an impermeable geomembrane (20 ft x 24 ft) that prevents water table drawdown. An underdrain system was designed to allow sampling of system effluents. Both cells were topped off with a 1-ft-deep layer of paver sand and planted with native vegetation including Blue Love Grass (*Eragrostis elliottii*), Sea Ox-eye Daisy (*Borrichia frutescens*), Frog Fruit (*Phyla nodiflora*), and Soft Rush (*Juncus effuses*). Plants are an important aesthetic element, which can also help to avoid erosion of the sand. Plants also play a role in nutrient uptake (Lucas and Greenway, 2011b). Native plants are recommended because they are adapted to the local weather patterns and do not need fertilization; however, vegetation requires maintenance, especially at the beginning until roots are established.

After some showers and thunderstorms during the winter of 2013-2014, erosion began occurring along the sides of the bioretention cells. High-velocity water from a nearby downspout and the setup of the liner were causing erosion inside and around the system. The liner began to collapse and plants and sod that were placed over the liner did not root and began to die. To solve these problems, the liner was cut back and nailed to the edge of the wooden frame, dead plants were replaced, and 3/8-in. river rock mulch was added over the sand. A splash block was placed below the downspout to reduce the velocity of the rainwater (Figure 8).

Figure 8. Rehabilitation of Geomembrane Liner and Plant Maintenance After First Winter

Conclusions

More stringent regulations for controlling nutrient discharges from urbanized areas have recently been adopted to protect and enhance the quality of surface waters; however, these measures present economic challenges to developers, as greater land areas will need to be devoted to on-site stormwater management systems. Detention with biofiltration systems can provide a solution to both of these problems. The research shows that these systems have the potential to increase nutrient removal, while decreasing the stormwater management system footprint. Additional laboratory research, modeling studies, and field studies are needed to have greater assurance that detention with biofiltration systems effectively manages stormwater runoff under Florida specific conditions.

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