Mississippi Water Resources Research Institute (MWRRI)
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Soil Media Compositions for Water Quality Improvements and Stormwater Management in Urban Flow-through Facilities

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ABSTRACT

Nutrient removal and volume reduction capabilities of a range of soil media mixtures in urban flow-through planters were investigated. Eighteen scaled flow-through mesocosms were evaluated for nitrogen and phosphorus removal rates and volume reduction by applying a synthetic stormwater solution over a simulated 2-inch, Type II storm hydrograph. Three replicates of six treatments were tested including four soil mixtures. Significant ($p<0.05$) reductions in volume for 100% sand, 75% sand, 50% sand content mesocosms compared to the controls, indicating bioretention mixes with higher sand content have greater water retention capabilities. For water quality results, both concentration and load reductions were calculated and compared, where load accounted for volume passing through the mesocosms and therefore more accurately represented water quality results. PO_4 load reduction was greater in treatments with less sand (up to 41% reduction). NO_3-N load reduction varied greatly (7% removal to 53% loading). Significant phosphate loading was observed at the peak of the hydrograph (between minutes 60 and 120) compared to the controls, indicating greater flow rates decreased the nutrient removal capabilities of bioretention in the experiment. Preferential flow patterns were observed which potentially led to higher than expected infiltration rates and therefore no observable peak flow reduction.

OBJECTIVES

The first overall goal of this research project was determine the water quality and quantity capabilities for a range of bioretention soil mixtures in scaled flow-through planter mesocosms. This was accomplished with the construction of a replicated lab experiment which was used to conduct initial water quality and quantity testing and was set up for future testing of other pollutants, different storm events, influences of plant material, facility geometry, inflow delivery and underdrain configuration.

The second goal of this project was to construct a transportable working model of a flow-through facility and an accompanying fact sheet to be used for outreach which includes findings from the experimental mesocosm research.

INTRODUCTION

Municipalities throughout the U.S. are cautiously moving toward a green infrastructure approach to mitigate the negative impacts of increased stormwater runoff from impervious surfaces. Green infrastructure or low impact development (LID) practices rely on the cumulative impact of many, small-scale, bioretention based best management practices (BMPs) to manage stormwater as close to the source as possible. These bioretention based BMPs utilize soil and plant material to reduce peak flows, reduce overall runoff volume and remove urban pollutants (Debo and Reese, 2003; Holman-Dodds, 2007; Boller 2004).

Bioretention based BMPs are designed to reduce peak flows by restricting stormwater to a pre-development runoff rate. This is accomplished through the infiltration rate of the designed soil mix, which effectively controls the rate at which runoff is allowed to move through the system. When inflow rates exceed the infiltration rate of the soil mixture, ponding occurs in the reservoir. Overall runoff reduction is accomplished in one of two ways. First, bioretention facilities encourage infiltration by creating a shallow depression, which concentrates runoff and allows it to infiltrate into in situ soils. Second, if infiltration is not possible, runoff is reduced by engineered soil media, absorbing rainwater and storing it where it is later available for plant uptake or is evaporated. In this “flow-through” configuration, water not absorbed moves through the soil media layer and is directed to an underdrain for collection and disposal.

Bioretention based BMPs are designed to improve water quality in two primary ways. First, they filter total suspended solids (TSS) which many urban pollutants bind to. Second, through biological and chemical processes such as adsorption and microbial and plant uptake, urban pollutants such as nutrients, heavy metals, oil, grease, and pathogens are broken down. Nitrogen (N) and phosphorus (P), two dominant nutrients found in runoff from urban environments, have been identified as major contributors to the degradation of aquatic ecosystems (Alexander et al., 2008; Carpenter et al., 1998).

Bioretention in Practice

Federal, state and city level guidelines for bioretention soil mixtures vary across the U.S. Three primary design objectives, which recommendations have attempted to balance, are: high enough infiltration rates to provide adequate drainage, low enough infiltration rates allow for adequate contact time for pollutant removal, and plant health (WSU, 2009). Most bioretention recommendations provide general soil type specifications such as sandy loam or loamy sand due to their adequate infiltration rates (PGC, 2009; LID Center, 2003; UC Davis Extension, 2012). Several municipalities recommend a more specific breakdown of soil media composition. More specific recommendations for engineered soil mixes consist of 50-60% sand, 20-30% leaf compost, and 20-30% topsoil (PGC, 2009 and Davis and McCuen, 2005). Portland Oregon's 2008 Stormwater Management Manual, which is widely referenced across the U.S., recommends a 1/3, 1/3, 1/3 mixes of sand, topsoil, and compost (Portland BES, 2008).

The actual removal efficiency of sediment and pollutants by bioretention systems varies greatly by media variations in each experiment (Lucas and Greenway, 2008; Davis et al., 2006, Cho et al., 2009). Lucas and Greenway (2008) found that mixtures with greater organic matter reduced P at a greater rate than those with 100% sand. However, most mixtures were found to load N and those mixtures with higher organic matter either were not as effective at retaining N or loaded N at a higher rate. These findings are supported by Davis et al., 2006. A few studies show promising removal rates of lab experiments with homogenous sandy mixtures with N as high as 99% and P removal rates as high as 99% (Davis et al. 2006).

Davis et. al. (2009) reviewed current literature related to bioretention research and determined that there is a need to fill gaps related to a range of design and performance issues including: pollution prevention and removal, peak flow reduction, soil/filter media composition, treatment processes, retention, and time of concentration issues. Field experiments have typically focused on the performance of installed bioretention cells and measured treatment removal capabilities based on actual rain events or a synthetic stormwater concentration delivered to the facility (Hunt et al., 2006, Li and Davis,2009; Trowsdale and Simcock 2011; Hatt et al., 2008; Dietz and Clausen, 2005). Total P removals ranged from as high as 87% removal rates in studies by Davis et al. (2003), to a net export of P in rain garden and bioretention cell studies of -110% to -240%, (Davis et al. 2006; Dietz and Clausen 2005b), respectively. Conversely, Dietz and Clausen showed significant removal rates of total nitrogen (TN) (51% total retention) and is consistent with other studies for TN retention (40-59%) retention of TN (Hunt et al, 2006; Dietz and Clausen, 2006; Davis et al., 2003). Lab experiments have included bioretention boxes and soil columns which typically focus on soil mixture pollutant removal efficiencies with a few that look at soil depth as well as different applied flow rates and varied pollutant input concentrations.

Davis et al (2006) varied flow rate over multiple experiments to observe the effects of flow rates and duration on pollutant removal efficiencies. They found that shorter and lower flow rates had higher removal efficiency for N and P due to longer contact time. Li and Davis (2006) also observed that soil depth can have a significant impact on nutrient removal by testing effluent at multiple depths of filtration. However, no studies to date have been identified that applied a simulated hydrograph to bioretention experiments.

METHODS

This current study tested N and P reduction capabilities of various soil mixes with scaled mesocosms designed to specifications found in practice. To reflect actual rainfall patterns, a synthetic stormwater runoff was delivered over a hydrograph versus a constant flow rate.

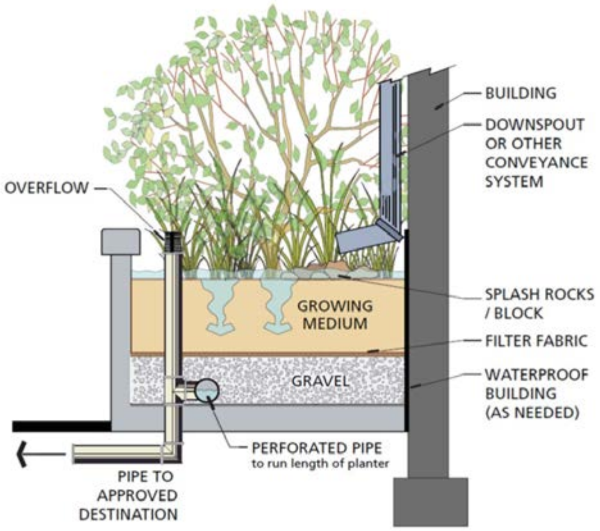

Fig. 1. Section of a flow-through planter per Portland's Bureau of Environmental Services

Experiment Components

Mesocosms were constructed to be replicates of, vertically scaled flow-through facilities based on the design specifications of the Portland, OR Bureau of Environmental Services (BES) flow-through planter. Mesocosms were scaled to a fourth of the typical flow-through facility. The flow-through facility type was selected because it has a single release point, which allows for a controlled measurement of outflow from the facility. Eighteen 30 in. x 18 in. x 12 in. mesocosms were assembled with three replications of six treatments. Each mesocosm was constructed with vertical layers of each mesocosm of a 3.0 in. layer of gravel; a filter fabric material; 4.5 in. of soil media and 3.0 in. of reservoir depth (fig. 2). Each mesocosm was fitted with a 0.75 in. I.D. (check style) outlet and perforated polyvinyl chloride (PVC) underdrain running the length of the facility. A "T" PVC fitting was attached to the underdrain and connected to a reverse elbow overflow, set to 3 in. above the soil media layer. Below the gravel layer was a 1.5 in. layer of sand, covered by a plastic sheeting, to allow the underdrain to rest on the bottom of the facility. The treatments included a control (containing the perforated PVC pipe), an underdrain assembly (which consisted of a gravel layer, filter fabric and perforated PVC pipe), and four different soil treatments. The soil treatments ranged from 25% sand with equal parts top soil and compost to 100% sand (table 1). A small pile of washed river rocks was placed in the corner of each mesocosm containing soil to create an energy disperser where the synthetic stormwater runoff would be directed into the mesocosm.

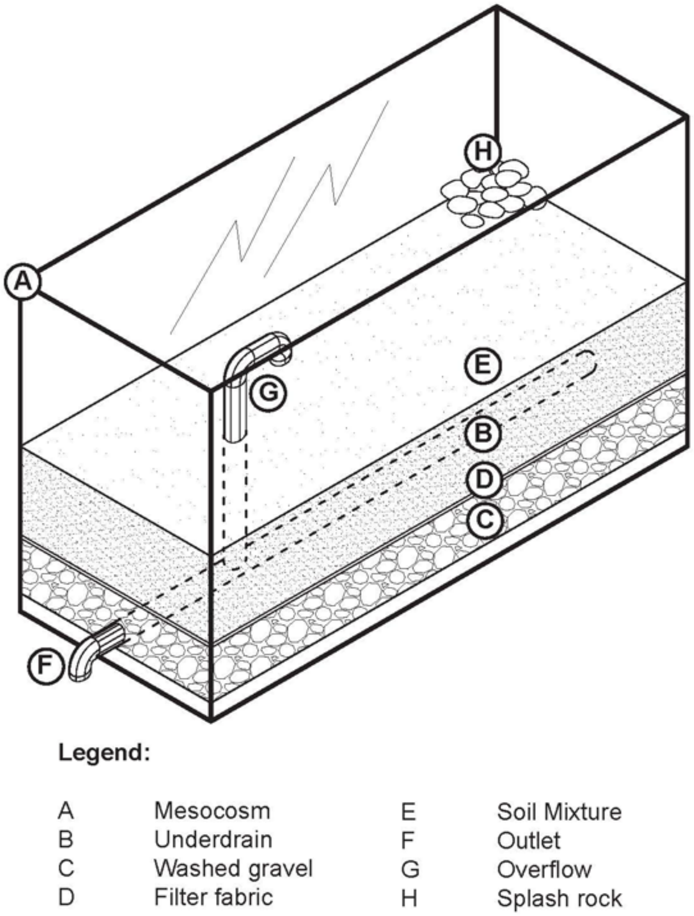

Fig. 2. Detail of mesocosm experiment components based on Portland, Oregon's specifications.

The gravel was 0.75- 1.0" washed aggregate acquired from a local distributer. Filter fabric (Mirati, 140NL, TenCate, Inc.) was a nonwoven geotextile designed specifically for filtration. Sand, top soil and compost used to make the individual soil mixtures was collected from a local earthwork materials distributor. Each soil mixture treatment was uniformly hand-mixed for the desired percentages and hand compacted to simulate compaction that would occur during installation. No plant materials were used in the facilities in order to focus results on the individual soil mixtures.

Table 1. Treatment mixtures and soil sample test results for native soil and treatment mixtures.

Soil	Sand (%)	Topsoil (%)	Compost (%)	Clay (%)	Silt (%)	Sand (%)	Texture
		Treatment Mixtures					
Native Topsoil	n/a	n/a	n/a	2.50	42.25	55.25	Loam
Native Sand	n/a	n/a	n/a	1.25	4.25	94.50	Sand
25% Sand Mixture	25	37.50	37.50	1.25	27.00	71.75	Loamy Sand
50% Sand Mixture	50	25.00	25.00	1.25	15.50	83.25	Loamy Sand

75% Sand Mixture	75	12.50	12.50	1.25	13.75	85.00	Loamy Sand
100% Sand Mixture	100	0.00	0.00	1.25	5.50	93.25	Sand

Synthetic Storm Event

Synthetic runoff was composed of non-chlorinated well water and a 2 ppm concentration of dipotassium phosphate (K_2HPO_4) and 2 ppm concentration of potassium nitrate (KNO_3). The synthetic solution was staged in a 500-gallon chamber and continually mixed with a 0.5 horsepower bilge pump (MANUFACTURER) placed at the bottom of the chamber. The synthetic runoff was delivered via a 0.375” clear vinyl tubing distributed to each tank. Manually controlled, variable rate pumps (QV300, Fluid Meleny, Inc., Syosset, NY) regulated the flow at which the runoff volume was delivered to the mesocosms. The end of the vinyl tubing was placed in the corner of each mesocosm and over the splash rock where applicable.

To generate the flow rate of a specific storm event, a time-step model based on the Santa Barbara Urban Hydrograph (SBUH) Method was modified to predict flow from a hypothetical impervious area into the mesocosm. The model uses synthetic curves developed by the Soil Conservation Service to predict rainfall in one of the four U.S. climatic regions. For the experiment, a 2.0 in. rain event was applied to a Type II synthetic storm curve. Using an assumed 2.0 in./hr. infiltration rate through the soil media, the model predicted that the mesocosm could manage 11.25 sq. ft. of impervious area before reaching the mesocosms’ maximum ponding depth of 3.0 in.

The model provided an inflow rate for every 10-minute time step, which could then be used to distribute synthetic runoff. Due to the low flow rate at the tails of the hydrograph, only the middle 4.5 hours of the 24-hour event was used for the experiment. The inflow rate over the experiment ranged from 32 ml/min. to a peak of 646 ml/min. Table 2 illustrates the flow rate for each 10-mintue time step for the 4.5 hr./240 min. experiment. The variable rate pumps were calibrated so that the maximum flow matched the peak flow required for the experiment. The pumps were then adjusted every 10-minutes to the percentage indicated.

Table 2. Flow rate and water quality (WQ) testing time steps over the 4.5 hr. experiment.

Minutes	**Pump Speed (%)**	**Flow Rate (mL/min.)**	**WQ Sample**
0	5%	32	
10	5%	32	
20	5%	32	
30	**6%**	**39**	**WQ**
40	7%	45	
50	7%	45	
60	**10%**	**65**	**WQ**
70	12%	78	
80	12%	78	
90	**54%**	**349**	**WQ**
100	98%	633	

110	100%	646	
120	**60%**	**388**	**WQ**
130	19%	123	
140	19%	123	
150	**15%**	**97**	**WQ**
160	10%	65	
170	10%	65	
180	**9%**	**58**	**WQ**
190	7%	45	
200	7%	45	
210	**6%**	**39**	**WQ**
220	6%	39	
230	6%	39	
240	**5%**	**32**	**WQ**
250	5%	32	
260	5%	32	
270	**0%**	**0**	**WQ**
280	0%	0	

Water Testing

Prior to running the experiment, each mesocosm was flooded with non-chlorinated well water and then allowed to dry for two-weeks. Water quality samples were collected in 250 mL polyethylene cups (Fisher Scientific, Pittsburgh, PA) every 30 min. if outflow was occurring. Samples were immediately placed on ice until they could be transported to a refrigerated unit for analysis. Outflow volume measurements were taken every 10 min. using graduated 5-gallon buckets marked at 500 mL and 1000 mL. Water samples were immediately filtered and prepared for flow injection analysis (Lachate 8500, Loveland, CO) which tested samples for NO_x [NO_3-N) and phosphate (PO_4) concentrations.

Water Analysis

Outflow volume measurements were scheduled to be collected 28 times during the experiment (table 2). Volume reduction was calculated at each 30-minute time step for the duration of the experiment. Percent volume reduction was calculated with the following equation:

$$\%\, \mathit{Volume\ Reduction} = \frac{(\mu V_t) - (\mu V_c)}{(\mu V_c)}$$

where μV_t represents the mean volume of the treatment replicates and μV_c represents the mean volume of the control replicates.

Water Quality Analysis

Water quality samples were scheduled to be collected 9 times during the experiment (table 2). However, several of the replicates did not have sufficient flow until 90-minutes for a water quality sample collection. Mean concentration difference was calculated at each 30-minute time step and for the overall experiment. Mean concentration difference was calculated for PO_4 and NO_3 with the following equation:

$$\%\,Concentration\,Difference = \frac{\mu C_t - \mu C_c}{\mu C_c}$$

where μC_t represents the mean concentration value of the treatment replicates and μC_c represents the mean concentration value of the control replicates. Additionally, Load reduction was calculated at each 30-minute time step and for the overall experiment. Percent load reduction was calculated for PO_4 and NO_3 with the following equation:

$$\%\,Load\,Reduction = \frac{(\mu C_t * \mu V_t) - (\mu C_c * \mu V_c)}{(\mu C_c * \mu V_c)}$$

where μC_t represents the mean concentration value of the treatment replicates, μV_t represents the mean volume of the treatment replicates, μC_c represents the mean concentration value of the control replicates, and μV_c represents the mean volume of the control replicates.

Statistical Analysis

The total outflow PO_4 load, and NO_3 loads were calculated in relation to the control replicates to determine the total load reduction for each set of treatments at each time step and cumulatively. Similarly, the total outflow volume was subtracted from the total inflow volume at each time step of the hydrograph and cumulatively over the entire experiment. The data were tested for normality using the Shapiro- Wilk test. All data were found to be non-normal and log transformation was not successful. All statistical analyses were performed using a Kruskal Wallis test or Mann-Whitney U test at an assumed alpha value of 0.05 (SPSS, version 20).

RESULTS

All treatments showed overall outflow volume reduction compared to the control with significant differences between the control and the 50% (K=9.333, *p*=0.032), 75% (K=12.667, *p*=0.004) and 100% (K=13.667, *p*=0.002) sand mixtures (fig. 3). Gravel and 25% sand showed no significant difference compared to the control's mean volume retention. Water volume retention in soil treatments ranged from 11% to 20%, with increasing levels of sand providing the greatest retention. When observed over 30-minute time steps all soil mixture treatments retained volume along the rising limb of the hydrograph and 30 minutes into the falling limb of the hydrograph, with a few containing more sand retaining some water at the end of the falling limb. Significant differences were primarily found at the rising limb of the hydrograph up to the 150-minute time step, with 50%, 75% and 100% sand mixtures resulting in the most significant values.

Each of the treatments' peak flow rates were observed during the 120-minute time step (table 3). Peak flow rates had only slight variability across all treatments. Only a small amount of ponding (<0.25 in.) was observed in the mesocosms at the peak.

Table 3. Peak flow time and volume for all treatments.

Treatment Means	**Peak** (minute)	**Peak Flow** (mL/min.)
Control	120	591.67
25% Sand	120	591.67
50% Sand	120	596.67
75% Sand	120	600.00
100% Sand	120	613.33
Gravel and Filter Fabric	120	550.00

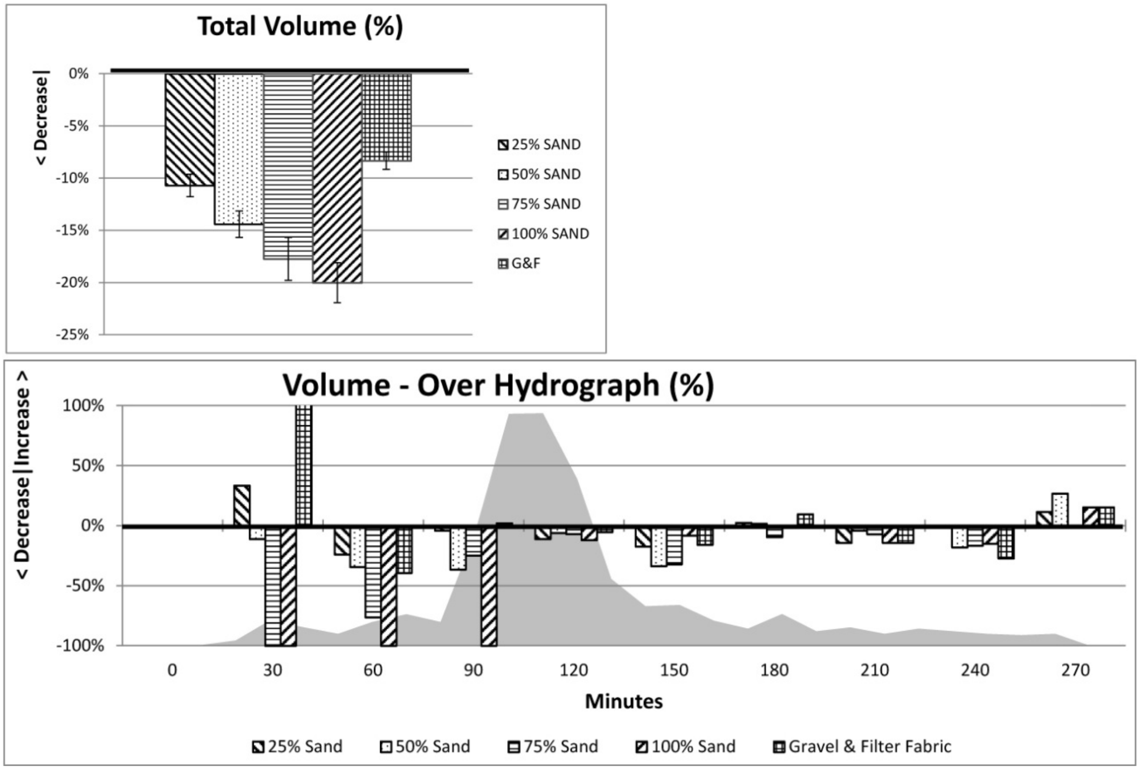

Fig. 3. Cumulative volume reduction percentages for all treatments and 30-minute increments of volume reduction percentages for all treatments graphed against the inflow hydrograph over the entire experiment (0-270 minutes). The 0% value line on both figures represents the controls.

All soil mixtures showed reduction in total load of PO_4, with gravel loading PO_4 over the course of the experiment. Reductions primarily occurred in the treatments with the least amount of sand or the greatest amount of organic matter. However, due to the variability in individual replicates and the low n of replicates, there were no significant differences found across the treatments with respect to PO_4 change in total load. When observed over 30-minute time steps, treatments retained PO_4 along the rising limb of the hydrograph and quickly began loading PO_4 after reaching the peak of the simulated rain event. There was significant load reduction at the 60-minute time step between the control and 75% sand and 100% sand (K=14.50, *p*=0.001 and K=9.50, *p*=0.028, respectively); and the 90-minute time step for the control and 100% sand (K=14.00, *p*=0.001). No other time steps showed significant reductions or loading compared to the control (*p*=>0.05).

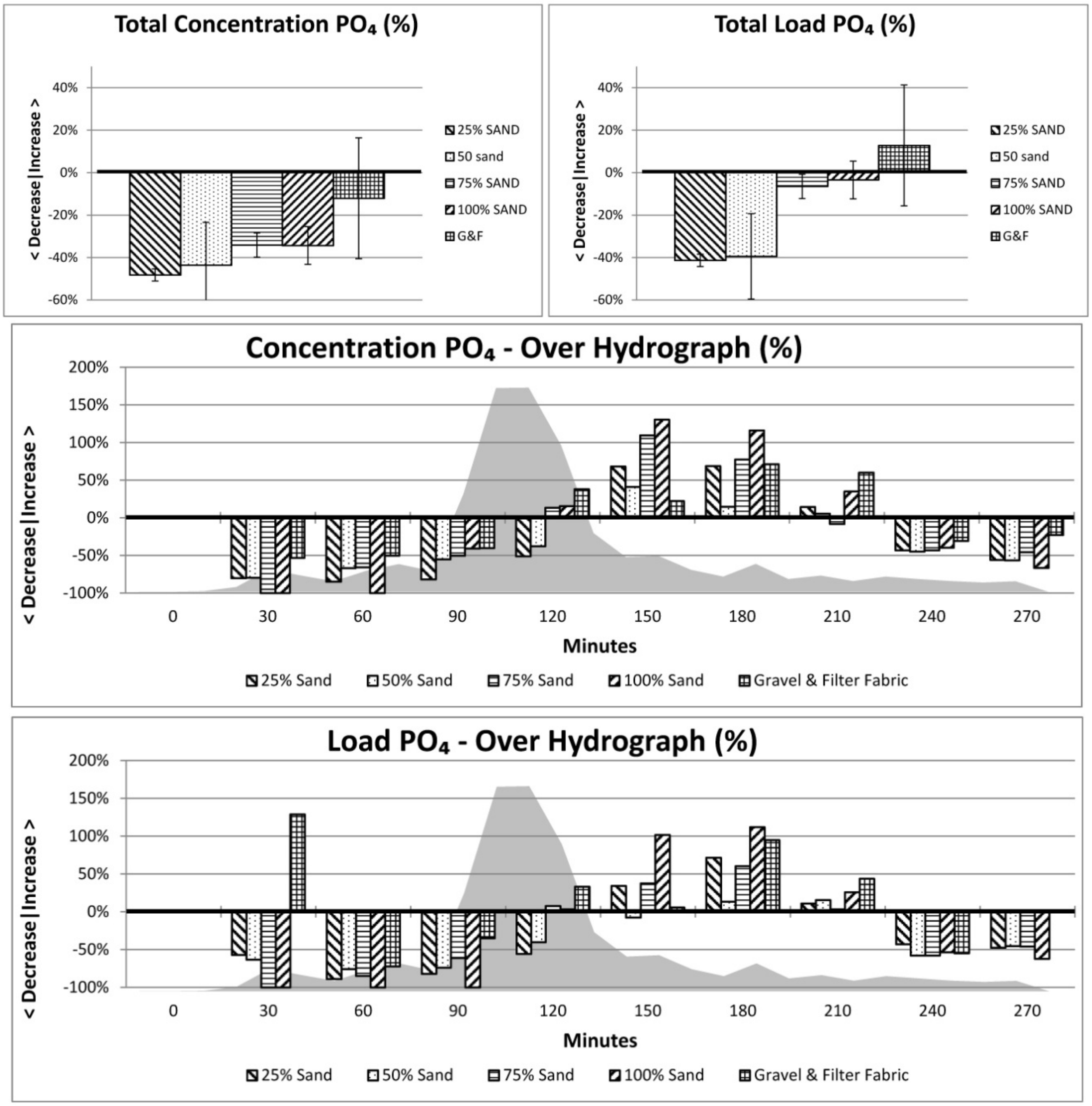

Fig. 4. Cumulative PO_4 percentages for all treatments and 30-minute increment percentages for all treatments graphed against the inflow hydrograph over the entire experiment. The 0% value line represents the controls.

Unlike, PO_4, there were no obvious patterns in NO_3-N removal in the relation of percentage of sand and the removal efficiency of the treatments. However, the 25% sand mixture was significantly different from the control (K=-9.00, *p*=0.039) and loaded much more NO_3-N than the other treatments (53%). When observed over 30-minute time steps, treatments retained NO_3-N along the rising limb of the hydrograph and quickly began loading NO_3-N after reaching the peak of the rain event. There were significant load reductions at the 60-minute time step between the control and 75% sand (K=9.167, *p*=0.034) and 100% sand (K=12.50, *p*=0.004). No other time steps showed significant reductions or loading compared to the control (*p*=>0.05).

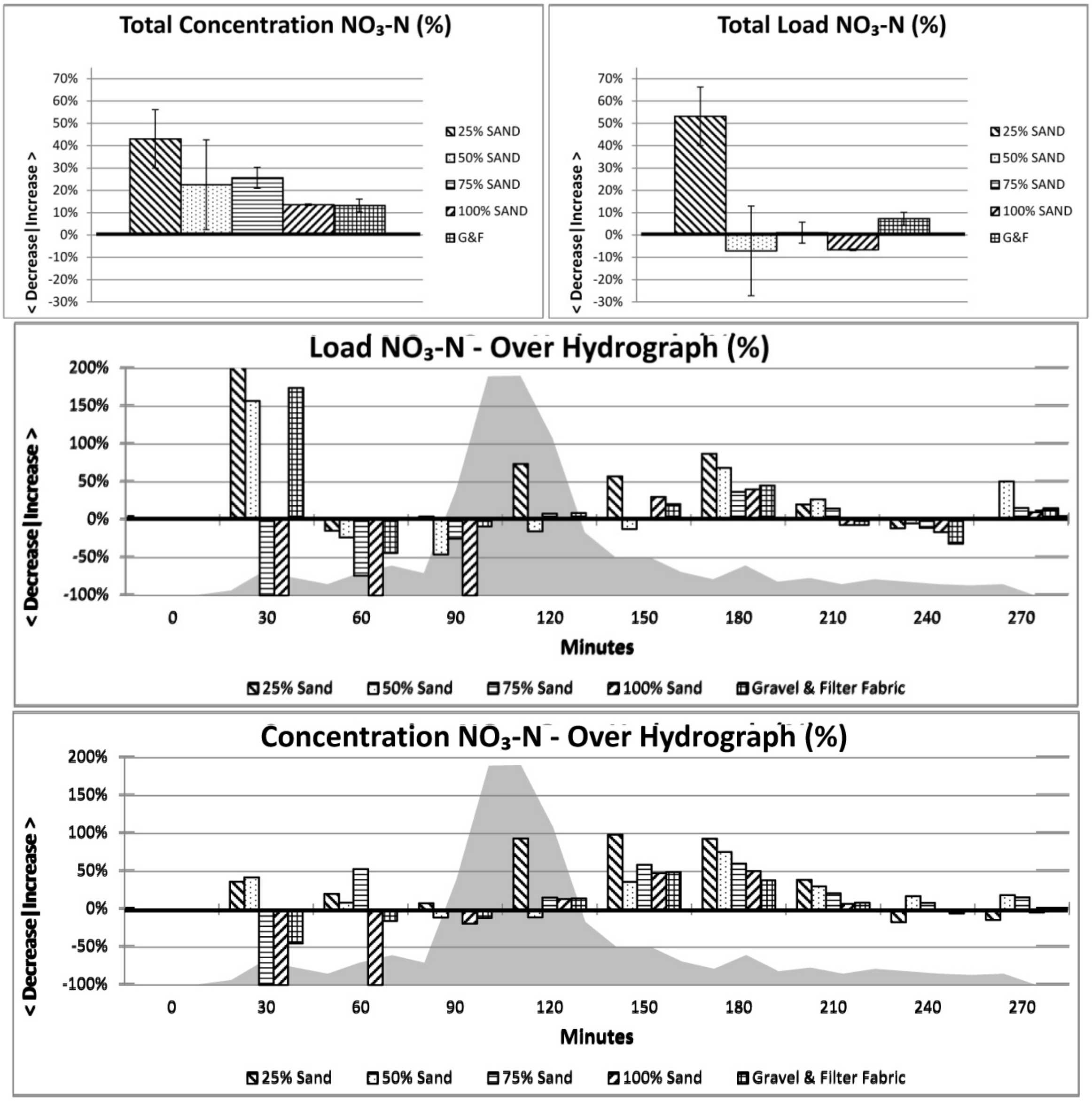

Fig. 5. Cumulative NO_3-N percentages for all treatments and 30-minute increment percentages for all treatments graphed against the inflow hydrograph over the entire experiment. The 0% value line represents the controls.

DISCUSSION AND CONCLUSIONS

Preferential Flow Path

With very little ponding observed in the mesocosms, it appeared that the inflow, concentrated at a specific point in the mesocosm, created a preferential flow path through the soil media. This potentially resulted in higher infiltration rates through the soil treatments. This may in part be due to the thin soil media layer in the experiment. However, Hsieh and Davis (2005) attributed nutrient loading to preferential flow paths in 43 in. (110 cm) column configurations. Anecdotally, Portland BES has observed field applications of flow-through bioretention facilities allowing water to move through them much faster than expected (Wethington, 2012).

The increased infiltration rates observed in the experiment potentially had an impact on both volume reduction and on pollutant removal by limiting the percentage of the overall soil media the synthetic stormwater solution came in contact with. This observation raises more questions about how water should be designed to enter and move through bio-retention facilities to maximize both volume reduction and pollutant removal.

Volume Reduction

The retention of volume in the four soil treatments was greatest along the rising limb of the hydrograph. However, once the treatments were saturated, they lost the ability to retain additional inflow. The treatments with the highest percentage of sand retained the highest amount of water relative to the control, which could be contributed to high matric potential of sand. The lack of difference between peak flow in any of the treatments is likely related to the soil layer in the experiment, but could also be influenced by a preferential flow path created through the soil media.

Nutrient Removal

While, only PO_4 results showed patterns in reduction rates over the entire experiment, there were observable patterns in the removal of both PO_4 and NO_3-N over the hydrograph. Nutrient removal was most effective on the rising limb of the hydrograph; this is supported by Davis et. al. (2006) who noted that faster flow rates limit contact time and therefore decrease pollutant removal potential. Removal of PO_4 was most effective in treatments with lower percentages of sand and higher percentages of organic matter. However, NO_3-N was variable across all treatments, which may be attributed to limited contact time in the mesocosms (Davis et al., 2006).

Mean Concentration vs. Load Reduction

Due to the methodologies of the experiment, both mean concentration reductions and load reductions were calculated. When observing total nutrient removal and nutrient removal over the hydrograph, both concentration and load illustrated similar trends. However, load resulted in a more accurate picture of the removal capabilities of the soil treatments during an actual storm event. Load accounted for two key factors. First, volume retention capacity influenced the nutrient removal potential of the systems. This can be seen when comparing PO_4 concentration and load reduction of the 75% and 100% sand mixtures. In both mixtures the concentrations showed very little reduction but the load, due to greater water retention showed a much greater reduction. Second, flow amplified the pollutant removal efficiency of the treatments. For example, a 10% concentration removal at 1000 ml/min. would remove a much greater amount of pollutant that a 10% concentration removal at 100 ml/min. Therefore, the load reduction calculation creates a more accurate picture of the cumulative nutrient removal capabilities of the treatments.

Summary

The methodologies of the experiment allowed for a unique insight into the nutrient removal capabilities of various soil mixtures. Specifically, the combination of the design of the mesocosms to be proportional to a real world bioretention application and the delivery of the synthetic stormwater solution over a storm event, created the opportunity to compare treatments in a controlled and replicated lab experiment that has implications for real world conditions. This combination allowed for several insights into bioretention design and function.

First, load may provide a more accurate picture of the nutrient removal capabilities of bioretention soil mixtures than concentration. The differences can be seen in both total load and concentration percent changes over the entire experiment and over the hydrograph. This is due to the second insight, which is the influence of flow rate observed over the hydrograph on nutrient removal. The removal trend can be clearly observed over the hydrograph, where treatments tended to remove nutrients on the rising limb and load soon after the peak.

Third, there may be a design flaw with a single concentrated inflow point into a flow-through facility where inflow is able to “short circuit” the system. While, this observation has to be confirmed in a full-depth system, it suggests that a dispersed inflow system may be more effective to ensure greater soil media contact with the runoff solution. Finally, due to the relatively thin 4.5 in. of soil media, the results of the experiment may not be comparable to other experiments, but do provide a relative comparison between treatments in this experiment. The results suggest directions for future experiments including testing the influence of a dispersed in-flow in nutrient removal and modifying the size of the storm event to compare nutrient removal in other regions of the U.S.

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INFORMATION TRANSFER AND DISSEMINATION

Presentations

Society of Wetland Scientists South Central Chapter Conference. October 19, 2012. Urban Flow-Through Facilities' Soil Media Compositions for Stormwater Quality & Quantity. Fort Worth, TX.

Mississippi Capitol Day for Mississippi's Public Universities. March 6, 2013. Flow-Through Demonstration Display. Jackson, MS.

Council of Educators in Landscape Architecture Conference. March 29, 2013. Urban Flow-Through Facilities' Soil Media Compositions for Stormwater Quality and Quantity Improvements. Austin, TX.

Mississippi Water Resources Research Institute Conference. April 2, 2013. Urban Flow-Through Facilities' Soil Media Compositions for Stormwater Quality and Quantity Improvements. Jackson, MS.

American Society of Landscape Architects Twin States Conference. April, 12, 2013. Flow-Through Planters for Stormwater Management. Orange Beach, AL.

Publication

Overbey, E., Gallo, C., Kroger, R. "Nutrient Removal and Flow Reduction Performance of Bioretention Soil Mixtures during a Specific Storm Event". Manuscript submitted to Journal of the American Water Resources Association for review in May 2013. (Manuscript Attached)

STUDENT TRAINING

To date, one graduate student was involved in this research.

FUTURE RESEARCH RECOMMENDATIONS

Further research that investigates the structural design of flow-through facilities should be conducted to determine if modifications can eliminate preferential flow patterns and thus improve water quality and quantity results. Additional testing should include varied storm events, solutions for internal water storage systems, hydrocarbon and pathogens removal, and stormwater inflow delivery methods.

PUBLICATION MANUSCRIPT

Nutrient Removal and Flow Reduction Performance of Bioretention Soil Mixtures during a Specific Storm Event