ABSTRACT

Title of Dissertation: ENGINEERING BIORETENTION FOR TREATMENT OF URBAN STORM WATER RUNOFF

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Bioretention, a "Low Impact Development" urban storm water best management practice, was developed in the early 1990's. Although bioretention has been used at many areas in the United States, the impact of this technology on ground and surface water quality as well as the optimal design of bioretention media for pollutant removal, have not been systematically investigated. The objectives of this study were to investigate the effectiveness of this technology for storm water runoff treatment and finally to give recommendations for future design. The methods used included developing pollutant removal performance curves for a variety of bioretention media mixes and evaluating the effectiveness of existing bioretention facilities. Synthetic runoff, which contained oil and grease (O/G), suspended solids (SS), lead (Pb), phosphorus (P), nitrate, and ammonium, was employed in laboratory experiments and 6 on-site bioretention evaluations. Two more on-site experiments were conducted during a rainfall event to compare with laboratory investigations.

Overall, all bioretention columns and on-site facilities demonstrated excellent removal for O/G and Pb. TSS removal was good in columns, but washing out of media particles was noted in field facilities, mostly from new installations. For nutrients treatment during a 6-hr experiment, the removal efficiency of Total P ranged widely and appears to be related not only to chemical properties of the media, but also to the flow behavior of runoff through the media. Results from batch P sorption tests on six media, three continuous column studies, and two repetitive 6-hr bioretention columns with total 28 repetitions showed that the medium with a higher P sorption capacity can retain more P from the infiltrating runoff after a high P loading. However, the sorption data alone is not adequate to predict the P retention through a bioretention column for a short-term experiment due to the complicated processes occurring between the runoff and media. Unless special provision were made, all media employed in this study were ineffective in removing nitrate and ammonium. The removal efficiency of both pollutants was improved by increasing the water holding capacity of the media and enhancing the development of nitrification and denitrification processes in the bioretention column.

Keyword: Bioretention, Low Impact Development, Best Management Practice

ENGINEERING BIORETENTION FOR TREATMENT OF URBAN STORM WATER RUNOFF

by

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CHAPTER 1:

INTRODUCTION

Ground water and surface water, which account for only 1% of the world's water, are the most important water resources for human beings. Without proper recharge of ground water, the ground water level will continually lower, endangering drinking water resources. The average precipitation in the United States (U.S.) during 1998 was 76 cm. However, only 0.3 cm of the total precipitation infiltrated into the ground water zone, whereas 53 cm returned to the atmosphere through evaporation processes. The other 22.7 cm of precipitation became runoff and flowed into the ocean (U.S. EPA, 1999a).

Storm water is a very important water resource because of its abundant volume. However, without proper drainage, a large volume of storm water runoff is produced from the growth of impervious surfaces (such as roads, parking lots, and rooftops) created during urbanization. As shown in Figure 1.1, peak discharge with a high volume and relatively short delay occurs during storms in urban areas, increasing the risk of flooding. Various pollutants (such as oil/grease (O/G), suspended solids (SS), nutrients, and heavy metals) are then washed off from potential storm water hotspots (such as commercial parking lots, construction sites, fueling stations, commercial nurseries, and vehicle washing facilities) located in urban areas, mobilizing them into the runoff. The resulting problem usually includes an increase in the rate and volume of runoff and increase in the variety and concentration of pollutants contained in the runoff. From a physical standpoint, the increase in the rate and volume of runoff results in higher risk of

erosion and flooding during storms. From a chemical viewpoint, the increase in the variety and concentration of pollutants contained in the runoff damages the water resource quality and increases subsequent treatment costs. As a result of the large areas of impervious surfaces and the various pollutants, these two problems are usually more prominent in urbanized locations.

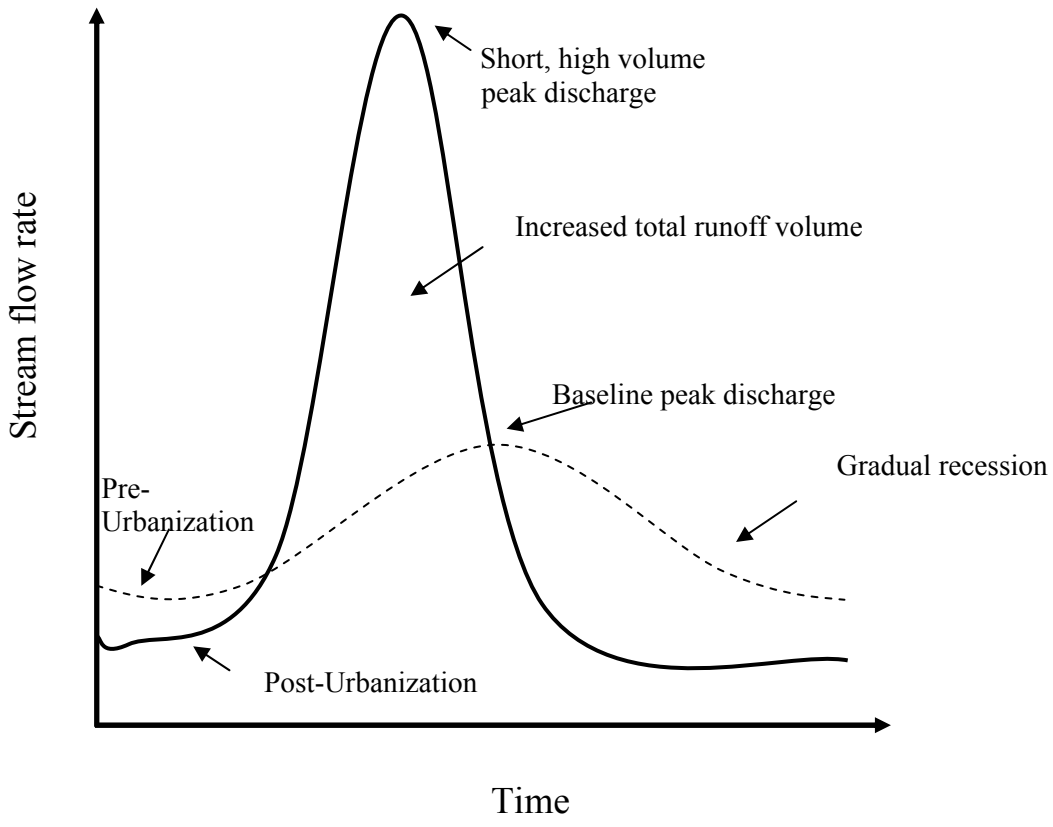


Figure 1.1. Impact of Urbanization on Stream Flow (Schueler, 1987)

In 1978, the U.S. Environmental Protection Agency (EPA) initiated the Nationwide Urban Runoff Program (NURP) to quantify the characteristics of urban runoff, assess the impacts of urban runoff on the water quality of receiving waters, and examine the effectiveness of control practices in removing pollutants found in urban runoff. An average of 28 storms for each of the 81 representative outfalls in 28 metropolitan areas was monitored from 1978 to 1983 (U.S. EPA, 1999b). Based on the results, NURP reinforced the findings of Statewide Water Quality Inventory and Assessments (required by CWA Section 305 b) in which contaminated storm water was identified as one of the primary water quality impairments. More recently, urban runoff is rapidly becoming a major source of nonpoint pollution (U.S. EPA, 1996) and is a leading impairment source for surface waters (including rivers, lakes, reservoirs, ponds, estuaries, and ocean shorelines) and ground water (U.S. EPA, 1998).

Ten pollutants, including total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus (TP), soluble phosphorus (SP), total Kjeldahl nitrogen (TKN), nitrate/nitrite, total copper, total lead, and total zinc, were selected for monitoring by NURP. The water quality of untreated urban runoff and domestic wastewater were compared and is summarized in Table 1.1 (U.S. EPA, 1999b). Again, it showed the loadings of pollutants from urban runoff can be higher than the ones from treated domestic wastewater. In addition, high variability of the runoff quality also raises the difficulty for runoff treatment.

Best management practices (BMPs) for storm water runoff are technologies or combinations of practices that provide treatment for storm water runoff. BMPs have been grouped into three categories: pollution prevention practices, source controls, and

treatment controls (Texas Natural Resource Conservation Commission, 2003). Pollution prevention practices serve to keep chemicals away from rainfall and/or runoff. Through source controls, the regulation of the amount and rate of runoff will minimize total runoff from directly- connected impervious areas, in addition to the management of the amount of pollution. Treatment control approaches are designed to remove pollutants from the runoff. Due to the variety of urban land uses and storm water runoff characteristics, one or more BMPs which are appropriate to the location and climate are generally applied to an area.

Table 1.1. Comparison of Water Quality Parameters in Urban Runoff with Domestic Wastewater (U.S. EPA, 1999b)

Pollutant	Urban Runoff		Domestic Wastewater
	Separate Sewers		After Secondary
	Range (mg/L)	Typical (mg/L)	Typical (mg/L)
TSS	20-2890	150	20
TP	0.02-4.3	0.36	2
TN	0.4-20	2	30
Lead	0.01-1.2	0.18	0.05
Copper	0.01-0.4	0.05	0.03
Zinc	0.01-2.9	0.02	0.08

Bioretention is an urban storm water BMP developed in the early 1990's to address runoff pollutants in an aesthetically pleasing manner. By employing integrated and

distributed micro-scale storm water retention areas, this approach causes less land disturbance, thereby, creating flexibility for different sites and runoff prevention plans. Runoff enters the bioretention facilities through runoff collecting pipes (Figure 1.2) or curb cut (Figure 1.3). Through treatment by bioretention media, contaminants in the runoff are removed and water quality is improved. In a conventional configuration, as shown in Figure 1.4, bioretention generally consists of a porous media layer, supporting a vegetative layer, with a topping layer of hardwood mulch. During storms when the runoff loading is higher than the infiltration rate into the bioretention, the ponding area can serve as storage space, providing more time for both the precipitation and the runoff to infiltrate into the media.

The design concept of bioretention is based on several considerations. First, by employing highly permeable media, runoff is expected to quickly infiltrate into the media upon flowing into the bioretention facility. Thus, the total amount of runoff for downstream water bodies is reduced. Second, the bioretention media are usually composed of natural soil, sand, and/or organic matter. These materials remove pollutants from storm water runoff through a variety of mechanisms, including sedimentation, filtration, sorption, ion exchange, biological uptake, and precipitation. Since the incoming runoff is collected near the sources and is expected to contain fewer pollutants than the runoff farther from the source, bioretention can treat larger amounts of runoff than conventional end-pipe treatment facilities before reaching the loading capacity (Figure 1.5). Consequently through the treatment by bioretention media, the runoff quality is improved.

Figure 1.2. Collected Runoff through Pipe during a Rain Event

Figure 1.3. Collected Runoff through Curb-Cut during a Rain Event

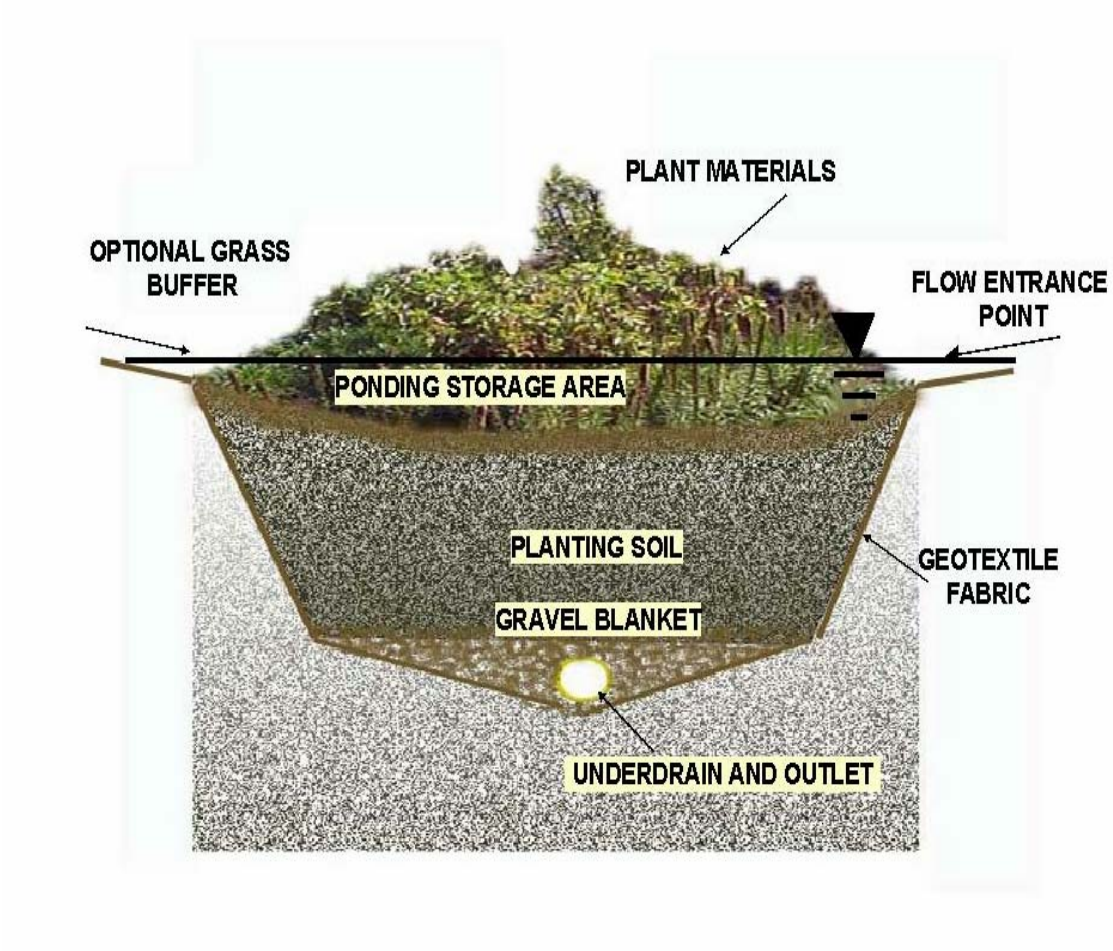
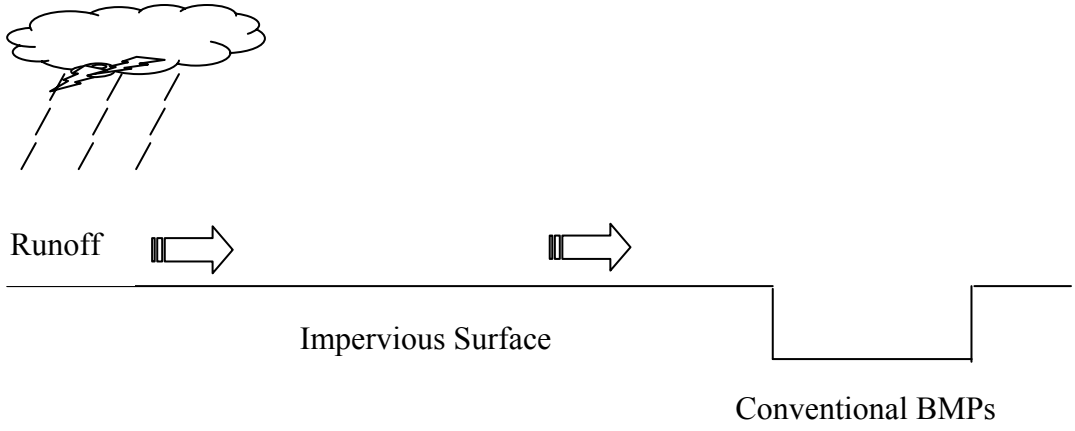


Figure 1.4. Typical Bioretention System (Davis, 2003a)

a.



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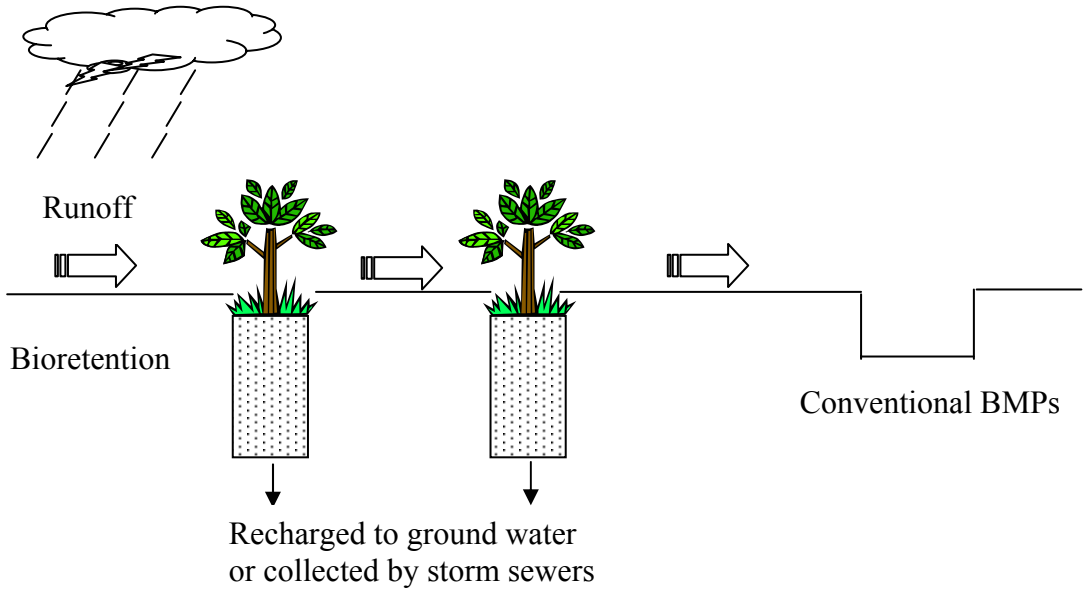

Figure 1.5. a. The Conventional End-of-Pipe BMPs for Storm Water Runoff Treatment,

b. The Bioretention System for Storm Water Runoff Treatment

1.1. Role of Bioretention Media for Treatment of Urban Storm Water Runoff

Bioretention and other Low Impact Development (LID) techniques are receiving increasing attention as municipalities struggle with ecological effects of urban growth. Although bioretention has been used at several urban and suburban areas in the United States, a limited amount of research data is available to assess its impact on ground and surface water quality (Claytor and Schueler, 1996). Currently, specifications for bioretention media are only based on the media texture (sand/silt/clay contents). However, characteristics of media (such as particle sizes and silt+ clay contents) and configurations of the media profile (layered or homogeneous) could affect the runoff infiltration rate and pollutant removals. If bioretention is to be employed as an urban BMP, it must have a high hydraulic conductivity to handle large water volumes directed from impervious areas. Fine fractions in soils tend to be the most chemically active, but high clay contents can be detrimental to infiltration; expanding clays tend to swell markedly after absorbing water and shrink while drying (Brady and Weil, 2002). Therefore, a balance needs to be developed between the permeability of the media and pollutant removal characteristics.

Experiments conducted previously in our laboratory have evaluated the effectiveness of bioretention with certain media for O/G, lead, TP, nitrate, and ammonium removals. However, the influence of media characteristics during runoff treatment processes has not been investigated. In this work, bioretention is assumed to be effective for improving both quantity (runoff infiltration rate) and quality aspects (O/G, TSS, Pb as a representative heavy metal, TP, nitrate, and ammonium removals) of urban runoff. The characteristics of the bioretention media profile, including media texture, chemical

properties, and media configuration, are hypothesized to be critical to this performance.

1.2. Long-Term Issues for Bioretention in the Treatment of Urban Storm Water Runoff

As mentioned, biological uptake is one of pollutant removal mechanisms of bioretention media. Under conditions of high runoff infiltration rate, microorganisms do not have sufficient time to degrade pollutants in infiltrating runoff. Alternatively, microorganisms may degrade the retained pollutants during the dormant period in between storm events, especially P and N, which serve as nutrients for their growth. For runoff infiltrating into bioretention facilities, SS accumulation in the media will decrease the hydraulic conductivity, finally leading to media clogging. Therefore, appropriate media to filter SS without clogging is critical for bioretention operation.

In this work, through several repetitive experiments, the significance of biological processes on bioretention performance was tested. The removal efficiency of TP and N (including nitrate and ammonium) from runoff is hypothesized as being affected after dormant periods. In addition, runoff infiltration rate is expected to decrease along with the accumulation of incoming SS.

1.3. Objectives and Research Benefits

Three primary objectives made up this study:

1) To provide insight on media characteristics in controlling bioretention behavior.

2) To evaluate long-term effectiveness of bioretention for runoff infiltration and pollutant removals.

3) To confirm the performance of existing bioretention facilities and compare field and laboratory results.

By employing 6-hr bioretention columns, the effect of media properties and configurations on bioretention performance was investigated. Through a moderate long-term period, two bioretention columns were tested for runoff infiltration under repetitive SS inputs and pollutant removals with several dormant periods. Also, 6-hr on-site experiments were conducted on six existing bioretention facilities to evaluate their performances with respect to pollutant removal. In order to exclude effects resulting from variation in incoming runoff chemistry and flow, a synthetic runoff solution was made up and used in these experiments. Two additional on-site experiments were conducted during an actual rainfall event for comparison with the simulated-runoff laboratory and field studies.

Overall, the optimal design of bioretention media for increasing pollutant removal by promoting certain physical, chemical, or biological processes, while maximizing infiltration characteristics through making up an appropriate media configuration is the primary benefit of this research. By doing the field tests, existing systems can be evaluated and compared with the column tests to determine improved ways for future design.

CHAPTER 2:

BACKGROUND INFORMATION

2.1. Urban Storm Water Runoff Management

Prevention of flooding and reduction of runoff pollution load usually are two issues of most concern relating to storm water management. Due to the intermittent and variable nature of rainfall and runoff, a structured strategy as presented in Figure 2.1(U.S. EPA, 1993) is generally an important basis for establishing an urban storm water runoff pollution prevention and control plan. Different performance goals and variation in runoff qualities can result in disparate efficiency estimation and cause significantly different performance.

Currently, many storm water runoff BMPs, as summarized in Table 2.1, are being developed and evaluated (International Stormwater Best Management Practices Database, 2003). Storm water runoff is conveyed to these facilities for further treatment. All of these approaches are attempting to offer significant advantages in controlling storm water runoff at the source, prevent downstream flooding, and promote ground water recharge. Performance data of selected BMPs are summarized in Table 2.2 (U.S. EPA, 1999b).

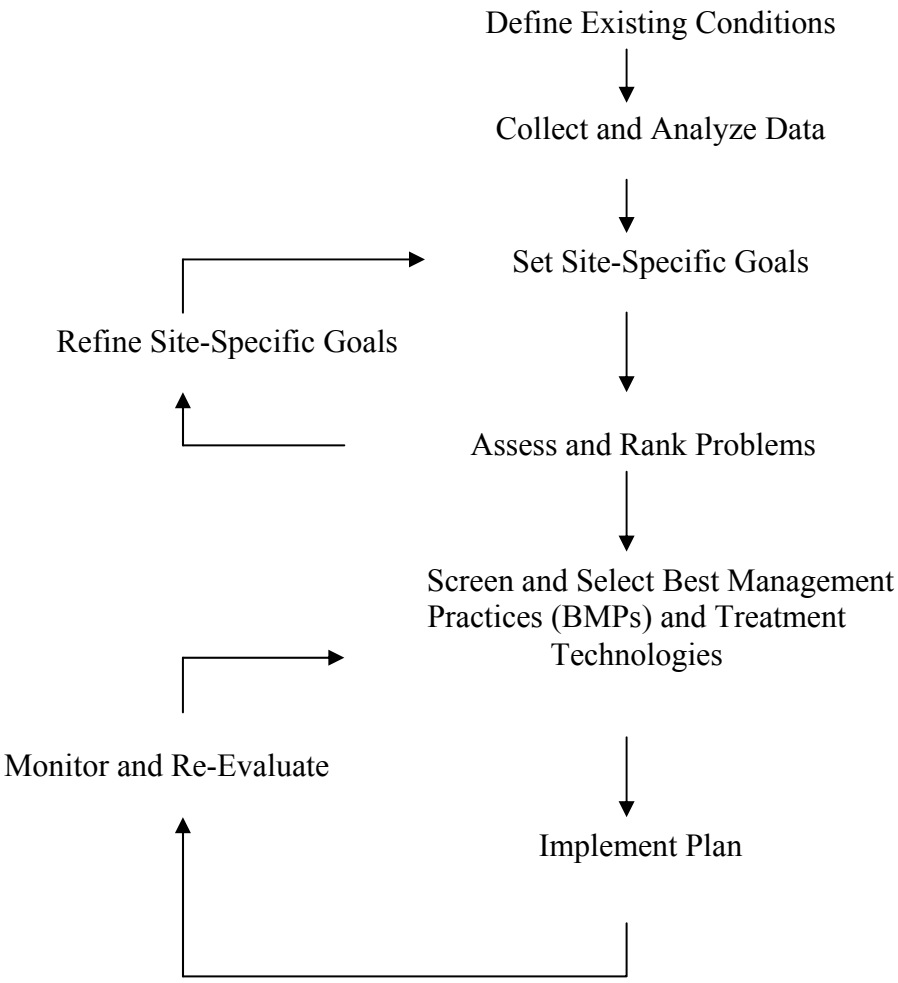

Figure 2.1. Structured Strategy for an Urban Storm Water Runoff Pollution Prevention and Control Plan (U.S. EPA, 1993)

Table 2.1. Numbers of Studies in the International Stormwater BMP Database (International Stormwater Best Management Practices Database, 2003)

BMP Category	Number of BMPs
Structural	
Biofilter	32
Detention basin	24
Hydrodynamic device	16
Media filter	30
Percolation trench/well	1
Porous pavement	5
Retention pond	33
Wetland basin	15
Wetland channel	14
Non-structural	
Maintenance practice	28

Table 2.2. Structural BMP Expected Pollutant Removal Efficiency (U.S. EPA, 1999b)

BMP Type	Typical Pollutant Removal Efficiency (%)			
	TSS	TN	TP	Metals
Dry Detention Basins	30-65	15-45	15-45	15-45
Retention Basins	50-80	30-65	30-65	50-80
Constructed Wetlands	50-80	< 30	15-45	50-80
Infiltration Basins	50-80	50-80	50-80	50-80
Infiltration Trenches	50-80	50-80	15-45	50-80
Grassed Swales	30-65	15-45	50-80	15-45
Vegetated Filter Strips	50-80	50-80	50-80	30-65
Surface Sand Filters	50-80	< 30	50-80	50-80

2.2. Bioretention Systems

Bioretention is an urban storm water best management practice developed in the early 1990's (U.S. EPA, 1999a). The removal efficiency of pollutants contained in urban storm water runoff is a function of bioretention media properties. Since the clay/silt fraction has larger chemical-active surfaces, these media are expected to retain greater

amounts of pollutants from runoff and can be preferred for bioretention media design. However, the media texture of the bioretention system generally determines the runoff infiltration rate. As shown in Table 2.3, media with a high content of clay result in a lower infiltration rate. Therefore, an optimal bioretention media composition is needed to employ the structured strategy procedure (Figure 2.1) before designing the system in order to satisfy the site-specific goals.

Table 2.3. Typical Infiltration Rates (Stahre and Urbonas, 1993)

SCS Group and Type	*Infiltration Rate (in/ hr)*
A. Sand	8.0
A. Loamy sand	2.0
B. Sandy loam	1.0
B. Loam	0.5
C. Silt loam	0.25
C. Sandy clay loam	0.15
D. Clay loam and silty clay loam	<0.09
D. Clays	<0.05

Several studies on the performance of bioretention facilities have been performed. Davis et al. (2001, 2003b, 2003c, submitted 2003d) employed two pilot bioretention systems (107 cm long x 76 cm width with 61 cm sandy loam soil, and 305 cm long x 152 cm width with 91 cm sandy loam soil) to test the performance of bioretention for metal (copper, lead and zinc) and nutrient (TKN, nitrate and phosphorus) removals under different environmental conditions (different runoff durations, pH values, media depths). Overall, the effect of runoff duration and variability on metal removal decreased along with media depth. Good removal efficiency of TKN and phosphorus were shown. However, nitrate was poorly removed. The buffer capacity of the media negated the pH variation of the runoff.

In order to improve nitrate removal efficiency, alternative bioretention designs, either incorporating a continuously submerged anoxic zone with an overdrain (Kim et al., 2003) or placing a less permeable soil layer in the bottom (Hunt et al., 2002), have been applied and evaluated. In addition, the effectiveness of a surface mulch layer for O/G removal from runoff via sorption, filtration, and subsequent biodegradation was also investigated (Hong, 2002). Results confirmed the efficient processes of sorption and filtration to remove O/G from infiltrating runoff, as well as the biodegradation for the sorbed O/G.

2.2.1. Media in the Bioretention Facility

Mulch, sand and soil are the three primary media usually employed in bioretention systems. Due to different textures and properties, their fractions in the media determine the performance of the bioretention system, including hydraulic conductivity and

pollutant removal ability.

2.2.1.1. Mulch

Generally, mulching serves as a temporary soil stabilization or erosion control practice. With respect to plant growth, mulch can help to hold the seeds, fertilizers, and topsoil in place; and to insulate against extreme temperatures. In a bioretention system, the mulch layer can slow runoff flow during storms and retain moisture in this layer during drought periods. Also, this layer helps to filter pollutants such as SS and provides a nutrient-rich environment conductive to microbial growth, promoting degradation of petroleum- based products and other organic materials (U.S. EPA, 1999a).

2.2.1.2. Sand

Because of their coarse particle size and low clay content, sands usually result in a higher runoff infiltration rate than soils. Different sands, however, usually have different pollutant removal capacities. For example, P removal capacities of different sands can vary considerably (Willman et al., 1981) and sands with a high metal content had a much higher P-removal capacity (Van Cuyk et al., 2001).

2.2.1.3. Soil

Soil consists of four major components – minerals, organic materials, water, and air. Sand (> 0.05 mm), silt (0.05- 0.002 mm), and clay (< 0.002 mm) are the three soil particle size fractions, found in different amounts. Clays have large specific surface areas and often are predominantly negatively charged. This property helps clays to retain

nutrients against leaching and react with hydrogen and aluminum ions, while buffering the soil from extreme pH changes (Newman, 1984). On the other hand, soil organic matter can coat clays and hydrous oxides, blocking the surfaces from sorbing pollutants. As a result, most of sorption reactions would have to occur on the organic matter coatings or on cations that are bound to the organic matter surfaces (Evans and Sorensen, 1985).

2.2.2. Water Flow in Bioretention Media

Infiltration is generally defined as the process of water entry into the soil (Hillel, 1998). Several primary factors, including particle sizes, textures, and configurations of media affect the flow pattern of water in bioretention media. Coarse sand results in a higher water infiltration rate than the fine sand because of the larger conducting pores among particles. As mentioned, water leaches faster into the media with lower of silt and clay contents. For the effect of media configuration, Hillel (1998) compared the flow of water in four different media (including homogeneous and layered media) and concluded that preferential flow occurred in the layered profile with a fine-textured layer overlying a coarse-textured layer. In addition, a capillary barrier was also noticed between two layers in which the medium with a lower hydraulic conductivity overlaid another medium (Stormont and Anderson, 1999). In this case, water did not enter the lower layer until the head was built up sufficiently to overcome the capillary tension between layers.

2.2.3. Pollutant Removal in the Bioretention System

Urban storm water runoff can contain significant concentrations of harmful

pollutants. Generally, the levels of contaminants found in runoff are related to the degree of urban development. Due to emissions or leakages from vehicles, the runoff from areas such as parking lots, streets/highways, vehicle service/fuel stations, and recycling centers, usually contains high levels of lead (Pb) and oil/grease (O/G). As reported (Claytor and Schueler, 1996), the concentration of Pb and O/G in the runoff from commercial and industrial sites ranged from 80 to 182 μg/L (national average: 18 μg/L) and 14 to 25 mg/L (national average: 1 to 2 mg/L), respectively. Additionally, a considerable total suspended solids (TSS) load usually appears in urban storm water runoff (Characklis and Wiesner, 1997). Since pollutants such as Pb are commonly associated with TSS (Sansalone and Buchberger, 1997), TSS is also a frequently reported parameter for runoff quality.

Excess inputs of phosphorus (P) and nitrogen (N) into the waterways often lead to eutrophication problems, which consequently, lead to depletion in oxygen and biodiversity. To date, nutrients (including N and P) are becoming leading pollutants for impaired surface waters (including rivers, lakes, reservoirs, ponds, estuaries, lake shorelines, and ocean shorelines) and ground water (U.S. EPA, 1998). Table 2.4 summaries the sources of metals, O/G, P, and N in urban runoff (U.S. EPA, 1999b).

Table 2.4. Sources of Contaminants in Urban Storm Water Runoff (U.S. EPA, 1999b)

Contaminant	Sources
Metals	Automobiles, bridges, atmospheric deposition, industrial areas, soil erosion, corroding metal surfaces, combustion processes
O/G	Roads, driveways, parking lots, vehicle maintenance areas, gas stations, illicit dumping to storm drains
P and N	Lawn fertilizers, atmospheric deposition, automobile exhaust, soil erosion, animal waste, or detergents

Different mechanisms might account for pollutant removal from runoff. For example, adsorption involves the electrostatic attachment of an ion onto a soil surface whereas colloid attachment is based on the London- van der Waals forces or covalent forces. Straining is a process in which particles or colloids are lodged within smaller pores and sedimentation of particles occurs due to density effects.

2.2.3.1. Oil/Grease

O/G is composed of a wide variety of organic compounds with different physical, chemical, and toxicological properties. Generally, adsorption and absorption are two primary mechanisms for O/G removal from storm water runoff (Lau and Stenstrom, 1995). Aluminum silicate is a popular sorbent used for O/G sorption. In soils, crystallized silicate minerals, such as allophane and imogolite, are primarily composed of aluminum silicates (Brady and Weil, 2002); therefore, these minerals could help to

remove O/G from storm water runoff. In addition, organic compounds either in suspended solids or in solid soils also contribute to O/G removal (Mader et al. 1997). The presence of certain functional groups, such as –OH, $-NH_2$, -NHR (R represents hydrocarbon group), $-CONH_2$, -COOR, and $-^{+}NR_3$, hydrogen bonding, and protonation can promote the adsorption of O/G onto the soil (Brady and Weil, 2002). Based on previous studies (Hong, 2002), mulch demonstrated excellent O/G removal (80 to 95%) through sorption and filtration processes, followed by efficient biodegradation (~ 90%) of these sorbed or filtered contaminant.

2.2.3.2. Total Suspended Solids

Suspended solids usually result in turbid water, interfering with the recreational and aesthetic uses of water bodies. Since abundant pollutants are associated with TSS, TSS is a frequently reported parameter as related to other storm water pollutants. TSS removal efficiency varied widely in different systems (Schueler, 1987). Therefore, system design and operation are both important factors determining the performance of a system.

2.2.3.3. Lead

Movement of Pb within the soil could occur by diffusion, either as a free ion or as a complex, by mass flow, or by movement of metal-laden particulates. Generally, diffusion of Pb occurs over a short distances and Pb could be uptaken by plants (Dowdy and Volk, 1983). As with other heavy metals, Pb can be removed from runoff by adsorption at the soil mineral surface, precipitation, or chelation with soil organic matter.

For example, Pb was found to accumulate in the top few centimeters of soil in basins used for the retention/recharge of urban storm water runoff (Nightingale, 1987). Also, the solubility of Pb in soils was found mostly to be regulated by $Pb(OH)_2$, $Pb_3(PO_4)_2$, $Pb_4O(PO_4)_2$, $Pb_5(PO_4)_3OH$ and $PbCO_3$, depending on the pH of soil solution (Medrano and Jurinak, 1975). Therefore, the runoff characteristics, such as pH, ionic strength and cation types, could affect the Pb removal efficiency.

2.2.3.4. Phosphorus

P is of concern for its contribution to water eutrophication. This leads to odor and taste problems in drinking water. In addition, resulting oxygen shortages in surface waters also lead to problems with recreational and industrial use. On the other hand, P is one of the primarily plant nutrients. Traditionally, soil is the growth medium for plants and plants mainly retrieve P from soil.

In runoff, P is distributed as both dissolved (DP, particle size < 0.45 μm as operational definition) and particulate (PP, P sorbed onto the solids before or after transport in the runoff (Sharpley, 1985) with particle size > 0.45 μm). Under horizontal flow, mass losses of total P (TP) in surface runoff were reduced by 27% by 4.6 m-long vegetated filter strips (Magette et al., 1989). Dissolved P (DP) in the surface runoff was mainly adsorbed by SS instead of surface soil over which runoff passed (Shapley et al., 1981). Under vertical flow, PP that was mostly transported through macropore flow in media could be removed through media filtration processes (Heathwaite and Dils, 2000). Through vegetative uptake, microorganism degradation, sorption, exchange reactions and precipitation, DP can be retained in soils (Reddy et al., 1999; Van Cuyk et al., 2001).

The properties of bioretention media could affect the P removal efficiency from infiltrating runoff. The most important characteristic of sands in determining their P-removal capacity under slightly alkaline conditions was Ca content, and Fe and Al at lower pH levels (Arias et al., 2001), relating to the formation of surface precipitates. The P removal efficiency is often high initially and then decreases after some time as the P sorption capacity of the sand is used up (Pell and Nyberg, 1989; Cinpa, 1996). Different soils generally possess different P sorption capacities. For example, sorption capacities varied more than 3 fold, from 9 mg/100 g for Merrimac to 29 mg/100 g for Paxon soil (Sawhney and Hill, 1975). Axt and Walbridge (1999) also reported that clay and silt contents were the two soil parameters most highly positively correlated with P sorption capacity. Additionally, pH-dependent precipitation reactions are important for P removal from runoff.

Generally, P fixation occurs in two steps: sorption on the soil solids, producing P which is more available to plants (Logan and Mclean, 1973), and conversion of the sorbed P into minerals (White and Dornbush, 1988). Lance (1977) suggested that adsorption occurred during the early period. After the adsorption capacity was exceeded, precipitation reactions accounted for most P retention.

On the other hand, soils that had been successively treated with P solution showed reduced P sorption capacity, but regained the capacity to adsorb P after drying and wetting cycles (Sawhney and Hill, 1975). Several findings reported that alternating periods of wetting and drying might bring fresh mineral surfaces into equilibrium with the soil solution, creating new surfaces for P sorption (Kao and Blanchar, 1972; Sawhney and Hill, 1975). In addition, total media height would also affect P removal in a column

system. Longer media depth generally had higher P removal efficiency because of the longer contact time with soil (Logan and Mclean, 1973; Levine et al., 1980; White and Dornbush, 1988).

2.2.3.5. Ammonium

Ammonium, which carries a positive charge, is usually immobilized by negatively charged clay and humus in soils (ASA and SSSA, 1983; Brady and Weil, 2002; Juang et al., 2001). Several mechanisms, such as adsorption, colloid attachment, straining, and sedimentation, can serve to retard the transport of ammonium in a rapid infiltration system (Sumner and Bradner, 1996). Due to the short retention time, biochemical transformation of ammonium may not be significant during runoff loading periods in bioretention facilities. However, this process could cause the transformation of retained ammonium during the wetting-drying periods. Through aerobic nitrification processes, captured ammonium ions in the soil are further oxidized by *Nitrosomonas* and *Nitrobacter species* and finally become nitrate.

$$NH_4^+ \xrightarrow{Nitrosomonas} NO_2^- \xrightarrow{Nitrobacter} NO_3^- \qquad (2.1)$$

2.2.3.6. Nitrate

In well-drained soils, most negatively-charged nitrate ions in runoff generally just leach from the soil to the ground water. Within poorly-drained soils, however, the held

water will impede diffusion of oxygen and may thereby create an anoxic zone, which is a precondition suitable for denitrification processes (Meyer et al., 2002; Brady and Weil, 2002). Nitrate existing in the soil solution then can return to the atmosphere through denitrification processes.

$$NO_3^- \rightarrow NO_2^- \rightarrow NO\uparrow \rightarrow N_2O\uparrow \rightarrow N_2\uparrow \tag{2.2}$$

CHAPTER 3:

EXPERIMENTAL METHODOLOGY

In order to fully investigate bioretention media performance, several different types of tests were completed. One, six-hr bioretention column tests were employed to investigate the performance of bioretention systems with different media compositions and configurations during a simulated 6-hr rainfall event. Two, long-term performance of bioretention systems was tested using repetitive bioretention column tests. Three, continuous column tests were conducted to measure the maximum P loading for different ratios of sand to soil. Finally, the effectiveness of existing bioretention systems was confirmed by 6-hr on-site tests.

3.1. Materials

3.1.1. Source of Storm Water Runoff

The 6 hr-bioretention column tests, repetitive bioretention column tests, and six on-site bioretention confirmation tests used synthetic storm water runoff that was made up in the Environmental Engineering Laboratory, University of Maryland, College Park. Tap water with stoichiometric $NaHSO_3$ added for dechlorination (Eq. 3.1) was employed in this study:

$$HOCl + HSO_3^- \rightarrow Cl^- + SO_4^{2-} + 2H^+ \quad (3.1)$$

The target pollutants for the experiments were O/G, TP, Pb, nitrate, ammonium, and TSS. Based on information from Prince George's County, Maryland, and other references on urban storm water runoff chemistry, a synthetic storm water runoff was produced. The characteristics of this water are presented in Table 3.1 (Davis et al., 2001). For continuous column tests, synthetic runoff contained only 3 mg-P/L. The pH was controlled at 7.

Table 3.1. Makeup of Synthetic Runoff Used in this Study (Davis et al., 2001)

	Value (mg/L, except pH)	Source
pH	7.0	HCl or NaOH
Total dissolved solids	120	$CaCl_2$
TP	3 (as P)	Na_2HPO_4
Nitrate	2 (as N)	$NaNO_3$
Ammonium	2 (as N)	NH_4Cl
Pb	0.1	$PbCl_2$
SS	150	Local soil sieved through a 0.0232 inch opening
Motor oil	20	Used oil from local garage

3.1.2. Sources and Characteristics of Media

Two sands, four soils, and a compost mulch, that varied in their physical and chemical properties were used in this study to evaluate their pollutant-removal performances. Both sands, with very different particle sizes, were obtained from a local home supply store. Before the experiment started, sands were washed using the Silica Sand Washing Procedure (Kunze and Dixon, 1989). After washing several times using tap water, hydrogen peroxide is consequently applied under 75^{o}C to oxide organic matter contained in the sand.

Three different soils were obtained from the Prince George County (MD) Department of Public Works and Transportation, while the other one was obtained from the Low Impact Development Center (Beltsville, MD). Mulch used in the experiments was obtained from the College Park City Department of Public Works. It was produced from locally-collected municipal leaves and grass clippings that had been composted.

Before the experiments, the soil, sand, and mulch samples were sent to the Soil Testing Laboratory of the Department of Agronomy, University of Maryland, College Park for analysis. Also, the particle-size distribution of all media (on a mass basis) was analyzed using dry-sieving techniques in the Geotechnical Engineering Laboratory, University of Maryland, College Park. The uniformity of the particle-size distribution (the uniformity coefficient) was calculated as the ratio between d_{60} (60% of the medium by mass is smaller than d_{60}) and d_{10} (10% of the medium by mass is smaller than d_{10}). All the results are presented in Table 3.2.

Table 3.2a. Bioretention Media Chemical and Mechanical Analyses

	d_{10}	d_{60}	d_{60} / d_{10}	pH	Mg	P	K	Ca	O.M.
	mm	mm			mg/100 g media				%
Sand (I)	0.17	0.30	1.8	7.1	9.5	5	3	2.8	0.15
Sand (II)	0.30	0.84	2.8	5.0	2.5	4	0.8	0.8	0.10
Soil (I)	0.09	0.20	2.2	7.8	29	12	21	> 44	2.20
Soil (II)	0.13	0.81	6.2	6.9	25	17	27	22	2.60
Soil (III)	0.09	0.29	3.2	6.7	28	7.5	35	*	4.40
Soil (IV)	0.10	0.32	3.2	7.1	27	9.9	18	68	3.50
Mulch	0.15	2.31	15.4	7.1	28	56	35	> 44	29.8

* no data collected

Table 3.2b. Bioretention Media Chemical and Mechanical Analyses

	CEC	Sand	Clay	Silt	Classification
	meq/100 g media	%	%	%	
Sand (I)	1.1	95	3	2	Sand
Sand (II)	0.4	92	5	3	Sand
Soil (I)	19	66	19	15	Sandy Loam
Soil (II)	6.3	79	12	9	Sandy Loam
Soil (III)	*	71	17	12	Sandy Loam
Soil (IV)	15	71	14	15	Sandy Loam
Mulch	34				

The experimental materials for the 6-hr and repetitive bioretention experiments consisted of a column and media. Two different Plexiglas column sizes were employed. The inner diameter of the large Plexiglas column was 19.1 cm and the height was 110 cm (Figure 3.1). Different mixtures of media were evaluated for their pollutant removal efficiencies and the resulting runoff infiltration rate. Media employed in these tests contained mulch, sand and soil. In addition, several different fractions of media were mixed homogeneously to yield a new mixed-medium for testing (Table 3.3). For continuous bioretention experiments, the inner diameter of the Plexiglas column was 6.4 cm with a height of 40 cm. Three homogeneous media mixtures with different soil/sand ratios were employed (soil III/ sand II: 70/30, 50/50, and 30/70 mass basis).

Table 3.3. Makeup of Synthetic Media

Synthetic media	Components	Component ratio on mass basis
I	mulch/soil I/sand I	1:2:2
II	soil III/sand II	4:1
III	soil III/sand II	1:1

Figure 3.1. Large Bioretention Laboratory Columns with Different Media Layers

3.2. Methods

3.2.1. Pollutants Sorption by SS

To determine the pollutant adsorption portion by SS in simulated runoff, 15 mg soil sieved through a 0.0232 inch (0.59 mm) sieve were suspended in 100 ml solution containing 100 μg/L Pb standard solution, 3 mg-P/L TP, 2 mg/L NO_3^--N, 2 mg/L NH_4^+-N, 20 mg/L O/G and 120 mg/L $CaCl_2$. The suspension was equilibrated by shaking at laboratory temperature (22^oC) for 24 hours. A similar solution without SS was used as the blank.

3.2.2. 6-hr Bioretention Column Experiments

A total of eighteen 6-hr column tests, using various media to investigate the effects of media characteristics (including size distribution, chemical properties, and configurations) on the water infiltration rate and pollutant removal, were performed. The media used in these types of experiments included not only layers of the native media (e.g., sand, soil, and mulch), but also some synthetic media made up by mixing several media homogeneously (Table 3.3).

During the testing period, the simulated runoff was made and mixed in a 200-L container with a large mixer. At the start of the experiment, runoff was pumped into the column from the top and the first sample was collected. Over a six-hr period, effluent samples were collected every hour from the bottom of the column and taken to calculate the flow rate and measure the pollutant concentration. The water head was maintained

constant at 15 cm by an overflow drain and by controlling the pumping rate during the experiment.

3.2.3. Repetitive Bioretention Column Experiments

Two different columns were used and three media layers were employed in each column. The first column included a top mulch layer (5 cm, 0.82 kg), a middle porous soil I layer (15 cm, 8.17 kg), and a bottom sand I layer (75 cm, 30.9 kg). In general, sand is more permeable than mulch or soil. Therefore, the less-permeable mulch and soil layers were designed to overlay the high-permeability sand layer in this testing column, which is also a typical configuration used in surface, organic and pocket sand filters. The media for the second column was composed of 3.06 kg mulch, 3.06 kg soil IV, and 6.13 kg sand II homogeneously mixed (30 cm) in the top layer, 23.2 kg sand I (55 cm) in the middle layer, and 5.9 kg soil IV (10 cm) in the bottom layer. Usually, mulch and soil contain abundant organic matter and can serve as the media for plant growth. Also, organic matter can serve as the carbon source for microorganism growth. Both of these are helpful to the operation of bioretention. In addition, because of the bigger media particle size, sand I can treat a larger volume of runoff before clogging. Therefore, mixing mulch and soil with sand I was considered to be a good mixture for the upper media layer. Twelve repetitions for the first repetitive column and sixteen for the second were completed. Runoff was reapplied into the bioretention column after a 4-14 day dormant period. The testing procedure for each run was similar to the 6-hr bioretention column experiments. The samples were analyzed for flow rate and the concentrations of the six pollutants. The objective of this series of experiments was to evaluate the system

performance under repetitive loadings and investigate processes that may occur during the dormant period between rainfall events.

Media samples were collected from different depths in the second repetitive column before and after testing. The media P investigations included environmental soil tests (Water soluble P (WSP) and calcium extractable P ($CaCl_2$-P)) and agronomic soil tests (Mehlich I extractable P and Mehlich III extractable P tests). WSP was determined by mixing 2.5 g of soil with 25 mL of deionized water for 1 hr. Calcium extractable P was analyzed by shaking 5 g of soil with 20 mL of 0.01 M $CaCl_2$ for 24 hrs. Mehlich I extractable P was determined by shaking 2.5 g of each media with 10 mL of Mehlich I reagent (0.05 M HCl+ 0.0125 M H_2SO_4) for 5 mins (Sims and Heckendorn, 1991). Mehlich III extractable P was determined by shaking 2.5 g of each media with 25 mL of Mehlich III reagent (0.2 N CH_3COOH+ 0.25 N NH_4NO_3+ 0.015 N NH_4F+ 0.013 N HNO_3+ 0.001 M EDTA) for 15 mins (Mehlich, 1984). Finally, P concentrations in all extractants were analyzed using the Murphy and Riley method (1962). The absorbance of the molybdophosphate complex was measured spectrophotometrically at 712 nm.

3.2.4. Continuous Bioretention Column Experiments

Three small columns (Plexiglas, 40 cm long by 6.4 cm inner diameter) with different ratios of sand/soil were employed to investigate maximum P loadings for the media. The media compositions (soil III/sand II % on mass basis, total mass= 1350 g) for these three columns were 30/70, 50/50 and 70/30. The flow rate was controlled as constant at 3.1 mL/min (5.9 cm/hr) employing a peristaltic pump. As mentioned, the influent only contained 3 mg-P/L Na_2HPO_4, maintained at pH 7. During the experiment, influent was

pumped from the top of the column continually and effluent was collected from the bottom of the column every day for a total of 29 days. The samples were analyzed for P concentration.

3.2.5. P Adsorption Capacity

To determine the P adsorption capacity of different media, different masses of each medium were shaken in 100 ml deionized water solution containing 3 mg-P/L Na_2HPO_4. Solution without any media served as the control. The suspension was equilibrated by shaking at laboratory temperature (22^oC) for 24 hours. The objective of this study was to determine the P adsorption isotherm for every medium at pH 7.

3.2.6. Evaluation of On-Site Bioretention Facilities

A total of six field experiments (Figures 3.2 to 3.7), one in Greenbelt, MD (GB), two in Hyattsville, MD (HV1 and HV2), and three in Landover, MD (LO1, LO2, and LO3), were completed. GB site was constructed in 1993, whereas HV1 and HV2 were built in 1998; LO1, LO2, and LO3 were finished in 2001. The synthetic runoff was stored in six 200-L containers and transported to each site. An area about 5.3 m^2 (2.3 m x 2.3 m) within each bioretention facility was selected adjacent to a manhole. During the experiment, runoff was mixed and pumped into the selected area at 2.8 L/min (3.2 cm/hr loading). Over a six-hr period, samples were collected from the facility underdrain outlet pipe in the manhole every half-hour using acid-washed amber glass bottles, along with selected influent samples. All collected samples were transported to the Environmental

Engineering Laboratory, University of Maryland, for measuring pollutant concentrations. Additionally, media samples were collected from each facility using a core sampler and were divided into two layers, 10 to 15 cm and 15 to 40 cm depth. Each layer sample was mixed homogeneously and sent to the Soil Testing Laboratory for characterization.

Two additional evaluations of bioretention facilities (Figures 3.8 and 3.9) were conducted in College Park, MD (CP1 and CP2) during a rainfall event on February 3, 2003. These are two adjacent, lined cells constructed for research and monitoring. CP1 was constructed according to the design modification of Kim et al. (2003), which includes a bottom sand media layer with shredded newspaper that serves as an electron donor. A raised underdrain pipe maintains anoxic conditions to promote denitrification. During rainfall events, runoff from the adjacent parking lot is split into two separate concrete inlet channels leading to the bioretention cells. Effluent is discharged from the underlying pipes into the adjacent creek. Influent runoff and effluent for both facilities were collected every half hour for 1.5 hours.

Figure 3.2. Bioretention Field Study (GB) -- Greenbelt, MD (08/22/01)

Figure 3.3. Bioretention Field Study (LO1) -- Largo, MD (09/19/01)

Figure 3.4. Bioretention Field Study (HV1) – Hyattsville, MD (06/12/02)

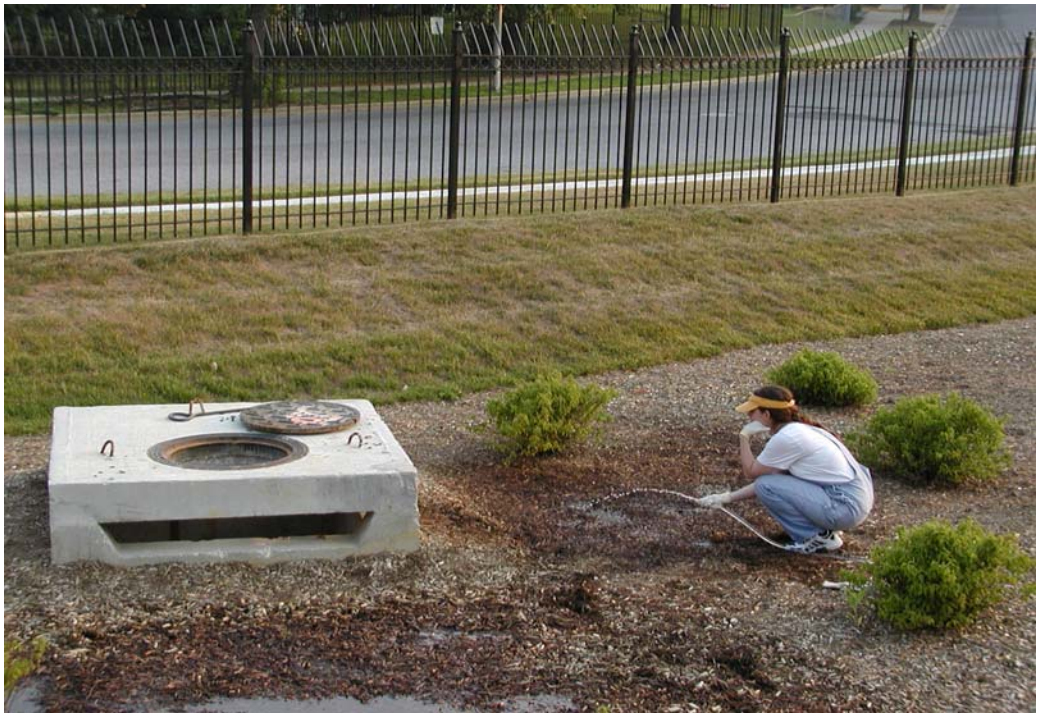

Figure 3.5. Bioretention Field Study (LO2) – Landover, MD (06/25/02)

Figure 3.6. Bioretention Field Study (HV2) – Hyattsville, MD (07/09/02)

Figure 3.7. Bioretention Field Study (LO3) – Landover, MD (07/23/02)

Figure 3.8. Bioretention Field Study (CP1) – College Park, MD (02/04/03)

Figure 3.9. Bioretention Field Study (CP2) – College Park, MD (02/04/03)

3.2.7. Analytical Methods

Analytical methods include analysis for TSS, O/G, TP/DP, Pb, nitrate-N, and ammonia-N.

3.2.7.1. O/G Analysis (Lau and Stenstrom, 1997)

1,000 mg C18 columns (obtained from Analytichem Corp., Folsom, CA) were first conditioned with 5 mL isopropanol, followed by 5 mL deionized water. A 500 mL runoff sample was pretreated by adding 25 mL isopropanol and 1 mL concentrated HCl. The sample was then passed through the column at a flow rate of 5 mL/min using a peristaltic pump. To remove O/G from the wall of the sample container, 5 mL isopropanol and 100 mL deionized water containing 0.1% concentrated HCl were added and the mixture was passed through the column as before. The column was then dried for 25 mins.

A tarred collection vial was placed under the column after it was dried. The column was eluted with 3 mL methylene chloride followed by 2 mL hexane. Each elution fraction in the collection tube was evaporated to dryness. The tube then was weighed to determine the mass of O/G eluted from the C18 column.

3.2.7.2. TSS Analysis

This test follows Section 2540D of Standard Methods (APHA et al., 1995). A well-mixed sample is filtered through a weighed standard glass-fiber filter and the residue

retained on the filter is dried to a constant weight at 103 to 105^{o}C for 1 h. The increase in weight of the filter represents the TSS.

3.2.7.3. Pb Analysis

Total Pb was analyzed by digesting samples at 95 ^{o}C, using 2 mL of concentrated nitric acid per 50 mL sample. An aliquot of the digested suspension was then centrifuged and filtered through a 0.2 μm syringe filter (cellulose acetate membrane). This test follows Section 3500-Pb of Standard Methods (APHA et al., 1995). Pb was analyzed on the furnace module of a Perkin Elmer Model 5100ZC atomic absorption spectrophotometer. Pb standards of 2, 5, 10, and 15 μg/L were prepared from 1000 mg/L Pb-reference solution (Fisher Scientific). A VWR Scientific hollow cathode lamp was used at a wavelength of 283.3 nm, slit width of 0.7 nm and an average lamp current of 8 milliamps. The detection limit for Pb was 2 μg/L. To analyze for dissolved Pb, samples were acidified, filtered, and then analyzed directly.

3.2.7.4. TP Analysis

The P analysis is divided into two general procedural steps: (a) conversion of P to dissolved orthophosphate, and (b) colorimetric determination of dissolved orthophosphate. Filtration through Pall Gelman GF/C filters (0.2 μm) separates dissolved from suspended forms of P. Because P may occur in combination with organic matter, a persulfate digestion method (APHA et al., 1995) is used to oxidize organic matter effectively to release P as orthophosphate.

After digestion, an aliquot of the suspension was centrifuged and filtered through Pall Gelman GF/C filters (0.2 μm). This test follows Section 4500-P of Standard Methods (APHA et al., 1995). A 50 mL sample was placed into an Erlenmeyer flask and one drop of phenolphthalein was added. If red color appeared, enough H_2SO_4 solution was added to discharge the color. Otherwise, 20 drops of H_2SO_4 solution were added to each flask, along with 0.5 g $K_2S_2O_8$ (J.T.Baker). The flasks were then boiled on a hot plate until about 10 mL of liquid remained. The flasks were then removed from the heat and allowed to cool. In addition to another drop of phenolphthalein, 20 mL of distilled water was filled to each flask. Finally, the liquid was neutralized to a faint pink color with NaOH.

Total volume of the solution in each flask was diluted to 100 mL with distilled water. Another drop of phenolphthalein was added to each flask. Once faint pink color appeared, enough H_2SO_4 solution was added to discharge this coloring. Then 4 mL of ammonium molybdate reagent I, and 10 drops of stannous chloride reagent I were added to each flask. The samples were allowed to sit for 10 minutes. Finally, the samples were placed into a spectrophotometer (Bausch and Lomb, Spectronic 21) to measure the color at 690 nm.

3.2.7.5. Nitrate Analysis

Nitrate-N was analyzed using a Dionex DX-100 ion chromatograph with a Dionex AS4 column. Before measuring, an aliquot of the suspension was centrifuged and filtered through a 0.2 μm syringe filter. A solution of 1.2 mM sodium carbonate/2.8 mM sodium bicarbonate (J.T.Baker) was employed as the eluent. During analysis, the flow

rate was adjusted to 1.4 mL/min to clearly differentiate nitrate and chloride. The concentration of nitrate in the samples was determined against standards prepared with sodium nitrate (Fisher Scientific) in deionized water. The detection limit for nitrate-N was 0.1 mg/L.

3.2.7.6. Ammonium Analysis

An aliquot of the suspension was centrifuged and filtered through a 0.2 μm syringe filter. Ammonium-N analysis was carried out using a Dionex DX-100 ion chromatograph with a CS12 column. 1.1 mN sulfuric acid (Fisher Scientific) was employed as the eluent and the flow rate was controlled at 0.4 mL/min to differentiate ammonium and sodium peaks. The ammonium concentrations in the samples were determined against standards prepared by dissolving required amounts of ammonium chloride (J.T.Baker) in deionized water. The detection limit for ammonium-N was 0.05 mg/L.

CHAPTER 4:

EVALUATION AND OPTIMIZATION OF BIORETENTION MEDIA FOR TREATMENT OF URBAN STORM WATER RUNOFF

4.1. Introduction

Bioretention media remove pollutants from storm water through a variety of mechanisms, including sedimentation, filtration, sorption, and precipitation. Accordingly, different media compositions are expected to demonstrate different pollutant removal efficiencies because of the respective effects on pollutant capture mechanisms. For example, Pb, Cu, Ni, and Zn adsorption by and desorption from several soils were affected by the pH of the soil (Harter, 1983). P retention and movement in soils is influenced by both influent and soil characteristics (Nagpal, 1985). Sands with different Ca, Fe, and Al contents resulted in about 3-fold differences in P removals in constructed reed bases (Arias et al., 2001).

Nonetheless, the hydraulic characteristics of bioretention media cannot be ignored. If bioretention is to be employed as an urban BMP, it must have a high hydraulic conductivity to infiltrate large water volumes directed from impervious areas. The hydraulic conductivity of the media depends primarily on the size of conducting pores and, generally, larger pores conduct water more rapidly (Hillel, 1998). Therefore, a sandy media is favored and high clay contents can be detrimental to infiltration; expanding clays tend to swell markedly after absorbing water and shrink as drying (Brady and Weil, 2002). Since fine fractions in soils tend to be the most chemically

active, however, a balance needs to be developed between the permeability of the media and pollutant removal characteristics. Consequently, design of the media profile is critical to determining bioretention performance characteristics.

Thus, three bioretention media issues are addressed in this chapter. Currently, specifications for bioretention media are only based on the media texture (sand/silt/clay contents). While this represents improvement over older designs, media particle sizes (d_{10}, d_{60}) and chemical properties can vary greatly within these three texture designations. Small variations in media sizes or media heterogeneity can result in very different runoff infiltration rates. Similarly, media components with different chemical properties will attenuate pollutants via different efficiencies and mechanisms. Therefore, the runoff infiltration rate and pollutant removal efficiencies can be very different among different media components, even if simple texture designations are similar.

Second, the configuration of the media can also influence bioretention performance. A thin silt/clay media layer with a low permeability could limit the infiltration rate of runoff through an entire bioretention facility. Because of different water heads, the infiltration rate through a facility with a less-permeable layer near the surface would be slower than one with this same layer at the bottom. Also, infiltration rates through a facility employing several media layers would be different from one employing the same media, but mixed homogeneously (Hillel, 1998). Layering and homogeneity may also lead to different pollutant removal efficiencies.

Finally, although bioretention has been implemented at several urban and suburban areas throughout the United States, only a limited amount of research and performance data are available to assess the impact of this technology on ground and surface water

quality. Evaluation of the performances of existing bioretention facilities will support findings from laboratory investigations and can serve as the basis for future design improvement, with a focus on media characteristics.

Bioretention is assumed to be effective for improving both quantity and quality aspects of urban runoff. However, the bioretention media profile is critical to this performance. The objective of this study was to provide insight on media characteristics in controlling bioretention behavior.

Eighteen 6-hr bioretention columns with different media mixtures and configurations were employed to compare results on runoff infiltration rate and pollutant removal efficiencies. Also, 6-hr on-site experiments were conducted on six existing bioretention facilities to evaluate their performances with respect to pollutant removal. In order to exclude effects resulting from variation in incoming runoff chemistry and flow, a synthetic runoff solution was made up and used in these experiments. Two additional on-site experiments were conducted during an actual rainfall event for comparison with the simulated-runoff laboratory and field studies.

4.2. 6-hr Bioretention Column Experiments

Current design specifications for bioretention are based on simple texture composition for the media (limits on clay/silt/sand contents). Nonetheless, it is clear that various types of sands and soils resulted in different runoff infiltration rates in 6-hr bioretention column experiments because of their wide range of particle sizes and textures (Table 4.1). Pollutant removal results are also summarized in Table 4.1.

Clearly, different characteristics of the media components promoted variation in removal performance for several pollutants.

Table 4.1a. Characteristics and Results of 6-hr Bioretention Column Tests

	Mass Ratio (%)			Experimental Set	Infil. Rate
Exp. No.	Mulch	Soil	Sand		cm/min
1[a]	0	0	100(I)	A, B	0.84±0.01
2[a]	0	0	100(II)	A	8.15±0.18
3[a]	2	93(I)	5(I)	A, B	0.28±0.04
4[a]	2	93(II)	5(I)	A	0.95±0.01
5[a]	2	93(III)	5(II)	A	0.40±0.02
6[a]	91	0	9(I)	A	0.28±0.01
7[a]	0	0	100(I)	-	0.81±0.02
8	3	0	97(I)	B	0.77±0.01
9[b]	2	21(I)	77(I)	C-1	0.32±0.02
10[b]	8	26(I)	66(I)	C-1	0.31±0.01
11[b]	6	32(I)	62(I)	C-1	0.30±0.01
12[b]	0	24(I)	76(I)	C-1	0.30±0.01
13[c]	3	43(I)	54(I)	B, C-2	0.48±0.02
14[c]	3	24(I)	73(I)	B, C-2	0.66±0.01
15[c]	11	19(I)	70(I)	B, C-2	0.71±0.02
16[d]	2	17(II)	81(II)	D	5.40±0.15
17[d]	2	72(III)	26(II)	D	1.15±0.02
18[d]	2	49(III)	49(II)	D	1.93±0.01

a: native media; b: column with upper soil I layer; c: column with synthetic media I (mixture of soil I/ mulch/ sand I); d: column with upper soil II or soil III layer; e: influent w/o suspended solids; (I), (II), (III): different types of sands and soils- see Table 3.1

Table 4.1b. Characteristics and Results of 6-hr Bioretention Column Tests

	Removal Efficiency (%)					
Exp. No.	TSS	O/G	Lead	TP	Nitrate	Ammonium
1[a]	>96	>96	>98	85±1.5	11±16.7	8±3.4
2[a]	>96	>96	96±0.7	10±3.1	1±0.7	15±0.8
3[a]	29±2.9	>96	>98	47±3.4	1±0.6	6±2.2
4[a]	88±0.9	>96	>98	41±4.5	14±2.2	24±0.8
5[a]	91±0.3	>96	>98	48±4.0	8±0.7	16±1.1
6[a]	86±1.0	>96	75±2.0	4±4.5	43±3.2	16±1.9
7[a]	-[e]	>96	66±7.0	84±1.3	13±6.4	5±1.7
8	>96	>96	>98	61±4.5	9±0.4	9±2.0
9[b]	66±2.5	>96	>98	47±4.6	3±0.8	2±1.1
10[b]	94±0.6	>96	>98	50±3.8	4±0.7	7±1.0
11[b]	93±0.9	>96	>98	39±4.0	4±0.5	7±0.8
12[b]	93±0.5	>96	>98	39±3.5	2±0.5	5±2.2
13[c]	>96	>96	>98	83±1.4	13±59	26±2.6
14[c]	>96	>96	>98	57±2.7	24±2.9	17±2.1
15[c]	>96	>96	>98	54±2.7	27±1.1	20±1.2
16[d]	>96	>96	97±0.2	24±3.8	6±1.5	11±0.6
17[d]	92±0.3	>96	>98	72±0.8	9±0.9	19±0.6
18[d]	93±0.3	>96	>98	74±0.9	8±0.5	20±0.5

4.2.1. Performance of Different Media Components

The infiltration results for the six native media columns (Exps. 1 to 6- - Set A) demonstrate that the rate through sand II (8.15± 0.18 cm/min) was nearly an order of magnitude faster than that through sand I (0.84± 0.01 cm/min) at 15-cm head. This is readily explained by the larger particle size of sand II (d_{10}= 0.30 mm) compared to sand I (d_{10}= 0.17 mm). Similarly, the infiltration rate using soil II as the dominant medium is much higher (0.95± 0.01 cm/min) than that for soil I (0.28± 0.04 cm/min) or soil III (0.40± 0.02 cm/min). Soil II has larger d_{10} and d_{60} (Table 2), and contains lower fractions of silt (9%) and clay (12%) than soil I (silt + clay= 34%) or soil III (silt + clay= 29%). In addition, visual examination of soil II shows large particles of organic material and sand. The d_{60}/d_{10} ratio is 6.2 for soil II, much larger than for soil I (2.2) and soil III (3.2). Larger pore sizes among media particles can result in a higher media permeability. All of these properties allow soil II to be the most permeable soil among the three employed.

Compared with other media, particle sizes of mulch components are quite heterogeneous (d_{60}/d_{10}= 15.4). Very high values of d_{60}/d_{10} may increase the risk of clogging (Arias et al., 2001) and can reduce permeability. The runoff infiltration rate through the mulch column is low at 0.28± 0.01 cm/min. Therefore, not only d_{10} but also uniformity is important in controlling runoff infiltration rate.

Turning to pollutant removals, both sands and all soils demonstrated excellent removal efficiencies for O/G and total Pb (Table 4.1). With mulch, O/G was removed > 96% (Exp. 6), however, less Pb (75± 2%) was removed using this medium as compared with the others. Very good TSS removal (> 86%) was noted in most of the native-media bioretention columns, except in the column in which soil I (29± 2.9%) was the dominant

medium. Visually, it was apparent that some of the soil particulate matter leached out from the soil I column during the testing period. This problem should disappear with subsequent runoff applications.

Based on the results from the batch experiment, 56% of the influent Pb was sorbed onto the TSS. Thus, this fraction of Pb can be removed via efficient filtration of TSS by the bioretention media. Removals greater than 56%, however, are found in all native media, indicating that some sorption of lead occurred onto the media. Results of sand I columns (Exps. 1 and 7) demonstrate that the removal efficiency of total Pb was > 98% for influent runoff with TSS and only 66± 7% without TSS. Therefore, it is evident that sorption of Pb occurred within the sand I layer and that TSS filtration contributed to Pb removal.

Sand I removed TP from the synthetic storm water runoff at 85± 1.5%, while sand II removed just 10± 3.1%. In addition to physical filtration, TP removal by sand columns may relate not only to simple adsorption, but also to complex sorption/precipitation processes (Arias et al., 2001). All three soils removed just 41 to 48% of TP. In the column with 91% mulch, only 4± 4.5% TP removal was found, indicating that mulch does not play an important role in TP removal. Although mulch is expected to retain P through complexation processes, these organic matter complexes may be in dissolved forms and can leach out.

The removal efficiency of nitrate by the native media ranged from 1 to 43%. The sands were mostly ineffective. The native media removal efficiencies for ammonium were low, ranging from 6 to 24%. Both types of sand produced similar low removal (8 to

15%). Soil I removed about 6± 2.2% ammonium, and soil II removed 24± 0.8%. Soil III and mulch removals were about 16%.

Since fixing the applied water head resulted in different flow rates for different media, the pollutant removals were evaluated on a mass basis. Input, output, and removed mass of pollutants for different media during 6-hr testing periods are calculated as:

$$M = \sum_{i=1}^{t_d} QC\Delta t \tag{4.1}$$

where M is the pollutant mass, Q is the infiltration flow rate, C is the pollutant concentration, and Δt is the measurement time increment. Both input and output pollutant masses are calculated using appropriate parameters, with the mass removal being the difference between input and output.

The results are summarized in Figure 4.1. O/G, TSS, and Pb were all removed effectively for all media and the plots for each look similar. On a mass basis, sand II removed much more of these three pollutants from the runoff than the other media because of the resulting high loading coupled with low output concentrations. Sand II therefore appears to be the best performer among these six media for TSS, Pb, and O/G removal. This analysis underscores the importance of particulate removal from urban storm water and the benefits of utilizing a sand filter as a BMP (Pell and Nyberg, 1989; Schueler and Holland, 2000), which is essentially what this single-media sand column

represents. Sand filters, however, do not have a number of water quality and ecological advantages, as do bioretention facilities.

Sand I appears to be the better choice for TP treatment since significant mass was removed and a lower output TP concentration was obtained as compared with other media. For nitrate and ammonium, none of the media performed exceptionally well and generally demonstrated minimal removal ability.

Overall, these results emphasize the importance of a high infiltration rate. When employing sand in bioretention media, a high permeability is recommended, with d_{10} near 0.30 mm (such as sand II). Because silt and clay generally contain more nutrient and water holding capacity than sands, soil is necessary for plant growth in the top media layer. The best performance with soils was also noted for that with high d_{10} and a value greater than 0.1 mm is recommended for bioretention soils. High d_{60}/d_{10} can result in high runoff infiltration rate and is desired. However, once the value of d_{60}/d_{10} is too high (such as the mulch used in this study, d_{60}/d_{10} =15.4), the small components among the media may disperse and be transported into media pores; consequently, the risk of clogging and reduction in runoff infiltration rate is increased. A d_{60}/d_{10} value less than 4 has been recommended (Arias et al., 2001).

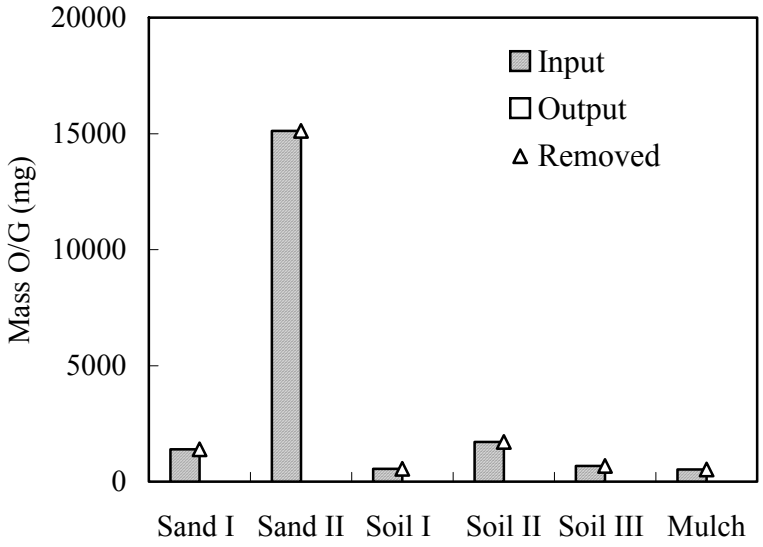

Figure 4.1a. Input, Output, and Removed Mass of O/G among Different Native Media for 6-hr Runoff Treatment

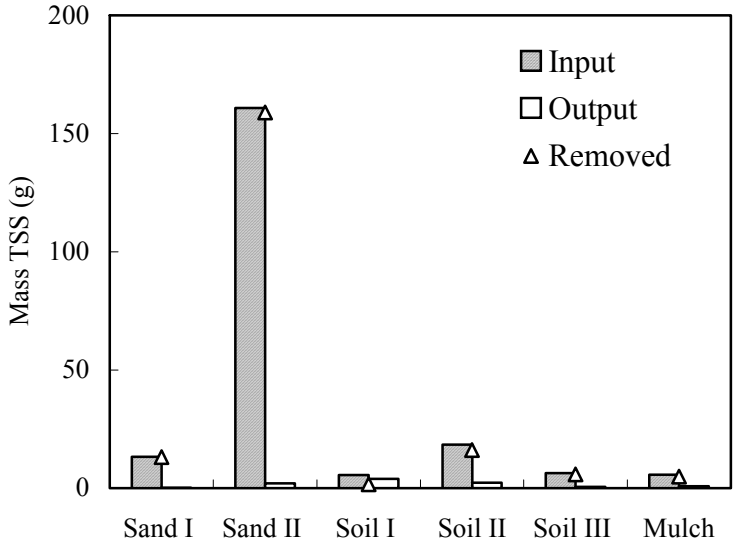

Figure 4.1b. Input, Output, and Removed Mass of TSS among Different Native Media for 6-hr Runoff Treatment

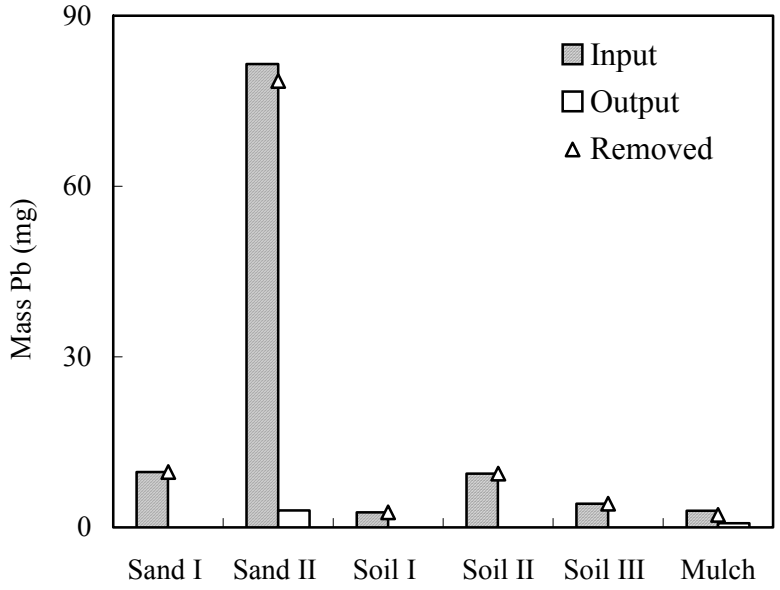

Figure 4.1c. Input, Output, and Removed Mass of Lead among Different Native Media for 6-hr Runoff Treatment

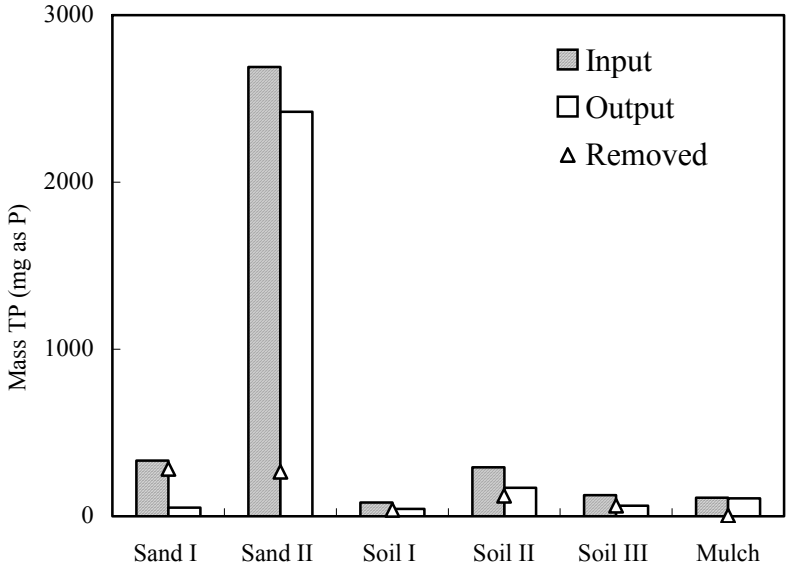

Figure 4.1d. Input, Output, and Removed Mass of TP among Different Native Media for 6-hr Runoff Treatment

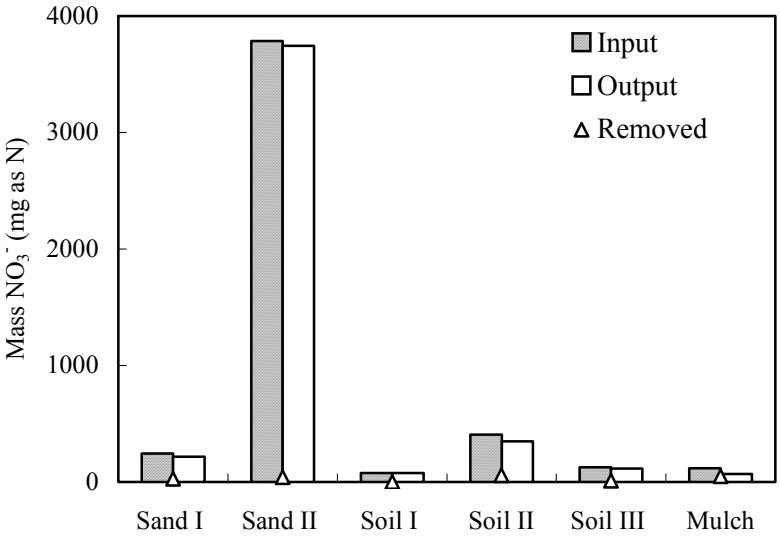

Figure 4.1e. Input, Output, and Removed Mass of Nitrate among Different Native Media for 6-hr Runoff Treatment

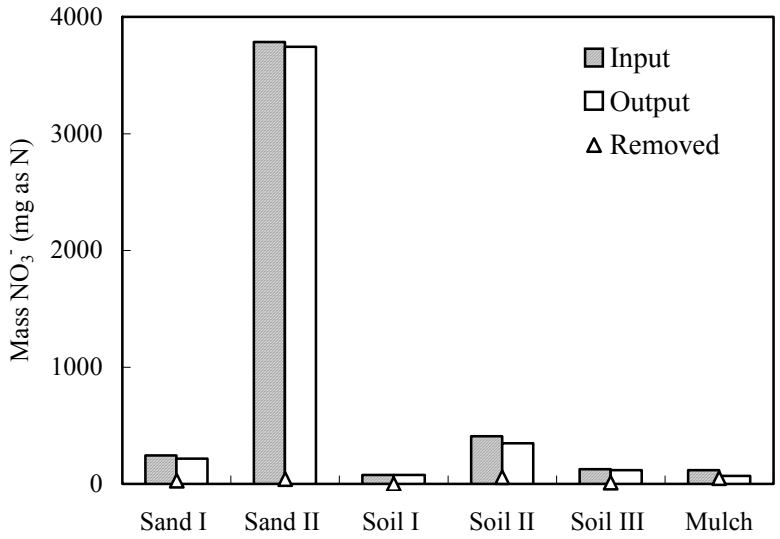

Figure 4.1f. Input, Output, and Removed Mass of Ammonium among Different Native Media for 6-hr Runoff Treatment

4.2.2. The Effect of Media Properties on the Performance of Bioretention

Since details on media properties are available, correlations of properties with pollutant removals by the six native media were examined. First, increased fractions of silt/clay in the medium lowered the runoff infiltration rate, as discussed above. From Table 3.2, it is seen that the soils composed of higher silt/clay contents had higher cation (Mg/Ca/K) contents, OM, and CEC, which are expected to improve runoff pollutant removal efficiencies. Since both sand (for high infiltration) and soil (for pollutant uptake) are desired, mixtures of these media were evaluated. Columns employing different media (sand I, soil I, or sand I/ soil I/mulch mixtures) with various clay+ silt contents were studied (Exps. 1, 3, 8, 13, 14, and 15- - Set B). The media layering of Exps. 13, 14, and 15 was: top mulch (5 cm), synthetic media I (25 to 82 cm), sand I (8 to 65 cm).

Again, excellent removal of input O/G, TSS, and Pb were found with all media (Table 4.1). Because these three pollutants are primarily removed through physical filtration, the treatment efficiency does not show any correlation with media chemical properties. Therefore, lower silt/clay contents produced higher infiltration rates, resulting in higher mass removal (Figure 4.2).

The media with the smaller silt+ clay fractions produced the higher runoff infiltration rates and greater TP mass removals during the 6-hr testing period (Figure 4.2); percent TP removal efficiency, however, varied. TP retention by bioretention media is expected to depend on media constituents. For example, TP removal by soil was positively correlated with soil OM content (Brejda, 1998). Fe-bound P was positively correlated with soil CEC (Samadi and Gilkes, 1999). Therefore, K+ Mg, P, OM, and CEC of the

soil (Table 3.2) all were individually correlated with TP removal efficiency of these six column tests using linear regression. No correlation, however, was found (R^2 ranged from 0.0681 to 0.1925). The runoff flow path in the column can affect the fate of dissolved substances. Some degree of preferential flow may be allowing TP to bypass the bulk soil media (Kung et al., 2000). Therefore, even though media with higher silt/clay contents have higher OM and cation levels that could help to complex phosphorus from infiltrating runoff, dynamic processes apparently prevent the TP removal efficiency from correlating with OM content or CEC.

Nitrate and ammonium removals also did not correlate with silt/clay contents in the media. Generally, nitrate compounds are quite soluble and primarily removed through biological degradation (ASA and SSSA, 1983). Ammonium can be adsorbed on exchange sites of contacting media or fixed within the clay or organic matrix (ASA and SSSA, 1983; Brady and Weil, 2002). Adsorption and desorption of ammonium have also been related to the contents of Ca and Mg in several sandy soils (Wang and Alva, 2000). The removal efficiency of nitrate and ammonium for all column tests was moderate-to-poor (Table 4.1) and was not significantly affected by media properties in this study.

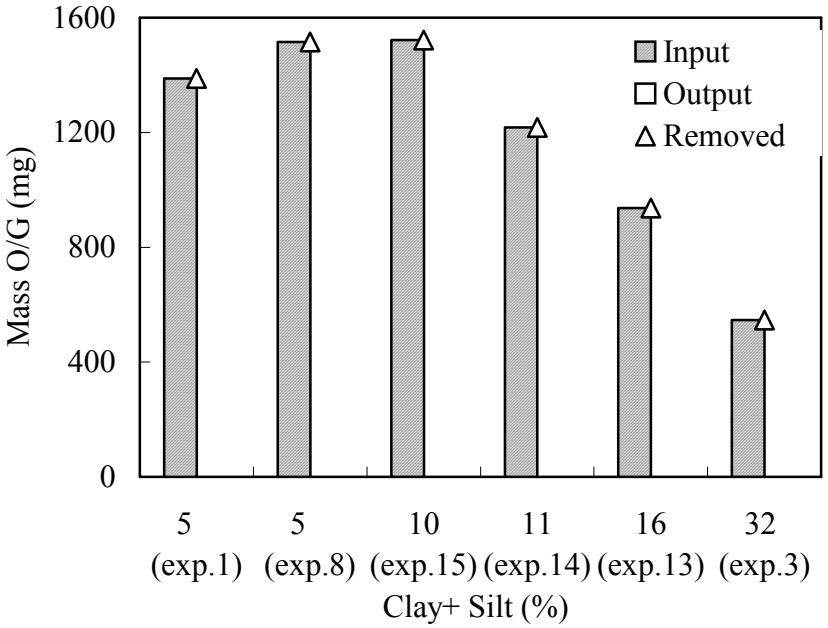

Figure 4.2a. Input, Output, and Removed Mass of O/G among Different Mixtures of Sand I and Soil I for 6-hr Runoff Treatment Columns

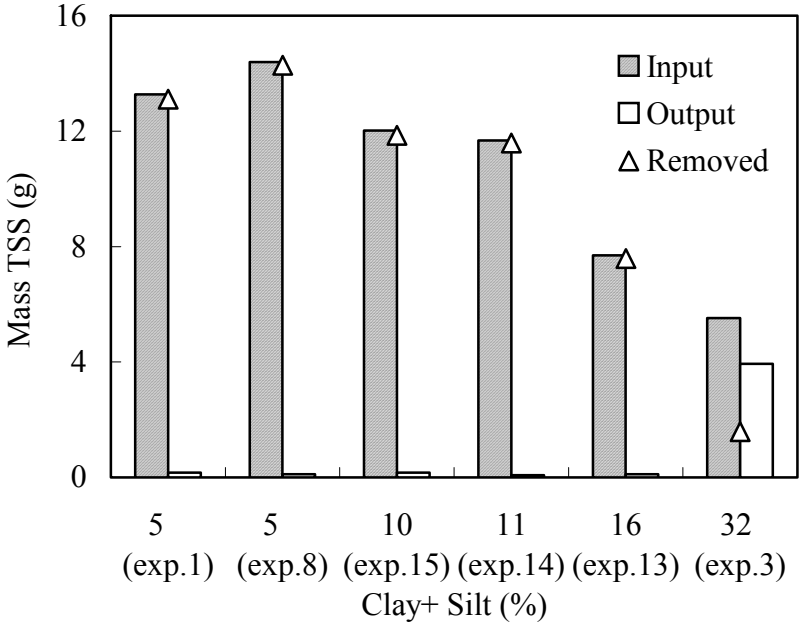

Figure 4.2b. Input, Output, and Removed Mass of TSS among Different Mixtures of Sand I and Soil I for 6-hr Runoff Treatment Columns

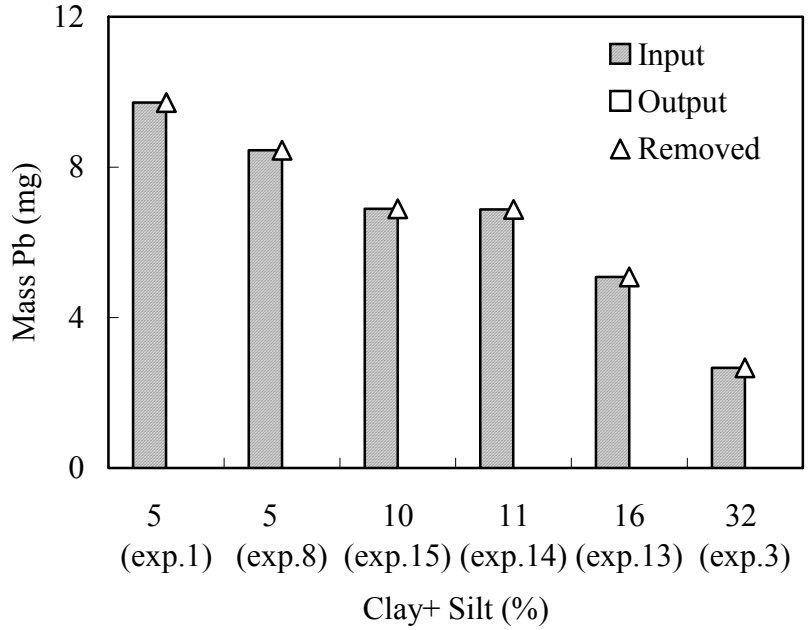

Figure 4.2c. Input, Output, and Removed Mass of Lead among Different Mixtures of Sand I and Soil I for 6-hr Runoff Treatment Columns

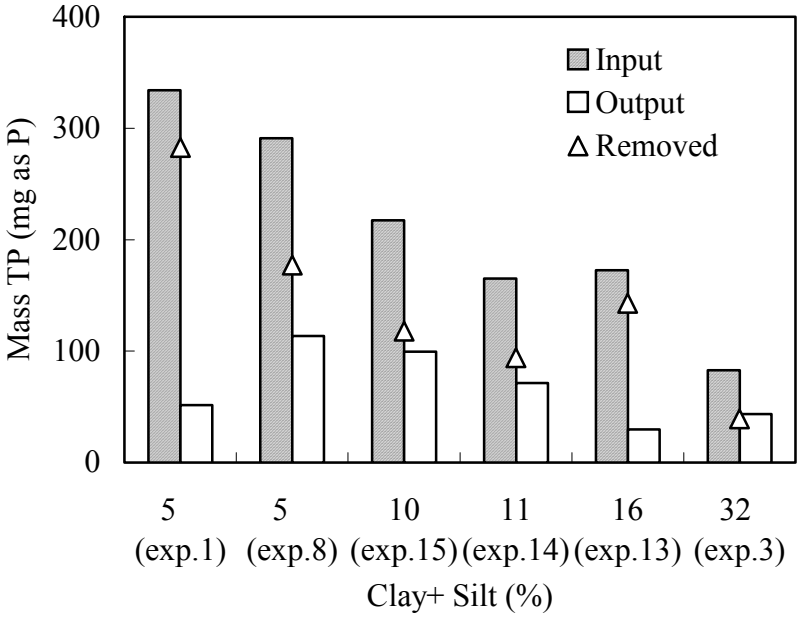

Figure 4.2d. Input, Output, and Removed Mass of TP among Different Mixtures of Sand I and Soil I for 6-hr Runoff Treatment Columns

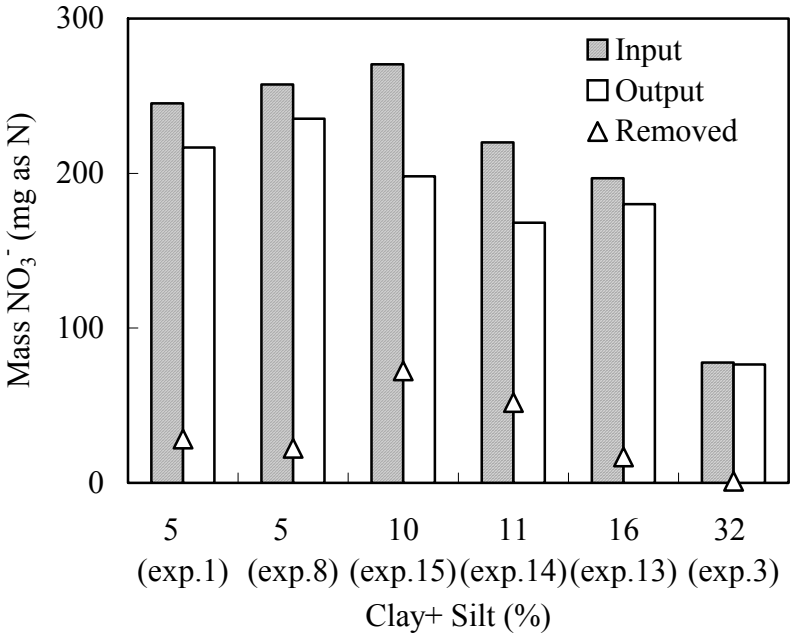

Figure 4.2e. Input, Output, and Removed Mass of Nitrate among Different Mixtures of Sand I and Soil I for 6-hr Runoff Treatment Columns

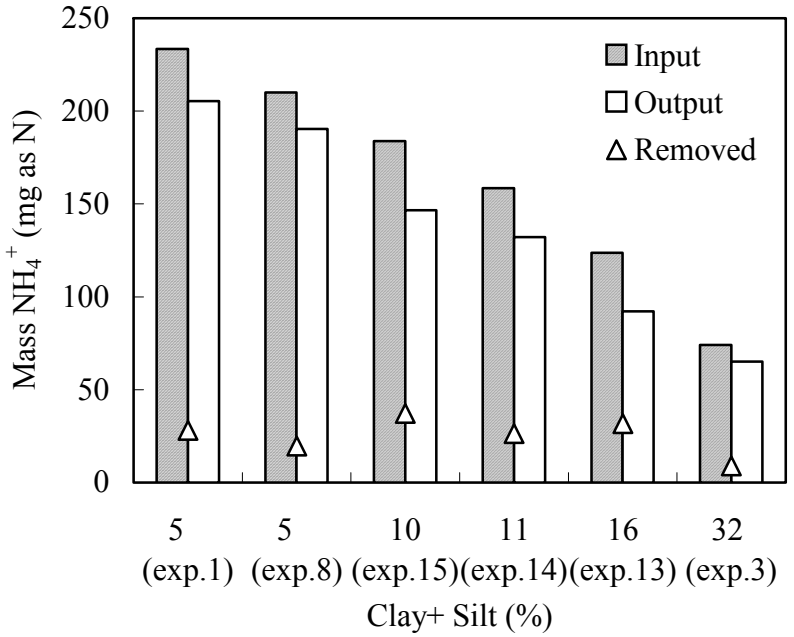

Figure 4.2f. Input, Output, and Removed Mass of Ammonium among Different Mixtures of Sand I and Soil I for 6-hr Runoff Treatment Columns

4.2.3. The Effect of Media Configuration on the Performance of Bioretention

Different media configurations (uniform vis-à-vis various layering) are expected to result in varied infiltration rates (Hillel, 1998) and pollutant removal efficiencies from infiltrating runoff. Uniform coarse-textured sand, as demonstrated above, is very efficient in promoting a high runoff infiltration rate and pollutant mass removal. Considering the vegetative and ecological aspects of bioretention, however, a certain depth of soil is necessary at the surface for plant growth. Also, coarse media may not be able to sustain pollutant removals over repetitive loadings and have less opportunity to support biological processes. Therefore, two series of layered columns were compared. In the first series of columns (Exps. 9, 10, 11, and 12- - Set C-1), an upper soil I layer (10 to 20 cm) sits on top of either 65 to 75 cm of sand I layer or 15 cm of synthetic media I, with a layer of sand I at the bottom. For the second group of columns (Exps. 13, 14, and 15- - Set C-2), the layer was: top mulch (5 cm), synthetic media I (25 to 82 cm), sand I (8 to 65 cm).

In Set C-1, it was apparent that the runoff infiltration rate was limited by the less-permeable soil I surface layer. All columns had identical rates of 0.30 to 0.32 cm/min. This rate was improved by mixing the soil I surface layer with a fraction (19 to 43%) of sand I, creating the C-2 series with infiltration rates from 0.48 to 0.71 cm/min. For O/G and Pb, both sets of layered columns resulted in excellent treatment (> 96% for O/G and > 98% for Pb). Some TSS (66% removal) leached from Exp. No. 9, which had a deeper (15 cm) soil I layer. Overall, columns with an upper soil I layer (C-1) demonstrated lower removal efficiency for nutrients (39 to 50% for TP, 2 to 4% for nitrate, and 2 to 7% for ammonium) than the ones with the more-permeable synthetic media I surface layer

(C-2; 54 to 83% for TP, 13 to 27% for nitrate, and 17 to 26% for ammonium). In less-permeable media, water usually infiltrates into the sublayer through preferential flow paths, concentrate at certain points rather than uniformly flooding through the entire layer (Hillel, 1998). This channeling reduces the total contacting surfaces between infiltrating runoff and media, leading to less pollutant removal.

Pollutant mass removals for both types of layered columns are presented in Figure 4.3. Because of the high permeability, combined with better pollutant removal, a permeable synthetic mixture layer performed better than the soil I surface layer. All of these results are also supported by Exps. 16 to 18 (Set D), which employed layers of mulch (5 cm), synthetic media II or III (85 cm) and sand II (5 cm), which combined a high permeability sand with a sandy soil. Therefore, a layered medium with a permeable sand/soil mixture layer appears to provide the best treatment efficiency for bioretention.

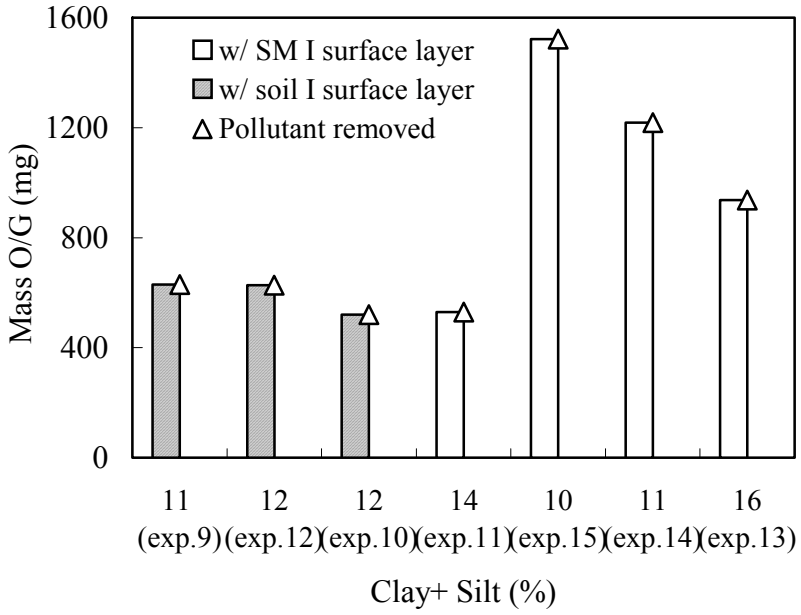

Figure 4.3a. Input, Output, and Removed Mass of O/G among Different Media Configurations for 6-hr Runoff Treatment

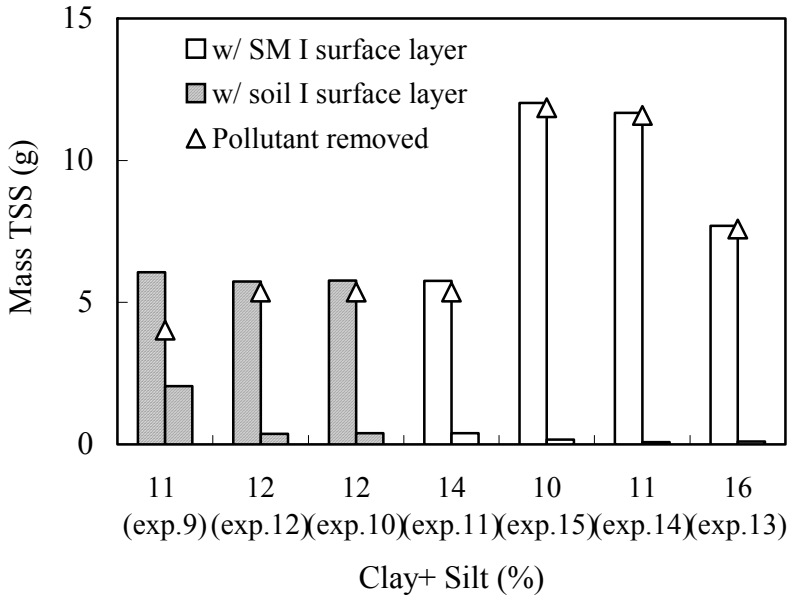

Figure 4.3b. Input, Output, and Removed Mass of TSS among Different Media Configurations for 6-hr Runoff Treatment

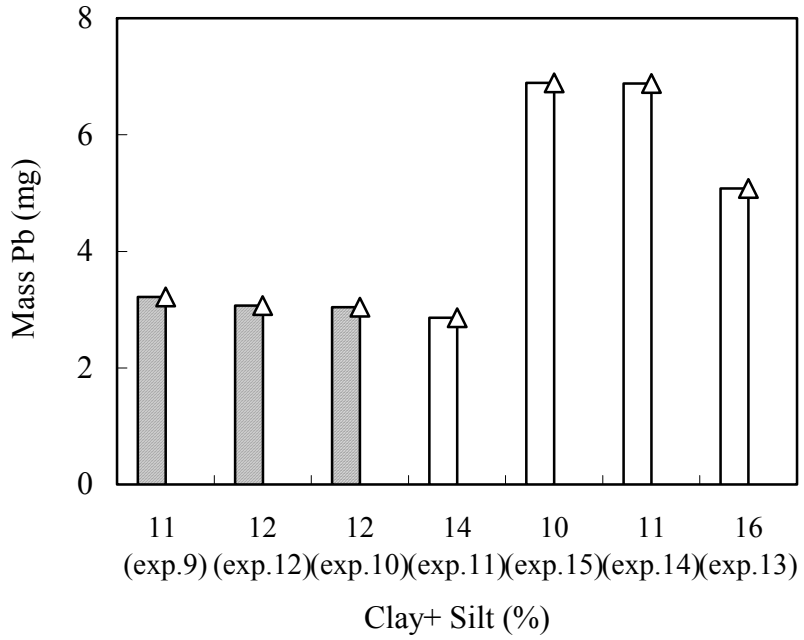

Figure 4.3c. Input, Output, and Removed Mass of Lead among Different Media Configurations for 6-hr Runoff Treatment

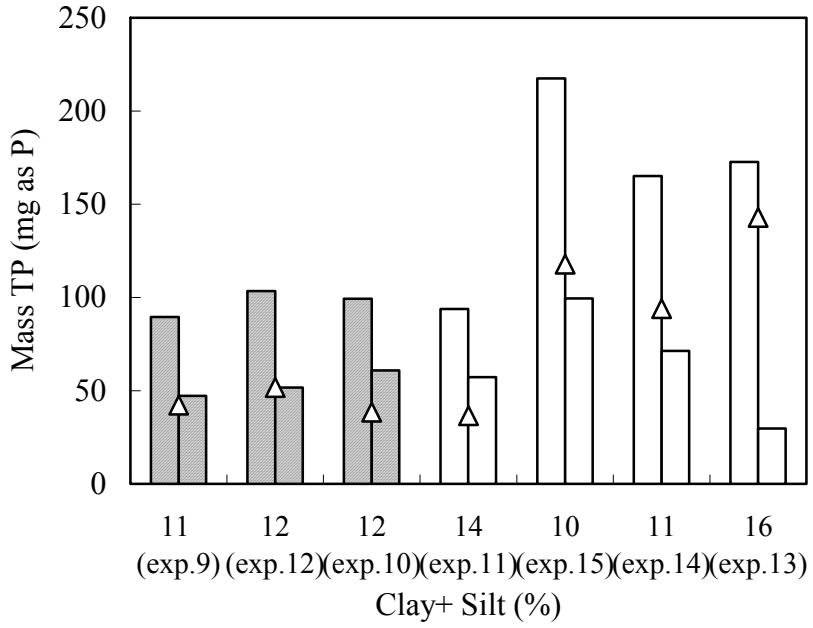

Figure 4.3d. Input, Output, and Removed Mass of TP among Different Media Configurations for 6-hr Runoff Treatment

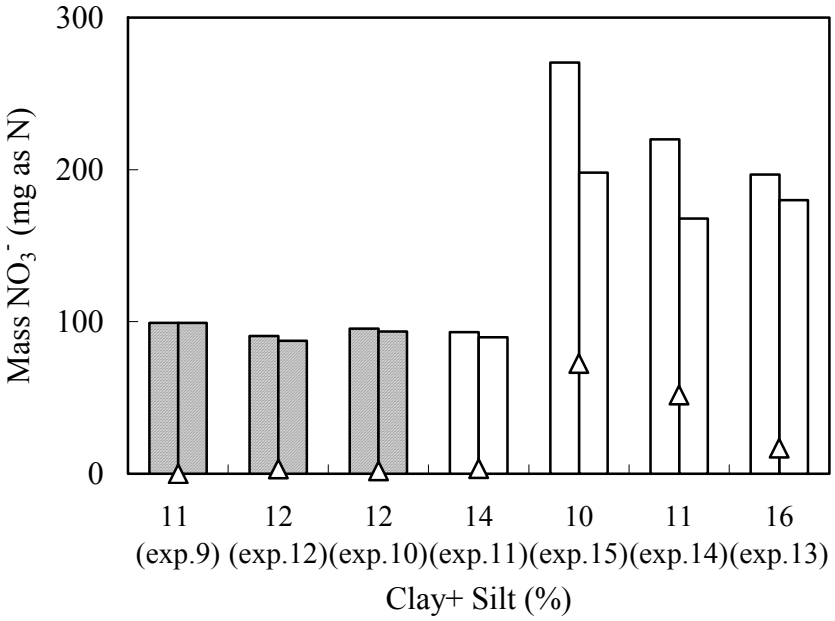

Figure 4.3e. Input, Output, and Removed Mass of Nitrate among Different Media Configurations for 6-hr Runoff Treatment

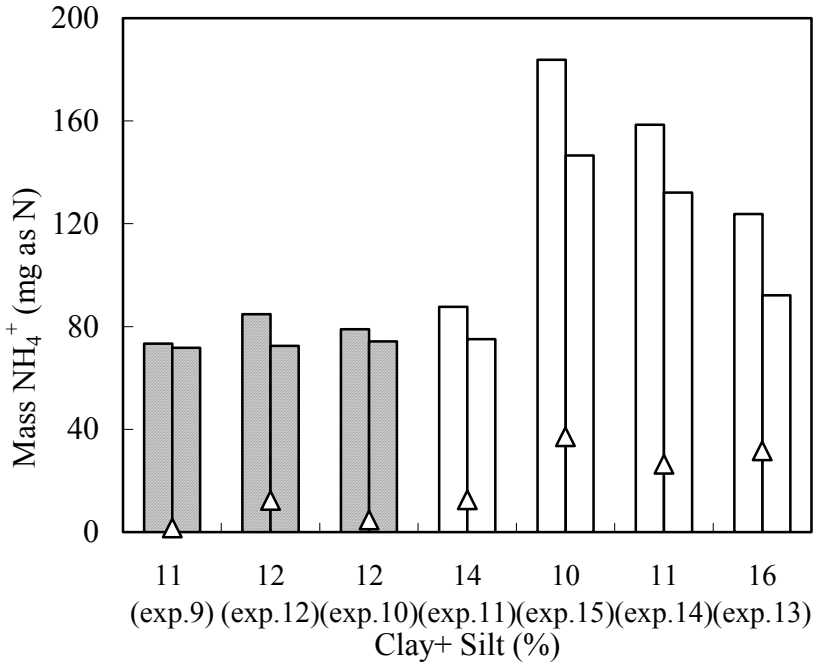

Figure 4.3f. Input, Output, and Removed Mass of Ammonium among Different Media Configurations for 6-hr Runoff Treatment

4.3. Evaluation of Existing Bioretention Facilities

Six existing bioretention sites were evaluated using synthetic runoff. Another two bioretention evaluations were conducted during a rainfall event. The performances of the bioretention facilities are discussed with respect to infiltration and water quality.

4.3.1. Infiltration Aspects

The infiltration rate of runoff through a bioretention cell should relate directly to the textures of the media, as was demonstrated in the column studies. As shown in Table 4.2, the silt/clay content in the upper media layer is higher than that in the bottom for three of the six sites, either because of the initial design or subsequent TSS accumulation from incoming storm water runoff. Therefore, the less-permeable upper layer of these sites would limit the infiltration rate. Because of the low water loading (3.2 cm/hr), pooling occurred only on two sites. Less than 5 cm pooling occurred at site HV1 after 35 minutes of pumping, and after 28 minutes for the LO3 site. Of the six, these two sites have the highest silt/clay contents in the upper media.

Table 4.2a. Results of Field Bioretention Media Chemical and Mechanical Analysis

Site (Media Depth)		pH	Mg	P	K	Ca	S.S	O. M	CEC
			mg/100g soil					%	meq/100g soil
GB (109 cm)	10-15 cm	7.1	29	16	16	*	*	3.4	*
	15-40 cm	7.3	29	17	14	*	*	2.5	*
LO1 (51 cm)	10-15 cm	7.3	29	18	13	> 44	38	6.2	17
	15-40 cm	6.8	23	9	7	> 44	17	3.8	12
LO2 (51 cm)	10-15 cm	7.0	29	28	43	37	17	2.1	10
	15-40 cm	7.0	24	5	16	148	96	1.4	30
LO3 (51 cm)	10-15 cm	5.4	16	5	13	11	17	1.8	4
	15-40 cm	5.4	18	5	10	11	17	2.0	5
HV1 (76 cm)	10-15 cm	6.8	24	9	14	37	17	3.3	9
	15-40 cm	7.6	25	7	9	67	17	1.0	14
HV2 (64 cm)	10-15 cm	7.0	25	8	12	44	17	2.3	10
	15-40 cm	7.7	18	10	2	15	17	0.1	4

S.S: soluble salts

* no data collected

Table 4.2b. Results of Field Bioretention Media Chemical and Mechanical Analysis

Site (Media Depth)		Sand %	Clay %	Silt %	Classification
GB (109 cm)	10-15 cm	66	21	13	Sandy Clay Loam
	15-40 cm	70	17	13	Sandy Loam
LO1 (51 cm)	10-15 cm	83	8	9	Loamy Sand
	15-40 cm	83	10	7	Loamy Sand
LO2 (51 cm)	10-15 cm	89	9	2	Loamy Sand
	15-40 cm	42	26	32	Loam
LO3 (51 cm)	10-15 cm	58	22	20	Sandy Clay Loam
	15-40 cm	48	28	24	Sandy Clay Loam
HV1 (76 cm)	10-15 cm	62	19	19	Sandy Loam
	15-40 cm	78	14	8	Sandy Loam
HV2 (64 cm)	10-15 cm	69	17	14	Sandy Loam
	15-40 cm	93	6	1	Sand

4.3.2. Water Quality Aspects

The water quality results from the first six field studies are presented in Figure 4.4. Unlike the laboratory column experiments, no or minimal water head existed. In addition, lateral flow is expected within the media. The results of runoff infiltration rate from column experiments showed the efficiency of various bioretention media to infiltrate the runoff into the facility. However, the permeability of on-site bioretention media could not be determined because the influent pumping rate was insufficient to saturate the media in most cases. Therefore, pollutant concentration reduction is the only factor to compare laboratory column experiments and field tests.

Similar to all laboratory studies, O/G was removed effectively (> 97%) in all six bioretention facilities. In addition, TSS removal ranged from 72 to 99%, and 80 to >98% total Pb removal was found. Pb removal efficiency positively correlated with that of TSS ($r^2 = 0.927$), clearly indicating a significant relationship and the importance of adsorbed Pb, which also was found in the column studies. Because of color differences, it was apparent that most of the effluent TSS was part of the bioretention media instead of the incoming TSS. Therefore, although input TSS was filtered by the media, some media particles washed out. The two facilities with the lowest TSS removal are also two of the newest.

The most variability in the field sites was found in TP removal efficiencies, which ranged from 37 to 99%. Media depth and texture were correlated with TP removal, but no significant relationship was found. For example, although site GB is much deeper than the others, the removal efficiency of TP was not the best among these facilities. A good correlation between TP removal and OM content appears, which was not noted in

laboratory studies. The highest OM was found at LO1, which demonstrated 93% TP removal. LO2 and HV2 have the lowest OM content and, correspondingly, the lowest TP removal.

For nitrate and ammonium, all six facilities produced similar low removal (2 to 7% for nitrate-N and 5 to 10% for ammonium-N at 5 sites), as was found with column experiments. The exception was site LO1, in which 49% ammonium-N was removed. The reason for this remains unclear.

The results for two additional tests conducted during a rainfall event are summarized in Table 4.3. Because sample collection began 4-hr after the beginning of the rain event, the water quality of inlet runoff samples should be better than those from first flush samples. Also, some pollutant loading from the parking lots was removed during transport through the channels to the bioretention cells. Based on Table 4.3, TP was not found above the detection limit in all inlet and effluent samples, whereas TSS, Pb, nitrate and ammonium input concentrations were lower than in the synthetic runoff employed in this study. High concentrations of O/G appeared in the inlet samples, which should be attributed to high vehicle activity in the parking lot being drained. In agreement with both laboratory and field studies, over 99% of O/G and 94% of Pb were removed by both bioretention facilities. Because these two sites had been just installed 3 months prior, the soil medium was still not stabilized and some TSS leached out, thus, negative removals were typically found.

More nitrate was removed by CP1 (31± 12%) than by CP2 (10± 10%), supporting the effectiveness of the CP1 denitrification layer. However, using the Hypothesis Test of Two Means with a 20% level of significance does not conclude that the means of these

two sets of samples are statistically different. Ammonium was removed to below the detection limit at both sites, but the input was relatively low.

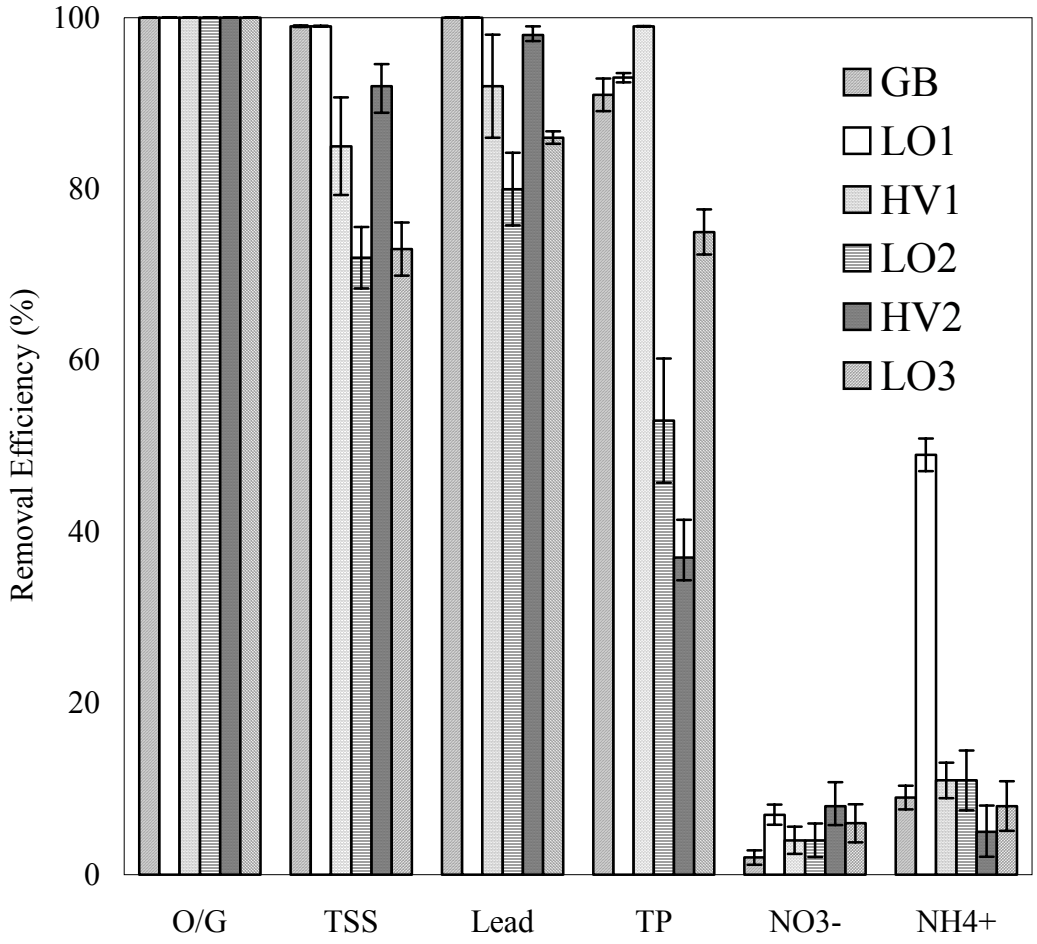

Figure 4.4. Results of Field Studies for 6-hr Synthetic Runoff Treatment

Table 4.3a. Results of On-Site Bioretention Evaluation during a Rainfall Event

(Mean± Standard Deviation, 3 analytical measurements/sample)

CP1							
Sample	Time	O/G	TSS	Pb	NO_3^-	NH_4^+	TP
	hr	mg/L	mg/L	μg/L	mg-N/L	mg-N/L	mg-P/L
Input	0	68± 4	17± 3	32± 0	0.13± 0.01	0.09± 0.01	< 0.05
Output		< 0.5	46± 5	< 2	0.08± 0.01	< 0.05	< 0.05
Removal (%)		> 99	-174± 43	> 93	40± 5	> 44	-
Input	0.5	53± 0	19± 5	41± 2	0.13± 0.01	0.08± 0.00	< 0.05
Output		< 0.5	33± 0	< 2	0.08± 0.00	< 0.05	< 0.05
Removal (%)		> 99	-78± 37	> 95	38± 6	> 37	-
Input	1	56± 1	17± 3	32± 2	0.11± 0.01	0.09± 0.01	< 0.05
Output		< 0.5	41± 4	< 2	0.09± 0.00	< 0.05	< 0.05
Removal (%)		> 99	-145± 39	> 93	14± 5	> 44	
Input	1.5	67± 3	23± 4	28± 0	0.13± 0.00	0.09± 0.01	< 0.05
Output		< 0.5	27± 0	< 2	0.09± 0.00	< 0.05	< 0.05
Removal (%)		> 99	-15± 13	> 92	31± 0	> 44	-
Mean							
Input		61± 7	19± 4	33± 5	0.12± 0.01	0.08± 0.01	< 0.05
Output		< 0.5	37± 8	< 2	0.08± 0.01	< 0.05	< 0.05
Removal (%)		> 99	-103± 71	> 94	31± 12	> 37	-

Table 4.3b. Results of On-Site Bioretention Evaluation during a Rainfall Event

(Mean± Standard Deviation, 3 analytical measurements/sample)

CP2							
Sample	Time hr	O/G mg/L	TSS mg/L	Pb µg/L	NO_3^- mg-N/L	NH_4^+ mg-N/L	TP mg-P/L
Input	0	65± 2	20± 0	36± 0	0.12± 0.01	0.08± 0.00	< 0.05
Output		< 0.5	14± 1	< 2	0.12± 0.00	< 0.05	< 0.05
Removal (%)		> 99	34± 3	> 94	-5± 5	> 37	-
Input	0.5	58± 0	21± 1	52± 2	0.12± 0.00	0.08± 0.01	< 0.05
Output		< 0.5	15± 3	< 2	0.10± 0.01	< 0.05	< 0.05
Removal (%)		> 99	27± 11	> 96	17± 10	> 37	-
Input	1	56± 4	16± 1	36± 2	0.09± 0.00	0.09± 0.01	< 0.05
Output		< 0.5	18± 2	< 2	0.08± 0.00	< 0.05	< 0.05
Removal (%)		> 99	-12± 11	> 93	11± 0	> 44	-
Input	1.5	67± 3	23± 4	28± 0	0.13± 0.00	0.09± 0.01	< 0.05
Output		< 0.5	27± 0	< 2	0.09± 0.00	< 0.05	< 0.05
Removal (%)		> 99	-7± 12	> 92	17± 16	> 44	-
Mean							
Input		63± 7	18± 2	39± 8	0.11± 0.01	0.09± 0.01	< 0.05
Output		< 0.5	16± 2	< 2	0.10± 0.02	< 0.05	< 0.05
Removal (%)		> 99	10± 23	> 95	10± 10	> 44	-

CHAPTER 5:

MULTIPLE-LOADING EVALUATION OF BIORETENTION FOR TREATMENT OF URBAN STORM WATER RUNOFF: RUNOFF INFILTRATION, TSS AND PHOSPHORUS REMOVAL

5.1. Introduction

Phosphorus (P) is an essential macronutrient for plant growth. Through leaching processes, however, excess P can endanger the quality of ground and surface waters. P inputs to water bodies are usually under close scrutiny due to the P contribution to water eutrophication and algal blooms, which result in the depletion of dissolved oxygen and high turbidity levels in aquatic ecosystems. These impairments, ultimately, can lead to poor water quality and the loss of biodiversity in the water bodies. According to recent surveys (U.S. EPA, 1998), P is becoming a leading pollutant for impaired surface waters (including rivers, lakes, reservoirs, ponds, estuaries, lake shorelines, and ocean shorelines) and ground water.

In urbanized areas, because impervious surfaces can result in a significant fraction of impinging rainfall becoming runoff, urban runoff is rapidly becoming a major source of nonpoint pollution (U.S. EPA, 1996), transporting abundant P into waterways. P found in urban runoff originates from lawn fertilizers, atmospheric deposition, automobile exhaust, soil erosion, animal waste, or detergents (U.S. EPA, 1999b). In runoff, P is distributed as both dissolved (DP, particle size < 0.45 μm as operational definition) and particulate (PP, P sorbed onto the solids before or after transport in the runoff (Sharpley,

1985) with particle size > 0.45 μm). A considerable total suspended solids (TSS) load usually appears in urban storm water runoff, as well (Characklis and Wiesner, 1997). Since several pollutants are commonly associated with TSS (Sansalone and Buchberger, 1997), TSS is also a frequently reported parameter for runoff quality.

Retention of P in bioretention facilities decreases the P load to downstream waterways. Retention mechanisms of P in soils combine biological, chemical, and physical processes. Under vertical flow, PP that was mostly transported through macropore flow could be removed via media filtration processes (Heathwaite and Dils, 2000). Through vegetative uptake, microorganism degradation, sorption, exchange reactions, precipitation, sedimentation and entrainment, DP can be retained in soils (Reddy et al., 1999; Van Cuyk et al., 2001). Previous work has shown that about 80% of DP was removed by a sandy loam soil in two laboratory-scale pilot bioretention facilities (Davis et al., 2001). Similar studies have demonstrated 70-85% P removal, correlated with media depth in pilot-scale and full-scale bioretention facilities (Davis et al., 2003c).

After being retained, captured P can be utilized as a nutrient for plant growth in bioretention facilities, which would allow a removal pathway via harvesting the vegetation. Phosphorus appears both in organic and inorganic forms in soils. For vegetative purposes, dissolved inorganic P is usually considered as bioavailable and can be used for plant nutrition (Rechcigl, 1995; Reddy et al., 1999). With respect to environmental concerns, the mobility of P compounds in soils determines the potential of retained P to present detrimental risk to ground and surface water quality. In summary, high plant availability and low mobility is preferred for environmental P management.

Three issues regarding P removal in bioretention were addressed in this study. In general, various bioretention media possess different P sorption capacities. For example, sorption capacities varied more than 3-fold, from 9 mg/100 g for Merrimac soil to 29 mg/100 g for Paxon soil (Sawhney and Hill, 1975). Sands with a high metal content (Ca, Al, or Fe) had much higher P-removal capacity than those with lower concentrations of these metals (Arias et al., 2001). However, although the P sorption characteristics of soil media affect P removal in bioretention facilities, the chemical properties of a soil may not accurately predict the mobility of P through media with macroporosity (Cox et al., 2000; Chapter 4) since P removal in columns may not occur by simple sorption processes alone (Van Cuyk et al., 2001).

The first objective of this work was to investigate correlations between media P sorption characteristics and TP removal through bioretention columns. As such, P sorption capacity of sands, soils, and mulch, used as bioretention media, along with three continuous-flow bioretention columns with media consisting of different soil/sand ratios were examined. Media with higher sorption capacity were expected to capture greater total mass of TP from high P loadings to the bioretention column.

Second, two bioretention columns (RP1 and RP2) were tested for P removal and accumulation over a multiple-loading period (80-120 days). Runoff was applied to the columns for 6-hr during each repetition with several days between repetitions, for a total of 12 repetitions for RP1 and 16 repetitions for RP2. The study objectives were to investigate the effect of two inverse configurations (RP1: media with low hydraulic conductivity overlaying one with high hydraulic conductivity; RP2: media with high hydraulic conductivity overlaying one with low hydraulic conductivity) on runoff

infiltration rate, and to evaluate the effectiveness of these two columns for P removal. Three-layer media with different media components and configurations were employed in each column to maximize the runoff infiltration rate and P removal efficiency. A capillary barrier between two media layers was hypothesized to form in RP1 to restrict runoff infiltration, thus, demonstrating the RP2 configuration to quantitatively perform better. Also, P removal efficiency was assumed to decrease with time for both columns due to the consumption of P sorption capacity of the media.

Finally, environmental and agronomic soil tests were conducted on the media samples before and after repetitive experiments (RP2). The objective was to test the potential for P leaching from the bioretention media and to quantify available P for future plant growth after repetitive experiments.

Overall, the effectiveness of alternative bioretention media and media configurations for P removal was evaluated. The significance of sorption processes in P removal through bioretention columns was investigated.

5.2. P Sorption

P sorption isotherms were determined for all media employed in this study at pH 7. Apparent P sorption capacity for each medium was calculated using the Langmuir equation (Sparks, 1995):

$$q = \frac{bKC}{1 + KC} \tag{5.1}$$

where C is the equilibrium aqueous P concentration, q is the amount of P sorbed (sorbate per unit mass of sorbent), b is the P sorption capacity of the media, and K is a constant related to P binding strength.

The TP isotherms for all employed media are shown in Figure 5.1. Except for mulch, the Langmuir equation provides a good fit to all data. Based on the results, P sorption capacities (b- Eq. 1) of sands varied from 20 μg/g for sand II to 89 μg/g for sand I. The sorption capacity of soil I was 130 μg/g, 128 μg/g for soil III, and 137 μg/g for soil IV. Mulch sorbed little P. As expected, the soils employed in this study had higher capacity than sands and mulch for removing P from solution. Sand I has higher sorption capacity than sand II, which is probably related to the higher Ca+Mg content in sand I (12.3 mg/100 g sand for sand I and 3.3 mg/100 g sand for sand II, Arias et al., 2001) and the possible formation of surface precipitates (Sparks, 1995). The P sorption capacities among the three soils were within 7%.

Media with higher P sorption capacity should capture greater amounts of TP in column studies. However, Sawhney and Hill (1975) noted that P removal depends not only on the P sorption capacity of the soil but also on the geometry of the system. Complex processes such as those proceeding at the soil-water surface as well as diffusion processes in the soil matrix have been suggested as affecting P retention through a wetland soil (Reddy et al., 1999).

In order to better understand the dynamic trends of P removal, three continuous flow columns with different media compositions were further tested. Three small columns at 30/70, 50/50 and 70/30 of soil III/sand II % were employed to investigate P uptake from a 3 mg/L input.

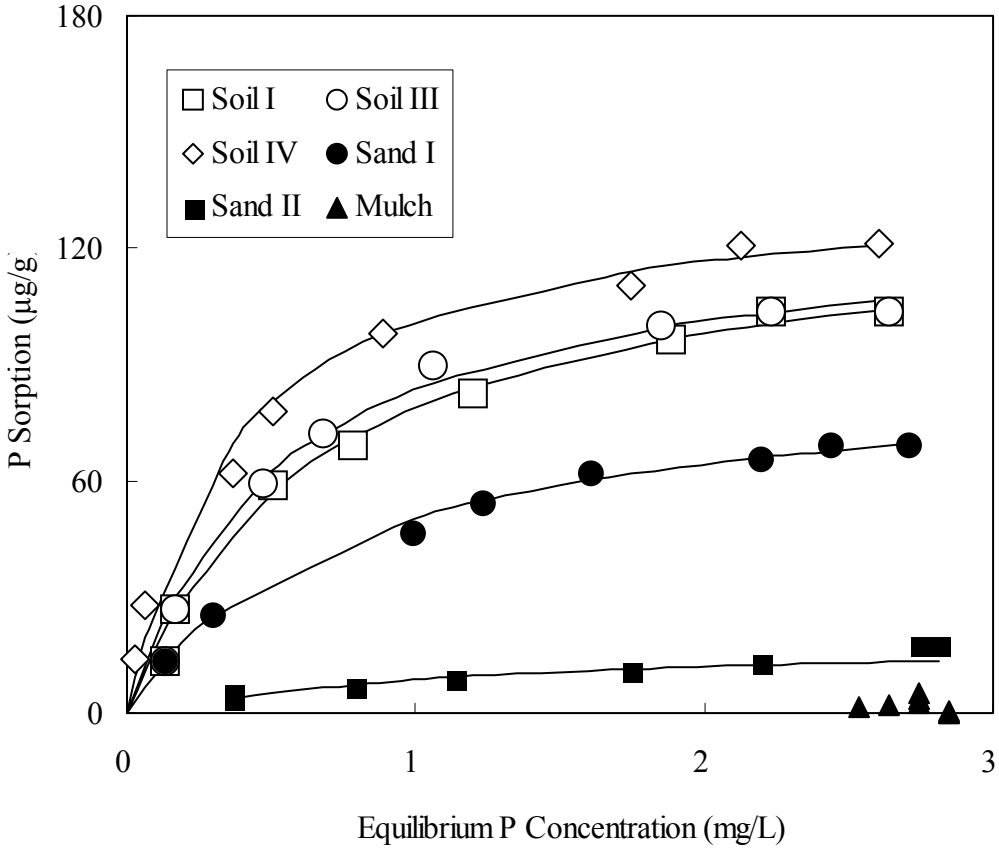

Figure 5.1. P Sorption Isotherms for Different Media (pH= 7, Temperature: 22^0C, Initial P= 2.85 mg/L, Media Concentration= 2 to 700 g/L, Line is equal to Langmuir isotherm fit to data.)

The results are shown in Figure 5.2. During the first 6 days, all columns demonstrated essentially the same P removal efficiency, which ranged from 72 to 77%. After this period, greater amounts of P gradually leached out from the columns that contained lower fractions of soil. The media containing more soil had greater P retaining capacity than the media containing predominantly sand. However, overall the TP sorption capacity of each medium calculated from batch studies cannot accurately predict the dynamic trend of TP removal efficiency in a vertical column. As mentioned, it might be due to the complex processes occurred between soil-water surfaces.

The total TP sorption capacity of each continuous column was calculated from the batch data and compared with the actual accumulated TP. Based on the results of batch P sorption data, TP sorption capacity for all three continuous columns was calculated as:

$$m = \sum q_i \times m_i \tag{5.2}$$

where m is the sorptive mass of TP by each continuous column, q_i is the TP sorption capacity of each media at initial 2.85 mg-P/L, obtained from isotherm data, m_i is each employed media mass, and the summation includes both the soil and sand in the column.

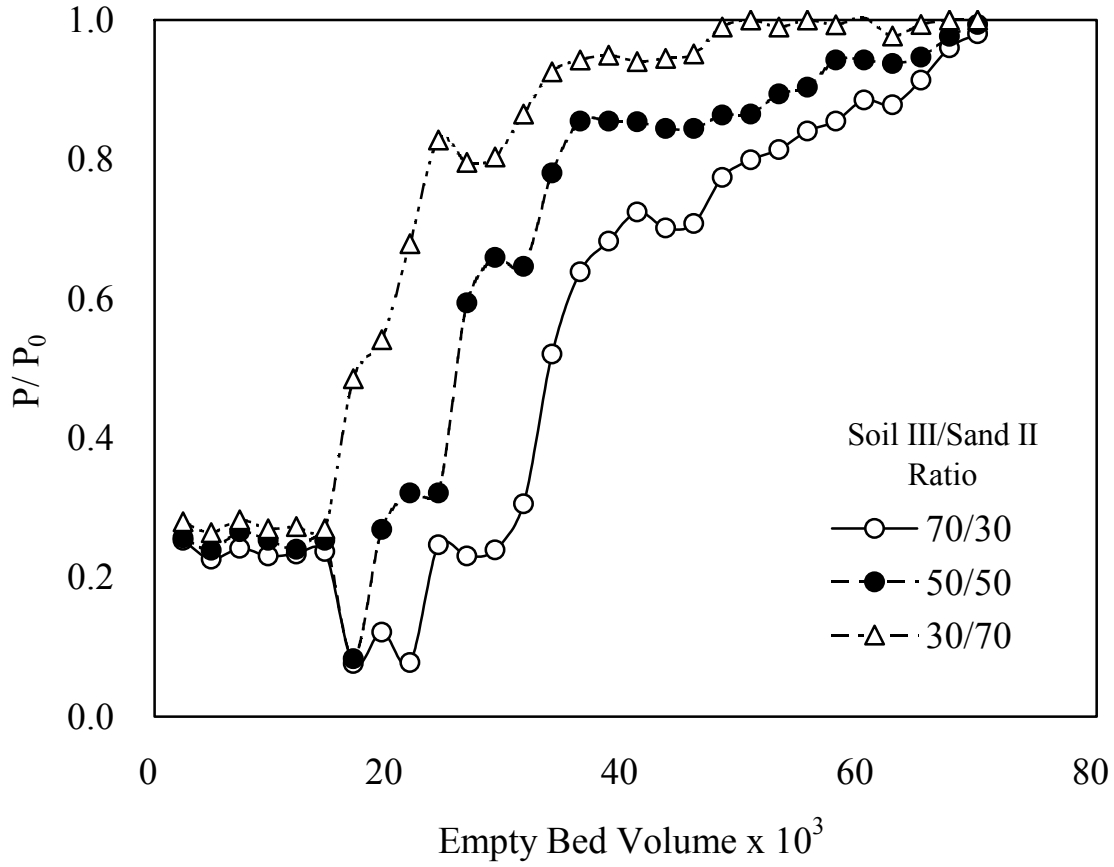

Figure 5.2. P Effluent Concentration Ratios from Continuous Flow Columns at Different Soil/Sand Mass Ratios (pH= 7, Input P= 3 mg/L)

Meanwhile, total accumulated TP mass, m_a, by each continuous column was calculated as:

$$m_a = \int_{t=0}^{t=29} (C_{in} - C_{out})\, Q\, dt \tag{5.3}$$

where C_{in} and C_{out} are the input and output TP concentrations, Q is flow rate, and t is the experimental period expressed in days.

During the testing period, the total input of TP for each column was 391 mg. As calculated from Eq. 5.2, total sorbable TP is 107 mg TP for the column with 70% soil I. This column, however, actually removed 184 mg of TP throughout the testing period as calculated from Eq. 5.3 (172%). For the column with 50% soil I, 82 mg of TP sorption was predicted, whereas 139 mg of TP was retained in the column (170%). For the column with only 30% soil I, the theoretical TP adsorption capacity was 57 mg and 92 mg-TP was finally accumulated in the media (163%). The medium mixture with the higher P sorption capacity retained twice as much P from the infiltrating runoff.

5.3. Repetitive Bioretention Column Tests

5.3.1. Infiltration Rate vs. TSS Removal

A total of twelve (RP1) and sixteen (RP2) repetitions were completed to test the performance of bioretention, with specific focus on the infiltration rate, TSS and P

removals, under multiple runoff loadings with 5- to14-day intervals between each event. After all repetitions, 87 g of TSS were applied into RP1, as well as 88 g of TSS for RP2. Except for the first repetition of RP1 and the first two repetitions of RP2, over 91% of TSS were filtered by the bioretention media. As shown (Figure 5.3), clogging appeared only in RP2 without a surface mulch layer. Similar to the results from studies conducted in newly constructed bioretention facilities (Chapter 4), some suspended solids washed out from the soil media and resulted in low calculated TSS removal efficiencies during the first two repetitions (91 and 57%, Figure 5.4). Afterward, the media stabilized and the removal efficiency of TSS was > 94% throughout the remaining experiments, indicating that bioretention can be very effective in TSS management.

Figure 5.3. SS Filtered by Surface Mulch Layer

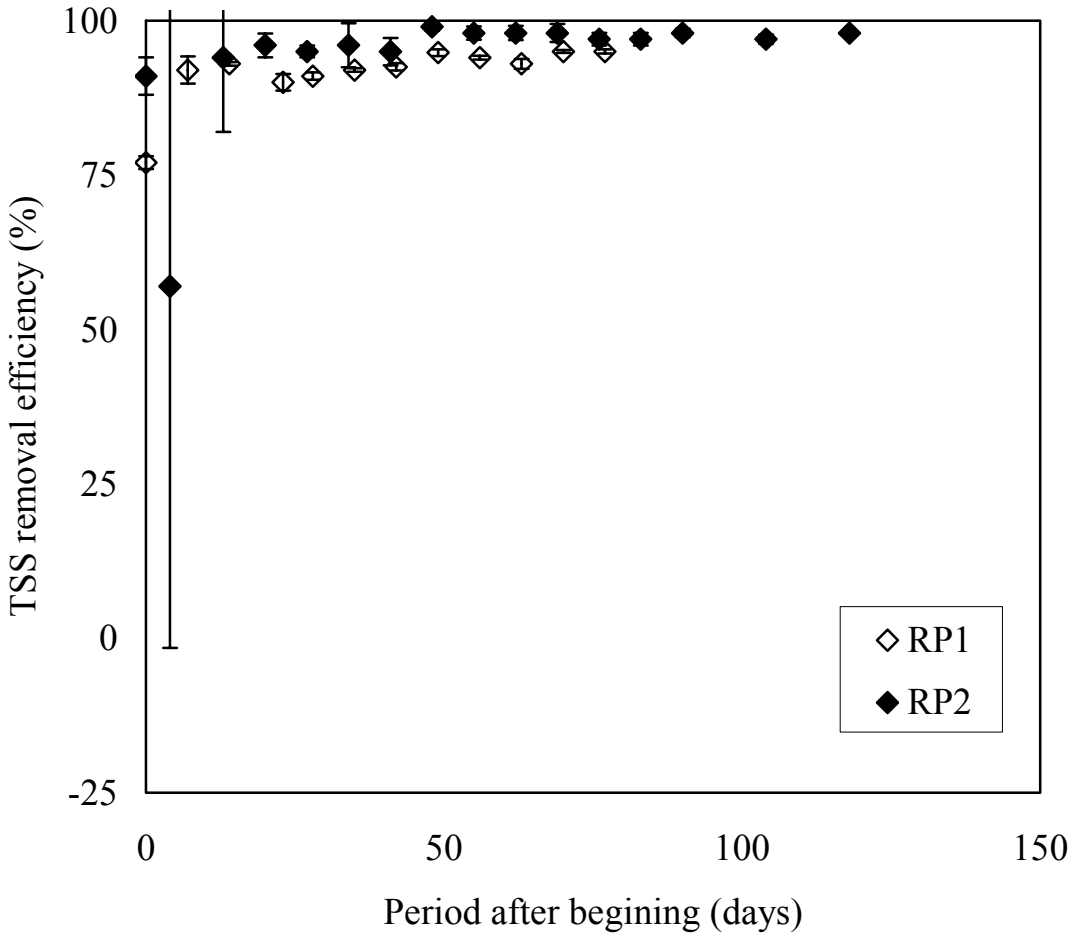

Figure 5.4. TSS Removal during Repetitive Experiments

The results for runoff infiltration rate at a 15-cm head are presented in Figure 5.5. The infiltration rate throughout all twelve repetitions in RP1 remained constant at 0.35 cm/min, which was near that for runoff flow through soil I (0.28 cm/min) only (Chapter 4). As noticed during the experiments, runoff did not enter the lower sand layer until the head was built up sufficiently to overcome the capillary tension between layers (Stormont and Anderson, 1999). Afterwards, infiltrating runoff flowed quickly through the bottom sand layer. It was apparent that infiltration of runoff was controlled by the top soil layer and the variability during each 6-hr experiment was not significant at a 15-cm fixed water head.

RP2 employed a high hydraulic conductivity media overlain one with low hydraulic conductivity. A media mixture (mulch/soil/coarse sand) with organic matter and soil for vegetative purpose and coarse sand for promoting runoff infiltration was designated as the surface layer. Below this layer, sand II (which can efficiently retain pollutants from runoff, Chapter 4) was chosen for efficient pollutant removal. The top two layers served as the bioretention media for the quick infiltration of first flush runoff with efficient pollutant removals. Finally, the less-permeable soil with high P removal capacity was placed in the bottom, with expectation to enhance P removal efficiency by increasing P contact time with bioretention media.

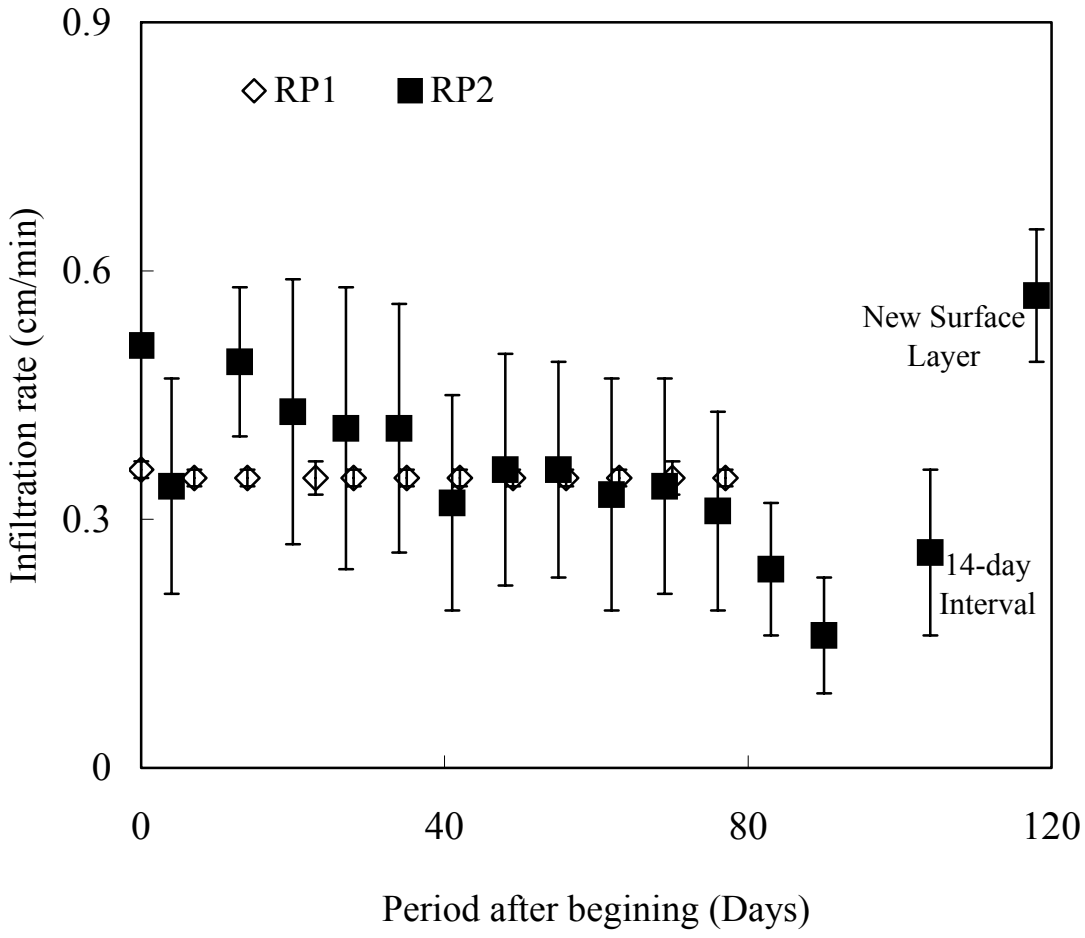

Figure 5.5. Results of Runoff Infiltration Rate for Repetitive Columns (RP1 and RP2)

As expected, runoff infiltrated into RP2 faster than into RP1 during the first few repetitions. However, based on Figure 4, the runoff infiltration rate gradually decreased from 0.51 to 0.16 cm/min throughout the first fourteen tests. Suspended solids in the runoff appeared to clog the media gradually throughout the first 14 repetitions. In addition, the runoff infiltration rate in RP2 had a high variability during each 6-hr experiment. The bottom soil layer should be the reason for this variability. Because the bottom soil layer was less permeable than the other two upper media layers, runoff could not flow through right the way after reaching this layer. As a result, the water head inside the media gradually built up and finally increased the overall runoff infiltration rate.

To simulate a field condition without rain for a longer period, the 15^{th} repetition was started 14 days after the 14^{th} repetition, which was twice as long as the period between the first 14 repetitions. Since the moisture content of the surface layer is expected to diminish more during the longer interval period (Hillel, 1998), runoff could be absorbed more readily during the 15^{th} repetition. The infiltration rate increased from 0.16 to 0.26 cm/min after the longer dry period. Also, in order to test a possible remediation method for addressing surface clogging, the top 5 cm of medium was removed and replaced with new original material. In response, the runoff infiltration rate recovered to the same level as the initial (~ 0.5 cm/min).

Comparing RP1 and RP2, the surface mulch layer prevented the column from clogging throughout 12 repetitions in RP1. The runoff infiltration rate remained almost constant (0.35 cm/min) in RP1, but decreased in RP2 (from 0.51 to 0.16 cm/min) during repetitive experiments. The reason for the difference between the two columns could be the various distributions of accumulated SS. Because the mulch layer employed in RP1

has a relatively high uniformity coefficient (d_{60}/d_{10}= 15.6) with many large pores among particles, input SS can move into the surface layer instead being strained on the surface, forming a mat, which restricted liquid flow (Vinten et al., 1983) as occurred in RP2.

5.3.2. TP Removal

Removal results of TP from RP1 and RP2 are presented in Figure 5.6. For RP1, the TP removal efficiency ranged from 47 to 68%. For RP2, TP was nearly all removed in the first 7 repetitions (41 days of operation). After this period, the TP removal efficiency gradually decreased and finally reached only 56% in the 14^{th} repetition, which might be as a result of the occupation of TP sorption surfaces in the media.

Similar to the runoff infiltration rate, TP removal efficiency recovered, increasing from 56 to 67% after 14 days drying. As reported by Sawhney and Hill (1975), soils that had been successively treated with P solution showed reduced P sorption capacity, but regained the capacity to sorb P after drying and wetting cycles. Therefore, this change can be attributed to P being initially adsorbed on the media surface and finally diffusing into the media matrix, releasing new surface for more P to sorb.

Additionally, the removal efficiency of TP was further increased to 89% after replacing the top 5-cm medium, which provided newly sorption surfaces for P. Because of the effectiveness of this newly-restored top 5-cm medium for TP removal, the importance of surface bioretention media was confirmed.

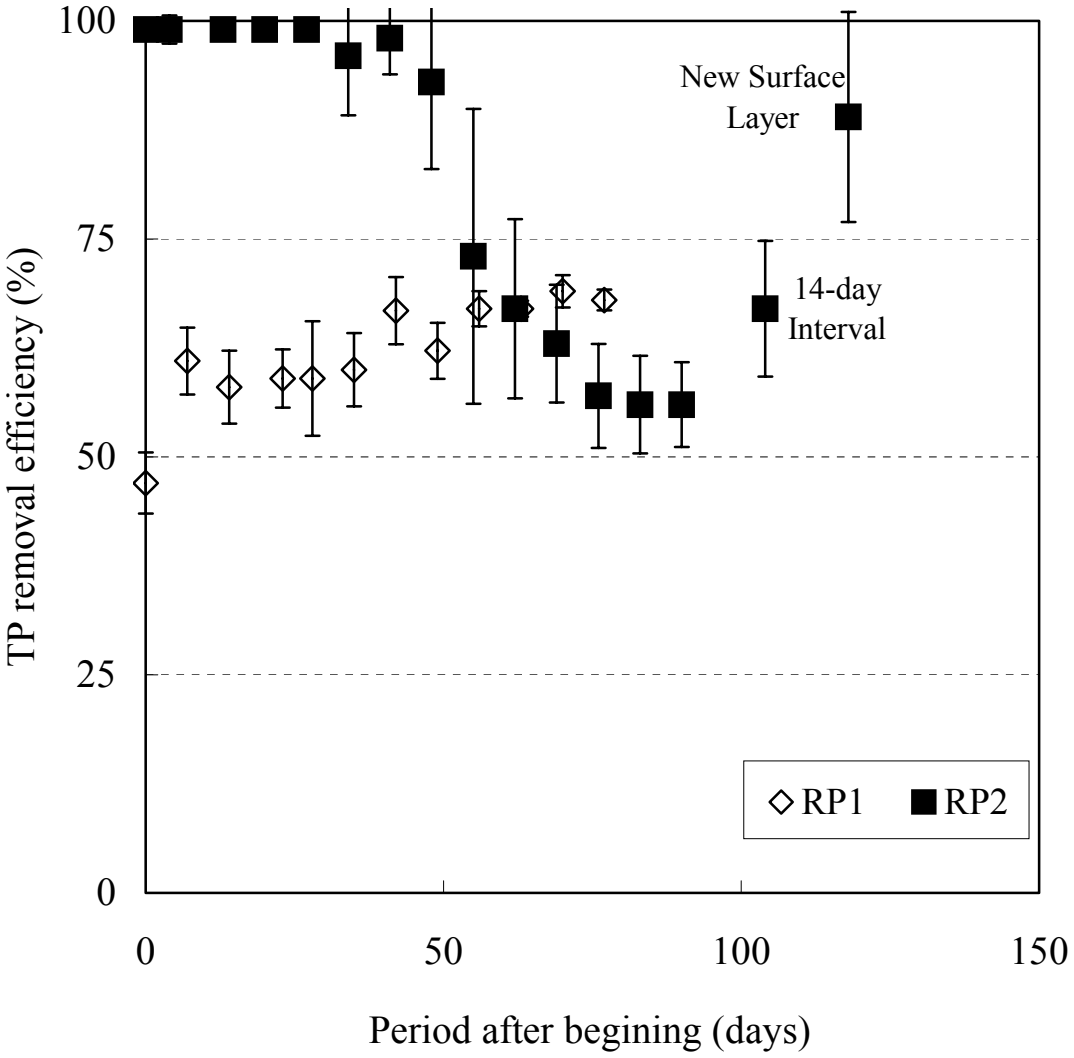

Figure 5.6. Results of TP Removal for Repetitive Columns (RP1 and RP2)

On a mass basis, input/output mass of TP for each column during repetitive periods is calculated as:

$$M = \sum_{1}^{n} \sum_{i=1}^{t_d} Q_{in} C_{in} \Delta t_{in} \qquad (5.4)$$

where M is the input/output TP mass, Q is the input/output rate of runoff, C is the input/output TP concentration, Δt is the measurement time increment over a single trial expressed in hour, *i* is the number of the measurement time increment, $t_d = 6/\Delta t$ and n, the number of trials, is 12 for RP1 and 16 for RP2.

Based on Eq. 5.4, total TP output was 0.6 g from a 1.62 g input for RP1 and 0.3 g output from 2.0 g input for RP2. The percent mass removal for RP1 (63%) was higher than the one for RP2 (85%), although greater amounts of DP were predicted to be sorbed by RP1 (3.8 g) than RP2 (3.4 g) when applying Eq. 2 and the isotherm data. P distributed in the runoff as either PP or DP form. PP containing in the input runoff included the sorbed DP and the original P in SS (containing 38.5 mg-P/100g SS). Based on the calculation above, overall 87 g of TSS were pumped into RP1, whereas 88 g for RP2. Therefore, the fraction of PP from original-P in SS was 33.5 mg-P for RP1 and 33.9 mg-P for RP2. In addition to applying the sorption results, about 3% of DP was sorbed onto the input SS, becoming PP in the influent. The fraction of PP from sorbed P was 48 mg-P for RP1 and 60 mg-P for RP2. Overall, the distribution of PP/DP in the input runoff was 0.08 g/1.52 g for RP1 and 0.09 g/1.91 g for RP2.

In the repetitive bioretention columns, PP was mostly filtered by the media. Not only sorption processes, but also biological uptake and precipitation processes might all account for DP removal. In RP1, the less-permeable surface soil layer limited the runoff infiltration rate and highly-permeable bottom sand layer decreased the overall retention time of runoff in the bioretention column. As such, a low infiltration rate and short water-soil contacting period occurred in RP1. By contrast, larger volumes of runoff entered RP2 in the beginning because of the highly permeable upper media layers and stayed longer in the column because of the less-permeable bottom soil layer. Therefore, either during each repetition or dormant periods, TP had more time to accumulate in the media of RP2 through forming precipitates, sorption and biological uptake processes. All of these reasons led to the higher DP accumulation in RP2 than in RP1.

5.3.3. P Distribution in Bioretention Media Profile

Based on the results above, bioretention media configuration significantly affected TP removal from runoff. Further understanding the distribution of captured P in the bioretention column assists in interpreting P movement within and out of the media. This information also can be used for choosing the better media for P accumulation. The P distribution was investigated by determining the P concentration of media at different depths before and after column experiments. The mass of TP captured by each layer, M_r, was calculated as:

$$M_r = S \times \Delta m_p \tag{5.5}$$

where S is the employed media mass, and Δm_p is the TP retained per unit mass of each media (calculated as the difference before and after the column runs). Dividing M_r by the TP retained in the column, the fraction of retained TP by each column layer is determined.

Because of the higher permeability, RP2 treated more water and greater input mass of P. As such, the P retention of different media layers was compared under the same media mass and TP input. Removed TP per unit mass of different media per input TP, m, is defined as:

$$m = \frac{M_r}{S \times M_{in}} \tag{5.6}$$

where M_{in} is the total input TP. The results are summarized in Table 5.1.

Table 5.1. P retained by Different Media Layers in Bioretention Columns RP1 and RP2

	RP1 *(total input: 1.6 g)*			***RP2*** *(total input: 2 g)*		
Medium	Layer	mg-P removed /kg-media	mg-P removed/kg-media/mg-P input	Layer	mg-P removed/kg-media	mg-P removed/kg-media/mg-P input
Mulch	Top	121	**76**	*	*	*****
Media mixture	*	*	*****	Top (U)	368	**184**
				Top (L)	82	**41**
Sand II	Bottom (U)	54	**34**	Middle (U)	26	**13**
	Bottom (L)	14	**9**	Middle (L)	31	**16**
Soil II	Middle	15	**9**	*	*	*****
Soil III	*	*	*****	Bottom	117	**59**

U: upper, L: lower

In both columns, the P concentration in all media layers increased after repetitive applications, indicating that the applied P moved through the whole column instead staying only on the surface layer. Visually, it was seen that most of the input SS was filtered by the surface mulch layer in RP1. Therefore, surface mulch filtered most of the input PP and contributed to 99 mg-P removal although mulch only sorbed little P from runoff according to the P sorption tests. Based on Table 5.1, it was apparent that unit mass of this top 5-cm layer in RP2 retained larger amounts of P (184 mg-P/kg-media/mg input) than other 25-cm layer (41 mg-P/kg-media/mg input) of this same surface medium. Most of the TP increase in this top 5-cm layer might be resulted from PP accumulation from the runoff.

Additionally, the upper sand II layer of RP1 removed about 4-fold more P (34 mg-removed P/kg-media/mg-input P) than the lower (9 mg-removed P/kg-media/mg-input P). Washout of soil particles from the middle soil layer to the sand layer occurred (silt+ clay contents increased from 5 to 6% in the upper sand layer). By filtering these particles, upper sand II in RP1 reached a high P level.

Comparing both columns, the sand layer in RP2 resulted in about 1.5 to 2 times more TP accumulation (13 to 16 mg-removed P/kg-media/mg-input P) than that of RP1 (9 mg-removed P/kg-media/mg-input P). The difference occurred using the same media, again supporting the importance of media configuration in TP removal.

A similar trend was also found between soil layers in RP1 and RP2. Although soil II and soil III had the same level P sorption capacity, the soil layer in RP2 demonstrated about 7 times more TP removal ability (59 mg-removed P/kg-media/mg-input P) than that in RP1 (9 mg-removed P/kg-media/mg-input P).

The surface mulch layer and middle fine sand captured most of SS from the runoff and upper media, increasing TP removals through PP filtration. Although sand I showed good TP removal efficiency during a single 6-hr experiment (Chapter 4), overall TP accumulation in sand was much lower than in soil. Media mixtures as employed in this study could improve TP accumulation of sand only, without decreasing the runoff infiltration rate. The bottom soil layer retained greater amounts of TP from runoff either by increasing the P sorption or enhancing microbial activity. Different configurations of media affected P movement in the media; consequently, different P removal efficiencies resulted.

5.4. Media P Affiliations

In addition to total accumulation of P, the affiliation of P with the media of RP2 was evaluated through different extractions. All results are summarized in Table 5.2.

5.4.1. Environmental P Soil Tests

Four extraction solutions were employed to predict the leaching potential of retained P from five different layers in RP2. WSP and $CaCl_2$-P were developed to simulate the ionic strength of the soil solution, predicting the potential of easily desorbable P leaching from the soil. Conversely, both Melich-I P and Mehlich-III P extractants are strong acid mixtures, and also have relevance to P leaching potential (Maguire and Sims, 2002). The level of WSP increased from < 0.05 mg-P/kg media for all testing media and after 16 repetitions, the distribution of WSP through the media depth was relatively uniform (2.7

to 7.2 mg WSP/kg-media). For $CaCl_2$-P, only the top medium increased (from 0.2 to 2.6 mg $CaCl_2$-P/kg-media for the upper top-medium and from 0.2 to 0.8 mg $CaCl_2$-P/kg-media for the lower top-medium).

The Melich-I P level for both layers in the top-medium did not have significant differences and the average increase was 30 mg Mehlich-I P/kg-media. Similarly, the average increase in Melich-I P was 11.5 mg P/kg-media for the middle-medium. A 24.3 mg Mehlich-I P/kg-media increase was shown in the bottom layer. As expected, larger amounts of P were extracted by Melich-III extractant for all media. The average increase for each layer was 43.5 mg Mehlich-III P/kg-media for the top-medium, 19.4 mg Mehlich-III P/kg-media for middle medium, and 66.9 mg Mehlich-III P/kg-media for the bottom layer.

Studies investigating correlations between these P extractions and P leaching potential are also summarized in Table 5.2. Above the change point, which was identified from a quadratic linear regression, the potential for P release from soil to water increases (Kleinman et al., 2000). Examing the results of this study, WSP levels for all media were below the suggested value (8.6 mg WSP/kg soil). $CaCl_2$-P in the upper top-medium (2.6 mg $CaCl_2$-P/kg soil) was higher than the change point (1.59 mg $CaCl_2$-P/kg soil) and leaching from this layer probably caused the increase in the lower top-medium $CaCl_2$-P level (0.8 mg $CaCl_2$-P/kg soil). Overall, all media were below the change points of P leaching while using Mehlich-I (81 mg Mehlich-I P/kg soil) and Mehlich-III (181 mg Mehlich-III P/kg soil) extractants. In summary, the leaching potential of bioretention media after treating a total of 2 g P in 16 runoff applications was still under the proposed change point.

Table 5.2. Soil Tests for Bioretention Media after 16 Runoff Applications (RP2) and Recommend Values of Soil P Leaching Potential and Soil P Fertility

Medium	Medium Depth	WSP	$CaCl_2$-P	Mehlich I- P	Mehlich III- P	TP
	cm	mg-P/kg-media				
Top	IC	< 0.05	0.2	20.8	48.1	231
	0-15	7.2	2.6	54.7	95.5	485
	15-30	5.0	0.8	47.2	87.5	478
Middle	IC	< 0.05	< 0.05	3.6	5.1	53
	30-53	2.7	< 0.05	14.4	24.0	133
	53-85	4.8	< 0.05	15.8	25.0	148
Bottom	IC	< 0.05	< 0.05	17.7	51.3	100
	85-95	5.1	< 0.05	42.0	118.2	460
Change Point (Maguire and Sims, 2002)		8.6	1.59	81	181	
Optimum for Nutrient Management (Sims et al., 2001)				25-50	50-100	

IC: Initial Condition, before runoff application

5.4.2. Agronomic P Soil Tests

For nutrient cycling, P can be stored in plants through assimilation processes. Concurrently, surfaces of the media for P sorption can be regained, promoting the P removal from subsequent runoff events (Reddy et al., 1999). Mehlich-I and Mehlich-III extractants are usually employed for assessing the fertility status of soils. Here, they were applied to assess the enhancement of media fertility for future vegetation by capturing P from percolating runoff. The optimum P range suggested by Sims et al. (2001) is 25 to 50 mg Mehlich-I P/kg soil and 50 to 100 mg Mehlich-III P/kg soil. Comparing values from Table 5.2, P fertility for all testing media was increased, but stayed under the excess range.

Fractions among different P forms of retained P in each media layer were compared and the results are shown in Figure 5.7. Without exceeding the change point for each test, most of the retained P in all layers stayed in the forms extractable by Mehlich-I and Mehlich-III solutions, which is optimum for future vegetation use through nutrient cycling.

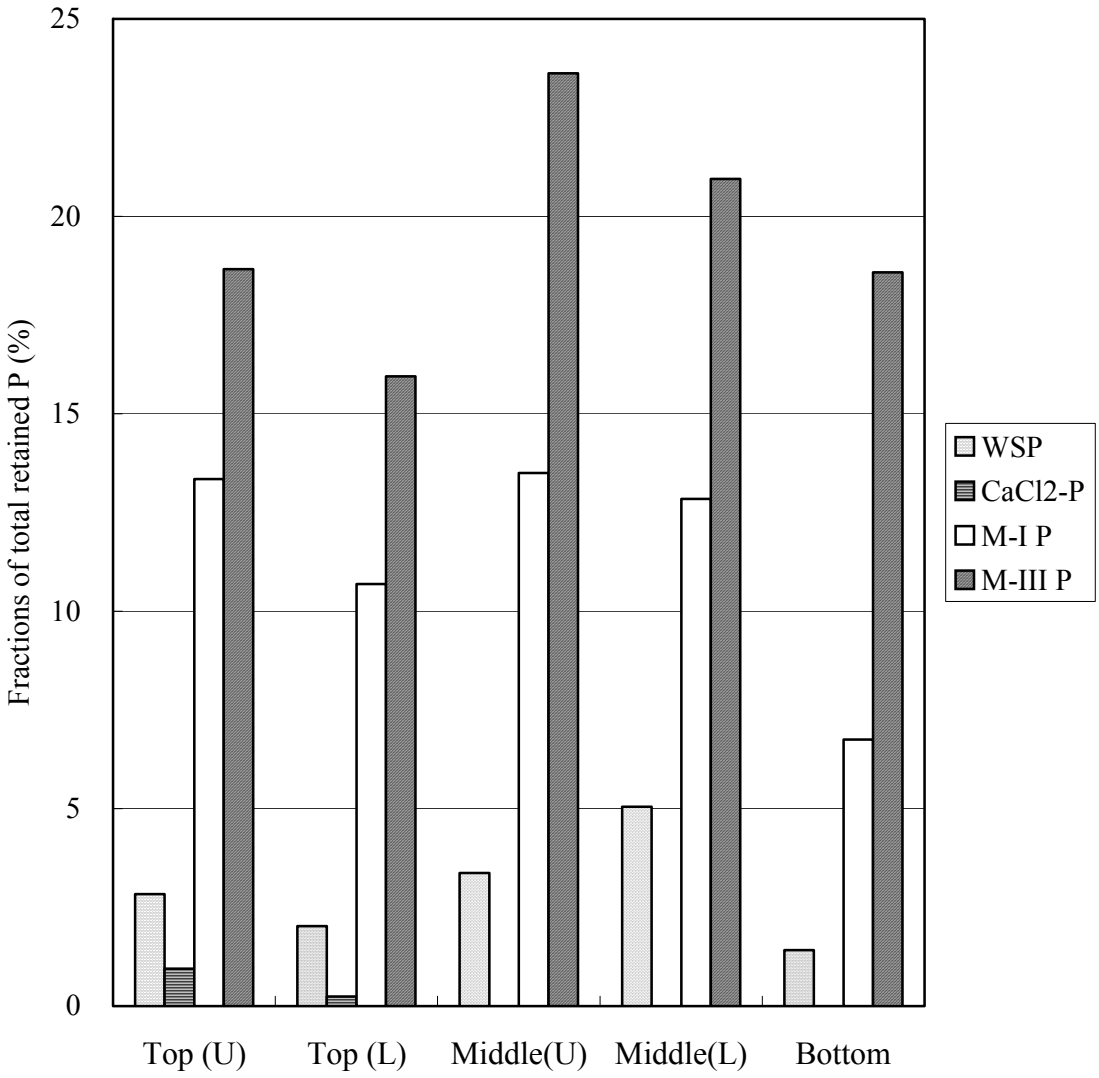

Figure 5.7. Fractions among Different P Forms of Total Retained P in Each Media Layer (RP2)

CHAPTER 6:

MULTIPLE-LOADING EVALUATION OF BIORETENTION FOR TREATMENT OF URBAN STORM WATER RUNOFF: OIL/GREASE, LEAD, AMMONIUM, AND NITRATE REMOVAL

6.1. Introduction

Four pollutants, including O/G, Pb as a representative heavy metal, nitrate, and ammonium, were selected in this chapter to test the effectiveness of bioretention under multiple loadings. Based on the results of Chapter 4, all bioretention columns and on-site facilities demonstrated excellent removal for O/G (> 96%). For Pb, over 90% of input Pb was captured by laboratory sandy-loam bioretention pilot-plant facilities under different pH, duration, intensity, and pollutant concentrations, supported by field-scale confirmation studies (Davis et al., 2003b). Total Pb removal decreased when the TSS level in the effluent increased due to the washout of sorbed Pb on suspended solids (Chapter 4).

Pilot-scale bioretention box studies with sandy-loam soil have demonstrated 60 to 80% removal of TKN and ammonium, but < 20% removal of nitrate by the media (Davis et al., 2001; Davis et al., submitted). Nitrate and ammonium were both poorly removed in 18 columns and 6 field tests (Chapter 4).

Two issues, based on multiple-loading bioretention column experiments were examined in this study. In Chapter 4, the effectiveness of 6-hr bioretention columns and

on-site facilities for O/G and Pb removals were evaluated, showing excellent removal for these pollutants. However, the removal performance of bioretention for these pollutants during a period with multiple loadings still has not been investigated. Along with accumulations, these pollutants may leach from the media under excess inputs. In this study, a total of 28 repetitive experiments were further conducted on two bioretention columns to evaluate the effectiveness of bioretention for repetitive O/G and Pb removals.

Second, since nitrogen is an essential nutrient, biological uptake was assumed to be a significant process for nitrogen fate in bioretention systems, especially during the wetting-drying cycles inherent to a storm water management facility. Alternative designs to keep bioretention media wet or submerged to promote microbial denitrification reactions have been reported to improve nitrate removal (Hunt et al., 2002; Kim et al., 2003). In this study, two separate three-layer bioretention columns were employed to evaluate bioretention behavior under multiple runoff loadings. Because of the media design, one of the columns held a larger amount of residual runoff, developing an anaerobic zone at the interface of a high permeable sand and a less permeable soil layer during the 16 wetting-drying cycles. A sequential combination system of nitrification and denitrification was hypothesized to form in this bioretention column. The objectives were to evaluate the performance of bioretention on O/G and Pb removals under multiple runoff loadings, and to evaluate and enhance the removal efficiency of ammonium and nitrate from the runoff.

6.2. O/G and Pb Removals

After all repetitions, 9.8 g of O/G and 51 mg of Pb were applied into RP1 (12 repetitions), as well as 10.2 g of O/G and 57 mg of Pb for RP2 (16 repetitions). The results of O/G and Pb removals by RP1 and RP2 are presented in Figure 6.1. O/G and Pb were both extremely well removed (> 97% for O/G and > 98% for Pb) during each 6-hr experimental period (Figures 6.1a and b). Sorption and filtration processes are expected to account for the primary removal mechanism for O/G (Hong, 2002). For Pb removal, 56% of Pb was sorbed onto SS containing in the input runoff (Chapter 4), which was filtered by bioretention media. Adsorption, ion exchange, and reaction with organic chelating reagents may all be responsible for dissolved Pb removal (Harrison and Laxen, 1981).

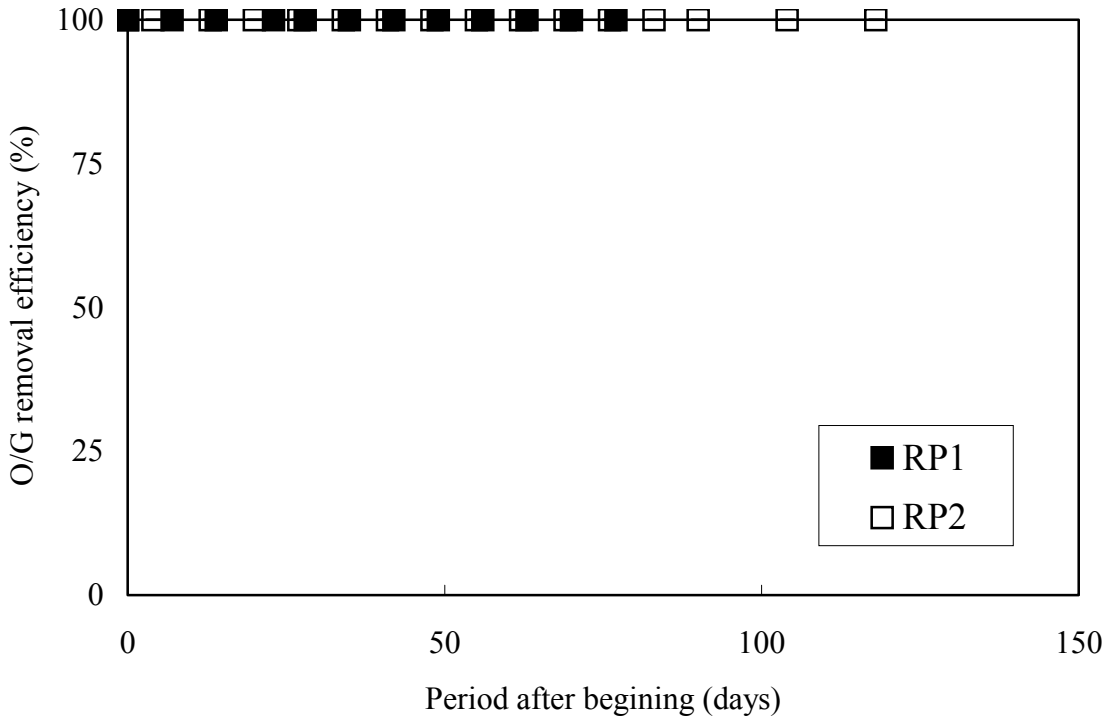

Figure 6.1a. O/G Removal during Repetitive Experiments

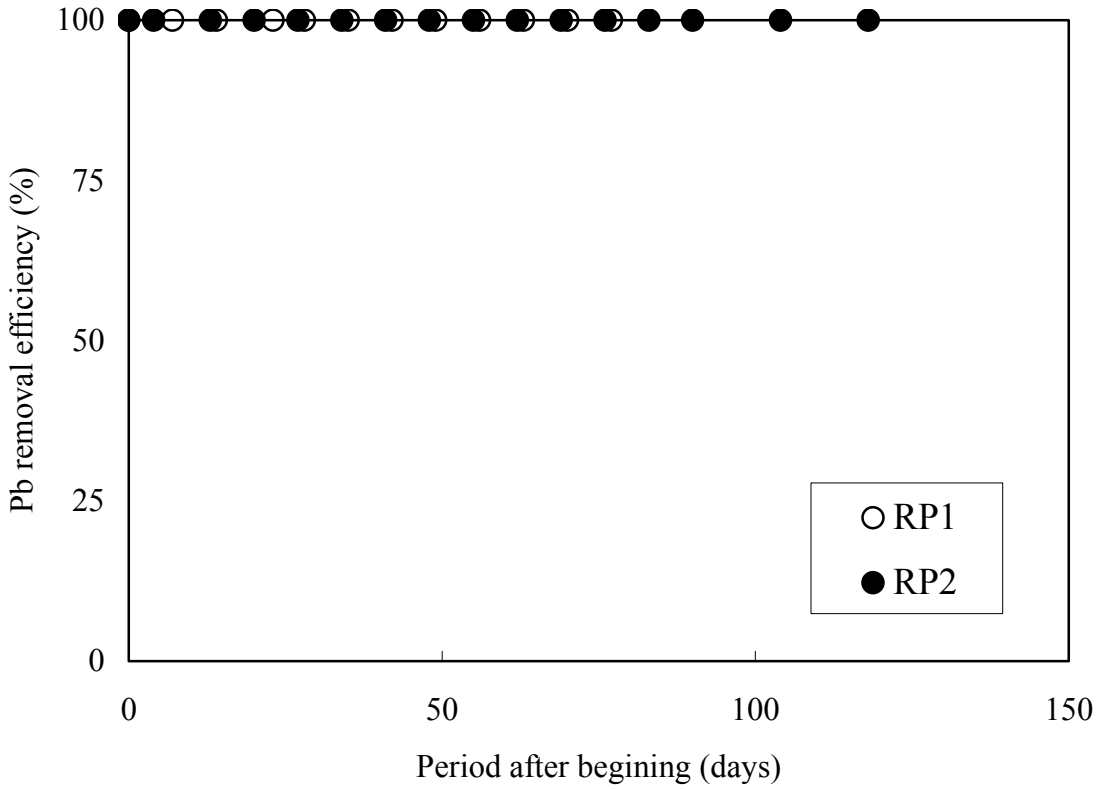

Figure 6.1b. Pb Removal during Repetitive Experiments

6.3. Ammonium and Nitrate Removals

In Chapter 4, all eighteen 6-hr columns showed poor-to-fair removal efficiency for ammonium (8 to 24% removal) and nitrate (1 to 43% removal). Apparently, physical and chemical processes accounted for most of ammonium and nitrate removals since there was insufficient time for microbial degradation in these eighteen columns. In this study, microbiological degradation was assumed to improve ammonium/nitrate removal through nitrification/denitrification processes that occurred in the columns. Between repetitions, different amounts of runoff were held in RP1 and RP2 because of the various media

configurations. Microorganisms grown in the media can uptake ammonium/nitrate through nitrification/denitrification processes during this period, resulting a better removal efficiency for these two pollutants from the residual runoff. In order to look at the effect of this possible mechanism under different media configurations, the removal efficiency (mean± standard deviation) of ammonium for each hour sample throughout the twelve repetitions of RP1 and sixteen repetitions of RP2 is first compared in Figure 6.2.

Based on Figure 6.2, similar low ammonium removal was shown in RP1 throughout all 6 hours. In RP1, the less permeable mulch and soil I made up the upper media layer (0-25 cm deep). Most of the runoff leached out from RP1 after each repetition because bottom sand I had only 5% silt+ clay content to hold runoff. Therefore, little water stayed in the upper mulch and soil layers during the dormant period. As a result, all of the RP1 effluent throughout each 6-hr repetition resulted almost entirely from the runoff input during experiments. The microbial effect on ammonium removal in RP1 was not significant.

In contrast to RP1, a less permeable soil was located in the bottom layer of RP2 (85-95 cm deep). Without sufficient head for drainage, some runoff water was held in RP2 after each experimental repetition. As such, in the subsequent repetition, most of the initial effluent of RP2 resulted from the residual water instead of the newly input runoff. Based on Figure 6.2, surprisingly, efficient removal of ammonium was noticed in RP2 during the first 2 hours (90± 2% for the 1st hour and 92± 2% for the 2nd hour), which corresponded to samples mostly composed of the residual water. Along with the increase of newly input runoff in the effluent, the removal efficiency was gradually decreased to 51± 16% after 6 hours.

The overall ammonium removal in both columns is summarized in Figure 6.3. RP2 performed significantly better for ammonium removal efficiency (68± 16%) than RP1 (12± 6%). During each 6-hr repetition, low variability of ammonium removal efficiency in RP1 was demonstrated (standard deviation ranged from 0.7 to 2%) whereas a significant variability always occurred in RP2 (standard deviation ranged from 7 to 31%). The reason for the significant variability in RP2 is the variation in time resulting from the larger amounts of residual runoff, as mentioned above and shown in Figure 6.2.

In short, high ammonium removal was achieved in residual runoff samples. The media holding a larger amount of runoff during dormant periods can result in an overall higher ammonium removal.

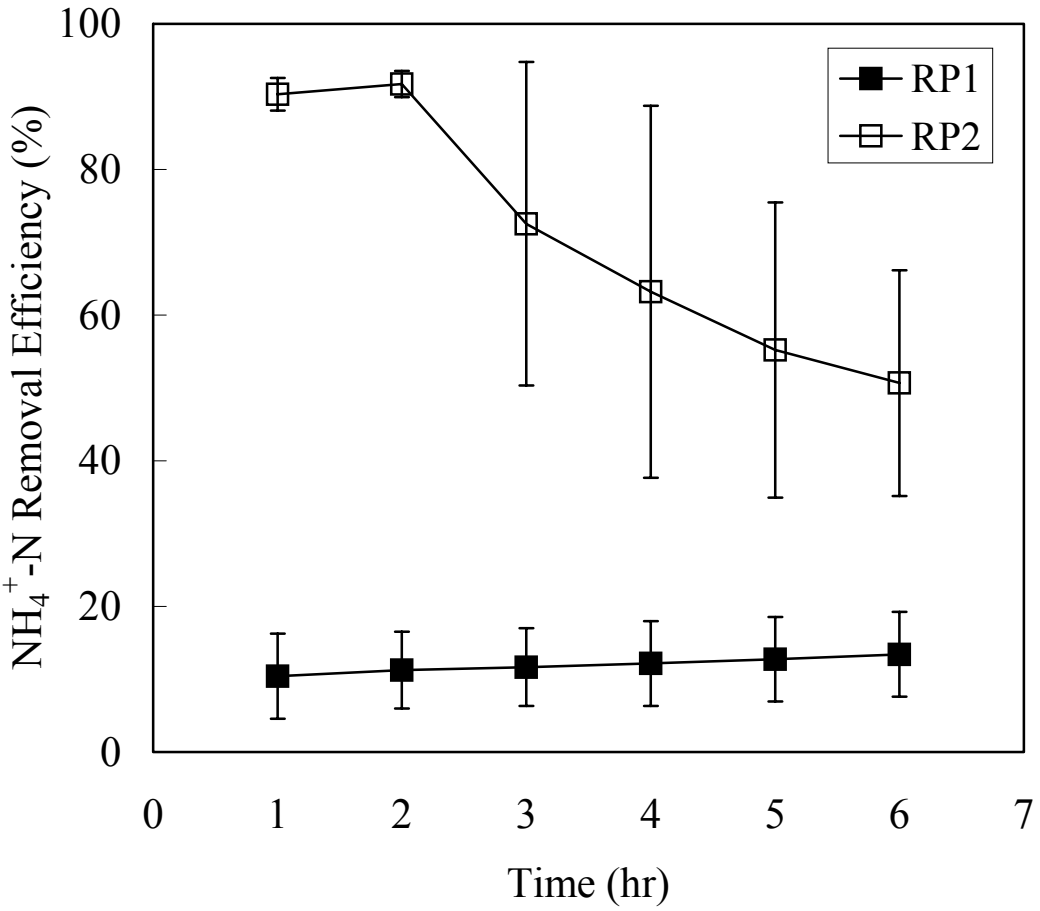

Figure 6.2. Ammonium Removal (mean± standard deviation) for each-hour Sample during the 1st to 12th Repetitive Experiments (RP1) the 2nd to 16th Repetitive Experiments (RP2)

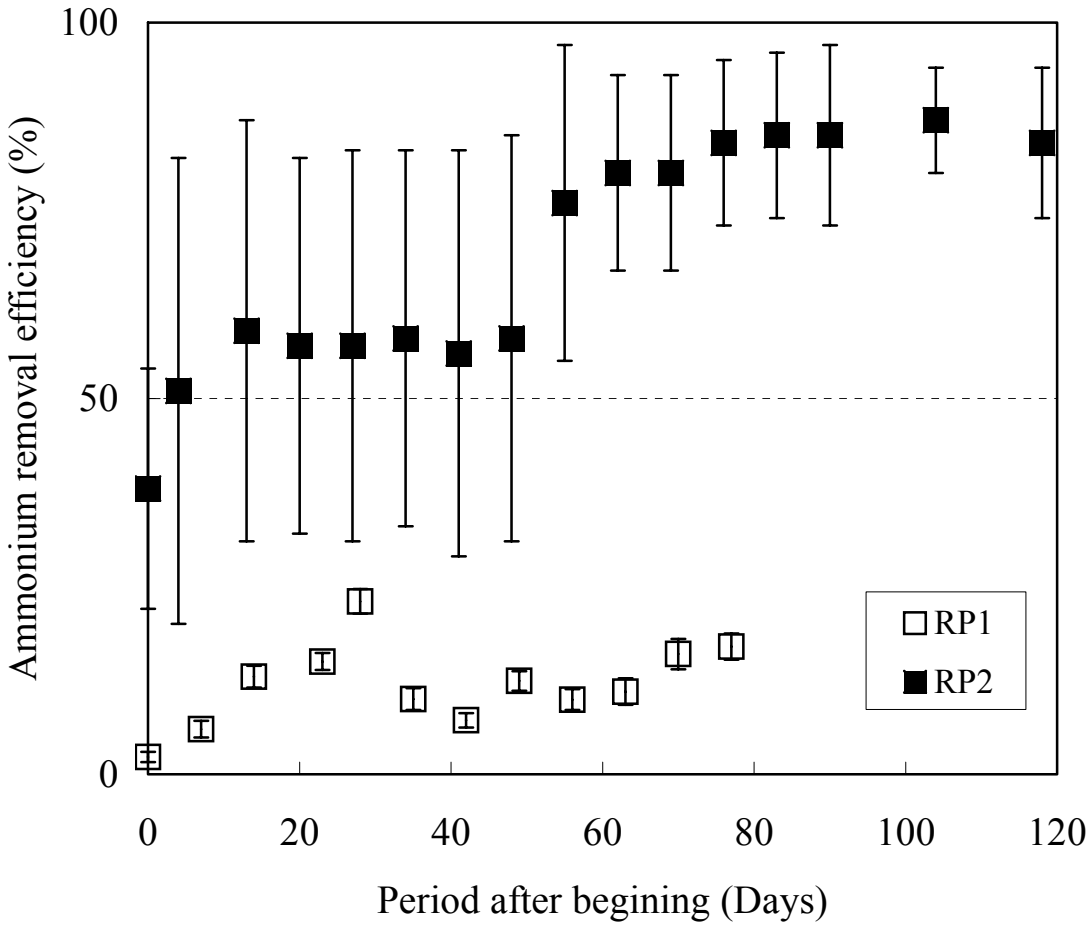

Figure 6.3. Ammonium Removal Efficiency (mean± standard deviation) during Repetitive Experiments (RP1 and RP2)

Figure 6.4 shows the nitrate level in each-hour effluent and the summary results of nitrate removal throughout the entire experimental program are presented in Figure 6.5. Looking at each repetition (Figure 6.5), nitrate removal efficiency in RP1was quite uniform after some initial leaching (standard deviation ranged from 0.7 to 2%). In contrast, the removal efficiency of nitrate in RP2 ranged widely, especially for the first six repetitions (removal efficiency range from -102± 216% to -17± 37%). Washout of nitrate originally contained in the media, combined with the buildup of the corresponding microbial populations could result in these fluctuations.

After the 6th repetition, high nitrate removal efficiency (75± 22%) consistently appeared in the first-hour sample of RP2 during each 6-hr experiment. Based on the runoff infiltration rate data (Chapter 5), this sample was composed of mostly residual water in the lower media (2 to 25 cm away from the bottom). Subsequently, a large amount of nitrate started to leach out from the column and nitrate removal efficiency was -204± 37% in the second-hour sample, which was mostly composed of the water held in the upper media (11 to 60 cm away from the bottom). Afterward, the effluent resulted from the newly input runoff and the removal efficiency of nitrate increased gradually from -125± 31% to -18± 6% in the 6th-hr sample.

Based on Figure 6.5, the media of RP1 and RP2 overall did not show good removal efficiency for nitrate (-9± 32% for RP1 and -54± 22% for RP2). For RP1, significant nitrate-N leached out from the column during the second to fifth repetitions (ranged from -21 to -64% removal). Here, most of the leaching nitrate was probably originally in the media. After this period, the average removal efficiency for nitrate-N ranged from 8± 1%

to 19± 1%. Similar to RP1, abundant nitrate either originally in the media or from the input of runoff leached out from RP2 (ranged from -17 to -102% removal).

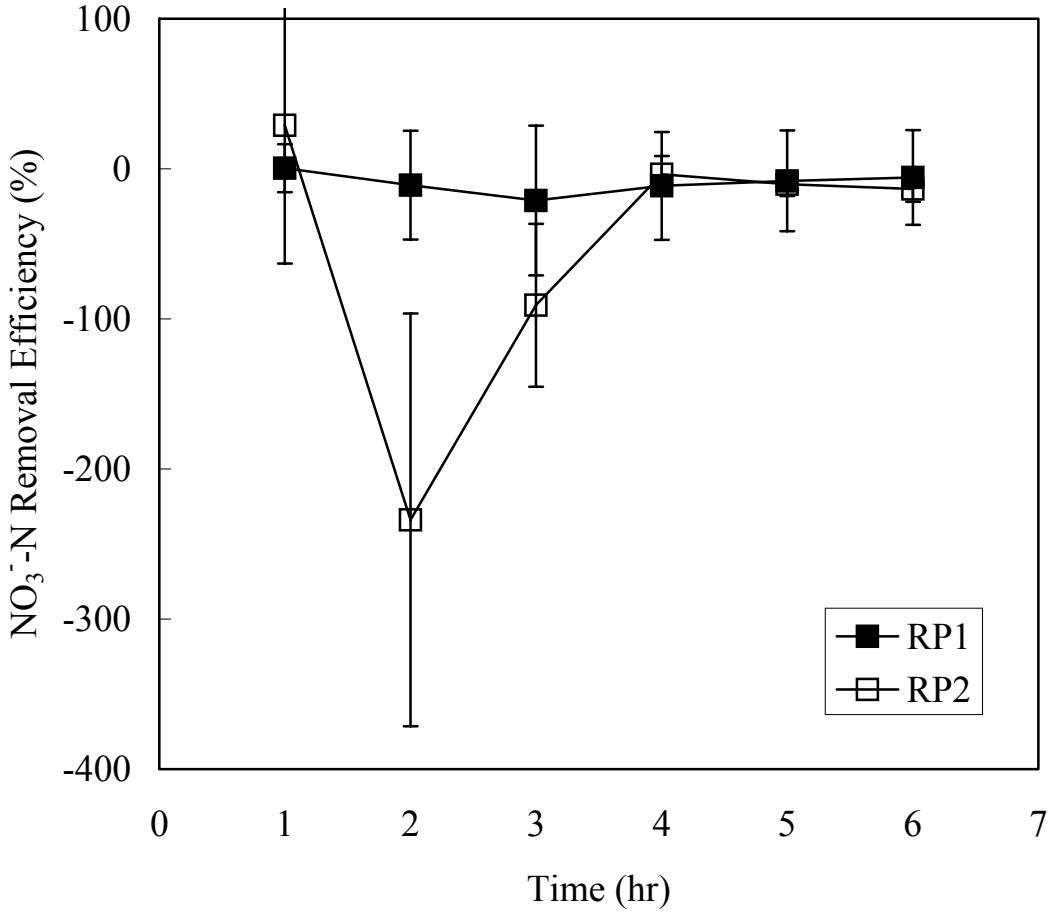

Figure 6.4. Nitrate Removal Efficiency (mean± standard deviation) for Each-hour Sample during Repetitive Experiments (RP1 and RP2)

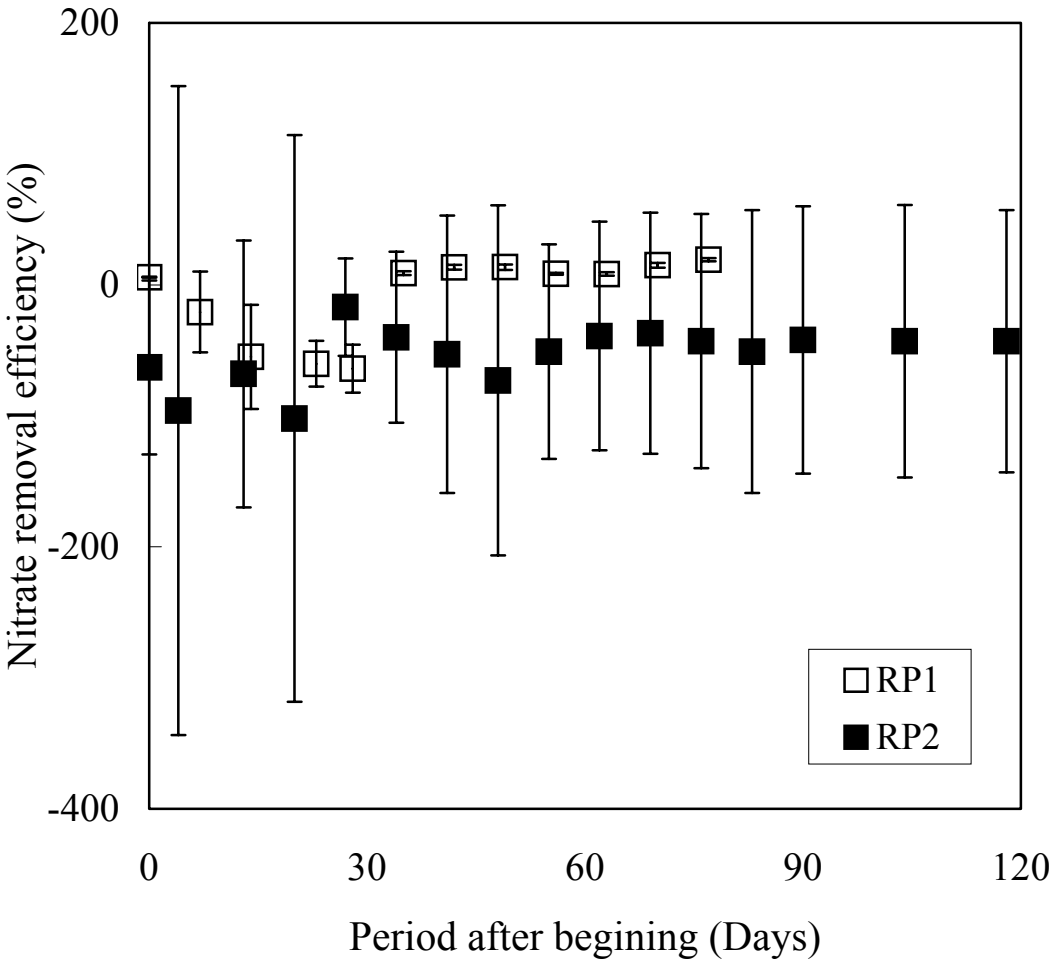

Figure 6.5. Nitrate Removal Efficiency (mean± standard deviation) during Repetitive Experiments (RP1 and RP2)

6.4. Nitrate Distribution in Bioretention Media Profile

The distribution of nitrate in the media was investigated to assist in understanding the retaining/leaching potential of nitrate in the media after wetting-drying cycles. The results are summarized in Figure 6.6. It appears that significant nitrate was lost from the surface media in both columns, which should cause the large nitrate flux in the effluent samples of the first few repetitions. The surface media of RP1 was mulch only and that of RP2 was a synthetic mixture of mulch, coarse sand, and soil.

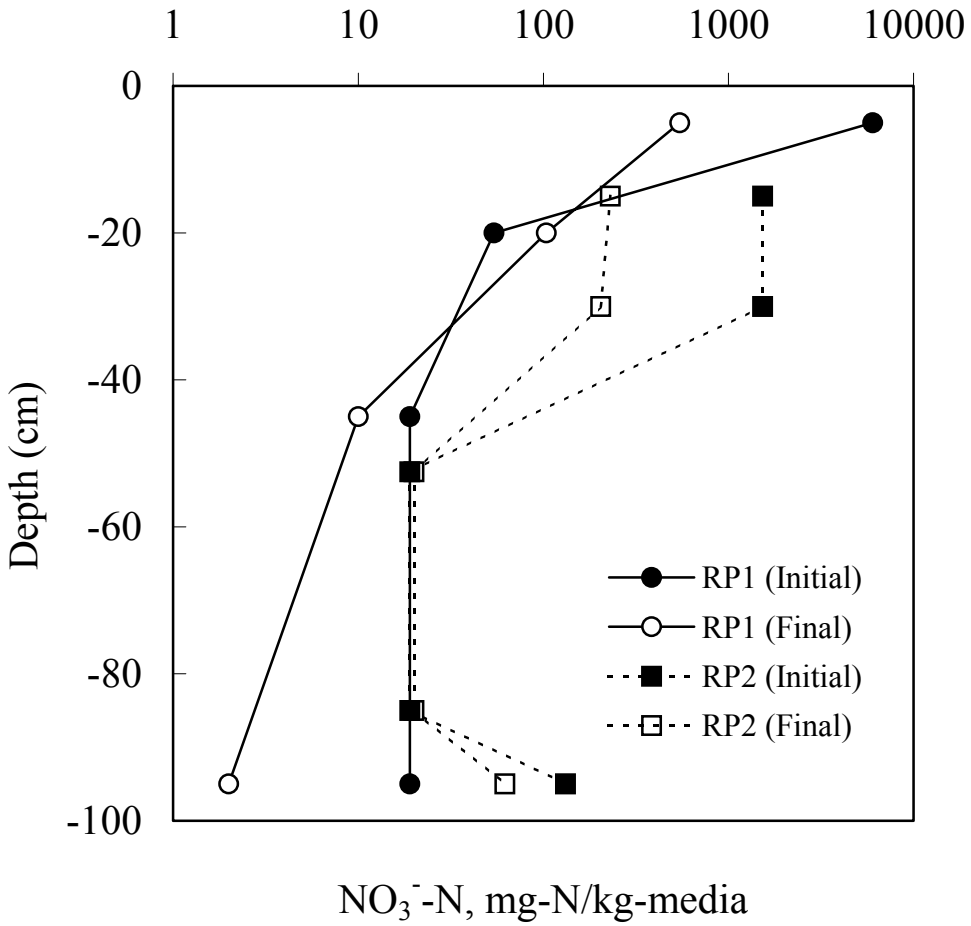

Figure 6.6. Nitrate-N Distribution in RP1 and RP2 before and after Repetitive Experiments

Due to different runoff infiltration rates and nitrate mass inputs in RP1 and RP2, the nitrate retaining/leaching potential of different media layers can be compared by normalizing these parameters. First, the nitrate distribution was investigated by determining the nitrate concentration of media at different depths before and after column experiments. The mass of nitrate captured by each layer was calculated as:

$$M_r = S \times \Delta m_p \tag{6.1}$$

where M_r is the mass of nitrate retained in each media layer, S is the employed media mass, and Δm_p is the nitrate retained per unit mass of each media (calculated as the difference before and after the column runs). Dividing M_r by the total nitrate retained in the column, the fraction of retained nitrate by each column layer is determined.

In addition, removal/leached nitrate-N per unit mass of different media per input nitrate-N (m) is defined as:

$$m = \frac{M_r}{M_{in}} \tag{6.2}$$

where M_{in} is the total mass of input nitrate-N. All of the results are summarized in Table 6.1.

Table 6.1. Nitrate-N Retaining/Leaching Potential in Different Media

Medium	RP1		RP2		RP1	RP2	RP1	RP2
	IC	F	IC	F	Difference			
	mg NO_3^--N/kg-media						mg NO_3^--N/kg-media/g-input NO_3^--N	
Mulch	1355	123			-1230		-770	
Media mixture			345	46~51		-299~-294		-210~-207
Sand I	4	0.2-2	4.3	4.5	-3.5~-2	0.2	-2.2~-1.3	0.14
Soil I	12	23			11		7	
Soil IV			30	14		-16		-11

IC: Initial Concentration

F: Final Concentration

Apparently, significant nitrate leached out from the mulch layer in RP1 (1230 mg-N/kg-media), which originally contained high concentration of nitrate (1355 mg-N/kg-mulch). Similar leaching of nitrate occurred in the surface mixture medium of RP2 (approximately 300 mg-N/kg-media), which also was composed of 50% mulch on a mass basis. In short, high concentrations of desorbable nitrate in the mulch proved detrimental to the performance of bioretention for nitrate removal.

Furthermore, comparing soil layers in RP1 and RP2, the nitrate concentration of soil I in RP1 increased (7 mg-N/kg-media/g-input NO_3^--N), whereas the nitrate level of Soil IV layer in the bottom layer of RP2 decreased (-11 mg-N/kg-media/g-input NO_3^--N). Due to small microbial populations, the retaining/leaching potential of nitrate in both sand I layers did not show significant differences (-1.3 to -2.2 mg-N/kg-media/g-input NO_3^--N for RP1 and 0.14 mg-N/kg-media/g-input NO_3^--N for RP2).

6.5. Mass Balance of Nitrate-N/Ammonium-N

Input and output mass (M) of both ammonium and nitrate for each column during repetitive periods is calculated as:

$$M = \sum_{1}^{n} \sum_{i=1}^{t_d} QC\,\Delta t \qquad (6.3)$$

where Q is the runoff flow rate, C is the input or output concentration, Δt is the measurement time increment, and n, the number of repetitions, is 12 for RP1 and 16 for RP2. Based on these calculations, a total of 0.16 g of ammonium-N was removed by RP1 and 0.86 g by RP2. Total input and output nitrate-N were 1.60 g and 1.85 g for RP1 and 1.42 g and 2.22 g for RP2. Accordingly, 0.25 g of nitrate-N was exported from RP1, whereas 0.8 g was exported from RP2.

In conclusion, media configuration affected the removal efficiency of ammonium and nitrate from runoff. Efficient ammonium and nitrate removals were shown in the early samples of RP2, followed by a significant nitrate flux. The washout nitrate gradually decreased in the later samples from RP2.

Mass balance of nitrate is calculated as:

$$M_{added} = M_{in} + \sum M_i L_{ii} \quad (6.4)$$

$$M_{leached} = M_{out} + \sum M_i L_{if} \quad (6.5)$$

where M_i is the mass of media employed, and L_{ii} and L_{if} are the nitrate-N concentration in the original media and in the media after the repetitive runoff applications. No data are available on the ammonium levels in the media, so a complete mass balance on ammonium cannot be completed. The results are shown in Table 6.2. Totally, 0.8 g of nitrate-N was lost from RP1, whereas 2.9 g loss occurred from RP2.

Table 6.2. Mass Balance Analysis of Nitrate-N from Sequential Events (RP1 and RP2)

Column	RP1		RP2	
	NH_4^+	NO_3^-	NH_4^+	NO_3^-
	g-N			
Input from runoff (A)	1.26	1.60	1.46	1.42
Loss from media (B)		1.02		3.72
Output from effluent (C)	1.10	1.85	0.6	2.22
Loss of Nitrogen (A+B-C)	0.16	0.77	0.86	2.92

Based on all of the results, it is evident that the configuration of the bioretention media significantly affected the removal of nitrate and ammonium from runoff. As mentioned, only small volumes of runoff stayed in the RP1column after each repetitive experiment and most of the effluent sample resulted from the input runoff. Due to the short retention time (12 to 340 minutes), microorganisms present in the media did not have sufficient time to metabolize ammonium and nitrate during each 6-hr repetition. Therefore, the removal efficiency of both pollutants was controlled by the rapid physical or chemical processes, with a less variability resulting. Similar low ammonium and nitrate removals were also shown in eighteen 6-hr bioretention columns with different media (Chapter 4).

In contrast, a larger amount of runoff was held between applications in RP2. The variability of ammonium and nitrate removals for first few effluent samples during each repetition of RP2 was significant. The variable removal efficiencies of ammonium and nitrate in RP2 are postulated to be occurring from biological transformation mechanisms operating during dormant periods. High nitrate removal regularly occurred in the first sample of RP2, which was composed of mostly residual water in the lower media. Nitrate in this water was depleted by the microorganisms through denitrification processes to gaseous nitrogen species, resulting in the decrease of nitrate in this poorly-drained layer. As shown (Meyer et al., 2002), maximum N_2 production rate in the bottom manure layer of a two-layer system reached 497 nmol $N/m^2/hr$ during an 18-day period.

Subsequently, a nitrate flux appeared in the second sample, which was mostly composed of the water held in the upper media. Lance et al. (1976) concluded that the nitrate formed through oxidizing the captured ammonium from the infiltrating sewage water during the drying period leached out the column either in a small concentrated volume or a more diffuse manner, depending on the sequent water infiltration rate. Combining these data with the efficient ammonium removal results occurring in the first two effluent samples, contributing to the increase of nitrate in soil I of RP1 indicate that ammonium in the residual water of the upper media was transformed to nitrate through nitrification processes during the wetting-drying cycles. Along with the inputs of nitrogen in the subsequent repetitions, excess nitrate leached out and appeared in the second effluent sample. Owing to a short retention period, most of nitrate contained in the latter input runoff just leached out along with the residual nitrate.

Overall, it was evident that nitrification processes proceeded in the upper media of RP2 because of the efficient ammonium removal of the first two-hour samples and the accumulation of nitrate in the middle sand layer as well. In addition, high nitrate flux in the second hour sample, which mostly was composed of the residual water in the upper media, also supported the occurrence of nitrification processes in this area. Meanwhile, since nitrate was regularly well removed from the first-hour sample, which mostly came from the water held in the bottom soil layer of RP2, denitrification processes apparently took place in this zone, which was also supported by the loss of nitrate-N in the media of RP2 according to the mass balance analysis. The relative appearance of nitrification and denitrification processes in RP2 is shown in Figure 6.7.

In summary, high concentrations of leachable nitrate in the mulch proved detrimental to the performance of bioretention for nitrate removal. Therefore, although compost mulch employed in this study was confirmed to prevent media from clogging (Chapter 5), the level of desorbable nitrate was unattractive. In addition, the ability of the bioretention media to retain runoff is another critical parameter for ammonium and nitrate removals. Since the removals of these contaminants were promoted by microbial transformation processes during wetting-drying cycles, media that can retain a larger volume of runoff will enhance the fraction of ammonium and nitrate proceeding in nitrification and denitrification processes. As a result, higher nitrogen removals can be achieved.

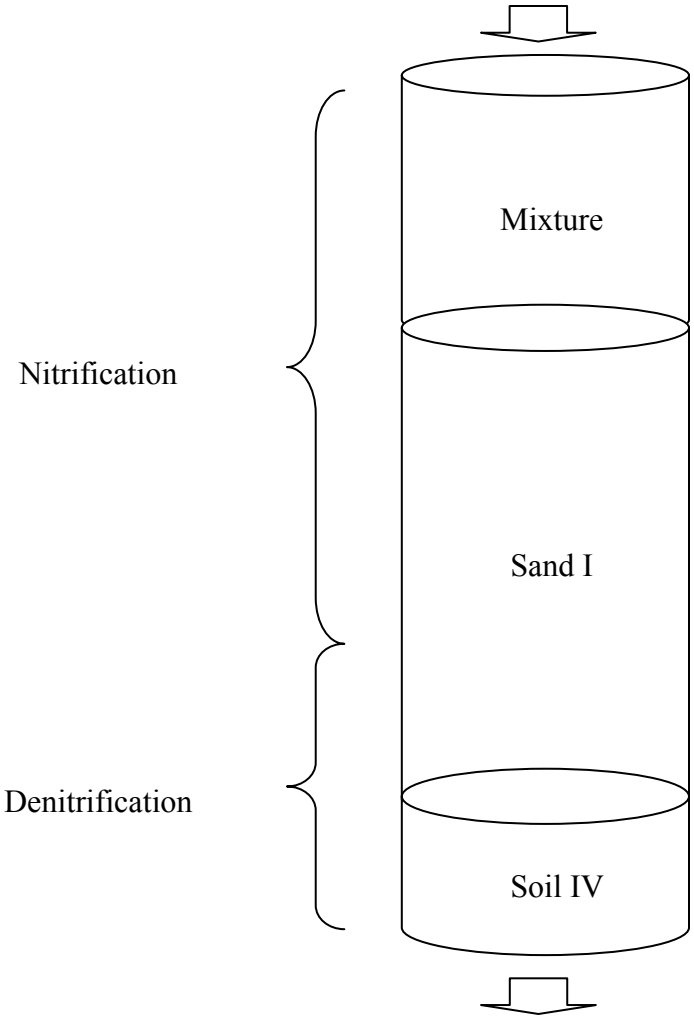

Figure 6.7. Relative Appearance of Nitrification/Denitrification Processes in RP2

CHAPTER 7:

CONCLUSIONS

7.1. Summary

Results from eighteen 6-hr bioretention columns with different media mixtures, six on-site bioretention facilities employing synthetic runoff, and two others conducted during a rainfall event provide a comprehensive picture on bioretention behavior during periods when runoff infiltrates into bioretention media. Overall, all bioretention columns and on-site facilities demonstrated excellent removal for O/G and Pb. TSS removal was good in columns, but leaching of media particles was noted in field facilities, mostly from new installations, before high degree of soil aggregation occurred in the media. Mulch with large pore sizes can be effective in preventing media from clogging under SS input. For nutrients treatment, the removal efficiency of TP ranged widely and appears to be related not only to chemical properties of the media, but also to the flow behavior of runoff through the media. Unless special provision were made, all media employed in this study were mostly ineffective in removing nitrate and ammonium efficiently.

Results from repetitive 6-hr bioretention columns and investigation of P and NO_3^--N distribution in the media before and after repetitive experiments provide comprehensive information on runoff infiltration, as well as pollutant removals during long-term periods that included several wetting-drying cycles. A series of environmental and agronomic P tests conducted on the media of repetitive columns show the distribution of retained P. In addition, experiments of batch P sorption tests on six media and three continuous column

studies help to understand the importance of sorption processes in P removal in bioretention facilities. The medium with a higher P sorption capacity can retain more P from the infiltrating runoff with a high P loading. However, the sorption data alone are not adequate to predict the P retention through a bioretention column for a short-term experiment due to the complicated processes occurring between the runoff and media. A specially-designed column, RP2 (media profile with high hydraulic conductivity media overlaying one with low hydraulic conductivity) resulted in a higher runoff infiltration rate (from 0.51 to 0.16 cm/min) and was more efficient in P (82± 18%) and NH_4^+-N (68± 16%) removals than RP1 (P: 62± 6.2%, NH_4^+-N: 12± 6%), which employed more traditional media design. Without exceeding the change point for each test (which indicates high risk for P leaching), most of the retained P in all media layers is optimum for future vegetation through biological uptake.

The removal efficiency of ammonium was low in RP1 (12± 6%) and was improved in RP2 (68± 16%). By combining the level of ammonium and nitrate in the subsequent effluent samples, as well as through nitrate mass balance analysis, the development of nitrification and denitrification processes in RP2 was strongly supported. Generally, the mulch, with high nitrate-leaching potential, resulted in poor removal efficiency in both bioretention columns. The media established in various configurations had different abilities to hold runoff and demonstrated different efficiencies for ammonium/nitrate removals. The upper media, under aerobic conditions, allowed microbial nitrification processes. Through nitrification processes proceeding during wetting-drying cycles, ammonium that had been captured on media surfaces were decreased and subsequent high ammonium removal efficiency was found from runoff. Via transformation by

denitrifying bacteria in the bottom anoxic/anaerobic soil layer, nitrate was consumed and apparently became nitrogen gas. In both columns, O/G, Pb, and TSS were consistently removed well under multiple-loadings.

7.2. Recommendations

Based on the results of this study, two schematic profiles of bioretention media are presented in Figures 7.1 and 7.2 as design recommendations. The permeability of the composted mulch used in this study was low and could limit runoff infiltration. However, a top mulch layer can filter incoming TSS and prevent the underlying media from clogging. In addition, a mulch layer can assist in maintaining soil moisture during dry weather and can provide nutrients for future vegetation. Therefore, mulch with TSS filtering ability and high permeability (d_{10}> 0.1 mm), with appropriate uniformity (a d_{60}/d_{10} value less than 4) is recommended as the top media layer in both designs. In addition to uniformity, a low desorbable nitrate level is also desired for the mulch employed.

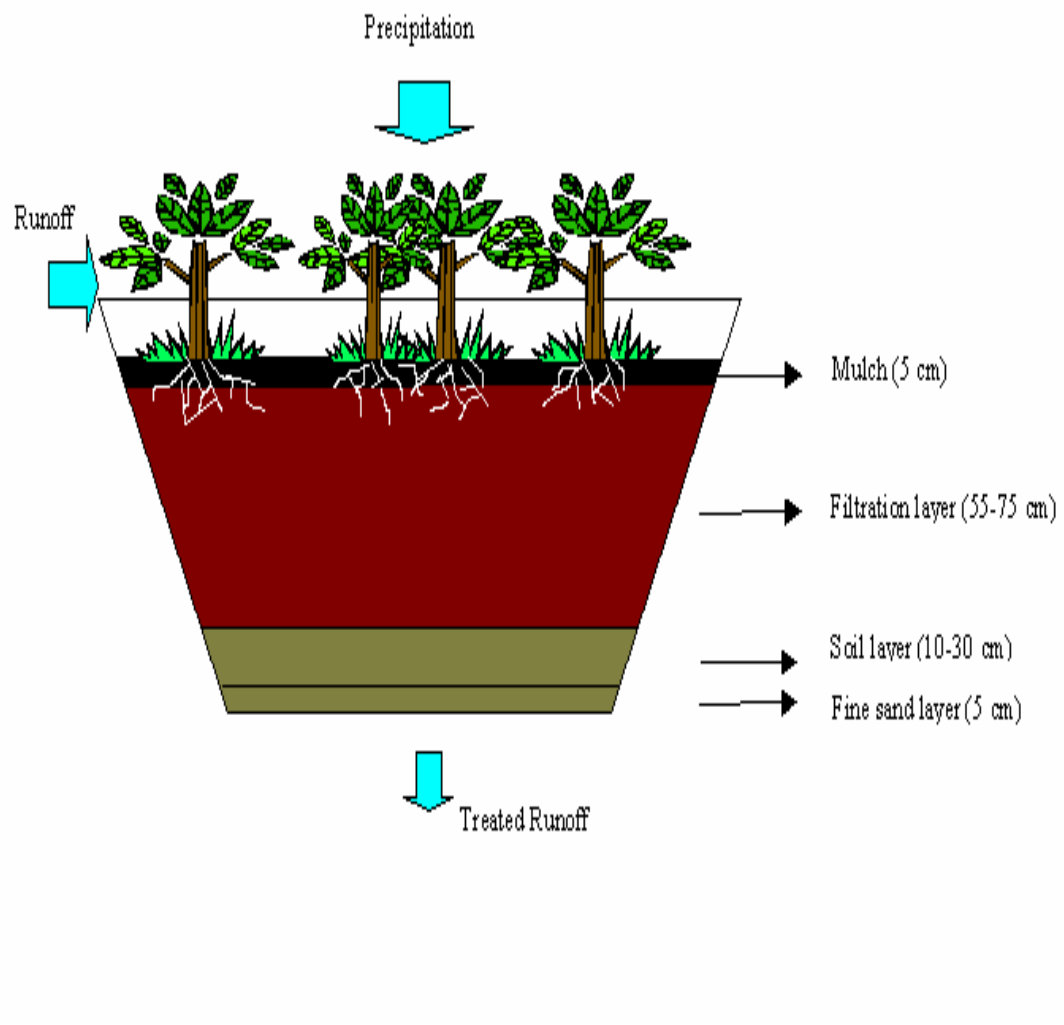

Figure 7.1. Proposed Profile of Bioretention Media (Single Filter Media)

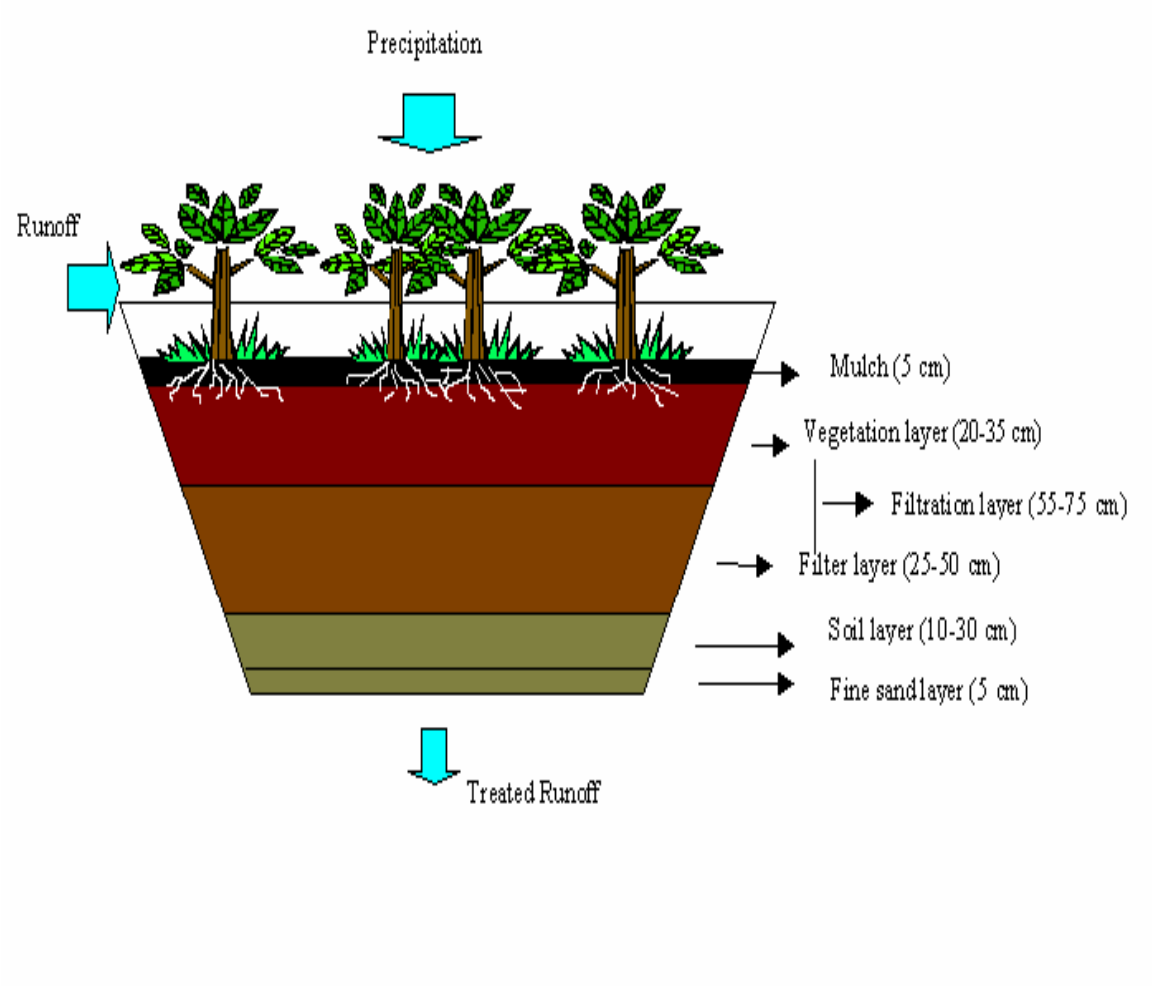

Figure 7.2. Proposed Profile of Bioretention Media (Dual Filter Media)

The differences between the two design recommendations are the components of the bulk filtration layers. From the perspectives of construction and maintenance, a uniform profile is a more cost-effect alternative than multi-layer media. Therefore, Figure 7.1 is proposed which includes a combined filtration and vegetative layer. As mentioned, this upper media layer is critical to bioretention performance because runoff will begin to pond on the bioretention surface once the runoff loading is higher than the infiltration rate into the top media layer. An impervious upper layer would limit the overall infiltration rate (e.g., Exps. 9, 10, 11, and 12- Table 4.1), even though lower layers may be highly permeable. In all cases, the hydraulic conductivity of the upper filtration layer should be higher than the lower soil layer to prevent the formation of a capillary barrier restricting infiltrating runoff.

With respect to pollutant removal, storing runoff temporally in upper media layers is better than having it pond on the surface. In this manner, pollutants contained in the runoff can be sorbed onto the media or assimilated by microorganisms present in the media. Column studies showed that a sand II/soil III mixture produced a high runoff infiltration rate (Exps. 16 to 18- Table 4.1) and very good pollutant mass removal. Therefore, a media layer created by mixing coarse sand (e.g., d_{10}> 0.30 mm) with a sandy soil (sandy loam texture), where the soil ratio (20 to 70% by mass) depends on the requirements for the plant species to be employed is recommended. The suggested depth is 55 to 75 cm. With this design, the initial runoff infiltration rate is expected at 1.2 to 5.4 cm/min at 15 cm water head (Exps. 16, 17, and 18- Table 4.1), which is 4 to 6 times faster than that through a sandy loam soil (Exp. 3, 0.28 cm/min). For pollutant removal,

> 96% of TSS, > 96% of O/G, > 98% of Pb, 24 to > 70% of TP, 6 to 9% of nitrate and 11 to 20% of ammonium are expected to be removed from the infiltrating runoff.

The second design contains separate vegetation and filter layers (Figure 7.2). The vegetation layer is employed to optimize vegetation survival, whereas the filter layer is optimized for pollutant removal. Bioretention plants provide several natural ecological functions to the facility and can also uptake some nutrients and heavy metals from the media. The advantage of this design is that it allows the filter layer to back up the deficiency of the vegetation layer in pollutant removal. Since supporting plant growth is not necessary, the same components are employed, coarse sand (e.g., d_{10}> 0.30 mm) with sandy loam soil, but at a greater sand/soil ratio of 50/50 (Exp. 18), which produced the best pollutant removal noted in column studies. The vegetation layer depth recommendation is 25 to 30 cm with the media tailored to meet the needs of the plants. The filter layer depth is recommended at 25 to 50 cm. Under this design, > 96% of TSS, > 96% of O/G, > 98% of Pb, >82% of TP, ~ 9% of nitrate and > 68% of ammonium are expected to be removed from the infiltrating runoff.

If nitrate removal is desired, an additional layer is required. Nitrate was poorly removed in all column and most field tests. As demonstrated in RP2, both single and dual layers of bioretention media with a less-permeable soil bottom layer could form an aerobic or anoxic/anaerobic zone for promoting nitrification/denitrification processes. With these designs, over 68% of input ammonium could be removed. Without washout of nitrate from the surface mulch layer, nitrate removal efficiency could be improved through denitrification processes that occurred during the dormant periods. A bottom

fine sand layer (5 cm, as used in the column experiments) is included to prevent soil particles from leaching and clogging. The total media depth is 65 to 115 cm.

Bioretention has potential for significant improvement in storm water runoff quality as well as slowing flows. Careful design is necessary to optimize water flow and quality characteristics. Establishment of a process to evaluate the media suitability in target pollutant removal, as well as runoff infiltration is recommended for future research. This work should be followed by utilizing the appropriate media into field designs to advance the environmental effectiveness of bioretention.

Appendix A: 6-hr Column Experiments

COLUMN 1							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	17	17	17	17	17	17
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	112	112	112	112	112	112
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	167	167	167	167	167	167
Effluent		2.1	2.3	1.8	1.5	2.4	1.8
TP							
Influent	mg/L	3.62	3.62	3.62	3.62	3.62	3.62
Effluent		0.64	0.58	0.61	0.65	0.55	0.56
NH_4^+							
Influent	mg-N/L	2.43	2.43	2.43	2.43	2.43	2.43
Effluent		2.31	2.28	2.32	2.31	2.25	2.13
NO_3^-							
Influent	mg-N/L	2.86	2.86	2.86	2.86	2.86	2.86
Effluent		1.04	2.70	2.83	2.86	2.82	2.65
Infil. Rate	cm/min	0.79	0.85	0.83	0.83	0.84	0.83

COLUMN 1 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	15	15	15	15	15	15
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	112	112	112	112	112	112
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	139	139	139	139	139	139
Effluent		1.7	2.0	2.1	1.8	1.7	1.8
TP							
Influent	mg/L	4.11	4.11	4.11	4.11	4.11	4.11
Effluent		0.54	0.63	0.62	0.59	0.57	0.58
NH_4^+							
Influent	mg-N/L	2.72	2.72	2.72	2.72	2.72	2.72
Effluent		2.35	2.47	2.37	2.48	2.61	2.52
NO_3^-							
Influent	mg-N/L	2.79	2.79	2.79	2.79	2.79	2.79
Effluent		2.53	2.51	2.50	2.48	2.53	2.55
Infil. Rate	cm/min	0.84	0.84	0.84	0.87	0.85	0.83

COLUMN 2							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	18	18	18	18	18	18
Effluent		< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Pb							
Influent	µg/L	97	97	97	97	97	97
Effluent		3.79	4.51	3.42	3.23	3.56	2.61
TSS							
Influent	mg/L	193	193	193	190	190	190
Effluent		2.3	2.5	2.3	2.3	2.5	2.3
TP							
Influent	mg/L	3.20	3.20	3.20	3.20	3.20	3.20
Effluent		3.03	2.92	2.90	2.71	2.94	2.94
NH_4^+							
Influent	mg-N/L	2.83	2.83	2.83	2.81	2.81	2.81
Effluent		2.14	2.11	2.17	2.15	2.15	2.13
NO_3^-							
Influent	mg-N/L	4.51	4.51	4.51	4.50	4.50	4.50
Effluent		4.47	4.50	4.46	4.46	4.45	4.40
Infil. Rate	cm/min	7.80	8.20	8.30	8.20	8.20	8.20

COLUMN 3							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	19	19	19	19	19	19
Effluent		< 1	< 1	< 1	< 1	< 1	< 1
Pb							
Influent	µg/L	94	94	94	94	94	94
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	194	194	194	194	194	194
Effluent		132	141	142	137	126	135
TP							
Influent	mg/L	3.11	3.11	3.11	3.11	3.11	3.11
Effluent		1.62	1.74	1.61	1.74	1.71	1.54
NH_4^+							
Influent	mg-N/L	2.62	2.62	2.62	2.62	2.62	2.62
Effluent		2.43	2.38	2.49	2.36	2.43	2.42
NO_3^-							
Influent	mg-N/L	2.76	2.76	2.76	2.76	2.76	2.76
Effluent		2.72	2.74	2.72	2.71	2.69	2.70
Infil. Rate	cm/min	0.23	0.23	0.25	0.24	0.25	0.27

COLUMN 3 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	19	19	19	19	19	19
Effluent		< 1	< 1	< 1	< 1	< 1	< 1
Pb							
Influent	µg/L	91	91	91	91	91	91
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	190	190	190	190	190	190
Effluent		142	138	131	142	136	138
TP							
Influent	mg/L	2.76	2.76	2.76	2.76	2.76	2.76
Effluent		1.33	1.41	1.41	1.33	1.57	1.61
NH_4^+							
Influent	mg-N/L	2.54	2.54	2.54	2.54	2.54	2.54
Effluent		2.43	2.42	2.46	2.43	2.44	2.43
NO_3^-							
Influent	mg-N/L	2.65	2.65	2.65	2.65	2.65	2.65
Effluent		2.61	2.64	2.62	2.62	2.60	2.62
Infil. Rate	cm/min	0.30	0.28	0.32	0.32	0.34	0.32

COLUMN 4							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	18	18	18	17	17	17
Effluent		< 0.25	< 0.25	< 0.25	< 0.25	< 0.25	< 0.25
Pb							
Influent	µg/L	97	97	97	97	97	97
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	187	187	187	190	190	190
Effluent		22	25	21	22	23	25
TP							
Influent	mg/L	3.31	3.31	3.31	2.74	2.74	2.74
Effluent		1.85	1.82	1.91	1.80	1.64	1.61
NH_4^+							
Influent	mg-N/L	2.83	2.83	2.83	2.81	2.81	2.81
Effluent		2.14	2.11	2.17	2.15	2.15	2.13
NO_3^-							
Influent	mg-N/L	4.19	4.19	4.19	4.16	4.16	4.16
Effluent		3.68	3.68	3.62	3.53	3.54	3.41
Infil. Rate	cm/min	0.93	0.95	0.95	0.96	0.95	0.94

COLUMN 5							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	18	18	18	16	16	16
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	105	105	105	105	105	105
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	164	164	164	161	161	161
Effluent		15.3	16.1	15.6	15.6	14.8	14.6
TP							
Influent	mg/L	3.21	3.21	3.21	3.21	3.21	3.21
Effluent		1.82	1.61	1.64	1.64	1.41	1.64
NH_4^+							
Influent	mg-N/L	2.86	2.86	2.86	2.82	2.82	2.82
Effluent		2.41	2.38	2.35	2.41	2.36	2.36
NO_3^-							
Influent	mg-N/L	3.21	3.21	3.21	3.18	3.18	3.18
Effluent		3.01	2.96	2.96	2.92	2.94	2.92
Infil. Rate	cm/min	0.36	0.38	0.38	0.40	0.38	0.40

COLUMN 6							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	17	17	17	17	17	17
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
Pb							
Influent	µg/L	97	97	97	97	97	97
Effluent		24	21	22	22	23	27
TSS							
Influent	mg/L	184	184	184	184	184	184
Effluent		26	28	26	23	26	26
TP							
Influent	mg/L	3.61	3.61	3.61	3.61	3.61	3.61
Effluent		3.52	3.52	3.24	3.61	3.61	3.53
NH_4^+							
Influent	mg-N/L	2.94	2.94	2.94	2.94	2.94	2.94
Effluent		2.45	2.65	2.47	2.46	2.47	2.46
NO_3^-							
Influent	mg-N/L	3.86	3.86	3.86	3.86	3.86	3.86
Effluent		2.42	2.34	2.32	2.32	2.28	2.27
Infil. Rate	cm/min	0.23	0.29	0.29	0.30	0.29	0.30

COLUMN 6 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	17	17	17	17	17	17
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
Pb							
Influent	µg/L	94	94	94	94	94	94
Effluent		22	26	26	25	26	26
TSS							
Influent	mg/L	184	184	184	184	184	184
Effluent		23	25	28	26	23	28
TP							
Influent	mg/L	3.61	3.61	3.61	3.61	3.61	3.61
Effluent		3.50	3.60	3.60	3.23	3.23	3.41
NH_4^+							
Influent	mg-N/L	2.92	2.92	2.92	2.92	2.92	2.92
Effluent		2.44	2.41	2.45	2.45	2.43	2.43
NO_3^-							
Influent	mg-N/L	3.84	3.84	3.84	3.84	3.84	3.84
Effluent		2.16	2.11	2.14	2.12	2.03	2.03
Infil. Rate	cm/min	0.30	0.32	0.30	0.31	0.30	0.31

COLUMN 7							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	16	16	16	16	16	16
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	107	107	107	107	107	107
Effluent		22	35	37	33	35	42
TP							
Influent	mg/L	3.80	3.80	3.80	3.80	3.80	3.80
Effluent		0.66	0.56	0.63	0.64	0.51	0.56
NH_4^+							
Influent	mg-N/L	2.74	2.74	2.74	2.74	2.74	2.74
Effluent		2.63	2.61	2.64	2.58	2.52	2.63
NO_3^-							
Influent	mg-N/L	3.34	3.34	3.34	3.34	3.34	3.34
Effluent		2.34	2.96	3.01	2.84	2.76	2.82
Infil. Rate	cm/min	0.79	0.79	0.81	0.83	0.76	0.79

COLUMN 7 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	15	15	15	15	15	15
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	113	113	113	113	113	113
Effluent		52	42	35	46	32	34
TP							
Influent	mg/L	3.32	3.32	3.32	3.32	3.32	3.32
Effluent		0.52	0.54	0.52	0.60	0.54	0.52
NH_4^+							
Influent	mg-N/L	2.72	2.72	2.72	2.72	2.72	2.72
Effluent		2.62	2.59	2.51	2.53	2.63	2.62
NO_3^-							
Influent	mg-N/L	2.96	2.96	2.96	2.96	2.96	2.96
Effluent		2.67	2.63	2.81	2.68	2.68	2.73
Infil. Rate	cm/min	0.84	0.81	0.83	0.79	0.80	0.81

COLUMN 8							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	19	19	19	19	19	19
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	106	106	106	106	106	106
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	182	182	182	182	182	182
Effluent		1.1	1.3	1.3	1.5	1.5	1.8
TP							
Influent	mg/L	3.83	3.83	3.83	3.83	3.83	3.83
Effluent		1.22	1.31	1.73	1.60	1.60	1.42
NH_4^+							
Influent	mg-N/L	2.65	2.65	2.65	2.65	2.65	2.65
Effluent		2.34	2.37	2.37	2.35	2.35	2.35
NO_3^-							
Influent	mg-N/L	3.24	3.24	3.24	3.24	3.24	3.24
Effluent		2.97	2.94	2.94	2.96	2.96	2.97
Infil. Rate	cm/min	0.75	0.76	0.78	0.78	0.77	0.76

COLUMN 8 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	19	19	19	19	19	19
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	106	106	106	106	106	106
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	179	179	179	179	179	179
Effluent		1.4	1.3	1.3	1.3	1.4	1.5
TP							
Influent	mg/L	3.51	3.51	3.51	3.51	3.51	3.51
Effluent		1.21	1.43	1.25	1.51	1.50	1.50
NH_4^+							
Influent	mg-N/L	2.62	2.62	2.62	2.62	2.62	2.62
Effluent		2.37	2.41	2.42	2.45	2.44	2.43
NO_3^-							
Influent	mg-N/L	3.22	3.22	3.22	3.22	3.22	3.22
Effluent		2.93	2.94	2.93	2.94	2.96	2.96
Infil. Rate	cm/min	0.78	0.78	0.77	0.78	0.78	0.78

COLUMN 9							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	19	19	19	19	19	19
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
Pb							
Influent	µg/L	97	97	97	97	97	97
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	183	183	183	183	183	183
Effluent		61	51	67	63	63	66
TP							
Influent	mg/L	2.72	2.72	2.72	2.72	2.72	2.72
Effluent		1.21	1.23	1.32	1.32	1.44	1.54
NH_4^+							
Influent	mg-N/L	2.21	2.21	2.21	2.21	2.21	2.21
Effluent		2.12	2.18	2.18	2.13	2.15	2.17
NO_3^-							
Influent	mg-N/L	2.99	2.99	2.99	2.99	2.99	2.99
Effluent		2.84	2.92	2.89	2.90	2.90	2.87
Infil. Rate	cm/min	0.28	0.31	0.31	0.29	0.34	0.32

COLUMN 9 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	19	19	19	19	19	19
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
Pb							
Influent	µg/L	97	97	97	97	97	97
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	183	183	183	183	183	183
Effluent		62	62	64	55	66	62
TP							
Influent	mg/L	2.72	2.72	2.72	2.72	2.72	2.72
Effluent		1.43	1.43	1.55	1.53	1.54	1.53
NH_4^+							
Influent	mg-N/L	2.21	2.21	2.21	2.21	2.21	2.21
Effluent		2.19	2.18	2.12	2.18	2.17	2.18
NO_3^-							
Influent	mg-N/L	2.99	2.99	2.99	2.99	2.99	2.99
Effluent		2.89	2.91	2.91	2.93	2.91	2.91
Infil. Rate	cm/min	0.32	0.34	0.36	0.33	0.31	0.32

COLUMN 10							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	21	21	21	21	21	21
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
Pb							
Influent	µg/L	103	103	103	103	103	103
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	185	185	185	185	185	185
Effluent		11	13	13	14	11	10
TP							
Influent	mg/L	3.44	3.44	3.44	3.44	3.44	3.44
Effluent		1.82	1.73	1.41	1.82	1.63	1.85
NH_4^+							
Influent	mg-N/L	2.71	2.71	2.71	2.71	2.71	2.71
Effluent		2.57	2.54	2.54	2.51	2.51	2.53
NO_3^-							
Influent	mg-N/L	2.93	2.93	2.93	2.93	2.93	2.93
Effluent		2.83	2.82	2.85	2.85	2.82	2.79
Infil. Rate	cm/min	0.23	0.28	0.31	0.31	0.32	0.30

COLUMN 10 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	19	19	19	19	19	19
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
Pb							
Influent	µg/L	93	93	93	93	93	93
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	181	181	181	181	181	181
Effluent		11	12	11	11	13	12
TP							
Influent	mg/L	3.21	3.21	3.21	3.21	3.21	3.21
Effluent		1.62	1.62	1.84	1.63	1.52	1.61
NH_4^+							
Influent	mg-N/L	2.70	2.70	2.70	2.70	2.70	2.70
Effluent		2.52	2.48	2.48	2.50	2.48	2.47
NO_3^-							
Influent	mg-N/L	2.85	2.85	2.85	2.85	2.85	2.85
Effluent		2.78	2.75	2.76	2.72	2.74	2.75
Infil. Rate	cm/min	0.31	0.30	0.31	0.31	0.32	0.30

COLUMN 11							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	18	18	18	18	18	18
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
Pb							
Influent	µg/L	96	96	96	96	96	96
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	196	196	196	196	196	196
Effluent		14	15	14	14	15	16
TP							
Influent	mg/L	3.11	3.11	3.11	3.11	3.11	3.11
Effluent		1.92	2.14	2.14	2.03	1.82	1.82
NH_4^+							
Influent	mg-N/L	2.91	2.91	2.91	2.91	2.91	2.91
Effluent		2.72	2.72	2.69	2.73	2.67	2.68
NO_3^-							
Influent	mg-N/L	3.12	3.12	3.12	3.12	3.12	3.12
Effluent		3.01	3.04	3.02	3.04	3.01	3.01
Infil. Rate	cm/min	0.25	0.27	0.32	0.29	0.29	0.30

COLUMN 11 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	17	17	17	17	17	17
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
Pb							
Influent	µg/L	93	93	93	93	93	93
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	185	185	185	185	185	185
Effluent		11	13	9	11	12	12
TP							
Influent	mg/L	3.11	3.11	3.11	3.11	3.11	3.11
Effluent		1.74	1.93	1.82	1.93	1.93	1.81
NH_4^+							
Influent	mg-N/L	2.89	2.89	2.89	2.89	2.89	2.89
Effluent		2.67	2.71	2.65	2.66	2.71	2.70
NO_3^-							
Influent	mg-N/L	3.04	3.04	3.04	3.04	3.04	3.04
Effluent		2.91	2.93	2.93	2.91	2.93	2.92
Infil. Rate	cm/min	0.30	0.29	0.30	0.29	0.30	0.30

COLUMN 12							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	17	17	17	17	17	17
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
Pb							
Influent	µg/L	101	101	101	101	101	101
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	189	189	189	189	189	189
Effluent		13	14	12	12	15	13
TP							
Influent	mg/L	3.32	3.32	3.32	3.32	3.32	3.32
Effluent		2.12	2.34	2.09	2.02	1.91	2.03
NH_4^+							
Influent	mg-N/L	2.62	2.62	2.62	2.62	2.62	2.62
Effluent		2.43	2.38	2.49	2.36	2.43	2.42
NO_3^-							
Influent	mg-N/L	3.20	3.20	3.20	3.20	3.20	3.20
Effluent		3.13	3.12	3.13	3.14	3.13	3.12
Infil. Rate	cm/min	0.27	0.28	0.30	0.31	0.30	0.29

COLUMN 12 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	17	17	17	17	17	17
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
Pb							
Influent	µg/L	98	98	98	98	98	98
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	188	188	188	188	188	188
Effluent		12	13	13	14	13	12
TP							
Influent	mg/L	3.23	3.23	3.23	3.23	3.23	3.23
Effluent		1.81	1.92	1.92	2.00	1.92	2.04
NH_4^+							
Influent	mg-N/L	2.54	2.54	2.54	2.54	2.54	2.54
Effluent		2.43	2.42	2.46	2.43	2.44	2.43
NO_3^-							
Influent	mg-N/L	3.04	3.04	3.04	3.04	3.04	3.04
Effluent		3.00	2.97	2.99	3.01	2.98	2.98
Infil. Rate	cm/min	0.30	0.29	0.31	0.30	0.30	0.30

COLUMN 13							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	19	19	19	19	19	19
Effluent		< 0.8	< 0.8	< 0.8	< 0.8	< 0.8	< 0.8
Pb							
Influent	µg/L	103	103	103	103	103	103
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	156	156	156	156	156	156
Effluent		2.3	2.2	3.1	2.1	1.8	1.8
TP							
Influent	mg/L	3.49	3.49	3.49	3.49	3.49	3.49
Effluent		0.67	0.69	0.67	0.58	0.56	0.59
NH_4^+							
Influent	mg-N/L	2.51	2.51	2.51	2.51	2.51	2.51
Effluent		1.96	1.98	1.87	1.83	1.75	1.84
NO_3^-							
Influent	mg-N/L	3.65	3.65	3.65	3.65	3.65	3.65
Effluent		8.84	7.37	4.16	3.73	3.74	3.71
Infil. Rate	cm/min	0.48	0.49	0.47	0.49	0.51	0.46

COLUMN 13 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	19	19	19	19	19	19
Effluent		< 0.8	< 0.8	< 0.8	< 0.8	< 0.8	< 0.8
Pb							
Influent	µg/L	103	103	103	103	103	103
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	156	156	156	156	156	156
Effluent		2.0	2.2	2.1	1.9	2.3	1.9
TP							
Influent	mg/L	3.49	3.49	3.49	3.49	3.49	3.49
Effluent		0.57	0.62	0.56	0.56	0.59	0.56
NH_4^+							
Influent	mg-N/L	2.51	2.51	2.51	2.51	2.51	2.51
Effluent		1.87	1.79	1.88	1.91	1.88	1.85
NO_3^-							
Influent	mg-N/L	3.65	3.65	3.65	3.65	3.65	3.65
Effluent		3.67	3.67	3.21	2.74	1.65	1.10
Infil. Rate	cm/min	0.46	0.46	0.48	0.50	0.47	0.46

COLUMN 14							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	19	19		19		19
Effluent		< 0.8	< 0.8		< 0.8		< 0.8
Pb							
Influent	µg/L	103	103	103	103	103	103
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	176	176		176		176
Effluent		1.9	2.2		2.3		2.0
TP							
Influent	mg/L	2.62	2.62	2.62	2.62	2.62	2.62
Effluent		1.12	1.08	1.06	1.09	1.02	1.02
NH_4^+							
Influent	mg-N/L	2.35	2.35	2.35	2.35	2.35	2.35
Effluent		2.09	1.98	1.88	1.96	1.96	1.94
NO_3^-							
Influent	mg-N/L	3.20	3.20	3.20	3.20	3.20	3.20
Effluent		2.56	2.62	2.52	2.49	2.51	2.46
Infil. Rate	cm/min	0.63	0.64	0.65	0.64	0.66	0.67

COLUMN 14 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	17	17		17		17
Effluent		< 0.8	< 0.8		< 0.8		< 0.8
Pb							
Influent	µg/L	101	101	101	101	101	101
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L		168		168		168
Effluent			2.3		1.8		1.9
TP							
Influent	mg/L	2.31	2.31	2.31	2.31	2.31	2.31
Effluent		1.05	1.05	1.05	1.07	1.04	1.03
NH_4^+							
Influent	mg-N/L	2.35	2.35	2.35	2.35	2.35	2.35
Effluent		1.95	1.96	1.95	1.97	1.94	1.93
NO_3^-							
Influent	mg-N/L	3.32	3.32	3.32	3.32	3.32	3.32
Effluent		2.44	2.46	2.51	2.46	2.43	2.44
Infil. Rate	cm/min	0.64	0.66	0.65	0.68	0.66	0.66

COLUMN 15							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	23	23		23		23
Effluent		< 0.8	< 0.8		< 0.8		< 0.8
Pb							
Influent	µg/L	97	97	97	97	97	97
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	164	164		164		164
Effluent		2.1	2.2		2.3		2.3
TP							
Influent	mg/L	3.20	3.20	3.20	3.20	3.20	3.20
Effluent		1.40	1.42	1.41	1.38	1.38	1.37
NH_4^+							
Influent	mg-N/L	2.60	2.60	2.60	2.60	2.60	2.60
Effluent		2.09	2.12	2.07	2.11	2.08	2.08
NO_3^-							
Influent	mg-N/L	3.82	3.82	3.82	3.82	3.82	3.82
Effluent		2.78	2.82	2.76	2.73	2.75	2.76
Infil. Rate	cm/min	0.64	0.68	0.70	0.71	0.70	0.73

COLUMN 15 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	19	19		19		19
Effluent		< 0.8	< 0.8		< 0.8		< 0.8
Pb							
Influent	µg/L	93	93	93	93	93	93
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	168	168		168		168
Effluent		2.1	2.5		2.1		2.4
TP							
Influent	mg/L	2.80	2.80	2.80	2.80	2.80	2.80
Effluent		1.41	1.38	1.36	1.32	1.34	1.31
NH_4^+							
Influent	mg-N/L	2.47	2.47	2.47	2.47	2.47	2.47
Effluent		1.99	1.96	1.93	1.97	1.96	1.91
NO_3^-							
Influent	mg-N/L	3.64	3.64	3.64	3.64	3.64	3.64
Effluent		2.72	2.72	2.68	2.67	2.70	2.69
Infil. Rate	cm/min	0.71	0.70	0.73	0.70	0.71	0.69

COLUMN 16							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	20	20	20	20	19	19
Effluent		< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Pb							
Influent	µg/L	101	101	101	101	100	100
Effluent		3.2	3.4	2.8	3.1	3.1	3.1
TSS							
Influent	mg/L	195	195	195	195	191	191
Effluent		2.7	2.3	2.3	2.1	2.6	2.3
TP							
Influent	mg/L	2.92	2.92	2.92	2.92	2.92	2.92
Effluent		2.31	2.23	2.21	2.34	2.23	2.01
NH_4^+							
Influent	mg-N/L	2.94	2.94	2.94	2.94	2.93	2.93
Effluent		2.66	2.63	2.63	2.62	2.62	2.60
NO_3^-							
Influent	mg-N/L	4.17	4.17	4.17	4.17	4.15	4.15
Effluent		4.01	3.96	3.92	3.87	3.87	3.82
Infil. Rate	cm/min	5.10	5.50	5.40	5.40	5.50	5.40

COLUMN 17							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	21	21	21	19	19	19
Effluent		< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Pb							
Influent	µg/L	108	108	108	106	106	106
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	153	153	153	148	148	148
Effluent		12.4	12.2	11.8	12.2	12.7	12.2
TP							
Influent	mg/L	2.94	2.94	2.94	2.94	2.94	2.94
Effluent		0.78	0.80	0.83	0.84	0.84	0.83
NH_4^+							
Influent	mg-N/L	2.92	2.92	2.92	2.94	2.94	2.94
Effluent		2.38	2.36	2.38	2.36	2.36	2.38
NO_3^-							
Influent	mg-N/L	3.16	3.16	3.16	3.12	3.12	3.12
Effluent		2.82	2.89	2.86	2.82	2.86	2.83
Infil. Rate	cm/min	1.12	1.14	1.16	1.17	1.16	1.17

COLUMN 18							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	18	18	18	21	21	21
Effluent		< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Pb							
Influent	µg/L	96	96	96	96	96	96
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	161	161	161	158	158	158
Effluent		11.3	11.6	12.3	12.5	11.8	11.8
TP							
Influent	mg/L	3.12	3.12	3.12	3.22	3.22	3.22
Effluent		0.86	0.82	0.82	0.80	0.82	0.85
NH_4^+							
Influent	mg-N/L	3.01	3.01	3.01	2.97	2.97	2.97
Effluent		2.41	2.43	2.41	2.36	2.36	2.38
NO_3^-							
Influent	mg-N/L	2.86	2.86	2.86	2.84	2.84	2.84
Effluent		2.64	2.66	2.66	2.61	2.61	2.63
Infil. Rate	cm/min	1.94	1.92	1.92	1.94	1.92	1.92

Appendix B: Field Evaluation Experiments

GB							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	18					
Effluent			< 1	< 1	< 1	< 1	< 1
Pb							
Influent	µg/L	103					
Effluent			< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	162					
Effluent			1.1	1.3	1.1	1.1	1.1
TP							
Influent	mg/L	3.22					
Effluent			0.40	0.40	0.31	0.31	0.28
NH_4^+							
Influent	mg-N/L	2.41					
Effluent			2.24	2.24	2.21	2.16	2.21
NO_3^-							
Influent	mg-N/L	2.86					
Effluent			2.84	2.82	2.82	2.84	2.82

GB (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	19					
Effluent		< 1	< 1	< 1	< 1	< 1	< 1
Pb							
Influent	µg/L	103					
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	156					
Effluent		1.3	1.3	1.5	1.1	1.1	1.3
TP							
Influent	mg/L	3.22					
Effluent		0.26	0.26	0.22	0.24	0.26	0.24
NH_4^+							
Influent	mg-N/L	2.43					
Effluent		2.23	2.21	2.18	2.21	2.18	2.16
NO_3^-							
Influent	mg-N/L	2.83					
Effluent		2.78	2.76	2.73	2.76	2.76	2.78

LO1							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	23					
Effluent			< 1	< 1	< 1	< 1	< 1
Pb							
Influent	µg/L	98					
Effluent			< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	156					
Effluent			1.3	1.1	1.1	1.3	1.1
TP							
Influent	mg/L	3.42					
Effluent			0.28	0.25	0.25	0.28	0.25
NH_4^+							
Influent	mg-N/L	2.42					
Effluent			1.32	1.28	1.28	1.24	1.24
NO_3^-							
Influent	mg-N/L	2.64					
Effluent			2.53	2.46	2.48	2.43	2.46

LO1 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	23					
Effluent		< 1	< 1	< 1	< 1	< 1	< 1
Pb							
Influent	µg/L	96					
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	153					
Effluent		1.1	1.1	1.3	1.1	1.1	1.1
TP							
Influent	mg/L	3.61					
Effluent		0.23	0.25	0.25	0.28	0.26	0.26
NH_4^+							
Influent	mg-N/L	2.4					
Effluent		1.18	1.2	1.2	1.16	1.18	1.2
NO_3^-							
Influent	mg-N/L	2.58					
Effluent		2.38	2.4	2.42	2.4	2.36	2.38

HV1							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	18					
Effluent		< 1	< 1	< 1	< 1	< 1	< 1
Pb							
Influent	µg/L	95.6					
Effluent		< 2	< 2	3.6	13.2	14.5	15.6
TSS							
Influent	mg/L	140					
Effluent		29	27	24	34	28	34
TP							
Influent	mg/L	3.11					
Effluent		< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
NH_4^+							
Influent	mg-N/L	2.11					
Effluent		1.89	1.87	1.89	1.89	1.78	1.81
NO_3^-							
Influent	mg-N/L	2.31					
Effluent		2.18	2.21	2.21	2.16	2.16	2.23

HV1 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	16			18		
Effluent		< 1	< 1	< 1	< 1	< 1	< 1
Pb							
Influent	µg/L	96.7			97.3		
Effluent		15.5	12.2	12.2	3.8	4.2	4.2
TSS							
Influent	mg/L	139			146		
Effluent		16	18	16	15	17	15
TP							
Influent	mg/L	3.11			2.97		
Effluent		< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
NH_4^+							
Influent	mg-N/L	2.21			1.98		
Effluent		1.96	1.94	1.91	1.81	1.81	1.76
NO_3^-							
Influent	mg-N/L	2.18			2.11		
Effluent		2.11	2.14	2.14	2.06	2.03	2.03

LO2							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	23					
Effluent		< 1	< 1	< 1	< 1	< 1	< 1
Pb							
Influent	µg/L	111.1					
Effluent		11.1	23.4	25.6	20.6	25.2	18.9
TSS							
Influent	mg/L	140					
Effluent		40	36	39	47	42	42
TP							
Influent	mg/L	2.99					
Effluent		1.51	2.07	1.37	1.37	1.37	1.37
NH_4^+							
Influent	mg-N/L	2.32					
Effluent		2.13	2.22	2.16	2.13	2.06	2.12
NO_3^-							
Influent	mg-N/L	2.01					
Effluent		1.96	1.96	1.98	1.91	1.91	1.98

LO2 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	23			19		
Effluent		< 1	< 1	< 1	< 1	< 1	< 1
Pb							
Influent	µg/L	113.5			105.8		
Effluent		23.7	15.9	21.1	23.9	26.4	22.2
TSS							
Influent	mg/L	161			150		
Effluent		36	42	46	41	48	32
TP							
Influent	mg/L	3.13			2.99		
Effluent		1.44	1.30	1.37	1.30	1.37	1.30
NH_4^+							
Influent	mg-N/L	2.11			1.98		
Effluent		1.93	1.85	1.81	1.74	1.71	1.71
NO_3^-							
Influent	mg-N/L	2.13			2.31		
Effluent		2.03	2.01	1.98	2.22	2.14	2.22

HV2							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	22					
Effluent					< 1	< 1	< 1
Pb							
Influent	µg/L	103.4					
Effluent					3.7	2.5	2.5
TSS							
Influent	mg/L	138					
Effluent					16	19	10
TP							
Influent	mg/L	3.13					
Effluent					2.14	2.14	1.93
NH_4^+							
Influent	mg-N/L	1.96					
Effluent					1.88	1.90	1.92
NO_3^-							
Influent	mg-N/L	2.19					
Effluent					1.98	1.98	1.92

HV2 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	16			18		
Effluent		< 1	< 1	< 1	< 1	< 1	< 1
Pb							
Influent	µg/L	101.2			106.2		
Effluent		3.1	< 2	2.2	< 2	< 2	< 2
TSS							
Influent	mg/L	160			156		
Effluent		11	10	12	11	13	10
TP							
Influent	mg/L	3.13			2.84		
Effluent		2.14	1.79	1.93	1.65	1.65	1.72
NH_4^+							
Influent	mg-N/L	2.10			1.98		
Effluent		1.88	1.88	2.04	1.92	1.90	1.90
NO_3^-							
Influent	mg-N/L	2.04			2.08		
Effluent		1.98	1.92	1.92	1.88	1.94	1.88

LO3							
TIME	hr	0.5	1	1.5	2	2.5	3
O/G							
Influent	mg/L	18					
Effluent			< 1	< 1	< 1	< 1	< 1
Pb							
Influent	µg/L	96.1					
Effluent			14.5	14.1	13.6	13.6	12.8
TSS							
Influent	mg/L	141					
Effluent			45	37	31	40	40
TP							
Influent	mg/L	3.62					
Effluent			1.08	0.87	0.80	0.94	0.94
NH_4^+							
Influent	mg-N/L	1.94					
Effluent			1.88	1.82	1.76	1.76	1.82
NO_3^-							
Influent	mg-N/L	2.06					
Effluent			2.01	1.89	1.92	1.88	1.92

LO3 (Continue)							
TIME	hr	3.5	4	4.5	5	5.5	6
O/G							
Influent	mg/L	22			22		
Effluent		< 1	< 1	< 1	< 1	< 1	< 1
Pb							
Influent	µg/L	98.3			96.1		
Effluent		13.2	12.6	12.6	12.8	12.4	13.1
TSS							
Influent	mg/L	159			146		
Effluent		43	45	43	46	38	37
TP							
Influent	mg/L	3.62			3.44		
Effluent		0.80	1.01	0.87	0.94	0.87	0.73
NH_4^+							
Influent	mg-N/L	1.92			2.01		
Effluent		1.82	1.80	1.78	1.76	1.82	1.80
NO_3^-							
Influent	mg-N/L	2.01			1.98		
Effluent		1.92	1.83	1.86	1.88	1.92	1.82

Appendix C: Repetitive Experiments (RP1)

REP. 1							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	18	18	18	17	17	17
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	97	97	97	97	97	97
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	187	187	187	190	190	190
Effluent		46	41	43	43	43	46
TP							
Influent	mg/L	3.31	3.31	3.31	2.74	2.74	2.74
Effluent		1.72	1.72	1.91	1.54	1.50	1.32
NH_4^+							
Influent	mg-N/L	2.83	2.83	2.83	2.81	2.81	2.81
Effluent		2.79	2.75	2.78	2.75	2.74	2.72
NO_3^-							
Influent	mg-N/L	4.19	4.19	4.19	4.16	4.16	4.16
Effluent		3.96	3.94	3.91	3.93	3.93	3.91
Infil. Rate	cm/min	0.36	0.35	0.35	0.36	0.36	0.35

REP. 2							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	18	18	18	18	18	18
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	97	97	97	97	97	97
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	193	193	193	190	190	190
Effluent		21	19	11	13	13	11
TP							
Influent	mg/L	3.21	3.21	3.21	3.21	3.21	3.21
Effluent		1.12	1.33	1.10	1.46	1.31	1.31
NH_4^+							
Influent	mg-N/L	2.83	2.83	2.83	2.81	2.81	2.81
Effluent		2.71	2.68	2.65	2.65	2.61	2.61
NO_3^-							
Influent	mg-N/L	4.51	4.51	4.51	4.50	4.50	4.50
Effluent		4.56	4.87	8.21	6.39	5.42	4.81
Infil. Rate	cm/min	0.34	0.36	0.35	0.35	0.36	0.36

REP. 3							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	20	20	20	19	19	19
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	101	101	101	100	100	100
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	195	195	195	191	191	191
Effluent		13	12	13	13	12	13
TP							
Influent	mg/L	2.92	2.92	2.92	2.92	2.92	2.92
Effluent		1.31	1.31	1.03	1.32	1.21	1.33
NH_4^+							
Influent	mg-N/L	2.94	2.94	2.94	2.93	2.93	2.93
Effluent		2.62	2.58	2.53	2.53	2.51	2.50
NO_3^-							
Influent	mg-N/L	4.17	4.17	4.17	4.15	4.15	4.15
Effluent		5.12	7.21	9.32	6.42	5.71	4.81
Infil. Rate	cm/min	0.33	0.35	0.36	0.35	0.36	0.36

REP. 4							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	20	20	20	19	19	19
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	101	101	101	100	100	100
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	186	186	186	183	183	183
Effluent		15	18	18	22	18	20
TP							
Influent	mg/L	3.13	3.13	3.13	3.13	3.13	3.13
Effluent		1.22	1.41	1.41	1.24	1.24	1.24
NH_4^+							
Influent	mg-N/L	3.02	3.02	3.02	3.00	3.00	3.00
Effluent		2.53	2.58	2.63	2.54	2.56	2.54
NO_3^-							
Influent	mg-N/L	3.86	3.86	3.86	3.84	3.84	3.84
Effluent		4.82	6.43	6.46	6.38	6.46	6.46
Infil. Rate	cm/min	0.32	0.36	0.36	0.36	0.36	0.36

REP. 5							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	18	18	18	18	18	18
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	97	97	97	96	96	96
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	193	193	193	190	190	190
Effluent		17	18	15	17	17	18
TP							
Influent	mg/L	3.31	3.31	3.31	3.31	3.31	3.31
Effluent		1.32	1.51	1.64	1.51	1.13	1.13
NH_4^+							
Influent	mg-N/L	2.98	2.98	2.98	2.96	2.96	2.96
Effluent		2.28	2.38	2.32	2.28	2.26	2.22
NO_3^-							
Influent	mg-N/L	3.92	3.92	3.92	3.92	3.92	3.92
Effluent		4.96	6.66	6.69	6.73	6.76	6.76
Infil. Rate	cm/min	0.33	0.35	0.36	0.36	0.36	0.36

REP. 6							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	21	21	21	21	21	21
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	96	96	96	96	96	96
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	156	156	156	153	153	153
Effluent		12	12	12	11	12	11
TP							
Influent	mg/L	2.91	2.91	2.91	2.91	2.91	2.91
Effluent		1.12	1.04	1.13	1.33	1.30	1.11
NH_4^+							
Influent	mg-N/L	2.14	2.14	2.14	2.12	2.12	2.12
Effluent		1.96	1.93	1.93	1.91	1.89	1.85
NO_3^-							
Influent	mg-N/L	2.30	2.30	2.30	2.28	2.28	2.28
Effluent		2.13	2.13	2.11	2.06	2.03	2.05
Infil. Rate	cm/min	0.34	0.36	0.36	0.36	0.36	0.36

REP. 7							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	18	18	18	18	18	18
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	99	99	99	99	99	99
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	146	146	146	148	148	148
Effluent		10	11	11	12	12	10
TP							
Influent	mg/L	3.22	3.22	3.22	2.94	2.94	2.94
Effluent		1.32	1.12	1.03	0.94	0.91	0.91
NH_4^+							
Influent	mg-N/L	2.06	2.06	2.06	2.03	2.03	2.03
Effluent		1.93	1.93	1.92	1.89	1.86	1.86
NO_3^-							
Influent	mg-N/L	2.50	2.50	2.50	2.50	2.50	2.50
Effluent		2.25	2.17	2.17	2.14	2.12	2.14
Infil. Rate	cm/min	0.35	0.35	0.36	0.35	0.35	0.36

REP. 8							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	23	23	23	21	21	21
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	102	102	102	102	102	102
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	149	149	149	147	147	147
Effluent		8	8	8	8	6	8
TP							
Influent	mg/L	2.84	2.84	2.84	2.73	2.73	2.73
Effluent		1.20	1.10	1.10	0.98	0.95	0.95
NH_4^+							
Influent	mg-N/L	2.21	2.21	2.21	2.17	2.17	2.17
Effluent		1.98	1.94	1.91	1.92	1.87	1.89
NO_3^-							
Influent	mg-N/L	2.60	2.60	2.60	2.70	2.70	2.70
Effluent		2.31	2.29	2.29	2.29	2.27	2.29
Infil. Rate	cm/min	0.35	0.35	0.35	0.36	0.35	0.36

REP. 9							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	19	19	19	18	18	18
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	98	98	98	97	97	97
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	156	156	156	154	154	154
Effluent		9	9	9	8	8	9
TP							
Influent	mg/L	3.10	3.10	3.10	3.06	3.06	3.06
Effluent		1.14	1.06	1.06	0.98	0.98	0.96
NH_4^+							
Influent	mg-N/L	2.14	2.14	2.14	2.12	2.12	2.12
Effluent		1.95	1.95	1.93	1.93	1.89	1.86
NO_3^-							
Influent	mg-N/L	2.60	2.60	2.60	2.60	2.60	2.60
Effluent		2.41	2.38	2.38	2.38	2.35	2.38
Infil. Rate	cm/min	0.34	0.36	0.35	0.35	0.35	0.36

REP. 10							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	18	18	18	18	18	18
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	107	107	107	107	107	107
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	162	162	162	159	159	159
Effluent		11	11	8	11	11	11
TP							
Influent	mg/L	3.53	3.53	3.53	3.71	3.71	3.71
Effluent		1.20	1.15	1.11	1.21	1.18	1.20
NH_4^+							
Influent	mg-N/L	1.98	1.98	1.98	2.00	2.00	2.00
Effluent		1.81	1.81	1.78	1.75	1.78	1.75
NO_3^-							
Influent	mg-N/L	2.30	2.30	2.30	2.27	2.27	2.27
Effluent		2.10	2.13	2.08	2.04	2.11	2.11
Infil. Rate	cm/min	0.33	0.35	0.36	0.36	0.35	0.36

REP. 11							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	23	23	23	20	20	20
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	96	96	96	98	98	98
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	163	163	163	166	166	166
Effluent		8	8	8	8	8	9
TP							
Influent	mg/L	3.62	3.62	3.62	3.54	3.54	3.54
Effluent		1.21	1.17	1.15	1.08	1.01	1.06
NH_4^+							
Influent	mg-N/L	2.31	2.31	2.31	2.28	2.28	2.28
Effluent		2.02	1.94	1.92	1.92	1.87	1.87
NO_3^-							
Influent	mg-N/L	2.30	2.30	2.30	2.50	2.50	2.50
Effluent		2.01	1.98	1.98	2.13	2.06	2.08
Infil. Rate	cm/min	0.32	0.36	0.36	0.36	0.35	0.36

REP. 12							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	16	16	16	15	15	15
Effluent		< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Pb							
Influent	µg/L	111	111	111	108	108	108
Effluent		< 2	< 2	< 2	< 2	< 2	< 2
TSS							
Influent	mg/L	161	161	161	160	160	160
Effluent		8	9	8	8	9	9
TP							
Influent	mg/L	3.23	3.23	3.23	3.20	3.20	3.20
Effluent		1.09	1.03	1.05	1.01	0.98	0.98
NH_4^+							
Influent	mg-N/L	2.08	2.08	2.08	2.08	2.08	2.08
Effluent		1.76	1.71	1.76	1.68	1.71	1.68
NO_3^-							
Influent	mg-N/L	2.10	2.10	2.10	2.07	2.07	2.07
Effluent		1.71	1.68	1.71	1.64	1.67	1.71
Infil. Rate	cm/min	0.34	0.34	0.36	0.35	0.35	0.36

Appendix D: Repetitive Experiments (RP2)

REP. 1							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	16		19		16	
Effluent		< 0.4		< 0.4		< 0.4	
Pb							
Influent	µg/L	106		103		111	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	135	135	151	151	147	147
Effluent		19	15	10	11	11	10
TP							
Influent	mg/L	3.16	3.16	3.17	3.17	3.17	3.17
Effluent		< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
NH_4^+							
Influent	mg-N/L	1.59	1.59	2.58	2.58	2.73	2.73
Effluent		1.3	1.3	1.34	1.3	1.41	1.43
NO_3^-							
Influent	mg-N/L	2.44	2.44	2.45	2.45	2.42	2.42
Effluent		6.32	5.73	3.35	2.82	2.82	2.73
Infil. Rate	cm/min	0.52	0.51	0.51	0.51	0.52	0.52

REP. 2							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	21		19		19	
Effluent		< 2.5		< 0.5		< 0.5	
Pb							
Influent	µg/L	111		108		103	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	90	90	115	115	119	119
Effluent		138	59	12	11	11	11
TP							
Influent	mg/L	3.02	3.02	3.02	3.02	2.94	2.94
Effluent		0.12	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
NH_4^+							
Influent	mg-N/L	2.25	2.25	1.95	1.95	2.28	2.28
Effluent		0.14	0.26	1.15	1.43	1.63	1.59
NO_3^-							
Influent	mg-N/L	1.93	1.93	1.91	1.91	1.92	1.92
Effluent		0.21	13.34	3.22	1.95	1.96	1.96
Infil. Rate	cm/min	0.08	0.33	0.42	0.37	0.42	0.41

REP. 3							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	16		19		16	
Effluent		< 1		< 0.4		< 0.4	
Pb							
Influent	µg/L	107		102		103	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	131	131	185	185	138	138
Effluent		40	2	1	1	3	2
TP							
Influent	mg/L	2.92	2.92	3.25	3.25	3.31	3.31
Effluent		< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
NH_4^+							
Influent	mg-N/L	2.64	2.64	2.52	2.52	2.28	2.28
Effluent		0.21	0.19	0.92	1.44	1.56	1.53
NO_3^-							
Influent	mg-N/L	1.94	1.94	1.92	1.92	1.93	1.93
Effluent		6.14	5.47	2.03	1.94	1.97	1.99
Infil. Rate	cm/min	0.30	0.55	0.52	0.53	0.51	0.52

REP. 4							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	18		21		16	
Effluent		< 2.5		< 0.4		< 0.4	
Pb							
Influent	µg/L	107		111		113	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	134	134	128	128	136	136
Effluent		10	3	6	6	3	6
TP							
Influent	mg/L	3.58	3.58	3.43	3.43	3.45	3.45
Effluent		< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
NH_4^+							
Influent	mg-N/L	2.14	2.14	2.15	2.15	2.26	2.26
Effluent		0.32	0.16	1.11	1.35	1.39	1.31
NO_3^-							
Influent	mg-N/L	1.67	1.67	1.64	1.64	1.73	1.73
Effluent		1.61	10.73	2.09	2.23	1.83	1.81
Infil. Rate	cm/min	0.12	0.38	0.52	0.52	0.50	0.51

REP. 5							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	18		18		21	
Effluent		< 2.5		< 0.4		< 0.4	
Pb							
Influent	µg/L	96		102		96	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	160	160	155	155	144	144
Effluent		10	6	6	8	6	6
TP							
Influent	mg/L	3.53	3.53	3.34	3.34	3.17	3.17
Effluent		< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
NH_4^+							
Influent	mg-N/L	2.13	2.13	2.06	2.06	2.13	2.13
Effluent		0.23	0.18	1.01	1.34	1.32	1.29
NO_3^-							
Influent	mg-N/L	2.22	2.22	2.2	2.2	2.32	2.32
Effluent		2.3	4.28	2.2	2.34	2.28	2.36
Infil. Rate	cm/min	0.10	0.33	0.49	0.50	0.51	0.51

REP. 6							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	16		18		18	
Effluent		< 2.5		< 0.4		< 0.4	
Pb							
Influent	µg/L	103		96		106	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	146	146	173	173	171	171
Effluent		16	3	5	5	2	5
TP							
Influent	mg/L	3.45	3.45	2.35	2.35	2.92	2.92
Effluent		< 0.05	< 0.05	< 0.05	< 0.05	0.44	0.32
NH_4^+							
Influent	mg-N/L	1.96	1.96	2.16	2.16	2.16	2.16
Effluent		0.23	0.16	1.13	1.21	1.35	1.28
NO_3^-							
Influent	mg-N/L	2.38	2.38	2.46	2.46	2.42	2.42
Effluent		2.34	6.23	4.18	2.52	2.55	2.54
Infil. Rate	cm/min	0.13	0.36	0.49	0.50	0.50	0.50

REP. 7							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	18		15		18	
Effluent		< 2.5		< 0.5		< 0.5	
Pb							
Influent	µg/L	103		103		98	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	126	126	138	138	110	110
Effluent		9	7	4	6	2	8
TP							
Influent	mg/L	2.46	2.46	2.43	2.43	2.67	2.67
Effluent		< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.27
NH_4^+							
Influent	mg-N/L	2.21	2.21	2.18	2.18	2.11	2.11
Effluent		0.27	0.16	1.26	1.37	1.32	1.32
NO_3^-							
Influent	mg-N/L	2.02	2.02	2.04	2.04	1.99	1.99
Effluent		0.87	6.81	4.4	2.12	2.17	2.22
Infil. Rate	cm/min	0.08	0.27	0.39	0.39	0.39	0.41

REP. 8							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	22		18		18	
Effluent		< 2.5		< 0.5		< 0.5	
Pb							
Influent	µg/L	111		105		108	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	128	128	136	136	120	120
Effluent		3	2	1	2	1	2
TP							
Influent	mg/L	2.53	2.53	2.5	2.5	2.5	2.5
Effluent		< 0.05	< 0.05	0.08	< 0.05	0.32	0.62
NH_4^+							
Influent	mg-N/L	2.13	2.13	2.13	2.13	2.07	2.07
Effluent		0.19	0.21	0.87	1.32	1.35	1.32
NO_3^-							
Influent	mg-N/L	1.58	1.58	1.53	1.53	1.52	1.52
Effluent		0.72	6.32	4.09	1.64	1.65	1.66
Infil. Rate	cm/min	0.10	0.28	0.41	0.45	0.45	0.45

REP. 9							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	17		17		17	
Effluent		< 2.5		< 0.5		< 0.5	
Pb							
Influent	µg/L	102		105		102	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	155	155	158	158	162	162
Effluent		2	6	2	2	2	4
TP							
Influent	mg/L	2.70	2.70	2.73	2.73	2.68	2.68
Effluent		0.38	0.49	0.35	0.53	1.1	1.45
NH_4^+							
Influent	mg-N/L	2.06	2.06	2.14	2.14	2.01	2.01
Effluent		0.21	0.21	0.16	0.36	0.82	1.21
NO_3^-							
Influent	mg-N/L	2.08	2.08	2.07	2.07	2.17	2.17
Effluent		1.6	6.2	4	2.42	2.33	2.41
Infil. Rate	cm/min	0.12	0.32	0.42	0.45	0.45	0.44

REP. 10							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	26		24		18	
Effluent		< 4		< 0.5		< 0.5	
Pb							
Influent	µg/L	111		102		106	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	167	167	156	156	141	141
Effluent		6	6	2	2	2	2
TP							
Influent	mg/L	2.57	2.57	2.67	2.67	2.57	2.57
Effluent		0.65	0.76	0.58	0.83	0.99	1.29
NH_4^+							
Influent	mg-N/L	2.21	2.21	2.18	2.18	2.21	2.21
Effluent		0.19	0.18	0.18	0.45	0.76	0.82
NO_3^-							
Influent	mg-N/L	2.34	2.34	2.20	2.20	2.20	2.20
Effluent		0.38	6.45	4.21	2.39	2.71	2.57
Infil. Rate	cm/min	0.06	0.26	0.39	0.42	0.42	0.42

REP. 11							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	19		21		17	
Effluent		< 2.5		< 0.5		< 0.5	
Pb							
Influent	µg/L	100		102		100	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	163	163	152	152	159	159
Effluent		7	5	1	1	2	4
TP							
Influent	mg/L	2.63	2.63	2.57	2.57	3.10	3.10
Effluent		1.02	1.02	0.76	0.78	1.06	1.48
NH_4^+							
Influent	mg-N/L	1.91	1.91	1.99	1.99	2.03	2.03
Effluent		0.18	0.21	0.18	0.36	0.57	0.87
NO_3^-							
Influent	mg-N/L	2.18	2.18	2.23	2.23	2.20	2.20
Effluent		0.29	6.23	4.16	2.21	2.65	2.61
Infil. Rate	cm/min	0.10	0.32	0.40	0.42	0.42	0.41

REP. 12							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	28		22		18	
Effluent		< 4		< 0.5		< 0.5	
Pb							
Influent	µg/L	91		107		100	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	161	161	154	154	158	158
Effluent		3	3	6	6	3	3
TP							
Influent	mg/L	2.85	2.85	2.85	2.85	2.85	2.85
Effluent		1.42	1.40	1.19	1.00	1.10	1.32
NH_4^+							
Influent	mg-N/L	2.22	2.22	1.98	1.98	2.11	2.11
Effluent		0.16	0.14	0.14	0.29	0.49	0.73
NO_3^-							
Influent	mg-N/L	2.01	2.01	2.23	2.23	2.19	2.19
Effluent		0.31	6.11	4.21	2.19	2.71	2.81
Infil. Rate	cm/min	0.07	0.28	0.36	0.38	0.38	0.37

REP. 13							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	20		17		17	
Effluent		< 4		< 1		< 1	
Pb							
Influent	µg/L	103		97		102	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	143	143	161	161	154	154
Effluent		6	3	6	6	3	3
TP							
Influent	mg/L	2.63	2.63	2.57	2.57	3.10	3.10
Effluent		1.02	1.02	0.76	0.78	1.06	1.48
NH_4^+							
Influent	mg-N/L	2.22	2.22	1.98	1.98	2.01	2.01
Effluent		0.19	0.16	0.14	0.18	0.48	0.68
NO_3^-							
Influent	mg-N/L	1.96	1.96	2.23	2.23	2.19	2.19
Effluent		0.28	5.89	5.78	2.01	2.52	2.72
Infil. Rate	cm/min	0.08	0.24	0.28	0.28	0.28	0.28

REP. 14							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	26		17		15	
Effluent		< 10		< 4		< 4	
Pb							
Influent	µg/L	95		97		95	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	137	137	161	161	148	148
Effluent		< 10	< 4	< 4	< 4	< 4	< 4
TP							
Influent	mg/L	2.93	2.93	2.80	2.80	2.83	2.83
Effluent		1.44	1.42	1.28	1.14	1.1	1.08
NH_4^+							
Influent	mg-N/L	2.11	2.11	2.11	2.11	2.31	2.31
Effluent		0.17	0.13	0.15	0.21	0.64	0.74
NO_3^-							
Influent	mg-N/L	2.01	2.01	2.19	2.19	2.23	2.23
Effluent		0.21	5.56	5.46	1.98	2.34	2.63
Infil. Rate	cm/min	0.03	0.15	0.17	0.18	0.19	0.23

REP. 15							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	19		21		18	
Effluent		< 4		< 1		< 1	
Pb							
Influent	µg/L	101		97		97	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	144	144	156	156	138	138
Effluent		6	3	6	6	4	4
TP							
Influent	mg/L	3.61	3.61	3.79	3.79	3.78	3.78
Effluent		1.54	1.44	1.35	1.14	0.94	0.91
NH_4^+							
Influent	mg-N/L	2.1	2.1	2.1	2.1	2.3	2.3
Effluent		0.24	0.19	0.19	0.21	0.31	0.63
NO_3^-							
Influent	mg-N/L	1.94	1.94	2.22	2.22	2.06	2.06
Effluent		0.18	5.61	5.35	1.93	2.22	2.55
Infil. Rate	cm/min	0.06	0.24	0.29	0.32	0.32	0.32

REP. 16							
TIME	hr	1	2	3	4	5	6
O/G							
Influent	mg/L	19		22		22	
Effluent		< 0.5		< 0.4		< 0.4	
Pb							
Influent	µg/L	122		103		107	
Effluent		< 2		< 2		< 2	
TSS							
Influent	mg/L	144	144	151	151	149	149
Effluent		3	3	3	3	3	3
TP							
Influent	mg/L	2.65	2.65	2.91	2.91	2.58	2.58
Effluent		<0.05	<0.05	0.07	0.20	0.52	0.79
NH_4^+							
Influent	mg-N/L	1.98	1.98	2.12	2.12	2.03	2.03
Effluent		0.18	0.15	0.21	0.27	0.56	0.61
NO_3^-							
Influent	mg-N/L	2.13	2.13	2.13	2.13	2.01	2.01
Effluent		0.16	5.71	5.39	2.01	2.31	2.46
Infil. Rate	cm/min	0.41	0.59	0.61	0.59	0.61	0.61

Appendix E: Continuous Column Experiments

Day	EBV	IC	Effluent		
			Column 1	Column 2	Column 3
		mg/L	mg/L		
1	2.4	3.04	0.77	0.78	0.85
2	4.8	3.14	0.71	0.75	0.83
3	7.2	2.94	0.71	0.78	0.83
4	9.6	3.08	0.71	0.78	0.83
5	12.1	3.04	0.71	0.73	0.83
6	14.5	3.08	0.73	0.78	0.83
7	16.9	3.01	0.23	0.25	1.46
8	19.3	3.05	0.37	0.82	1.65
9	21.7	2.96	0.23	0.95	2.01
10	24.1	2.96	0.73	0.95	2.45
11	26.5	3.08	0.71	1.83	2.45
12	28.9	3.05	0.73	2.01	2.45
13	31.3	3.11	0.95	2.01	2.69
14	33.7	2.96	1.54	2.31	2.74
15	36.2	2.96	1.89	2.53	2.79
16	38.6	2.96	2.02	2.53	2.81
17	41	3.01	2.18	2.57	2.83
18	43.4	3.08	2.16	2.60	2.91
19	45.8	3.08	2.18	2.60	2.93
20	48.2	3.01	2.33	2.60	2.98
21	50.6	3.04	2.43	2.63	3.04

Day	EBV	IC	Effluent		
			Column 1	Column 2	Column 3
		mg/L	mg/L		
22	53	3.01	2.45	2.69	2.98
23	55.4	3.01	2.53	2.72	3.01
24	57.8	2.96	2.53	2.79	2.94
25	60.3	2.96	2.62	2.79	2.97
26	62.7	3.04	2.67	2.85	2.97
27	65.1	3.01	2.75	2.85	2.99
28	67.5	3.01	2.89	2.94	3.01
29	69.9	3.01	2.95	2.99	3.01

Appendix F: P Sorption Experiments

Sand I

C_0	Ce	x	m	q= x/m
mg/L		µg	g	µg/g
2.85	2.71	14	0.2	70
2.85	2.44	41	0.6	68
2.85	2.19	66	1	66
2.85	1.61	124	2	62
2.85	1.23	162	3	54
2.85	0.99	186	4	47
2.85	0.30	255	10	26
2.85	0.13	272	20	14

Sand II

C_0	Ce	x	m	q= x/m
mg/L		µg	g	µg/g
2.85	2.81	4	0.2	20
2.85	2.75	10	0.6	17
2.85	2.19	66	5	13
2.85	1.75	110	10	11
2.85	1.14	171	20	9
2.85	0.79	206	30	7
2.85	0.37	248	50	5
2.85	0.37	248	70	4

Soil I

C_0	Ce	x	m	q= x/m
mg/L		µg	g	µg/g
2.85	2.64	21	0.2	105
2.85	2.23	62	0.6	103
2.85	1.88	97	1	97
2.85	1.20	165	2	83
2.85	0.78	207	3	69
2.85	0.51	234	4	59
2.85	0.16	269	10	27
2.85	0.13	272	20	14

Soil II

C_0	Ce	x	m	q= x/m
mg/L		µg	g	µg/g
2.85	2.68	17	0.2	85
2.85	2.37	48	0.6	80
2.85	2.09	76	1	76
2.85	1.54	131	2	66
2.85	1.13	172	3	57
2.85	0.85	200	4	50
2.85	0.30	255	10	26
2.85	0.20	265	20	13

Soil III

C_0	Ce	x	m	q= x/m
mg/L		µg	g	µg/g
2.85	2.64	21	0.2	105
2.85	2.23	62	0.6	103
2.85	1.85	100	1	100
2.85	1.06	179	2	90
2.85	0.68	217	3	72
2.85	0.47	238	4	60
2.85	0.16	269	10	27
2.85	0.13	272	20	14

Soil IV

C_0	Ce	x	m	q= x/m
mg/L		µg	g	µg/g
2.85	2.61	24	0.2	120
2.85	2.13	72	0.6	120
2.85	1.75	110	1	110
2.85	0.89	196	2	98
2.85	0.51	234	3	78
2.85	0.37	248	4	62
2.85	0.06	279	10	28
2.85	<0.05			

Mulch			
C_0	Ce	x	m
mg/L		µg	g
2.85	2.85	0	0.2
2.85	2.85	0	0.6
2.85	2.85	0	1
2.85	2.75	10	2
2.85	2.75	10	3
2.85	2.75	10	4
2.85	2.64	21	10
2.85	2.54	31	20

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