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Performance Comparison of Stormwater Biofiltration Designs

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Abstract

Performance Comparison of Stormwater Biofiltration Designs

A biofiltration system is a stormwater Best Management Practice (BMP) that uses a biologically active filtration bed to remove contaminants. This type of BMP is preferred because it provides the opportunity for pollutant uptake (particularly nutrients) by vegetation in an aesthetically pleasing design. The goals of this research, proposed by the City of Austin, Texas, are to assess the role of plants in nutrient removal and to compare the pollutant removal effectiveness of biofiltration systems containing different media, plant species and designs. A laboratory column study was conducted with nineteen experiments using synthetic stormwater and one experiment using real stormwater. The results of this study show a significant improvement in nutrient removal with the presence of plants and a submerged zone with a carbon source in the filter. The columns without plants were found to export up to twice the nitrate/nitrite input, whereas the columns with plants showed significant removal of all nutrients (Nitrate 30-50%, Total Kjeldhal Nitrogen 65-85%, Total Phosphorus 80-90%). The difference between the two biofiltration media was not significant. Metals (Copper, Lead, Zinc) removal by all columns was very high (>95%) compared to similar field studies. Total Suspended Solids removal remained high through the whole set of experiments for all the columns (85-95%).

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Chapter 1: Introduction

1.1 BACKGROUND

Stormwater runoff quality is a major concern for the City of Austin, Texas, and sand filters have been the standard treatment technology since the early 1980's. Sand filters are an excellent choice for removal of particles and associated pollutants; however, their performance for dissolved constituents is markedly worse. In recent years, the City of Austin has become increasingly interested in the removal of nutrients and other dissolved constituents, preferably in a device with the same physical characteristics as a sand filter (maximum water depth, footprint, etc.), which would facilitate both adoption for new construction as well as retrofit of existing sand filters.

A bioretention system is a stormwater Best Management Practice (BMP) that uses a biologically active filtration bed to remove contaminants. This type of BMP is preferred because it provides the opportunity for pollutant uptake (particularly nutrients) by vegetation in an aesthetically pleasing BMP. In a typical bioretention system, runoff flows over a vegetated swale to a filter bed and out through an underdrain (Figure 1).

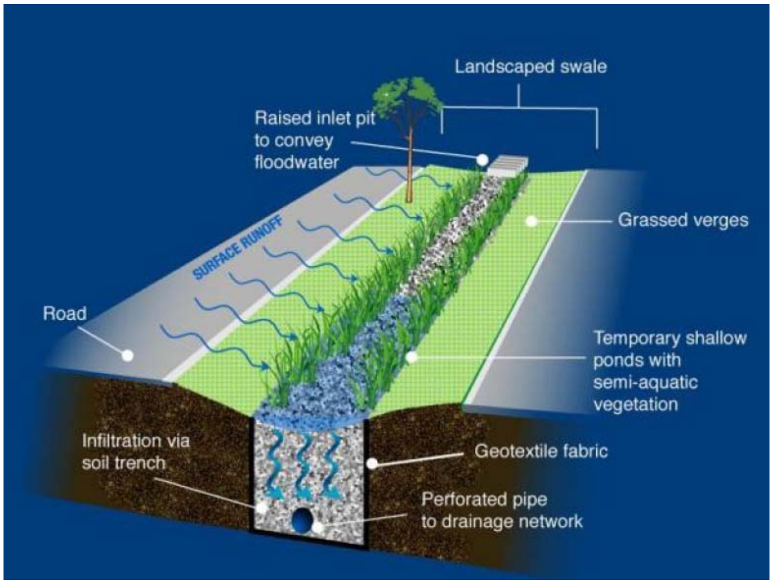

Figure 1 - Schematic of typical bioretention system (FAWB 2008)

The City of Austin initiated this study to evaluate whether transforming their conventional sand filters into “biofiltration” facilities would substantially improve the performance of the City’s stormwater filtration design. The biofiltration term was adopted to indicate the incorporation of plants and organic media into the conventional Austin sand filtration system. The difference between biofiltration and bioretention is primarily the greater water depth allowed over the filter media in the biofiltration design. The research consisted in comparing different biofiltration and sand filter designs in order to see if biofiltration is an appropriate option for the City of Austin and to determine which design would provide the best pollutant removal.

1.2 OBJECTIVES

The main objectives of this project were to answer the following questions:

1. How does the pollutant removal of filter medium meeting newly developed biofiltration criteria and a well documented mix used in Australia compare to pollutant removal observed using concrete sand (current standard filter medium)?
2. Which native plants will thrive in these conditions and produce the largest reduction in nitrogen and phosphorus concentrations?
3. Does the presence of a submerged, anaerobic zone with a carbon source promote denitrification?
4. Will the submerged zone increase the water available for evapotranspiration and support plants during the extended dry periods encountered in this climate?
5. Will biofiltration systems operate effectively long term with ponding depths as great as three feet (similar to sand filter design)?
6. Does water depth affect pollutant removal?

1.3 SCOPE OF WORK

To answer those questions, a laboratory study was conducted at the Center for Research in Water Resources at the University of Texas at Austin. To achieve the objectives identified above, the specific tasks required were:

1. Select the different media
2. Select the different plants
3. Choose the twelve different configurations

4. Design the columns
5. Build the columns
6. Create the cocktail for the synthetic stormwater
7. Dose the columns periodically with synthetic stormwater and measure the effluent water quality
8. Measure the hydraulic conductivity periodically
9. Analyze the results

1.4 ORGANIZATION OF REPORT

Chapter Two provides a summary of the published literature related to previous investigations of bioretention performance. The experimental methods are detailed in Chapter Three followed by the results of the different experiments and a discussion of those results in Chapter Four. Finally, the conclusion and answers to the objective questions, leading to design guidelines for biofiltration facilities for the City of Austin, can be found in Chapter Five.

Chapter 2: Literature Review

2.1 DESCRIPTION

The published literature does not include any research on facilities identical to what the City of Austin envisions. The type of existing BMP most similar to the biofiltration systems the City of Austin proposes is bioretention (especially in regard to unit processes). The fundamental difference between bioretention and biofiltration is the greater water depth in the latter; consequently, the literature review focuses on bioretention performance.

Bioretention has been studied extensively in the last several years. Most of the study results are reported in the form of conference proceedings, though some journal articles are available. The bioretention systems previously investigated are similar in many ways to a sand filter, but the filtration medium contains various amendments to promote vegetation. Bioretention systems, despite a water quality focus, are also effective in reducing peak discharge control, which enhances channel protection. In addition to their ability to reduce and delay peak flow, they are also efficient in reducing the yearly volume of runoff (Ermilio and Traver 2006).

2.2 STORMWATER POLLUTANT REMOVAL

Bioretention removes stormwater pollutants through a variety of physical and biological processes (EPA 1999) including:

- Particle removal occurs through straining at the media/air interface
- Particle removal occurs through depth filtration in the media
- Adsorption may remove dissolved constituents depending on the properties of the media
- Plant uptake occurs through roots, though the amount is heavily dependent on plant species
- Biological transformation of nitrogen may occur at the root/media interface.

Performance data from bioretention systems is somewhat limited at the current time. One major problem with historical research is that much of the data is presented as a percent reduction in load (Hatt et al. 2008, Hunt et al. 2006). This style of presentation makes it more difficult to compare results between different studies and to draw clear conclusions, because an unknown amount of the pollution reduction occurs through volume loss rather than concentration reduction and because the percent removal depends on the mass loading rate.

2.2.1 Total suspended solids (TSS)

The removal mechanisms for TSS in bioretention systems include sedimentation and filtration. TSS appear to be very efficiently and consistently removed in every study, with a percent removal consistently between 91% (Hsieh & Davis 2005a) and 98% (Read et al. 2008). TSS is primarily removed within the top 10 cm of the media (Li and Davis 2008). This pattern is very similar to that observed in sand filters, where little obvious transport of the sediment occurs deep within the filter. This accumulation near the surface increases the possibility of clogging, which is described later in the document.

2.2.2 Metals

Laboratory and field data are available for copper (Cu), lead (Pb) and zinc (Zn). Both dissolved and particulate-bound metals appear to be efficiently removed by bioretention in both vegetated (Bratieres (2008) removals: Cu 82%, Pb 98%, Zn 98%) and non-vegetated (Hatt (2008) removals: Cu 95%, Pb 98%, Zn 97%) studies. Total metals concentrations discharged from bioretention facilities are generally in the low µg/L (ppb) levels and sometimes below detection limit. Cu removal rates appear to be the most variable among the three metals studied (Bratieres 2008).

Research by Davis et al. (2001) indicates that metal removal occurs very rapidly and is not rate dependent. Most of the metal removal appears to occur in the upper surface layers of the media (10-20 cm), as shown in Figure 2, through both filtration of particulate metals and adsorption of dissolved forms.

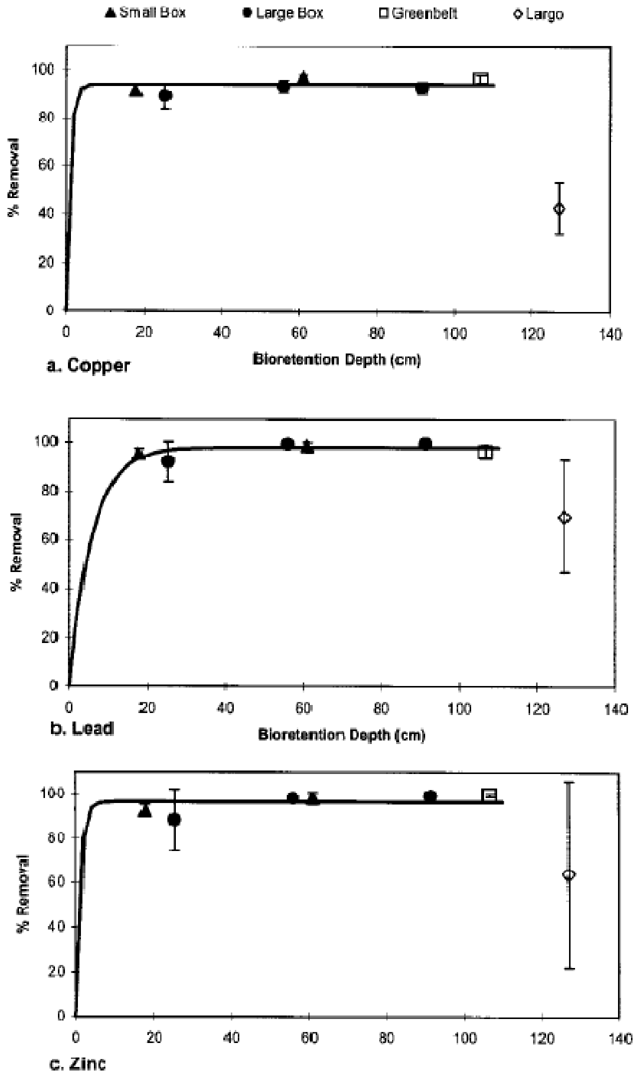

Figure 2 - Heavy metals removals as a function of bioretention depth (Davies et al. 2001)

2.2.3 Nitrogen species

Removal rates for the various nitrogen species have been highly variable, likely because of the biogeochemical complexity of the nitrogen species. Generally, substantial reduction in total Kjeldhal nitrogen (TKN) and total nitrogen (TN) concentrations are observed, but nitrate concentrations often increase. Results of various studies for TN and nitrate are not consistent as shown in Table 1, and the data lack the detail needed to draw general conclusions about the causes of the conflicting results.

The increase in nitrate observed in many studies, such as the -25% removal observed by Davis (2006), is frequently observed in stormwater filtration systems without vegetation (Barrett, 2010). Nitrates are highly soluble and should be readily absorbed and assimilated by plants. Consequently, this increase in a bioretention system is likely due to conversion of ammonia and organic nitrogen to nitrate during and between storm events. It appears that biological nitrification and denitrification processes can take place in bioretention media, depending on design and operating conditions, both in the field (Dietz and Clausen 2005) and in laboratory columns (Hsieh et al 2007b).

Table 1 - Nitrogen species removal rates in different studies

Study	TN (Total Nitrogen)			Nitrate		
	Influent (mg/L)	Effluent (mg/L)	Removal (%)	Influent (mg/L)	Effluent (mg/L)	Removal (%)
Read et al. 2008	1.02	1.69	-66	0.393	0.083	79
Davis 2006	3.1	1.2	60	0.34	0.26	24
	3.8	1.3	66	0.32	0.40	-25
	4.2	1.1	74	0.39	0.46	-13
	4.1	1.1	83	0.35	0.07	79
Hunt et al. 2008	1.68	1.14	32	0.41	0.43	-5

2.2.4 Phosphorus

Phosphorus removal tends to be better than nitrogen because phosphate is adsorbed by compounds containing iron, aluminum and calcium. Moreover, phosphorus is necessary for plant growth and production. Generally, phosphorus removal in bioretention systems is significant, as shown in Table 2.

2.2.5 Bacteria

Pathogenic bacteria are a major water quality concern in waterbodies designated for contact recreation. Conceptually, bioretention should remove most species of bacteria due to its ability to collect and filter water, and then dry out, exposing bacteria to dry conditions and sunlight. Bacteria data from bioretention facilities are rare; however, the basic processes (filtration, attachment, and biological uptake/degradation) for bacteria removal are essentially the same as those in septic system drain fields. Consequently, the estimate of 90% reduction in bacteria concentrations made by Prince George's County's Department of Environmental Resources is reasonable (Lampe et al. 2004).

Table 2 - Total Phosphorus removal rates in different studies

Study	**Influent (mg/L)**	**Effluent (mg/L)**	**Removal (%)**
Read et al. 2008	0.26	0.082	69
Davis 2006	0.44	0.13	71
	0.52	0.10	81
	0.44	0.10	77
	0.44	0.07	83
	0.47	0.06	87
Hunt et al. 2008	0.19	0.13	31

The few studies that have been conducted showed good removal, as expected. Initial studies in Charlotte, NC, show significant reduction of indicator species: fecal coliform and *E. coli* removal rates were approximately 70% with effluent concentrations at or below the state (North Carolina) level for water with humans contact (Hunt et al. 2008). A recent laboratory study found very high fecal coliform removal rates, with a mean of 91.6% (Rusciano and Obropta 2007). Bratieres (2008) showed 98% removal of *E. coli* after a wet period and 69% after a dry period. As the gaps between soil particles increase, because of cracks and macro-pore development, the filtering capacity is reduced after a dry period. More studies and long-term performance data are needed to fully document bacteria reductions.

2.3 INFLUENCE OF DESIGN PARAMETERS

Pollutant removal varies with bioretention systems design. The type of medium, the vegetation and the general design of the system have been found to affect the efficiency of the systems. These factors are described in detail below.

2.3.1 Influence of bioretention media

The medium used in a bioretention system plays an important role in the treatment performance and must balance several competing needs. It must be able to drain the design event in an acceptable time, which suggests high sand content, but also provide enough soil for plant growth. An unfortunate aspect of much of the research conducted to date is the lack of good characterization of the filter media properties (e.g., Ermilio and Traver 2006, Read et al. 2008). Many studies describe percentages of various components but fail to provide quantitative information on particle size distribution, organic matter content, type of organic matter, permeability, cation exchange capacity, water holding capacity, or other properties. The two properties that have been shown to impact stormwater pollutant removal are soil/sand ratio and organic matter content.

An important component of any future study is detailed characterization of the media properties, so that differences in stormwater pollutant removal and changes in permeability can be associated with identified physical properties of the filter media.

2.3.1.1 Influence of soil/sand ratio

Hsieh and Davis (2005) conducted 18 experiments to evaluated various bioretention media. They recommended a blend of course sand and sandy loam soil for the filter layer, with the ratio dependent on the requirements of the vegetation. Other authors (e.g., Avellaneda 2010) observed that pure sand provides better TSS removal than any blend of soil and sand, but this may be due to some of the soil washing out of the mix rather than transport of solids in runoff through the filter. The central issue is providing enough soil to support vegetation, while maintaining the infiltration capacity of the filter.

Hsieh and Davis (2005b) showed a tendency for the medium to have better removal of total phosphorus when the mass ratio soil/sand is greater than one. In Figure 3, one can see that the medium that seems to have the best phosphorus removal is a 70/30 mixture of soil to sand. On the other hand, after 100 empty bed volumes of rainfall, the removal for every medium is very close to zero, which for the Austin area is equivalent to about 5 months of rainfall - a very short time period.

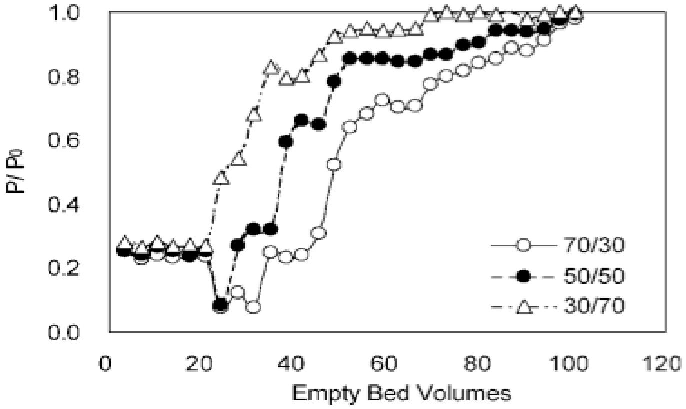

Figure 2—Phosphorus effluent from continuous flow columns, soil/sand ratio (pH = 7, initial phosphorus = 3 mg/L, flowrate = 3.1 mL/min). One empty bed volume = 1290 mL.

Figure 3 - Phosphorus effluent from continuous flow columns, soil/sand ratio (empty bed volume=1290mL) (Hsieh et al. 2007a)

2.3.1.2 Influence of organic matter content

Bratieres (2008) observed that the addition of organic matter to the medium could result in a significant decrease in TP removal, when the phosphorus contained in the organic matter breaks down and PO_4^{3-} is discharged. So, FAWB (2008) guidelines recommended less than 5% organic matter to prevent nutrient leaching. However, Hsieh and Davis (2005b) found a much better total phosphorus removal in bioretention facilities where the media had the highest organic matter (6.2%) content but this appears to be the only study reporting this phenomenon. In addition, organic matter in the filter medium, especially compost, can act as an additional source of nitrogen and might contribute to the negative removal rate for nitrate reported by some studies (Read et al. 2008).

2.3.2 Influence of vegetation

The presence and type of vegetation are critical for nitrogen species removal (Read et al. 2008, Bratieres 2008), as is shown in Figure 4. These experiments led by Bratieres (2008) showed the impact of some types of vegetation (Carex and Malaleuca) on total nitrogen removal compared to others species and non-vegetated media. Vegetation also plays a significant role in phosphorus removal. Read et al. (2008) observed a 59% TP removal without plants and 69% with plants. Solids retention is much more important (90% of the total removal) than plant uptake in metals removal (Sun and Davis 2007), so uptake by vegetation is not substantial.

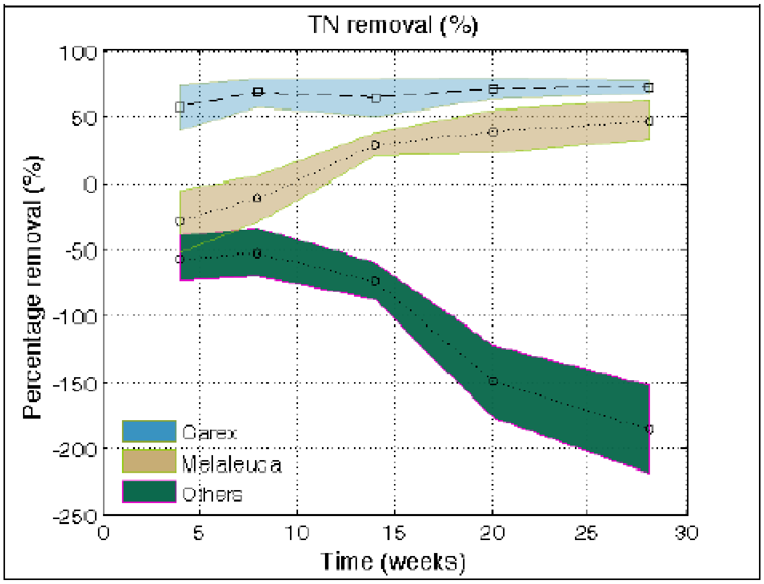

Figure 4 - Mean and 95% confidence interval for TN removal over time relative to vegetation species: Carex (top), Malaleuca (center) and 'others' (bottom). Due to similar performance, other species used and non-vegetated columns have been represented as a single group.

2.3.3 Influence of general design

Hsieh et al (2007) showed that if the bioretention medium is allowed to remain saturated for a significant period, either naturally or through modification of the design, some denitrification is possible. The processes of nitrification/denitrification were also demonstrated by Hunt et al. (2006). He documented excellent nitrate removal (75%) in one facility, which had isolated saturate zones in portions of the media (Greensboro), but much less (13%) in another site (Chapel Hill), which did not. Moreover, Chapel Hill medium did not contain any organic matter and this could have inhibited denitrification. Consequently, a saturated zone at the bottom of the facility, and containing a carbon source (organic matter) was shown to promote denitrification and to significantly improve nitrate removal (Hunt et al 2006). This saturated zone can be easily created by simply raising the outlet.

FAWB (2008) also showed the importance of a carbon source in the saturated zone to increase nitrate removal and found the best performance for a 450-mm-deep saturated zone (Figure 5) for an 1150-mm-deep facility. Moreover, the saturated zone is also good for supporting plant survival during dry periods, which may allow additional TN removal through uptake by vegetation.

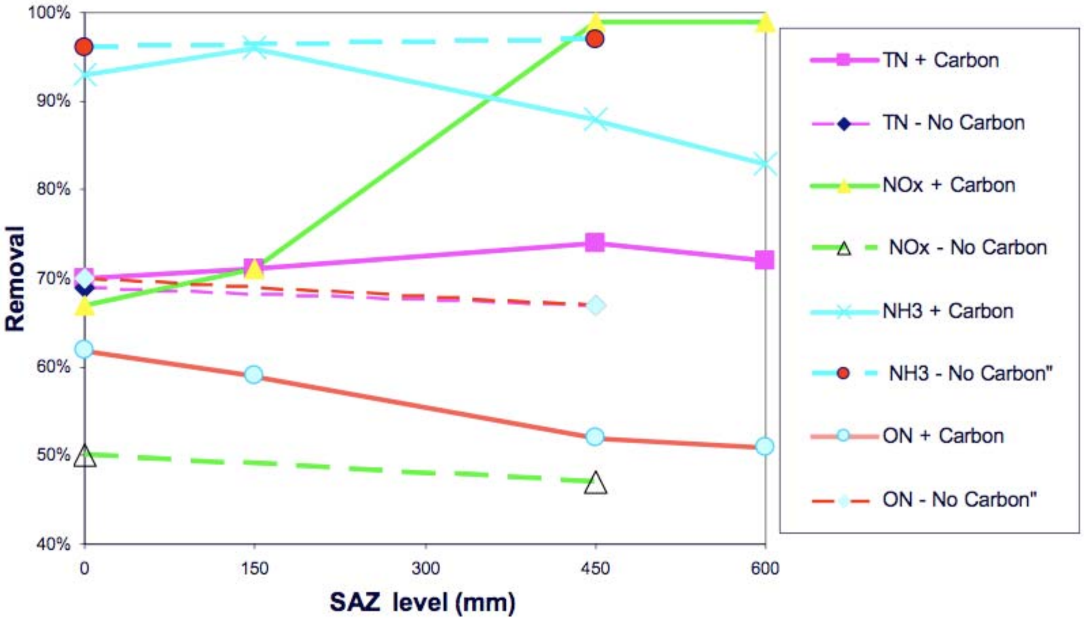

Figure 5 - Nitrogen species removal under a range of SAZ (saturated zones) level (Taken from Zinger et al. 2007b, as reported by FAWB 2008)

Figure 6 shows the effect of drying on TN removal. Note that the change during the drying period is not linear and the first two points are joined for presentation reasons only. It is apparent that the system without a submerged zone and a carbon source, even if it recovered relatively quickly, began leaching TN after three weeks of drying. The system with a submerged zone and a carbon source would take seven weeks to experience the same effects. Contrary to nitrogen species removal, phosphorus removal does not seem to be affected by the presence of a saturated zone in the media (FAWB 2008).

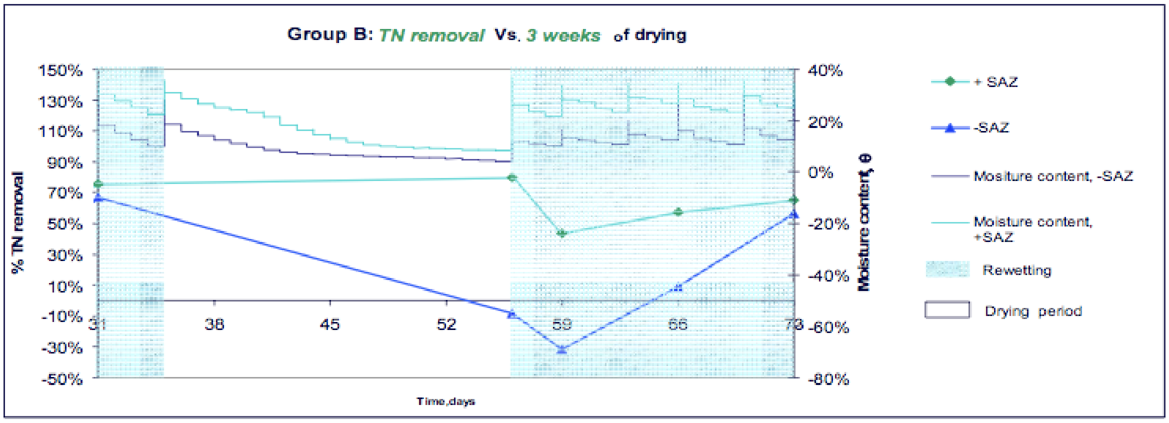

Figure 6 - Impact of three weeks drying on TN removal (Zinger et al. 2007b from FAWB 2008)

2.4 HYDRAULIC CONDUCTIVITY

The hydraulic conductivity is the rate of movement of water through the medium. Clogging is a real issue for bioretention facilities because it reduces treatment performance. This phenomenon is not yet completely understood but some studies have been conducted to find the design parameters that influence it. Li and Davies (2008) have shown that runoff with smaller TSS particles had a stronger tendency to clog the medium.

Le Coustumer (2008) showed that the hydraulic conductivity (K) is dependent on many design variables. In general, a decrease in K is observed, as shown in Figure 7, where the hydraulic conductivity was only 27% of its initial value after 72 weeks.

Vegetation type can have a significant effect on K. Le Coustumer (2008) found that one type of vegetation, Melaleuca, increased K over time whereas filters planted with all the other different species showed the same significant decrease in K as systems with no vegetation (Figure 8). Melaleuca has thick roots, which can help in creating macropores in the soil.

Time (weeks)	4	8	14	20	28	39	60	72
Mean (mm/h)	234	189	176	190	152	99	71	68
Median (mm/h)	186	160	148	157	125	88	46	51
σ (mm/h)	143	117	103	108	81	60	79	59
2.5th	98	74	69	72	40	3	5	2
97.5 th	588	519	445	513	336	240	334	257
Cv (%)	61	62	58	57	53	61	112	87
n	124	124	124	125	125	125	87	79

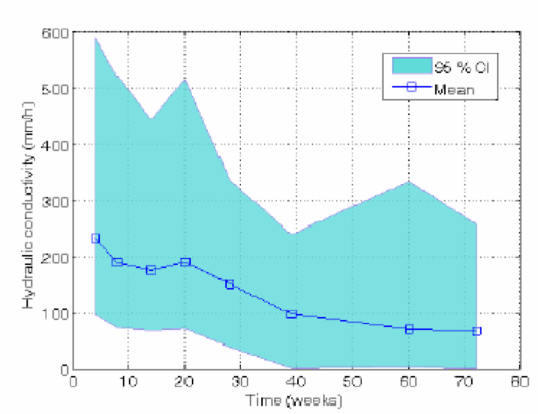

Figure 7 - Evolution of hydraulic conductivity with time (mean, 95% confidence interval) (Le Coustumer 2008)

	K_{ini} (4 weeks) (mm/h)	K_{final} (60 weeks) (mm/h)	p
No vegetation	199 (29%)	53 (41%)	0.002
Carex	251 (49%)	51 (65%)	0.009
Dianella	232 (61%)	88 (45%)*	0.043
Microleana	150 (17%)	49 (35%)	0.001
Leucophyta	231 (29%)	66 (43%)	0.004
Melaleuca	155 (34%)	295 (38%)	0.012

* results after 39 weeks

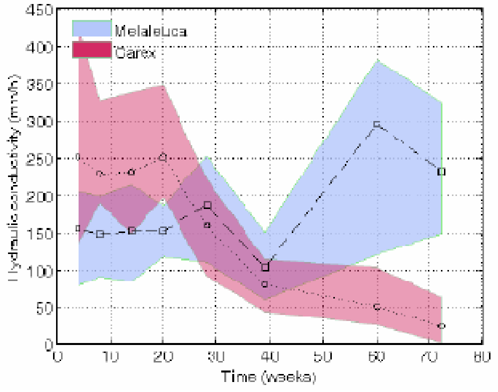

Figure 8 - Evolution of K with time for the Carex and Melaleuca solution (Le Coustumer 2008)

The size of the bioretention system relative to its catchment also has a large influence. A comparison of two systems with the same initial K found that by the time the smallest system (0.7% of the watershed) was almost clogged, the K of largest system (4% of the watershed) was still 120 mm/h. Furthermore, the composition of the media is important for the hydraulic conductivity. The addition of compost or vermiculite and perlite has been shown to increase K in comparison with sandy loam soil (Le Coustumer 2008). The last variable that has been shown to have an influence on the hydraulic conductivity is the concentration of sediments in the inflow. As expected, a high loading of sediments reduces the hydraulic conductivity much faster (Le Coustumer 2008).

All these variables influence the rate of decrease of K over time; however, clogging appears to be inevitable except perhaps when the system is planted with selected species that help preserve porosity and permeability. A common maintenance practice at this time for sand filters is the replacement of the top 10 cm layer of filter media. This activity results in a substantial increase in hydraulic conductivity restoration (Li and Davis 2008), but is more problematic in a vegetated filter, where the vegetation must be removed prior to media replacement.

2.5 CONCLUSIONS

As has been demonstrated, it is difficult to draw definitive conclusions about the processes and designs that affect bioretention performance. The reasons for this difficulty are many and include:

- A lack of detailed information about the filter medium composition
- The lack of consistency in experimental methods
- The wide variation in how results are reported (load reduction vs. concentration change)
- The lack of explicitly accounting for losses due to infiltration

Even those researchers that have been intimately involved in past research on bioretention design and performance now seem to realize that these shortcomings have severely reduced the ability to draw general conclusions from their work. As noted just recently by the most prominent researchers in this area, many questions remain (Davis et al. 2009). They conclude that:

> “Nonetheless, many design questions persist for this practice, such as maximum pooling bowl depth, minimum fill media depth, fill media composition and configuration, underdrain configuration, pretreatment options, and vegetation selection. Moreover, the exact nature and impact of bioretention maintenance is still evolving, which will dictate long-term performance and life cycle costs.”

Consequently, it is important that any new research be conducted under very controlled conditions and that detailed information on the properties of the medium being tested be developed.

Chapter 3: Experimental Methods and Materials

To evaluate possible designs for biofiltration facilities, columns were constructed to simulate full-scale systems. These columns were dosed with synthetic stormwater over the course of a year, at a rate equivalent to the average TSS load a system in the field would experience from a typical urban watershed in a year of average rainfall. The following sections describe the methods and materials in detail.

3.1 EXPERIMENTAL SET-UP

3.1.1 Column Descriptions

Columns were built using the largest type of PVC pipe (20.3 cm (8 in.) diameter) available in order to minimize boundary effects from the sides of the columns and to provide sufficient space for normal plant growth. Twelve biofiltration columns were built according to the design shown in Figure 9, and a photo of all the vegetated columns taken during an experimental run is presented in Figure 10.

The total column height was 101 cm (40 in.) and consisted of 60.9 cm (24 inches) of PVC pipe topped with a 40.6 cm (16 inches) length of acrylic pipe, joined with a PVC coupling. The acrylic pipe was used to hold the water during experimental runs while allowing sunlight to reach the plants. The columns were attached to a 60.9 cm (24 inches) square piece of plywood using a PVC flange and blind. A gasket was placed between the flange and the blind to keep everything watertight. The plywood board was supported by two pieces of lumber (2" x 4") and placed on two rows of concrete blocks to drain easily into the collection system. The outlet from the column was a 1.3 cm (0.5 inch) diameter plastic tube that discharged to the collection system. To completely collect the relatively large volume of runoff discharged, 75.5 L (20 gal.) garbage cans were used. Prior to each experiment, the cans were lined with a new garbage bag to ensure there was no contamination from the preceding experiment.

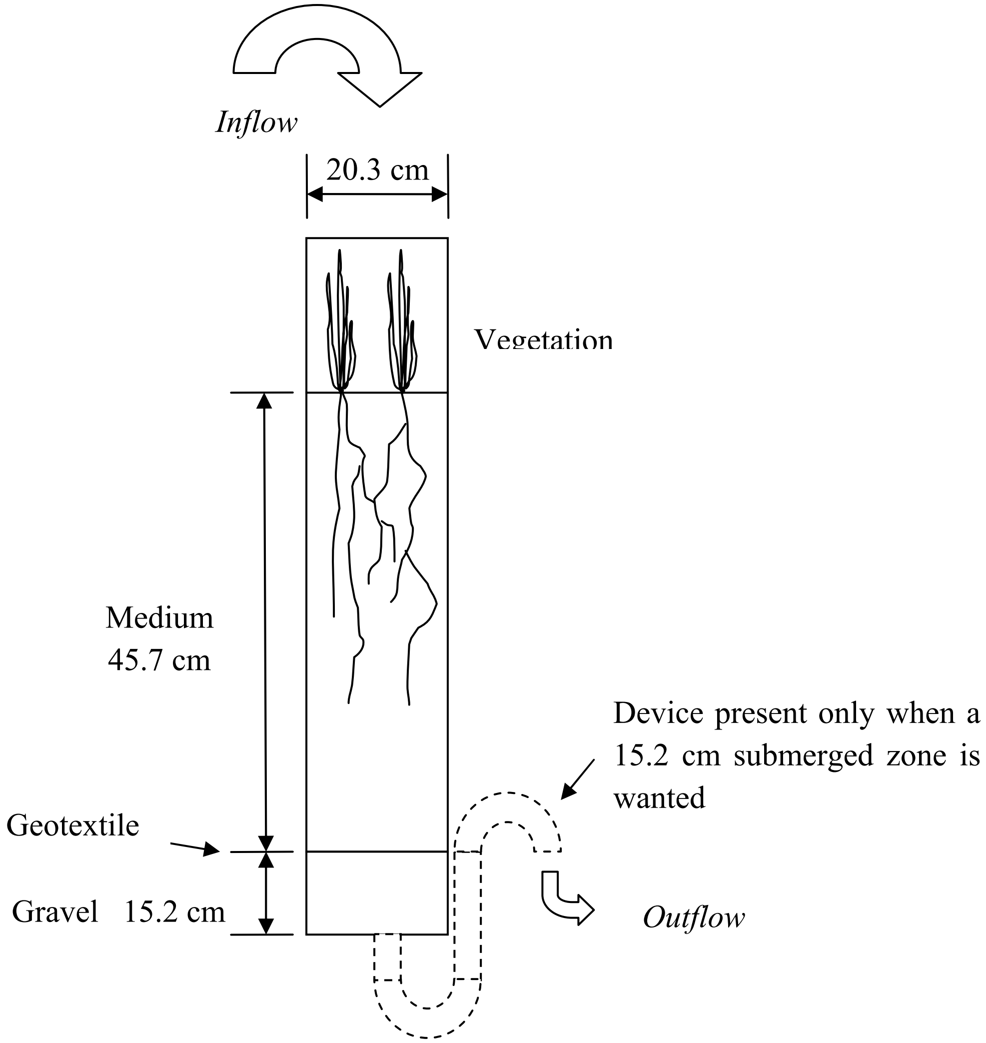

Figure 9 - Schematic of a biofiltration column

Figure 10 - Vegetated Test Columns during Pollutant Dosing

The bottom of each column was filled with 15.2 cm (6 inches) of washed river gravel, which is the standard specification for underdrain materials in Austin sand filters. A geotextile layer was placed on top of the gravel and covered with 45.7 cm (18 inches) of filter medium. The City of Austin specifications for biofiltration systems have very specific requirements for this geotextile. It has to be "made of non-woven or woven material which is water permeable but will trap water-borne sediment for protection of curb inlets with an opening to allow the passage of runoff for higher flows." In addition, the fabric must correspond to requirements shown in Table 3. The "PolySpun 300", landscape fabric, manufactured by Easy Gardener (Waco, TX), was one of the only fabrics found meeting the above criteria and was used to separate the medium and the gravel underdrain.

Table 3 - Geotextile Requirements

Property	Test Method	ASTM Requirements
Fabric Weight	D 3776	≥3.0 ounces/square yard
Ultraviolet (UV) Radiation Stability	D 4355	70% strength retained min., After 500 hours in xenon arc device
Mullen Burst Strength	D 3786	≥120 pound per square inch
Water Flow Rate	D 4491	≥275 gallons/minute/square feet

The columns with submerged zones (SZ) had their outlet raised by 15.2 cm (6 inches) to keep the gravel layer submerged. Texas native hardwood mulch (from Austin wood recycling) was placed in the submerged zone as a carbon source at a ratio of 1/10 by volume. The height of this saturated zone is one fourth of the total height of the column. FAWB 2008 recommended a higher saturated zone (450mm, being one third to one half of their facility) but it was more convenient to have it only as high as the drainage layer.

All the columns were covered with a shade fabric for the summer so that the plants would not burn in the 40°C heat experienced during plant establishment. During the winter period, a greenhouse was built (late November 2009) to keep them from freezing, but was left open when it was not freezing to keep their environment the closest possible to the actual outside temperature. The greenhouse also prevented the columns from capturing rainwater between experiments, which could have affected both the volume and quality of the discharge during experimental runs.

3.1.2 Media Selection

The Facility for Advancing Water Bioretention (FAWB) in Australia conducted one of the most comprehensive assessments of biofiltration media and has developed a specification that they recommend. Their tests included the pollutant removal performance of six different blends of various thicknesses. These blends contain varying amounts of sand, sandy loam, and additives such as vermiculite, perlite, compost, and mulch. Their recommended mixture contains very little organic matter (<5% by weight), no compost, almost no silt and clay (<3%), and a large fraction of medium to coarse sand (up to 70%).

The City of Austin has a draft specification for biofiltration media based on initial testing. The specifications include requirements for porosity, cation exchange capacity, organic matter (in the form of compost), and a relatively large fraction of silt and clay (up to 25%). COA media composition was selected by city staff after reviewing available literature, hypothesizing about which media properties might enhance pollutant removal, and then selecting a media that would retain water for plant growth, prevent leaching of nutrients from addition of compost, provide sufficient permeability to convey captured stormwater, and also be readily available. CEC capacity was thought to be important based on other studies and opinions so this was also specified. Recent research has indicated that compost can be a substantial source of nutrients, so the City of Austin is currently amending its draft specification to eliminate this component. The mix tested in these experiments did not contain compost.

For this study, The City of Austin wanted to compare its newly developed biofiltration medium with the medium that showed very good performance in the literature (FAWB 2008) and with its basic sand filter medium to see how efficient it would be to replace their existing sand filters with biofiltration facilities. Consequently, the different media selected for evaluation were:

- Concrete sand (ASTM C-33), current standard sand filter medium
- City of Austin medium (COA biofiltration). This complies with the newly developed specification for medium used in bioretention facilities around the City of Austin. It is made of a mix of concrete sand and sandy loam. Texas Organic Products, the only accredited supplier for this medium in Austin, provided it. Detailed specifications are provided below.
- Masonry sand. The specifications of the medium used in FAWB (2008) are very close to masonry sand (ASTM C-144), as shown by Table 5, so basic masonry sand was used as the third medium, since it is widely available.

The measured media grain size distribution, organic matter content, cation exchange capacity (CEC) and the grading for the different media are reported in Table 4, while Table 5 presents the general size specifications for the different media. The specifications for the City of Austin medium are the following:

- Porosity $n \geq 0.45$
- Saturated Hydraulic Conductivity $K \geq 2$ in/hr
- Percent Organic Matter (by weight) of 1 - 4%

- Cation Exchange Capacity CEC ≥ 10 meq/100g
- Texture Analysis (particle size distribution):
    - ➢ Percent Sand 70 - 90%
    - ➢ Percent Clay 2 - 10%
    - ➢ Percent Silt plus Clay ≤ 25%"

Table 4 - Media grain size distributions and properties measured by Midwest laboratories

Medium	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	CEC (meq/100g)
COA sand filter	88	10	2	0.1	5.3
COA biofiltration	73	18	9	0.4	9.8
Masonry sand	94	2	4	0.1	0.9

Table 5 - Grading of the different media (% Passing)

Sieve Size	ASTM C-33 (Concrete Sand)	FAWB 2008	ASTM C-144 (Masonry Sand)	COA Biofiltration
9.5 mm (3/8")	100			
4.75 mm (No. 4)	95 – 100	100	100	
2.36 mm (No. 8)	80 – 100	97 – 100	95-100	100
1.18 mm (No. 16)	50 – 85	90 – 97	70-100	70 – 100
600 µm (No. 30)	25 – 60	55 – 90	40-75	55 – 90
300 µm (No. 50)	5 – 30	15 - 60	20-40	35 – 60
150 µm (No. 100)	0 – 10	8 – 33	10-25	12 – 25
50 µm		0 – 3	0-10	10 – 25
2 µm				2 – 10

In addition to the grain size distribution for the FAWB mix, they also recommend the following specification:

- Organic Matter Content – less than 5% (w/w). An organic content higher than 5% is likely to result in leaching of nutrients.
- pH – as specified for „natural soils and soil blends" 5.5 – 7.5 (pH 1:5 in water).

- Electrical Conductivity (EC) – as specified for „natural soils and soil blends‟ <1.2 dS/m.
- Phosphorus - <100 mg/kg. Soils with phosphorus concentrations >100 mg/kg should be tested for potential leaching. Where plants with moderate phosphorus sensitivity are to be used, phosphorus concentrations should be <20 mg/kg.

3.1.2 Vegetation Selection

As explained in Section 1.2, one of the objectives of this study was to determine which native plants would show the best nutrient removal. The two plants chosen were a turfgrass, Buffalograss 609, and a bunchgrass, Big Muhly, both commonly found in Texas. It was important to choose native Texan plants so that less maintenance is needed and they will be more likely survive in the Texas climate. These two plants differ in size, growth, and habitat. Buffalograss 609 was installed as sod about 1 inch thick, while the Big Muhly was container grown. Most of the soil in which the Big Muhly was growing was removed before placing the plants in the columns. The plants were planted in the summer and were grown and watered for two months before the beginning of the experiments, so that they would be well established.

3.1.3 Column Combinations

Twelve different combinations of the different media, plants and designs presented above were chosen. The combination of media, plants and submerged zone for each column is shown in Table 6. It was important for each medium to have a column without vegetation to show the influence of vegetation. The column with concrete sand was not planted because the City did not see a scenario in which they would try to vegetate an existing concrete sand filter. For each media and for both plants, one column without a submerged zone and one column with a submerged zone were used to see the influence of the submerged zone on the performance of each plant and each medium.

3.2 SYNTHETIC STORMWATER

The pollutant removal of the various columns was evaluated by dosing them with synthetic stormwater, except for one experiment where real stormwater was used (details in Section 3.3). For each experiment, a 1 L concentrated stock solution and a 500 mL lead nitrate solution were prepared in advance and dissolved and mixed in 170 L of deionized water. Lead nitrate solutions were prepared separately to avoid precipitation of lead chloride and lead sulfate. All the solutions were prepared four at a time to facilitate the weighing of the chemicals. The sediments used for TSS were collected from a low spot on a residential street (Lucas Dr.) in Austin, Texas. Table 7 was used to calculate the amount of each constituent needed to prepare the stock solutions and the lead nitrate solutions. Average influent concentrations obtained are provided in Table 8. Although a consistent recipe was used to create the synthetic stormwater, some variability in influent concentrations was observed. This variability is likely due to variation in the composition and density of the sediment used in the mixture. Because the sediment included some larger size fractions, not all of the sediment could be suspended in the tank.

Table 6 - Column Configurations

	Media	**Plant**	**SZ**	**Short Name**
1	COA sand filter	No	No	SF/NP
2	COA biofiltration	No	No	COA/NP
3	COA biofiltration	Buffalo	Yes	COA/Bu/SZ
4	COA biofiltration	Big Muhly	Yes	COA/BM/SZ
5	COA biofiltration	Buffalo	No	COA/Bu
6	COA biofiltration	Big Muhly	No	COA/BM
7	Masonry sand	No	No	MS/NP
8	Masonry sand	Buffalo	Yes	MS/Bu/SZ
9	Masonry sand	Big Muhly	Yes	MS/BM/SZ
10	Masonry sand	Buffalo	No	MS/Bu
11	Masonry sand	Big Muhly	No	MS/BM
12	COA sand filter	No	Yes	SF/NP/SZ

Table 7 - Stock Solutions Preparation

Pollutant	**Targeted value (mg/L)**	**Targeted value *170L (mol/L)**	**Chemical used**	**Weight of chemical (mg)**	**Weight of chemical*4 (mg)**
NO_X	0.74	8.979E-03	KNO_3	884.67	3538.69
NH_3 as N	0.59	7.159E-03	NH_4Cl	382.73	1530.92
DON	0.85	1.031E-02	$C_6H_5O_2N$	1269.35	5077.41
DP	0.35	1.921E-03	KH_2PO_4	261.42	1045.68
Total Copper	0.1	2.675E-04	$CuSO_4$	66.79	267.16
Total Zinc	0.25	6.498E-04	$ZnCl_2$	88.57	354.30
Total Lead	0.14	1.149E-04	$Pb(NO_3)_2$	38.05	152.18

A 170 L tank was used to mix the synthetic stormwater. The tank was a cylindrical plastic tank, 80 cm high and 55 cm in diameter. The mixer was a Lightnin Mixer with a 91 cm long metal propeller with three blades. It was fixed to a wooden structure for stability and was capable of providing vigorous mixing of the entire contents.

Table 8 - Average Measured Influent Concentrations

Pollutant	Concentration (mg/L)	Standard Deviation
Total Suspended Solids (TSS)	127	58.5
Nitrate + Nitrite (NO_X) as N	0.79	0.07
Total Kjeldhal Nitrogen	3.08	1.31
Dissolved Phosphorus (DP)	0.36	0.05
Total Phosphorus (TP)	0.66	0.11
Dissolved Copper (DCu)	0.013	0.010
Total Copper (TCu)	0.075	0.007
Dissolved Zinc (DZn)	0.046	0.014
Total Zinc (TZn)	0.17	0.024
Dissolved Lead (DPb)	0.008	0.019
Total Lead (TPb)	0.12	0.023

3.3 REAL STORMWATER

As mentioned previously, one experiment was done with real stormwater. The goal of this experiment was to compare the performance of the filters with real and synthetic stormwater to get a more realistic idea of the performance of the columns and to determine bacteria removals. Synthetic stormwater does not have the same distribution between dissolved and particulate-bound metals as actual stormwater, so this run allowed the difference in the column performance between the synthetic and real stormwater to be determined. The real stormwater was collected during a 0.7 inch storm on April 15 on a residential street (Beverly Skyline) in Austin, Texas and was kept in a cold room (4ºC) for three days before the experiment was done. Influent concentrations of the real stormwater collected are provided in Table 9.

Table 9 - Influent Concentrations for Real Stormwater

Pollutant	**Concentration (mg/L)**
Total Suspended Solids (TSS)	336
Nitrate + Nitrite (NO_X)	0.104
Total Kjeldhal Nitrogen (TKN)	9.67
Dissolved Phosphorus (DP)	0.217
Total Phosphorus (TP)	1.57
Dissolved Copper (DCu)	0.007
Total Copper (TCu)	0.021
Dissolved Zinc (DZn)	0.015
Total Zinc (TZn)	0.130
Dissolved Lead (DPb)	0.003
Total Lead (TPb)	0.018
E. Coli (CFU/100mL)	32600
Fecal Coliform (CFU/100mL)	30200

3.4 EXPERIMENTAL SCHEDULE

An experiment was run every 10 to 15 days during nine months according to the schedule in Table 10. Experiment 19 is the only experiment run with real stormwater. The depth indicates the depth of water that was poured into each column. A depth of 30 cm (one foot) of water corresponds to 9.9 L, and 91 cm (three feet) corresponds to 29.7 L of water. These two different depths were used to see the effect of the submerged zone on the quality of the effluent. An experiment with one foot of water will have 17% of its effluent being the previous submerged zone that stayed in the column for up to two weeks, whereas a three-foot experiment will have only 6% of the effluent being the water previously in the submerged zone.

Only every other experiment was analyzed due to cost consideration. During non-analyzed experiments, the volume of water in and out of each column was recorded with a graduated cylinder to develop a water balance and quantify the effects of evapotranspiration (Section 3.6). Non-analyzed experiments were all done with only 30 cm of water because of a time constraint but were dosed with three times as much TSS concentration so that overall the TSS loading (mass) is at least the same as what would occur in the field. It was important in terms of clogging to have a realistic TSS loading. Total solids loading to the columns over all the experiments was 0.12 g/cm^2.

Table 10 - Experimental Schedule

Run	**Date**	**Depth (cm)**	**Analyzed**
1	25-Aug	30	
2	10-Sep	30	Yes
3	22-Sep	30	
4	01-Oct	91	Yes
5	15-Oct	30	
6	27-Oct	30	Yes
7	10-Nov	30	
8	19-Nov	91	Yes
9	02-Dec	30	
10	14-Dec	30	Yes
11	11-Jan	30	
12	20-Jan	91	Yes
13	2-Feb	30	
14	16-Feb	30	Yes
15	2-Mar	30	
16	10-Mar	91	Yes
17	31-Mar	30	
18	6-Apr	30	Yes
19	18-Apr	30	Yes – Real stormwater
20	4-May	30	
21	20-May	91	Yes
22	3-June	30	

3.5 EXPERIMENTAL PROCEDURE

For each run, the following experimental procedure was used:

1. Stock solution and lead nitrate solution preparation.
2. Filling of the mixing tank with deionized water, while pouring both solutions in the tank.
3. Mixing of the tank.
4. Addition of the sediments and additional 10 minutes of mixing.
5. Once the tank is well mixed, filling of each of 12 buckets with 9.9 L in each. Because of the size of the tank, the mixing was not perfect, so the filling of the buckets was done in two parts. First, the first half of all buckets was filled and then, the second half, to avoid one bucket receiving only water from the bottom or the top of the tank.
6. Filling of each column with one bucket of synthetic stormwater.
7. Synthetic stormwater was left to drain into the columns for several hours (sometimes overnight) before samples were taken.

For each analyzed run, 3-L samples were taken out of each effluent container and analyzed by an accredited laboratory. The pollutants analyzed were total suspended solids (TSS), nitrate + nitrite (NO_x), total Kjeldahl nitrogen (TKN), dissolved phosphorus (DP), total phosphorus (TP), chemical oxygen demand (COD), dissolved copper (DCu), total copper (TCu), dissolved zinc (DZn), total zinc (TZn), dissolved lead (DPb), and total lead (TPb) for each experiment, plus *E. coli* and fecal coliform for the experiment with real stormwater. For non-analyzed runs, only volumes were recorded and no samples were collected. A paired t-test was used to determine whether the effluent quality of comparable columns (e.g, COA/Bu/SZ vs. FAWB/Bu/SZ) was significantly different.

3.6 VOLUME MEASUREMENTS

The volume of the runoff discharged from the columns was measured for each experimental run where samples were not collected for laboratory analysis. The goal was to determine whether the various column configurations resulted in different volume reductions. The influent volume for each column was 9.9 L and, once all the stormwater had discharged from the column, the volume of the effluent was measured using a graduated cylinder. The difference between the influent and the effluent volumes was then calculated as a measure of the evapotranspiration in the column.

3. 7 HYDRAULIC CONDUCTIVITY MEASUREMENTS

A falling-head test was used to measure hydraulic conductivity. The formula to calculate the hydraulic conductivity K (cm/s) was the following:

$$K=aL/At*\ln(H_0/H_1),$$

Where:

a = area through which the water falls (cm^2),

A = area of the filter medium in the column (cm^2),

L = length of the media (cm) and

t = time for the water lever to fall from H_0 to H_1 (sec).

In the experimental setup a and A are equal. Four hydraulic conductivity tests were run; one before the beginning of the experiments (August 22, 2009), one at the end (June 23, 2010) and two during the course of the experiments (January 7, 2010 and March 29, 2010). Tap water was used in each test, and those tests were run prior to a non-analyzed experiment in order not to affect the water quality results of analyzed experiments.

3. 8 PARTICLE SIZE DISTRIBUTION (PSD)

Particle size distribution (PSD) was measured on the influent and effluent from the experimental runs 2 - 4. The PSD is made using the electrical sensing zone method and Coulter Counter with the Multisizer3 software. The Coulter Counter provides number, volume, mass and surface area size distributions in one measurement, with an overall sizing range of 0.4 μm to 1,200 µm. Its response is unaffected by particle color, shape, composition or refractive index.

To count the particles, a constant current is passed through the small aperture which is immersed in the sample. Particles suspended in a weak electrolyte solution are drawn through the aperture, separating two electrodes between which an electric current flows. The voltage applied across the aperture creates a "sensing zone." As particles pass through the aperture (sensing zone), they displace their own volume of electrolyte, momentarily increasing the impedance of the aperture. This change in impedance produces a pulse that is digitally processed in real time. The Coulter Principle states that the peak of the pulse is directly proportional to the volume of the particle that produced it. It is this relationship between aperture resistance change and particle volume that gives the ESZ method good accuracy compared to several other methods of particle size measurement. Analyzing these pulses enables a size distribution to be acquired and displayed in volume (μm^3) and diameter (µm). In addition, a metering device is used to draw a known volume of the particle suspension through the aperture; a count of the number of pulses can then yield the concentration of particles in the sample.

The measurement range for any aperture is 2% to 40% of its diameter. A 30 μm aperture tube is capable of analyzing the particle concentration and size distribution from 0.6 μm to 18 μm, 100 μm from 2 μm to 40 μm, and 200 μm from 4 μm to 80 μm. Calibration was done for all the different size apertures used in the experiments with suspensions containing uniform diameter latex microsphere beads. Each aperture was calibrated using four different sized beads.

3.9 STATISTICAL ANALYSIS

There are a variety of ways to calculate summary statistics and to determine whether significant differences among the columns exist. This is complicated to some extent in this analysis since the effluent concentrations for some constituents are predominantly lognormally distributed, while for others they are normally distributed. One goal in performing these analyses was to provide as much consistency as possible.

For each of the constituents and columns considered, an average influent and effluent concentration has been calculated. These are arithmetic means for the individual experiments. The percent removal reported is the difference between the average influent and effluent concentrations for all events. To determine whether the differences between columns were significant paired t-tests were conducted. If the distribution of the effluent concentrations was predominantly lognormal, the test was performed with transformed values, otherwise the test was done using untransformed data. Comparison between groups of columns were made using sequential paired tests.

Chapter 4: Results and Discussion

This chapter presents all the results of the research project starting with the results of the synthetic and real stormwater experiments for each pollutant analyzed (TSS, NO_x, TKN, TN, DP, TP, Cu, Zn, Pb, COD, *E. coli*, and fecal coliform). The results of the water balance and hydraulic conductivity measurements are also provided.

For each constituent a figure is presented reporting results from all of the synthetic stormwater experiments. Each line corresponds to a different column with the red line being the influent and each set of points represents a different experiment. The abscissa is a time line and the ordinate represents the concentration of the pollutant concerned. The different markers indicate the different types of vegetation: crosses correspond to columns without plants, squares to columns with Big Muhly (BM) and triangles to columns with Buffalograss (Bu). The different types of line correspond to the different media, with square dots being the COA Biofiltration medium (COA), dashes being the Masonry Sand (MS) and dash dots being the Sand Filter medium (SF). Tables with all the data used to make these figures can be found in Appendix A. In addition, a table is provided for each constituent showing the average effluent concentration and the percentage change in pollutant concentration. Finally, the results of the single experiment with actual stormwater are presented to provide some guidance as to whether the synthetic stormwater runs were realistic.

4.1 TOTAL SUSPENDED SOLIDS (TSS)

4.1.1 Synthetic stormwater results

The TSS results of the nine experiments with synthetic stormwater are plotted in Figure 11, using a logarithmic scale for the concentration axis. TSS concentration in the effluent was shown to be below 10 mg/L for the vast majority of experimental runs. The data indicate that removal was very good and stayed consistent through time for all the columns.

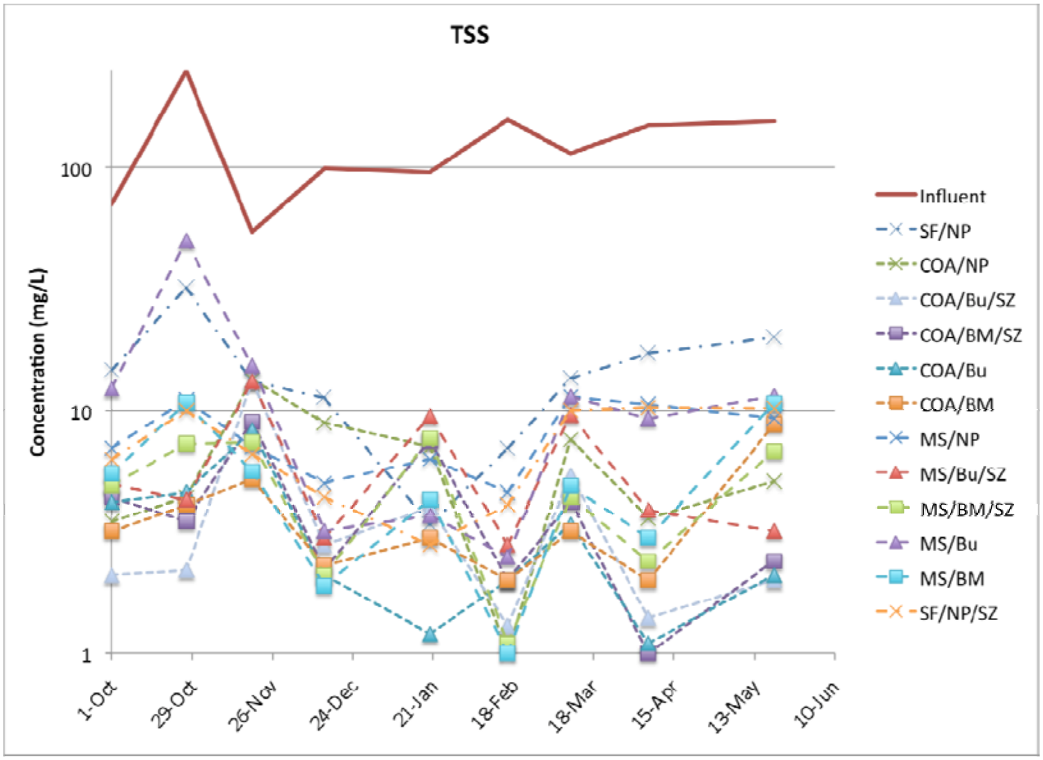

Figure 11 - TSS influent and effluent concentrations for synthetic stormwater experiments

Table 11 lists the average effluent concentrations and removals for each column. Effluent concentrations were normally distributed for eight of the twelve columns; consequently, a paired t-test on measured data was used to investigate differences in performance between the various column configurations.

The type of filter medium had a significant influence on TSS removal. The SF medium was less effective for TSS removal than MS, which, in turn, was less effective than the COA medium. The average TSS effluent concentrations in columns filled with MS were all higher on average than the ones in columns with the COA medium, with three of the five being significantly higher (Bu/SZ, p=0.006; Bu, p=0.059, BM, p=0.070). Even though the difference in effluent quality between these two media was significant, the TSS concentrations were very low for both. These results are consistent with the grain size distribution of each medium, the COA medium being the finest of the three and SF medium being the coarsest. Consequently, we would expect the best performance from the COA mix. The type or presence of vegetation and the presence of a saturated zone did not appear to have a significant influence on TSS removal, except for the SF column with a saturated zone, which had significantly lower effluent concentrations than the comparable column without a saturated zone.

Table 11 - Average TSS influent and effluent concentrations and removals

Column	**Synthetic Stormwater**		**Real Stormwater**	
	Concentration (mg/L)	**Removal (%)**	**Concentration (mg/L)**	**Removal (%)**
Influent	**126.9**		**336**	
SF/NP	14.7	88	34.8	90
COA/NP	6.1	95	30.7	91
COA/Bu/SZ	3.8	97	18.8	94
COA/BM/SZ	4.0	97	13.6	96
COA/Bu	3.2	97	17.2	95
COA/BM	3.8	97	21.2	94
MS/NP	8.0	94	22.8	93
MS/Bu/SZ	6.1	95	13.2	96
MS/BM/SZ	4.9	96	9	97
MS/Bu	13.2	90	29.2	91
MS/BM	5.3	96	21.2	94
SF/NP/SZ	7.2	94	14.8	96

Figure 12 displays the inflow and the outflow of particle size distributions from Experiment 2 for the samples collected from the three columns without plants. The particle size distributions for the other samples are located in Appendix B and show similar trends. The data are presented as both a volume distribution, which is the same as the mass distribution if the density is constant, and as a particle size distribution function. The particle size distribution function is a normalized way of showing the number distribution of particles throughout a wide size range. The normalization (i.e., dividing the number concentration (ΔN) in a small size range by the width of that size range (Δd_p) allows for the direct comparison of measurements made by different investigators with different instruments. When plotted on a logarithmic basis as a function of particle diameter $\left(\text{i.e., } \log\frac{\Delta \text{N}}{\Delta d_p} \text{ vs. } \log d_p\right)$, the complete distribution is visual; that is, this plot yields the most complete visual picture of the distribution that is spread over a wide size range and with a several order of magnitude difference in particle number concentration over that size range.

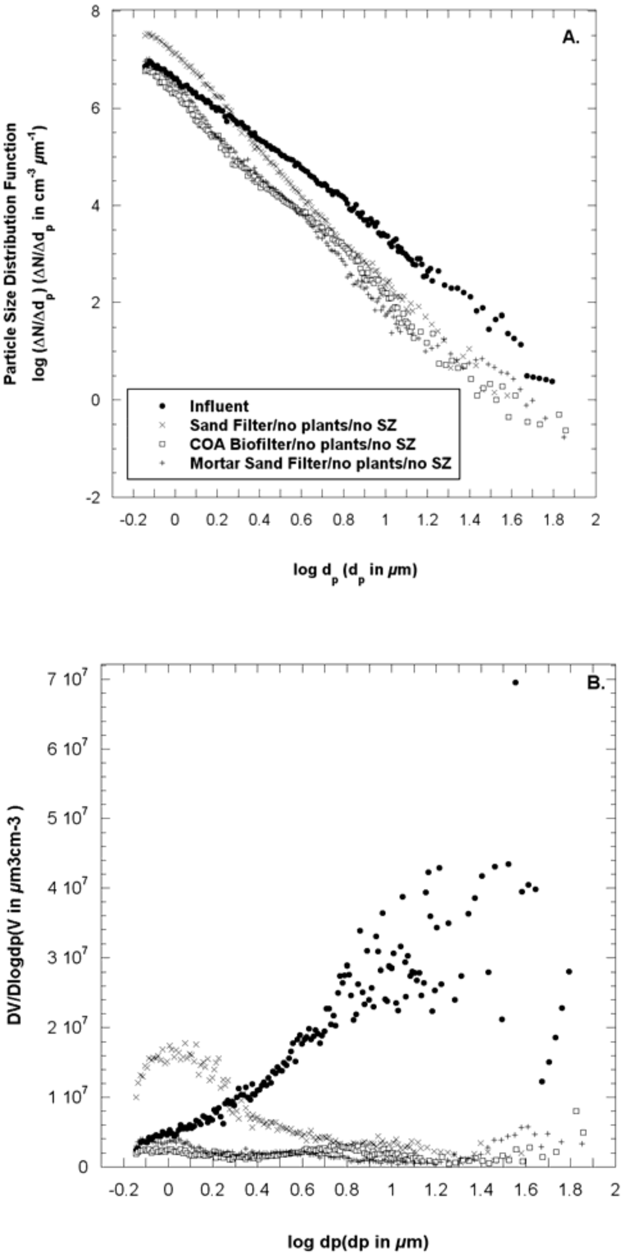

Figure 12 (A) Particle size distribution function and (B) volume distribution function of sand filter, COA mix, and, MS filter without submerged zone and plants from Experiment 2.

The particle size function distributions of the COA mix and the mortar sand filters documents efficient removal of particles with a diameter larger than 1 μm ($\log d_p > 0$)**,** and the volume distributions illustrates a significant decrease in volume for the particles with a diameter larger than 1.1 μm ($\log d_p > 0.05$). The concentration of the sand filter effluent is very small compared to the influent, but the column exports particles in the range of 0.8 μm to 2 μm ($- 0.1 < \log d_p < 0.3$). The mortar sand filter and the COA filter followed the same trend, but the mortar sand filter was slightly more efficient in removing medium sized particles in the range of 4 μm to 25 μm ($0.6 < \log d_p < 1.4$), whereas the COA mix was efficient in removing large particles in the range of 25 μm to 79 μm ($1.4 < \log d_p < 1.9$). The information gathered supports the conclusion that the sand filter medium is less efficient than either the COA mix or masonry sand at particle removal

4.1.2 Real stormwater results

The TSS results for the real stormwater experiment are presented in Table 11 and are plotted in Figure 13. The horizontal black line is the influent concentration and each bar provides the effluent concentration for the individual columns. The TSS results for real stormwater were consistent with the results for synthetic stormwater, with an average reduction of 94%. However, in the real stormwater experiment, the COA medium performed better than the MS medium for only one column, so there was not the same clear ranking between the three media for TSS removal in the real stormwater experiment as observed in the synthetic stormwater experiments. Nevertheless, this real stormwater experiment was conducted only once, so significant differences in performance may be difficult to observe since the effluent concentrations of the different column configurations are similar.

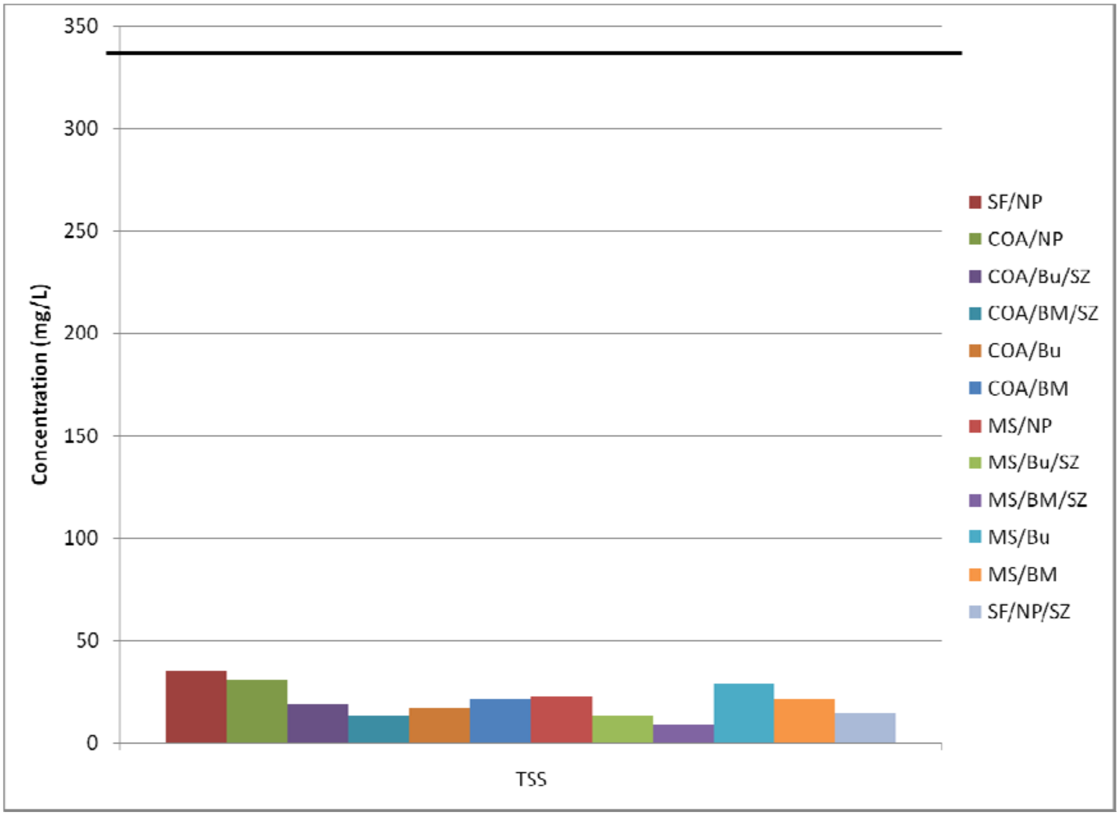

Figure 13 - TSS influent and effluent concentrations for the real stormwater experiment

4.1.3 Discussion

Several Austin Sand Filters have been in operation for many years and have been monitored by the City of Austin. According to a study by Barrett (2010), their effluent average concentrations varied between 13 and 25 mg/L, with average influent concentrations ranging from 69 to 304. This resulted in an average removal of 91%. This value is very similar to the average 88% observed in the experiments with synthetic stormwater. Consequently, we can be confident that the results of the synthetic stormwater experiments were realistic and comparable to what we would expect to observe in the field for the other test columns. However, some field studies (e.g, Hunt et al. 2008) found lower TSS removals compared to laboratory studies.

MS is very close to the recommended medium by FAWB (2008). So, a comparison can be made between these columns with MS and results from their study. For TSS, FAWB (2008) obtained lower effluent concentrations for a similar influent concentration for vegetated and non-vegetated columns with an effluent of 1.3 mg/L TSS for non-vegetated and Carex columns and 4.2 mg/L for columns with Malaleuca. FAWB (2008) results are slightly better than the results observed in this study (8 mg/L for MS/NP, 13.2 mg/L for MS/Bu and 5.3 for MS/BM) but the difference may be due to the greater filter depth in the FAWB experiments. If we apply the exponential decay of TSS in filters for MS/NP to a depth of 700 mm (depth of the FAWB (2008) filters) for their influent concentration (126.9 mg/L), we would have obtained an effluent of 2.3 mg/L and FAWB (2008) reported an effluent of 1.3 mg/L (98% removal). Consequently, our results confirmed their observations.

TSS removals, for both synthetic and real stormwater experiments, were comparable to the ones found in the literature, with between 91% (Hsieh and Davis 2005a) and 98% (Read et al. 2008) removal. In comparison, the average removal for all columns in these experiments was 94%. As expected, the vegetation and the saturated zone did not have an influence on TSS removal and the finest media (COA) removed more TSS than the coarser ones. The clogging associated with this TSS removal is discussed later in Section 4.11.

4.2 NITRATE/NITRITE (NO_X)

4.2.1 Synthetic stormwater results

NO_x is one of the most important pollutants studied during this project because the conventional sand filters used in the City of Austin generally export nitrate. Results for nitrate/nitrite effluent concentrations are reported in Figure 14. It is apparent that the columns without plants (lines with X markers) exported NO_x in each experiment, while the column configurations with plants performed much better.

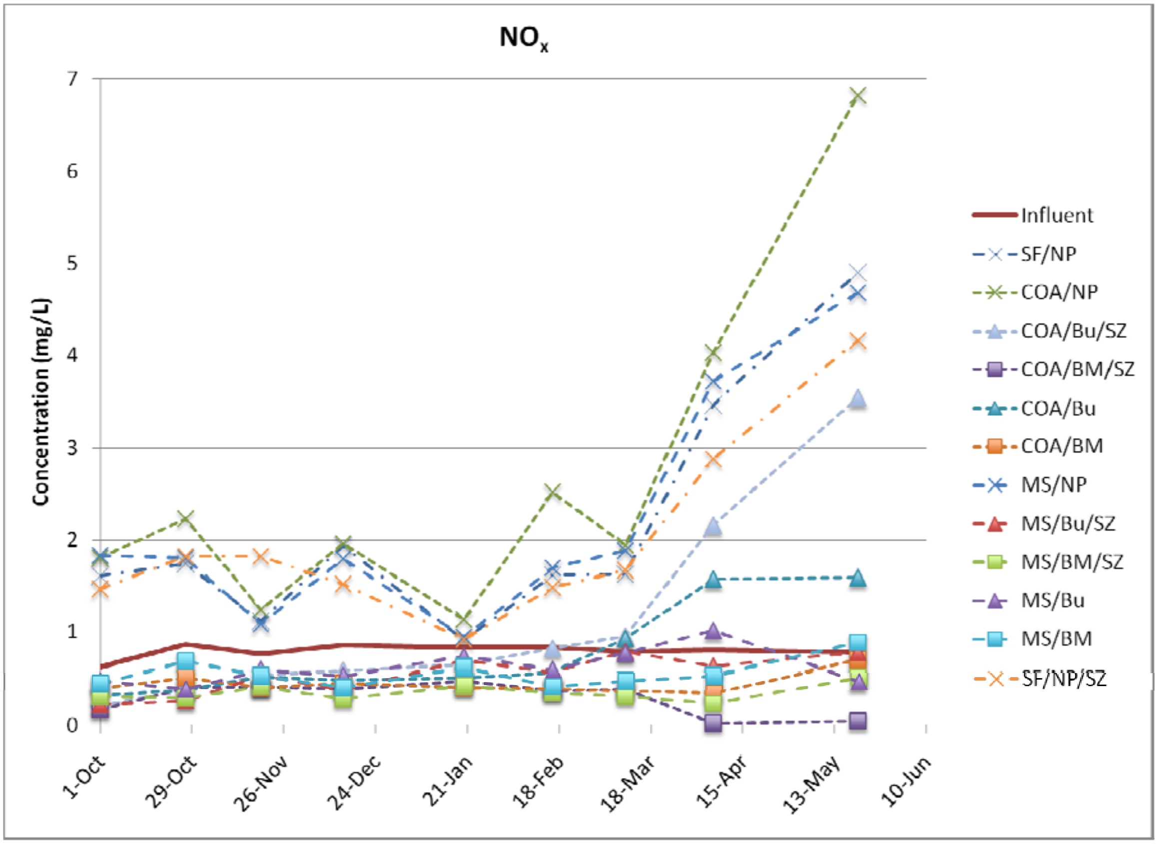

Figure 14 - NO_x influent and effluent concentrations for synthetic stormwater experiments

The mean effluent concentrations and removal efficiencies for NO_x are presented in Table 12. Data were lognormally distributed for eight of the twelve columns; consequently, paired t-tests were performed on log-transformed concentrations. The COA medium was less efficient at removing nitrate than either the MS or the SF medium in non-vegetated columns. The performance of the Masonry Sand and COA Biofiltration medium was not significantly different when vegetation was present. Columns with vegetation showed significantly better removal ($p < 0.002$) than those without vegetation.

Table 12 - Average NO_x influent and effluent concentrations and removals over time for each column

Column	**Synthetic Stormwater**		**Real Stormwater**	
	Concentration (mg/L)	**Removal (%)**	**Concentration (mg/L)**	**Removal (%)**
Influent	**0.79**		**0.104**	
SF/NP	2.10	-165	3.92	-3669
COA/NP	2.63	-232	4.91	-4621
COA/Bu/SZ	1.09	-38	2.68	-2477
COA/BM/SZ	0.30	62	0.02	81
COA/Bu	0.77	3	0.915	-780
COA/BM	0.45	44	0.02	81
MS/NP	2.16	-172	3.34	-3112
MS/Bu/SZ	0.54	32	0.143	-38
MS/BM/SZ	0.35	56	0.267	-157
MS/Bu	0.62	22	0.038	63
MS/BM	0.56	30	0.064	38
SF/NP/SZ	1.97	-149	3.38	-3150

One of the objectives of the study was to determine if NO_x removal would be improved by the presence of a submerged zone. Since the volume of the submerged zone was smaller than the volume of the stormwater dose, experiments were done with two different influent volumes (91 cm and 30 cm of feed water) to see if this might impact NO_x removal. When the effluent concentrations of all experiments are compared, the only columns where the submerged zone appeared to reduce NO_x concentrations were MS/BM/SZ ($p< 0.000$) and COA/BM/SZ ($p = 0.099$). An analysis of just the experimental runs with 30 cm of feed water, indicates that NO_x removal was not consistently better. Consequently, the submerged zone did not consistently reduce concentrations. This may be because the saturated zone did not go anaerobic or that its thickness was not great enough. FAWB (2008) found that a minimum thickness of 450 mm was required for denitrification, which was several times the length provided in this study. The NO_x reduction observed in this study may be due to plant uptake by the Big Muhly rather than denitrification. However, denitrification could occur with a thicker saturated zone and even better NO_x removal could be expected.

Figure 15 shows the nitrate results for only vegetated columns, the expanded scale of this graph allows one to see better the effects of plant type. Big Muhly performed significantly better than Buffalograss for three of the four paired columns, with only MS without a submerged zone demonstrating no significant difference. Buffalograss efficiency in the columns with the COA mix was decreasing through time and exporting NO_x in the last experiments. Bratieres (2008) also demonstrated the importance of the presence and type of vegetation and a decrease with time in efficiency for some plants while others (e.g., Malaleuca and Carex) maintained an elevated NO_x removal. It is not clear at this time what differences in plant characteristics are required for long term NO_x removal.

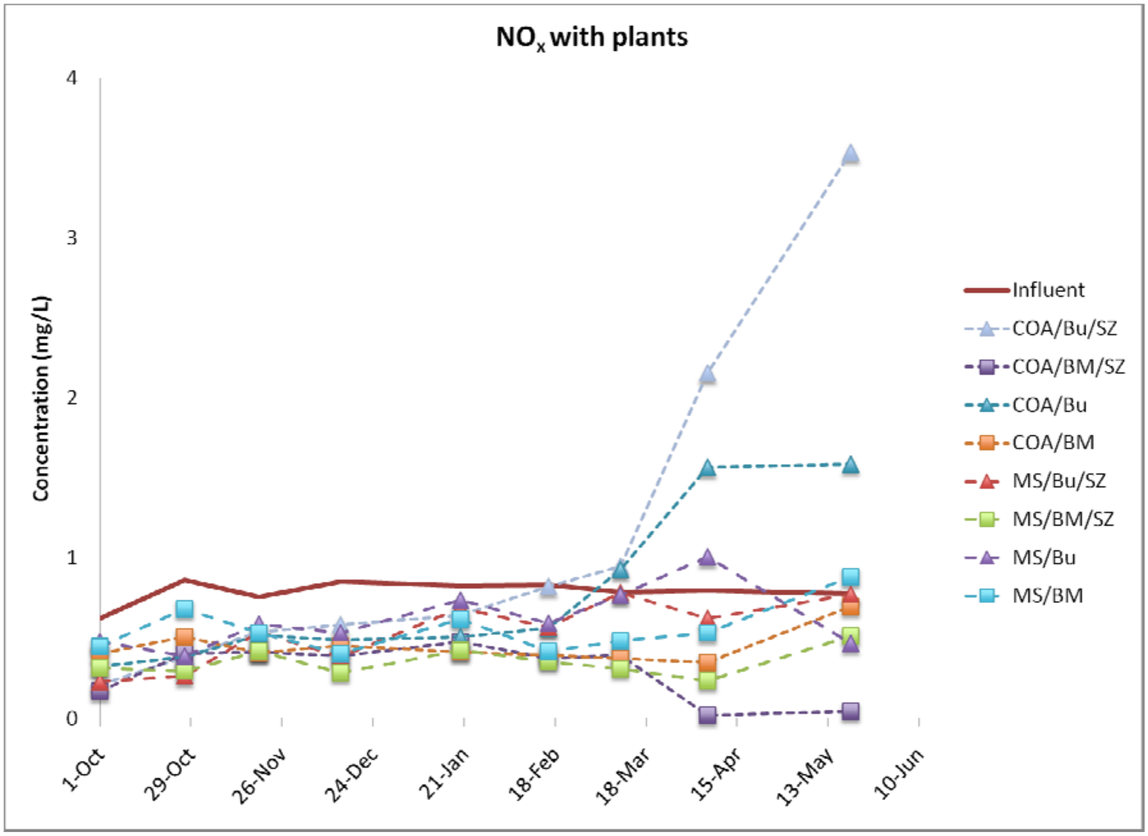

Figure 15 - NO_x influent and effluent concentrations for vegetated columns for synthetic stormwater experiments

4.2.2 Real stormwater results

NO_x concentrations for the experiment with actual stormwater are presented in Table 12 and plotted in Figure 16. The columns with Big Muhly performed better than those with

Buffalograss, which is consistent with the synthetic stormwater experiments, with only one column with Big Muhly exporting a small amount of NO_x, while three columns with Buffalograss export NO_x, two of them at relatively high concentrations. As observed in the synthetic stormwater experiments, vegetation improved NO_x removal, with the four columns exporting the most NO_x being the non-vegetated ones. In this experiment, the presence of a saturated zone also did not improve NO_x removal.

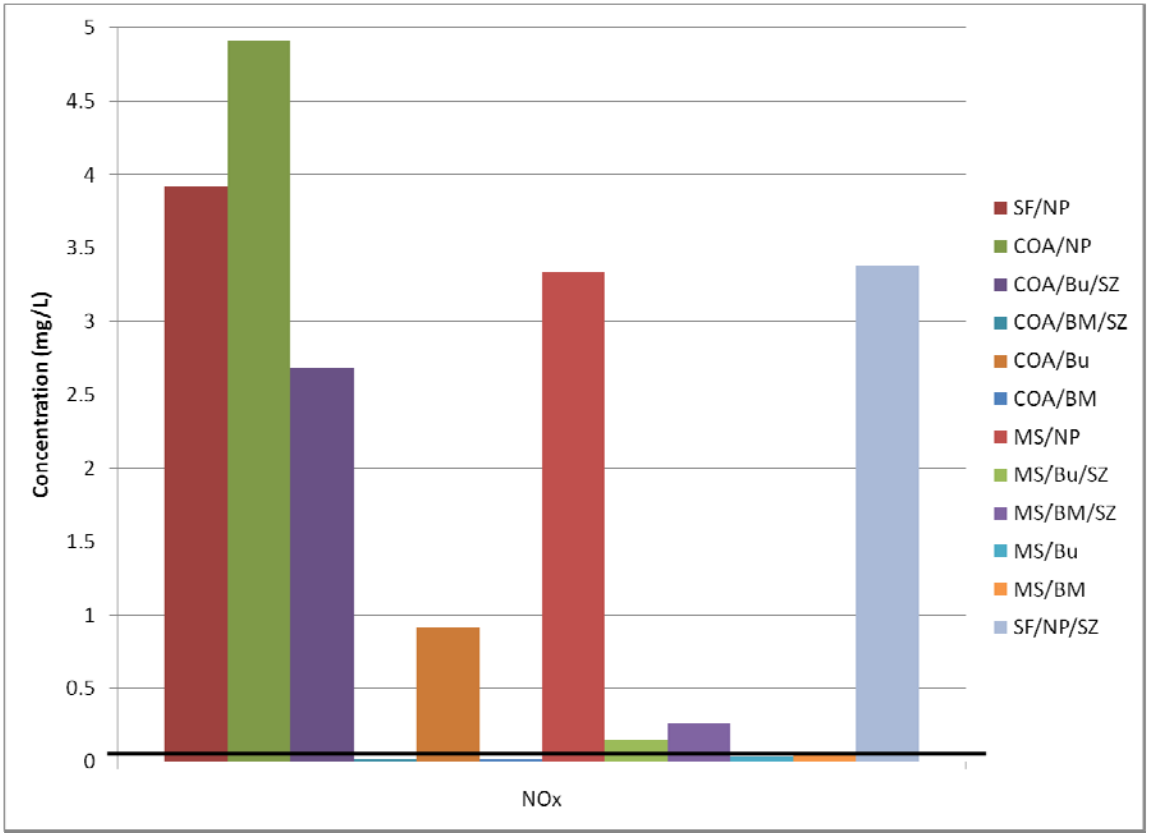

Figure 16 - NO_x influent and effluent concentrations for the real stormwater experiment

The influent NO_x concentration is very low in this real stormwater experiment compared to what is typically observed in urban runoff. At the time the experiment was run, the stormwater had been stored for 3 days and was possibly on the way to becoming anaerobic. The high TKN concentration observed (Section 4.5.2) supports this hypothesis.

4.2.3 Discussion

Field monitoring results for NO_x discharges from Austin Sand Filters indicate less export than observed in SF/NP column using synthetic stormwater (Barrett, 2010). Reported removals in the field varied between -21% and -160% while the SF/NP configuration had an average removal of -165%. The difference is not very large and may be the result of higher influent concentrations in the laboratory study (0.79 mg/L) compared with the field studies (between 0.24 and 0.56 mg/L). Consequently, it can be concluded that our results are transferable to the field.

FAWB (2008) had similar influent concentrations for NO_x so it is easy to compare their results with these. For the non-vegetated column, both studies found an export in NO_x but the MS/NP had a -175% removal while FAWB (2008) found a -560% removal. On the other hand, FAWB (2008) had significantly higher removal for vegetated columns than our study, with a 96% removal for Carex and 52% for Malaleuca. The choice of plants in the current study may not have been optimum for NO_x removal; however, it is shown subsequently that TN removal was better in this study. Even if the results are somewhat different, the overall conclusion that some plants help remove NO_x was confirmed in our study by both plant types.

The presence of vegetation and particularly Big Muhly showed a clear improvement in NO_x removal for both the synthetic and actual stormwater experiments. Read et al. (2008) also reported a variation in pollutant removal among plants species, where root mass explained 20-37% of the difference in effluent concentration. Big Muhly, as its name implies, is visibly bigger than Buffalograss and did perform better.

4.3 TOTAL KJELDAHL NITROGEN (TKN)

4.3.1 Synthetic stormwater results

TKN influent and effluent concentrations are presented in Figure 17 for all the experiments with synthetic stormwater. It can be seen that the effluent concentrations remained relatively constant over the duration of the experiment, even though the influent concentrations were substantially higher in the later runs. The variability of the influent may be due to the portion of organic nitrogen contained in the suspended solids, which was hard to control.

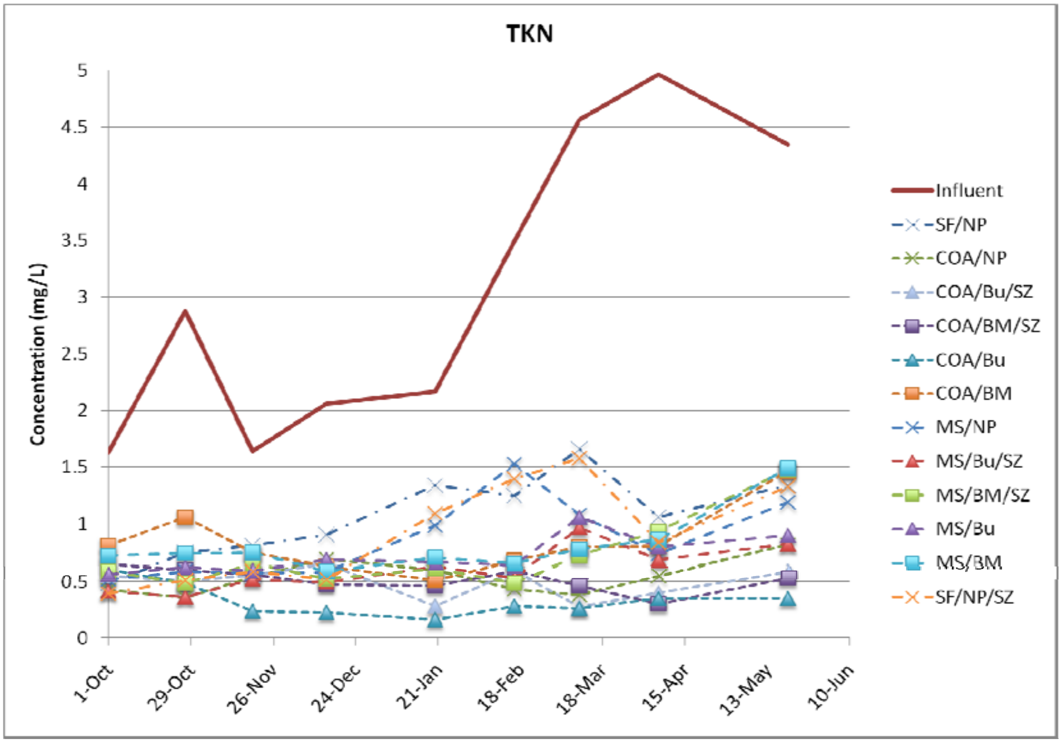

Figure 17 - TKN influent and effluent concentrations for synthetic stormwater experiments

The data presented in Table 13 demonstrates significant TKN removal for all the columns, with an average of 77%. Data for TKN were normally distributed for nine columns out of twelve; consequently, paired t-tests were run with untransformed data to identify differences in performance among the columns. For non-vegetated columns, COA medium had the highest removal followed by MS and then SF.

The presence of vegetation was shown to significantly improve TKN removal in only two of eight cases and to significantly worsen it in one case. Consequently, vegetation did not play an important role in TKN removal. It is therefore not surprising that type of vegetation did not appear to have a significant influence on TKN effluent concentrations. The TKN effluent concentrations were not significantly different in three out of four tests comparing COA and MS media. Surprisingly, TKN effluent concentration was significantly lower in four of five columns with a submerged zone (p=0.001 to 0.023). The only column for which there was an increase was the COA/Bu configuration (p=0.022). The combined results for the submerged zone for nitrate (where no denitrification was seen) and TKN (where removal was improved) suggest that the submerged zone was aerobic and able to nitrify ammonia to nitrate. However, because no export in nitrate was observed in presence of a saturated zone, the nitrate formed must have been consumed by the bacteria in the hardwood mulch.

Table 13 - Average TKN influent and effluent concentrations and removals over time for each column

Column	Synthetic Stormwater		Real Stormwater	
	Concentration (mg/L)	Removal (%)	Concentration (mg/L)	Removal (%)
Influent	**3.1**		**9.67**	
SF/NP	1.07	65	1.42	85
COA/NP	0.53	83	1.01	90
COA/Bu/SZ	0.49	84	0.589	94
COA/BM/SZ	0.51	83	0.69	93
COA/Bu	0.33	89	0.672	93
COA/BM	0.84	73	0.951	90
MS/NP	0.86	72	1.16	88
MS/Bu/SZ	0.60	80	0.921	90
MS/BM/SZ	0.72	77	0.796	92
MS/Bu	0.73	76	0.956	90
MS/BM	0.81	74	1.18	88
SF/NP/SZ	0.92	70	1.41	85

4.3.2 Real stormwater results

Figure 18 shows the results for TKN for the experiment with actual stormwater. Here, contrary to what was observed in the synthetic stormwater experiments, vegetated columns did appear to have better removal of TKN than non-vegetated ones. The COA medium showed a slightly better performance than MS, and MS a better performance than the SF medium. The average TKN removal for the real stormwater experiment was 90%. As stated previously, the TKN influent concentration in this experiment was higher than expected. There are two likely explanations for this high concentration. The sample was collected during the first flush of a storm during April, the height of the pollen season. Consequently, that is a possible cause of higher concentrations of organic matter. In addition, the extended time between the collection of the stormwater and the experiment could have provided an opportunity for the stormwater to start going anaerobic.

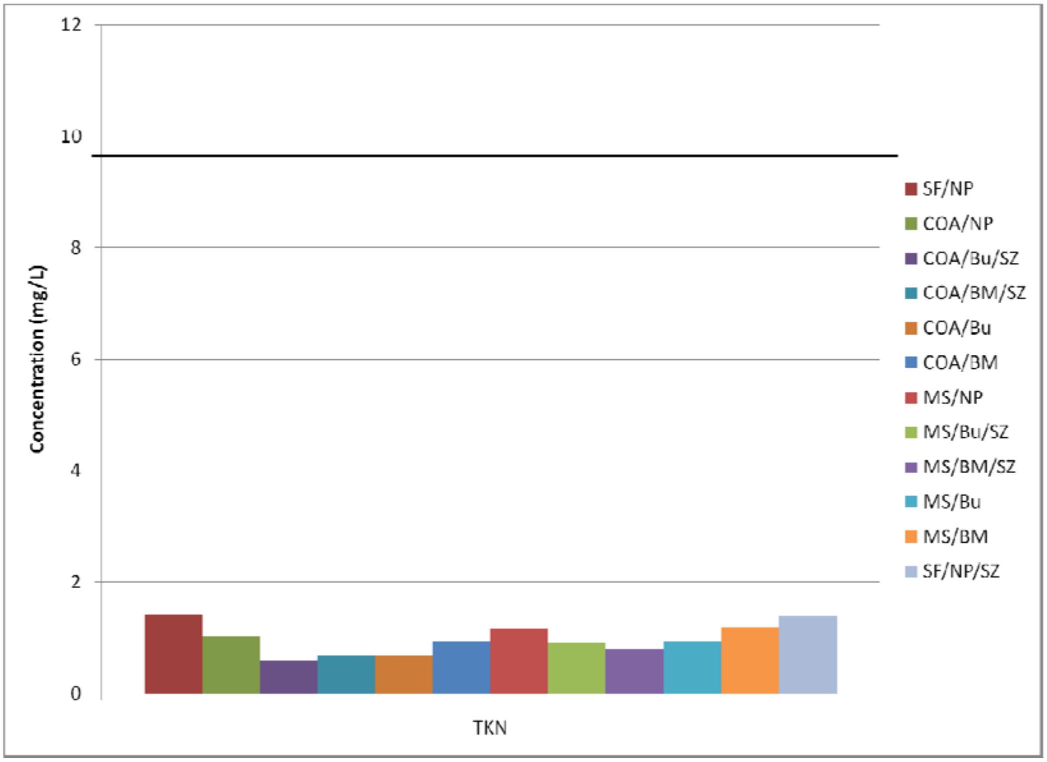

Figure 18 - TKN influent and effluent concentrations for the real stormwater experiment

4.3.3 Discussion

TKN results for the SF/NP column were slightly better than what was observed in the field (Barrett, 2010). The average influent concentration in the field varied between 0.59 to 1.35 mg/L and the average effluent concentration between 0.40 and 0.64 mg/L. So both influent and effluent concentrations observed in the field were lower than observed in this test with elevated first flush concentrations. The average removal was also lower at the field sites (between 27% and 55% in Austin Sand Filters) compared to the SF/NP control column (65%). Also, Hunt et al. (2008) found a 44% removal in a vegetated bioretention facility with an influent of 1.26 mg/L. Consequently, the TKN removals in the laboratory study may have been slightly higher than one would expect to see in the field because of the elevated influent TKN concentration.

The presence of a saturated zone improved TKN performances and MS and COA medium performed better than SF. It is difficult to determine the role that plants played in TKN removal because of the contradictory results between synthetic and actual stormwater experiments. Moreover, only a few studies report TKN results, so it is difficult to compare our conclusions to previous resarch. Davis et al. (2006), however, concluded that the surface mulch layer in his experiments played an important role in TKN capture and achieved a 74% removal with vegetated columns. Our columns show an identical performance with no mulch, so we would question the Davis et al. (2006) conclusion.

4.4 TOTAL NITROGEN (TN)

4.4.1 Synthetic stormwater results

The TN effluent concentrations are presented in Figure 19 for each of the experimental runs. These concentrations generally increased over the course of the study, and that is particularly evident for the columns without vegetation. The gradual increase may be related to oxidation of retained organic matter from previous runs. In general the effluent concentrations for the columns without vegetation are slightly below the influent concentration, indicating modest removal. Export of TN was observed in the final experiment for the columns without vegetation. The experiment was performed after the dosing of the columns with actual stormwater and oxidation of some of the retained organic matter from that run may be responsible for export observed in the last experiment with synthetic stormwater. The columns with vegetation apparently were able to reduce these concentrations substantially.

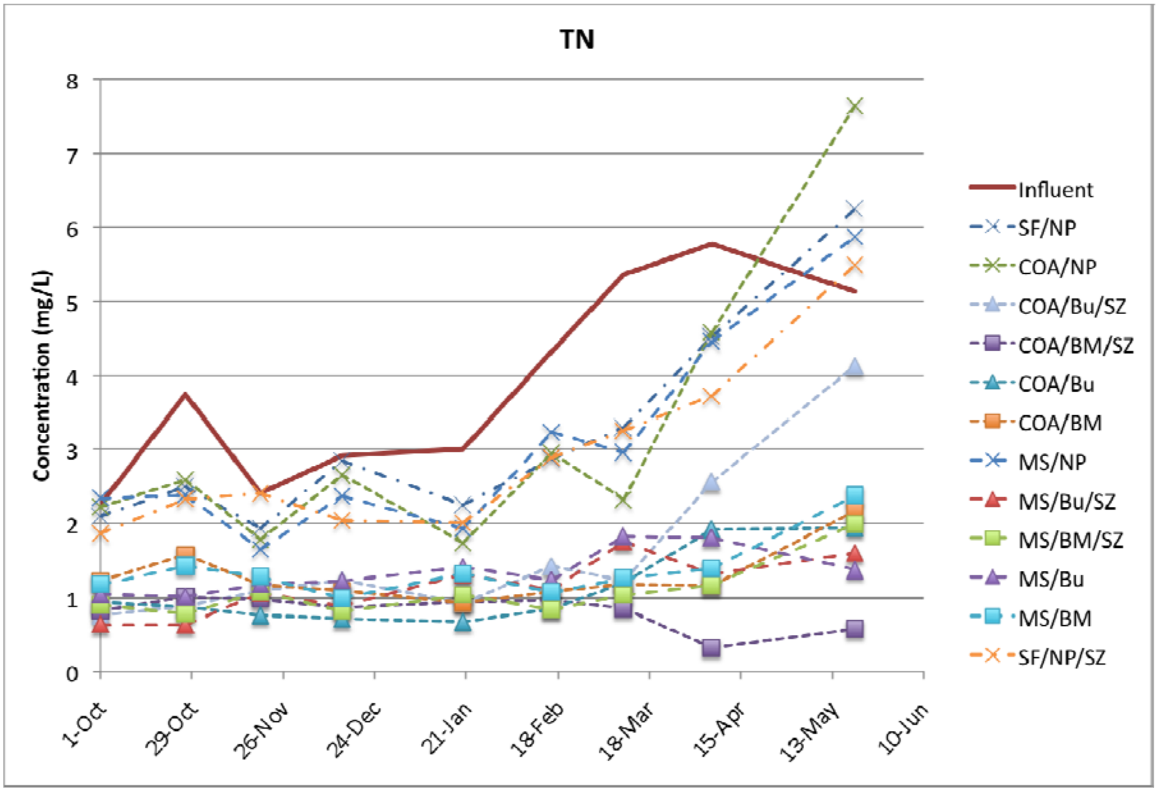

Figure 19 - TN influent and effluent concentrations for synthetic stormwater experiments

Table 14 presents the mean concentrations and removal efficiencies for each of the columns. The data for TN were lognormally distributed for seven columns out of twelve; consequently, statistical tests were performed with log-transformed data. The three media did not differ significantly in TN removal. The presence of plants improved performance in all eight cases (p between 0.000 and 0.001), as expected, which was mainly due to the substantial improvement in NO_x removal.

The type of media was not a significant factor in TN removal for three of four vegetated columns. However, the presence of a submerged zone significantly improved performance in three of five configurations. The two configurations where no improvement in TN removal was observed are COA/Bu (p=0.019), which is a function of the TKN performance, and SF/NP (p=0.144). Although BM had better NO_x removal than Bu, this was only the case for columns with a saturated zone.

Table 14 - Average TN influent and effluent concentrations and removals over time for each column

Column	Concentration (mg/L)	Removal
Influent	**3.9**	
SF/NP	3.17	18%
COA/NP	3.16	18%
COA/Bu/SZ	1.58	59%
COA/BM/SZ	0.81	79%
COA/Bu	1.09	72%
COA/BM	1.28	67%
MS/NP	3.02	22%
MS/Bu/SZ	1.14	70%
MS/BM/SZ	1.07	72%
MS/Bu	1.35	65%
MS/BM	1.37	65%
SF/NP/SZ	2.89	25%

4.4.2 Real stormwater results

The results for TN for the real stormwater experiment are plotted in Figure 20. In this figure, it is clear that the presence of vegetation in the columns significantly improved TN removal. The difference between media was not meaningful in this experiment. Both of these conclusions are consistent with the result of the synthetic stormwater experiments. TN removal in three of five configurations with a saturated zone was better; however, those three configurations were not the same that produced better results in the synthetic stormwater experiments. BM had lower effluent concentrations than Bu in three of four columns.

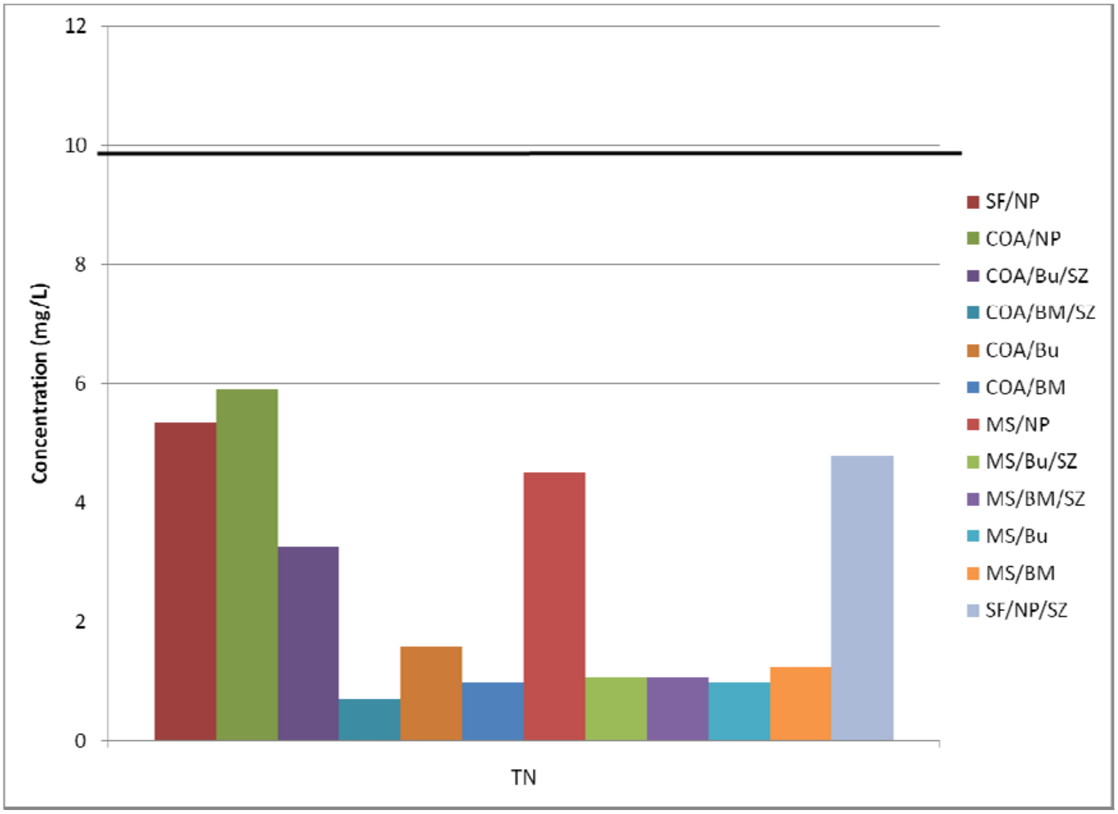

Figure 20 - TN influent and effluent concentrations for the real stormwater experiment

4.4.3 Discussion

The data indicate that columns with a saturated zone provided better TN removal, and BM performed better than Bu with a saturated zone; consequently, the preferred configuration would be BM and a saturated zone and any type of media (COA or MS). This confirms results from Read et al. (2008) and Bratieres (2008) on nitrogen species removal that showed the importance of vegetation in TN removal and the differences between different plant species. The TN removal in the columns without vegetation was better than that observed by FAWB (2008). While their non-vegetated columns exported TN, the lowest removal in our experiments was 18% for MS/NP. For vegetated columns, the results are similar with a 71% TN removal for Carex and a 46% TN removal for Malaleuca compared to a 67% TN removal for Buffalograss and a 71% TN removal for Big Muhly.

4.5 DISSOLVED PHOSPHORUS (DP)

4.5.1 Synthetic stormwater results

DP effluent concentrations are plotted in Figure 21. The columns lacking vegetation tended to have the highest effluent concentrations, which increased over time. Conversely, the columns with plants had effluent concentrations at the end of the study that were almost as low as those observed at the beginning. In general, DP effluent concentrations were lower for runs with only 30 cm of water than for those with 91 cm of water (the events with 91 cm of water indicated in figure).

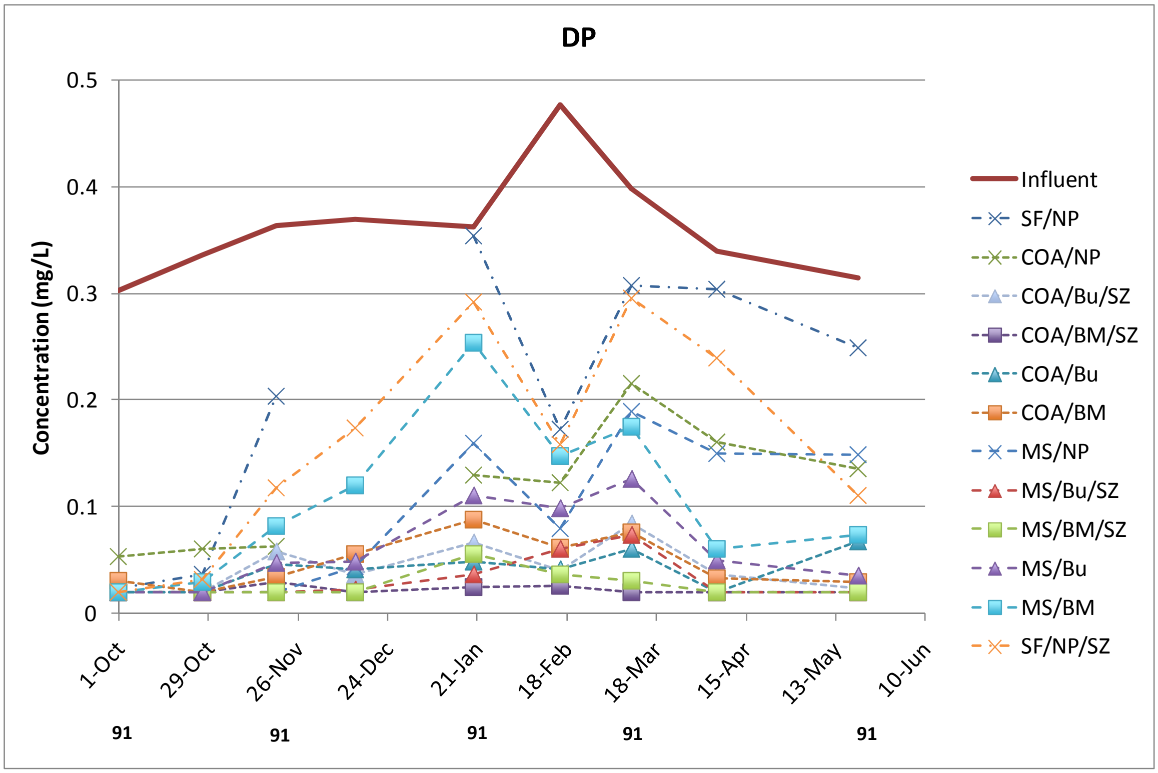

Figure 21 - DP influent and effluent concentrations for synthetic stormwater experiments

Table 15 presents the mean concentrations and removal efficiencies for each of the column configurations. The data for DP were normally distributed for nine columns out of twelve. The distribution of the other columns was complicated by the presence of a substantial number of values at the detection limit. Statistical tests were performed with non-transformed values for this dataset. For non-vegetated columns, the effluent concentrations for the SF medium were higher than the ones for the COA medium, which, in turn, were higher than the ones for MS. In the columns with plants, the MS and the COA medium were not significantly different. The presence of plants significantly improved the discharge concentrations in six of eight columns (p = 0.002 to 0.020). The two columns where the presence of vegetation did not significantly improve DP removal were MS/Buffalograss (p=0.118) and MS/Big Muhly (p=0.534). Consequently, the presence of plants provided more benefit for the columns with COA medium than for the ones with MS.

Table 15 - Average DP influent and effluent concentrations and removal

Column	Concentration (mg/L)	Removal
Influent	**0.36**	
SF/NP	0.21	43%
COA/NP	0.12	68%
COA/Bu/SZ	0.04	88%
COA/BM/SZ	<0.02	94%
COA/Bu	0.04	89%
COA/BM	0.05	87%
MS/NP	0.09	75%
MS/Bu/SZ	0.03	91%
MS/BM/SZ	0.03	93%
MS/Bu	0.06	83%
MS/BM	0.11	71%
SF/NP/SZ	0.16	56%

The presence of a submerged zone improved DP removal in four of five configurations (COA/BM p=0.010, MS/Bu p=0.006, MS/BM p=0.006, SF/NP p=0.026). For COA/Bu, the DP removal was not improved by the presence of the submerged zone (p=0.079). The impact of the submerged zone on DP removal was unexpected. The effect of vegetation on DP removal was demonstrated previously by Read et al. (2008); however, DP removal resulting from a saturated zone has not been reported previously. DP can precipitate (slow reaction) as calcium hydroxyapatite [$Ca_5(PO_4)_3(OH)$] in limestone aquifers (Strang and Wareham 2006). Consequently, the additional residence time provided by the saturated zone could allow the precipitation to occur. The gravel was tested with HCl, which showed that three out of four individual samples contained limestone.

Consequently, this hypothesis seems to be the best explanation of the effect of the saturated zone on DP removal.

Real stormwater results, presented in Figure 22, showed an export of DP for the non-vegetated columns. This was not seen in the synthetic stormwater experiments but has been reported in the literature (Hunt et al. 2006). Davis et al. (2006) showed that the phosphorus sorption capacity decreases slightly with pH under acidic conditions, so the actual stormwater may have had a significantly lower pH that could have affected DP removal.

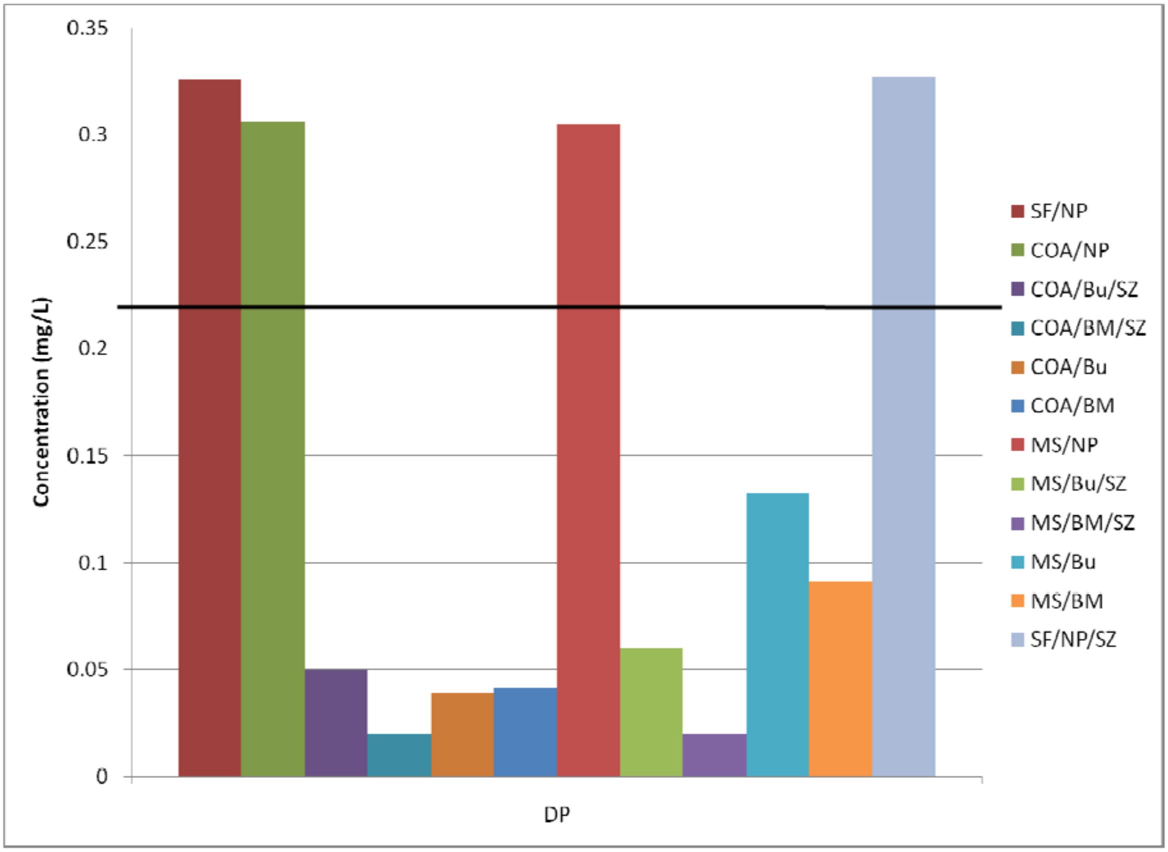

Figure 22 - DP influent and effluent concentrations for the real stormwater experiment

As in the synthetic stormwater experiments, vegetation definitely improved removal of DP. For three columns out of five, the saturated zone improved DP removal. We observed this improvement for the same three columns in the synthetic stormwater experiments. Overall, the COA medium provided better DP removal that MS.

4.5.3 Discussion

For both synthetic and real stormwater experiments, the presence of vegetation and a saturated zone was shown to improve DP removal. The importance of the presence of vegetation was shown by Read et al. (2008), who also showed a significant variability in DP removal among plant species. This variability was not observed for the two plants used in our experiments. The importance of a submerged zone has not been reported in the literature, probably because none of the previous studies used limestone gravel in their underdrain.

The SF/NP results and data from Austin Sand Filters are consistent, despite with higher concentrations (influent and effluent) for the synthetic stormwater experiments than observed in field monitoring. Average removal in this study was about 43%, compared with a range of 39% to 52% observed in actual filters (Barrett, 2010). Consequently, the column study results for the other configurations are likely similar to what would be observed in actual facilities.

4.6 TOTAL PHOSPHORUS (TP)

4.6.1 Synthetic stormwater results

Figure 23 displays the results for the synthetic stormwater experiments. In the first experiment, the effluent concentrations for all the column configurations were at or near the detection limit. As the study proceeded, the differences between the columns became more evident, with the non-vegetated columns tending to have the highest effluent concentrations. It appears that less removal occurred with a greater water depth (91 cm), as was the case for DP. The runs with the greater depth are indicated on Figure 23.

Table 16 presents the mean effluent concentrations and removal efficiencies for all the columns. The data for all the columns were normally distributed, so statistical tests were performed on the observed data. The effluent concentrations from the COA and MS columns lacking vegetation were not significantly different; however, both were statistically better than SF.

Vegetation significantly improved TP removal in six of eight columns. The two columns where it was not improved were MS/Bu (p=0.486) and MS/BM (p=0.269). No significant difference between the two types of plants was observed. Comparing both media with plants, COA performed significantly better than MS for columns without a saturated zone (Bu p=0.009 and BM p=0.011), but similarly for columns with a saturated zone. The presence of the saturated zone significantly improved TP removal in four of five columns (the same columns as for DP), with the only exception being the COA/Bu configuration (p=0.063).

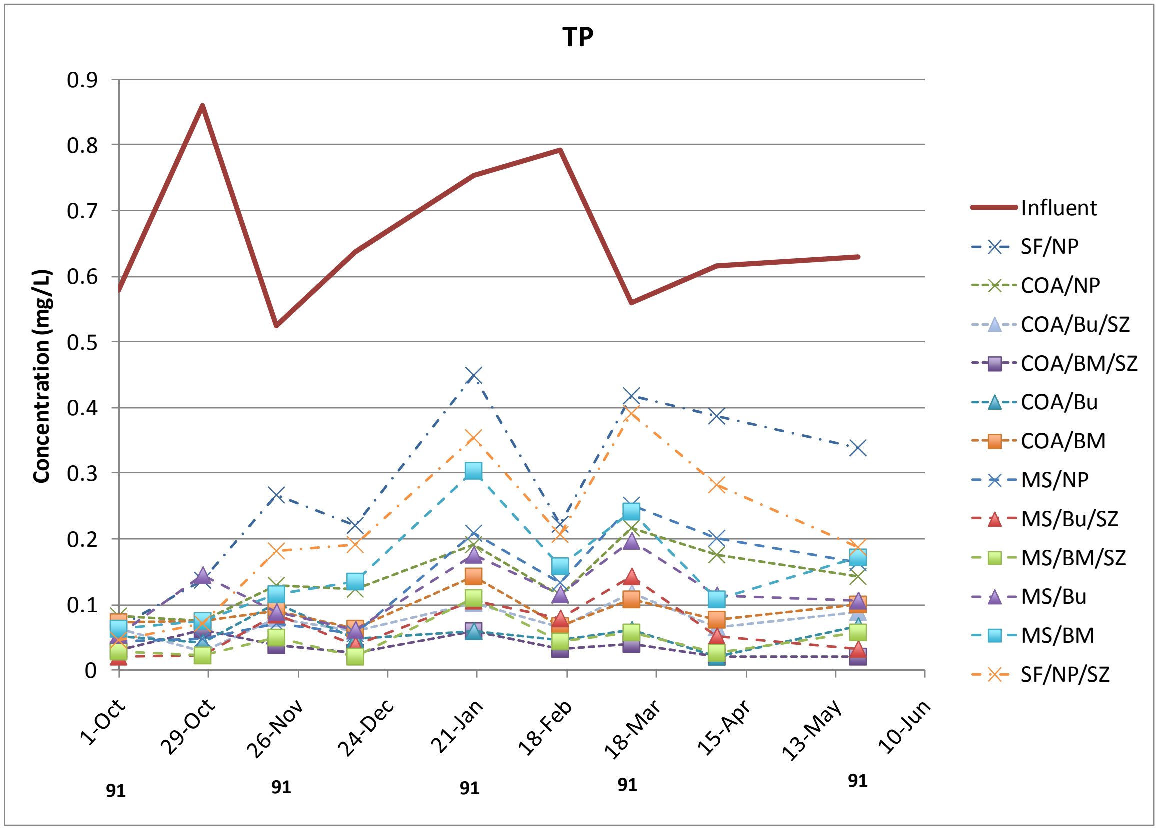

Figure 23 - TP influent and effluent concentrations for synthetic stormwater experiments

Table 16 - Average TP influent and effluent concentrations and removals over time for each column

Column	Concentration (mg/L)	Removal
Influent	**0.66**	
SF/NP	0.28	58%
COA/NP	0.14	79%
COA/Bu/SZ	0.07	89%
COA/BM/SZ	0.04	94%
COA/Bu	0.06	92%
COA/BM	0.09	87%
MS/NP	0.13	80%
MS/Bu/SZ	0.06	90%
MS/BM/SZ	0.05	93%
MS/Bu	0.12	82%
MS/BM	0.15	77%
SF/NP/SZ	0.21	68%

4.6.2 Real stormwater results

Effluent TP concentrations for the experiment with actual stormwater are presented in Figure 24. The results from this run were consistent with those observed in the experiments with synthetic stormwater. Vegetation was obviously an important factor in TP removal in the real stormwater experiment; however, vegetation type did not appear to be critical. The COA medium performed better for three out of five columns and the presence of a saturated zone improved TP removal compared to the columns without one.

4.6.3 Discussion

The observed TP performance for the SF/NP control columns was similar to that observed at field sites, with higher concentrations in both the influent and the effluent in the column study but a similar removal. Two field facilities were shown to export phosphorus, but the other ones had removal between 47% and 69% (Barrett, 2010), while the control column had a removal of 58%. Therefore, phosphorus (both dissolved and total) results in our column study are a good indicator of the results that would be expected in the field.

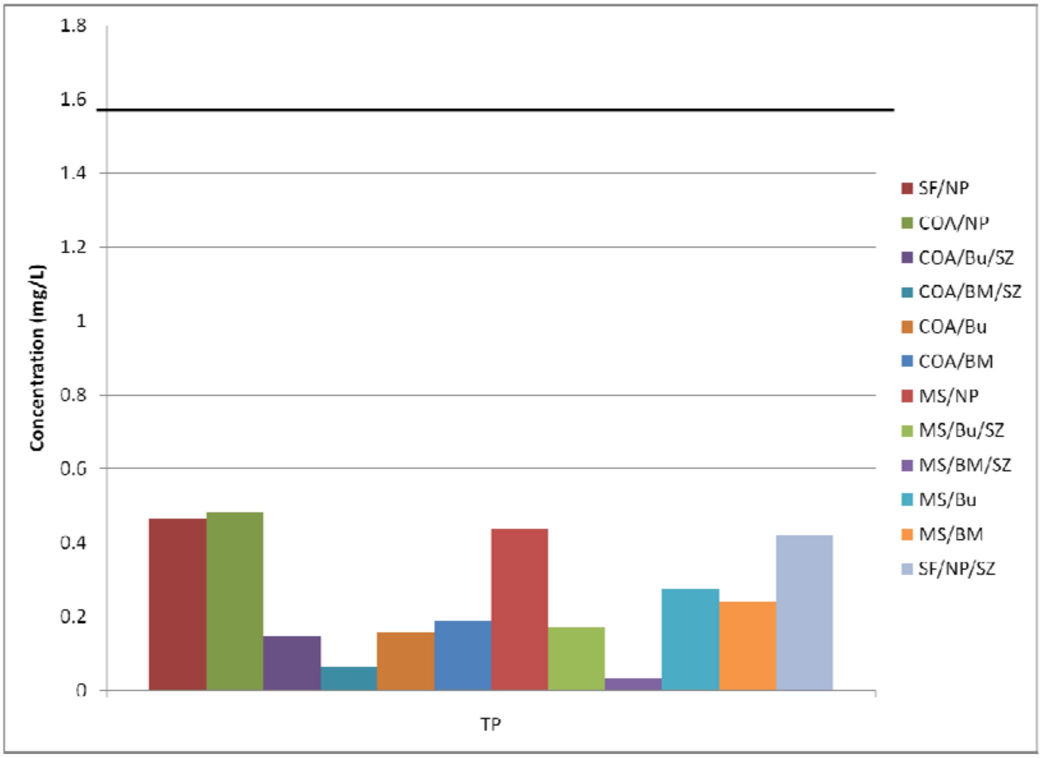

Figure 24 - TP influent and effluent concentrations for the real stormwater experiment

FAWB (2008) data for TP were very close to the data for MS columns. MS/NP had a TP removal of 80% while FAWB found an 81% removal. For vegetated columns, MS/Bu and MS /BM showed 82% and 77% of TP removal while Carex and Malaleuca showed 95% and 84% of TP removal. Consequently, we can conclude that these experiments confirmed the FAWB findings.

The presence of vegetation and a saturated zone in the column improved TP removal (similarly to DP), but the type of vegetation did not appear to matter. Read et al. (2008) showed differences in TP performance between plant species. The two plants chosen here may not have been different enough to produce a difference in TP removal. Hatt et al. (2008) did a non-vegetated study and recommended a soil-based media with low organic matter (OM) for phosphorus removal. Similarly, Hsieh et al. (2005b) showed a good correlation between TP removal and OM content with the lowest OM content leading to the lowest TP removal. However, our results showed that for non-vegetated columns, no soil or organic matter was needed to achieve good TP removal. MS had very good removal and performed as well as the COA mix and had no soil and no organic matter.

4.7 METALS

The following sections describe the performance of the various columns for metals removal. Like many previous laboratory studies, the effluent concentrations were often very low with many of the laboratory results coming back as non-detectable. Because of the large number of these values, a statistical analysis of the results was not conducted.

4.7.1 Synthetic stormwater results

4.7.1.1 Copper (Cu)

Dissolved and Total Copper influent and effluent concentrations are presented in Figure 25 and Figure 26, respectively. For all metals a logarithmic scale was used on the concentration axis and concentrations are given in micrograms per liter. These figures show that the concentrations remained relatively constant and near the detection limit through the first six experiments. At that point, concentrations began to gradually increase for most of the columns.

This increase can be explained by the filling of the Cu adsorption sites in the medium. In addition, the last experiment was done after the experiment with real stormwater, which had a very elevated organic content (COD concentration over 300 mg/L). It is possible that the large amount of organic matter in the real stormwater stayed in the columns and affected results of the next experiment. The ionic form of Cu used in the column experiments could have bound with dissolved organic matter (Metreveli 2010) and then would not be absorbed by the media, but discharged from the columns along with the organic matter.

Table 17 presents the effluent concentrations and removal for total and dissolved Cu. The COA medium appeared to perform slightly better than MS and the SF medium overall but the difference between media was not large. No clear influence of vegetation or saturated zone appeared. Sun and Davis (2007) found that metals that accumulated in the vegetation only accounted for 0.5% to 3.3% of metals removal, which is why the influence of vegetation can be difficult to observe.

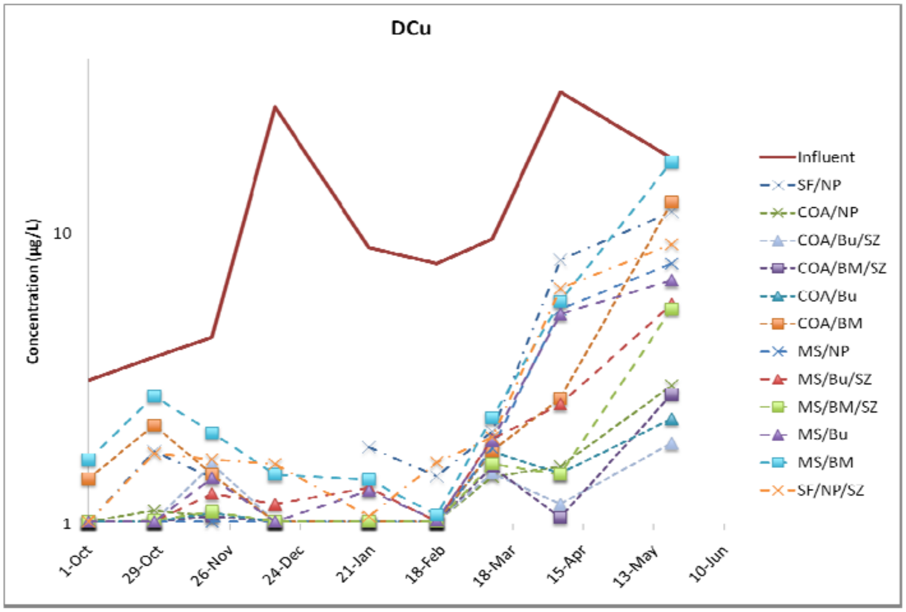

Figure 25 - DCu influent and effluent concentrations for synthetic stormwater experiments

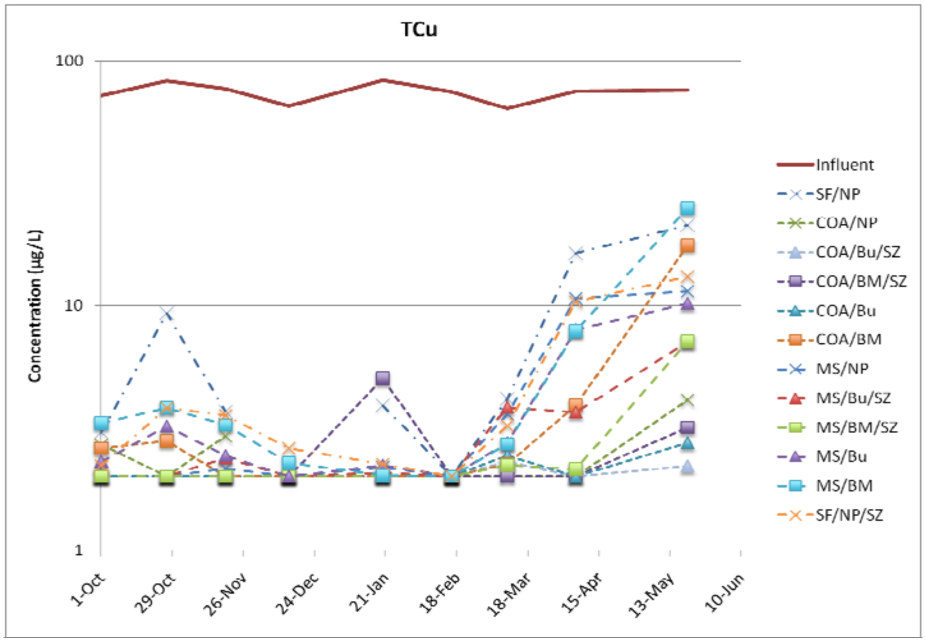

Figure 26 - TCu influent and effluent concentrations for synthetic stormwater experiments

Table 17 - Average DCu and TCu influent and effluent concentrations and removals over time for each column

Column	DCu		TCu	
	Concentration (μg/L)	**Removal**	**Concentration (μg/L)**	**Removal**
Influent	**12.7**		**74.7**	
SF/NP	3.70	71%	7.98	89%
COA/NP	1.41	89%	2.47	97%
COA/Bu/SZ	1.25	90%	2.06	97%
COA/BM/SZ	1.29	90%	2.47	97%
COA/Bu	1.31	90%	2.13	97%
COA/BM	2.83	78%	4.14	94%
MS/NP	2.37	81%	4.24	94%
MS/Bu/SZ	1.90	85%	3.01	96%
MS/BM/SZ	1.64	87%	2.62	96%
MS/Bu	2.33	82%	3.90	95%
MS/BM	4.04	68%	5.82	92%
SF/NP/SZ	2.93	77%	4.81	94%

The TCu removal observed in the SF/NP control column was substantially better than previously observed in the field. The field sites had average influent concentrations between 6 and 15.3 μg/L and an average effluent concentration between 5 and 6.7 μg/L, resulting in average TCu removal between 14% and 59% (Barrett, 2010). On the other hand, the SF/NP column in our project had an average removal of 89%. The influent concentration was 5 to 10 times higher in these experiments than in actual Austin facilities, but the effluent concentrations were very close. Consequently, it is likely that Cu removal will certainly be lower in an actual facility than they are in these experiments.

4.7.1.2 Zinc (Zn)

Dissolved and Total Zinc effluent concentrations are presented in Figure 27 and Figure 28, respectively. As is apparent in Figure 27, the DZn concentrations in the effluent were effectively below the detection limit for all columns for all experiments. A substantial amount of Zn was present in the sediments used to create the solids slurry; however, removal rates of the particulate portion were also extremely high.

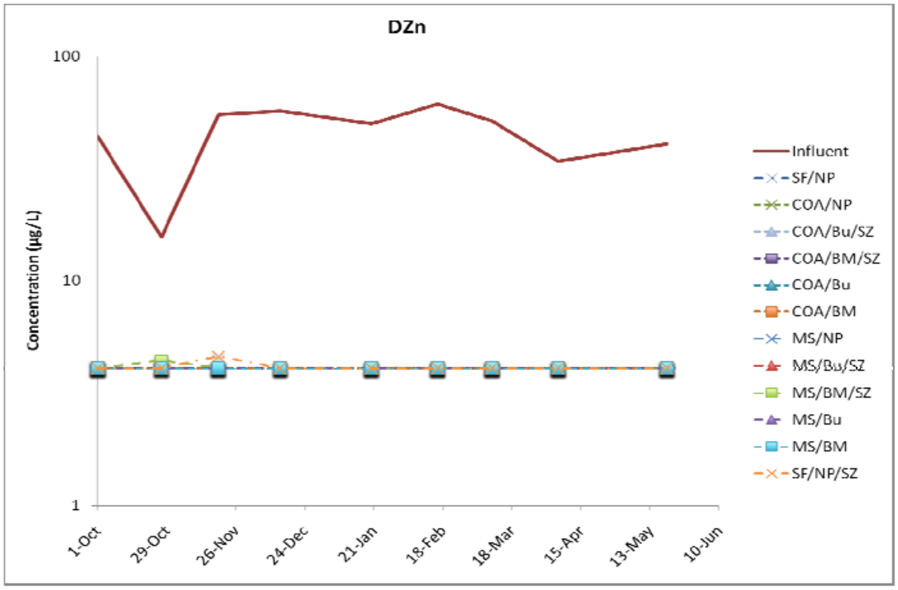

Figure 27 - DZn influent and effluent concentrations for synthetic stormwater experiments

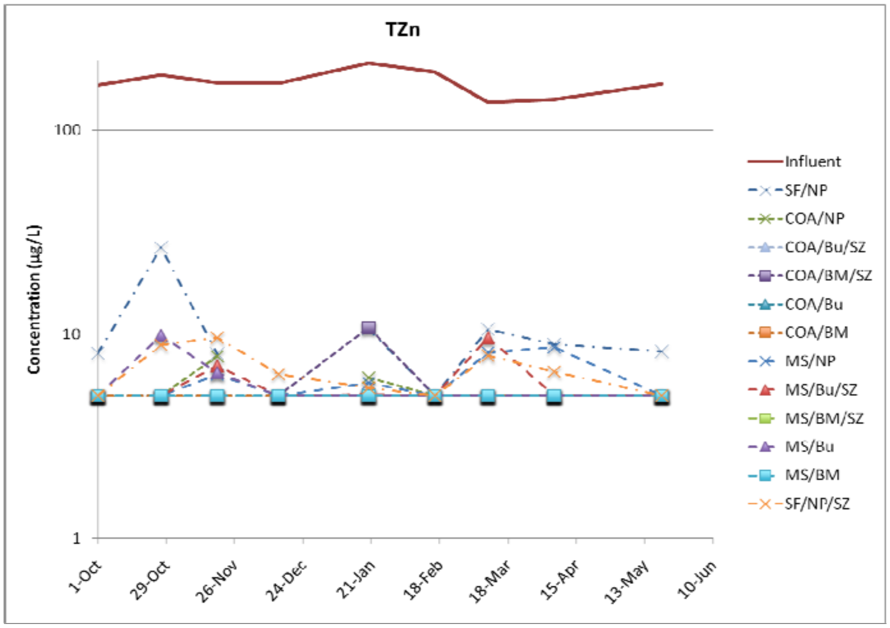

Figure 28 - TZn influent and effluent concentrations for synthetic stormwater experiments

Zn did not show the same increase in discharge concentrations for the last experiment as the other two metals. This difference could be explained by the fact that Zn binds less easily with organic matter. Metreveli (2010) showed that the binding capacity of the NOM (Natural Organic Matter) for metals improves in the following order Zn<Pb<Cu.

Table 18 presents the average effluent concentrations and removal for each column configuration. Most of the concentrations were below detection limit (4.08 µg/L for DZn and 5.0 µg/L for TZn), so a comparison between columns is not feasible. No medium, vegetation or design appeared to perform better than any other. The main conclusion that can be drawn is that all the columns demonstrated very good removal of zinc, dissolved and total, and that this removal did not change through time.

Table 18 - Average DZn and TZn influent and effluent concentrations and removals over time for each column

Column	**DZn**		**TZn**	
	Concentration (µg/L)	**Removal**	**Concentration (µg/L)**	**Removal**
Influent	**45.4**		**172.2**	
SF/NP	<4.08	91%	10.8	94%
COA/NP	<4.08	91%	5.5	97%
COA/Bu/SZ	<4.08	91%	<5.0	97%
COA/BM/SZ	<4.08	91%	5.6	97%
COA/Bu	<4.08	91%	<5.0	97%
COA/BM	<4.08	91%	<5.0	97%
MS/NP	<4.08	91%	6.0	97%
MS/Bu/SZ	<4.08	91%	5.8	97%
MS/BM/SZ	4.12	91%	<5.0	97%
MS/Bu	<4.08	91%	5.7	97%
MS/BM	<4.08	91%	<5.0	97%
SF/NP/SZ	4.13	91%	6.7	96%

TZn removals for actual Austin Sand Filters were lower than observed for the SF/NP control column, as they were for copper. Removal efficiencies in the field were between 35% and 87%, while it was 94% in the column experiment. The average influent concentrations in the real facilities were lower (between 45 and 127 µg/L) while the effluent concentrations were higher (between 15 and 38 µg/L). Consequently, one would expect the removal of Zn in the field to be slightly lower than what is observed in the laboratory study.

4.7.1.3 Lead (Pb)

Dissolved and total lead influent and effluent concentrations are displayed in Figure 29 and Figure 30. Except for the last experiment, effluent concentrations of DPb and TPb were always close to detection limit so it is difficult to draw general conclusions about the influence of vegetation, medium and a saturated zone on Pb removal.

Even though the synthetic stormwater for all the experiments was created using the same recipe, the dissolved component in the last experiment was substantially larger than any of the preceding, amounting to about half of the total lead, rather than the small fraction observed previously. In addition, the effluent concentrations, which had always been near the detection limit was substantially higher. The most likely explanation is that the pH for this run was substantially lower resulting in a greater dissolved fraction and less removal in the columns.

Table 19 lists the average concentrations and removals for Pb. The detection limit for DPb and TPb was 1.0 µg/L. The effluent concentration for TPb for all the columns was always in the low µg/L. TPb removal was closer to what has been observed in the field than the other two metals but was still better in the column study. Average influent concentrations in the field were between 7.5 and 27 µg/L (Barrett, 2010), which is substantially lower than in our synthetic stormwater. Average effluent concentrations were also lower in the field (between 1.9 and 4.8 µg/L) than in the columns. Consequently, the average TPb removal for actual Austin Sand Filters ranged between 61% and 86%, which is just slightly lower than the 88% obtained in the SF/NP control column.

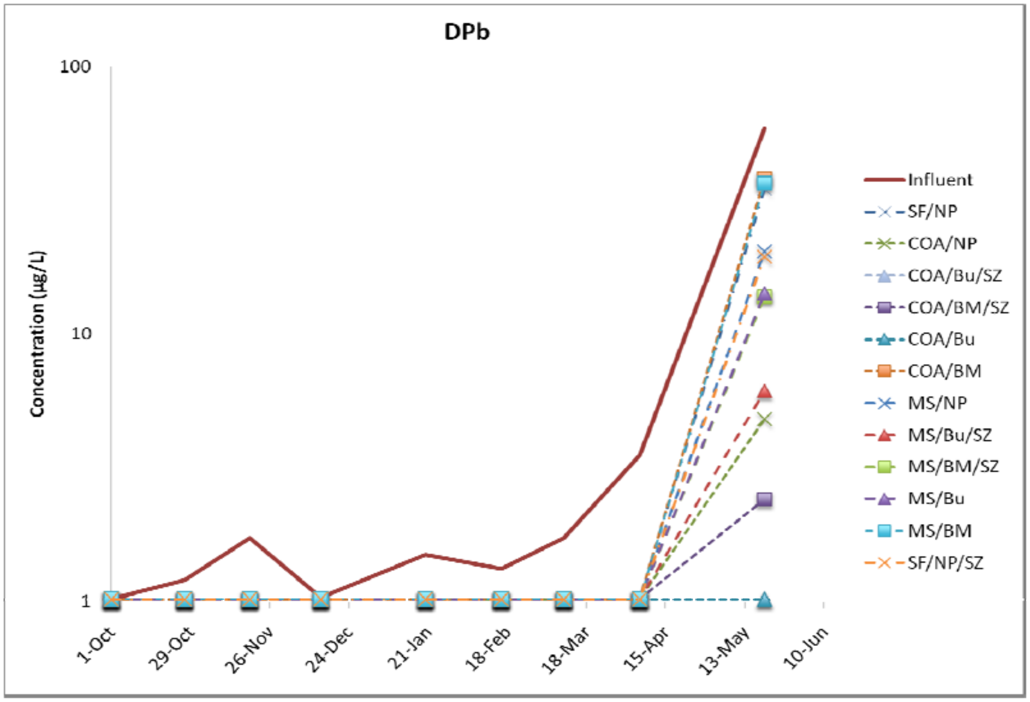

Figure 29 - DPb influent and effluent concentrations for synthetic stormwater

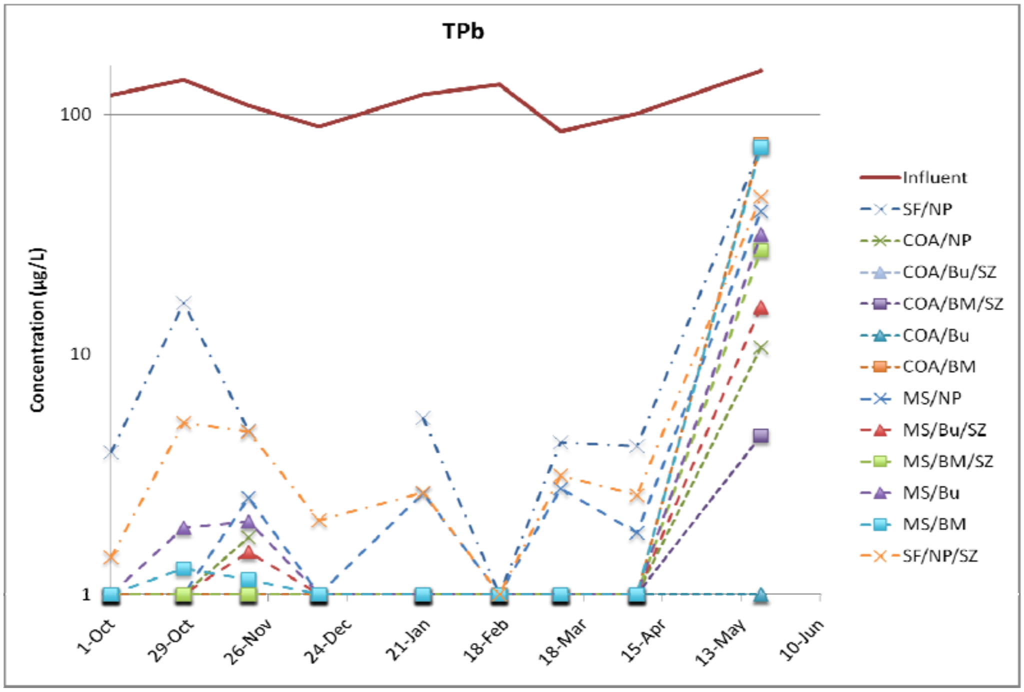

Figure 30 - TPb influent and effluent concentrations for synthetic stormwater

Table 19 - Average DPb and TPb influent and effluent concentrations and removals over time for each column

Column	DPb		TPb	
	Concentration (µg/L)	Removal	Concentration (µg/L)	Removal
Influent	**7.8**		**117.1**	
SF/NP	5.3	34%	14.2	88%
COA/NP	1.5	81%	2.3	98%
COA/Bu/SZ	<1.0	87%	<1.0	99%
COA/BM/SZ	1.2	85%	1.4	99%
COA/Bu	<1.0	87%	<1.0	99%
COA/BM	5.1	35%	9.3	92%
MS/NP	3.2	60%	5.9	95%
MS/Bu/SZ	1.6	80%	2.7	98%
MS/BM/SZ	2.4	69%	3.9	97%
MS/Bu	2.5	69%	4.6	96%
MS/BM	5.0	37%	9.1	92%
SF/NP/SZ	3.1	62%	7.7	94%

4.7.2 Real stormwater results

Metals results for the real stormwater experiment are shown in Figure 31 through Figure 34. No figures for DZn and DPb are presented because the effluent concentrations were all below the detection limit.

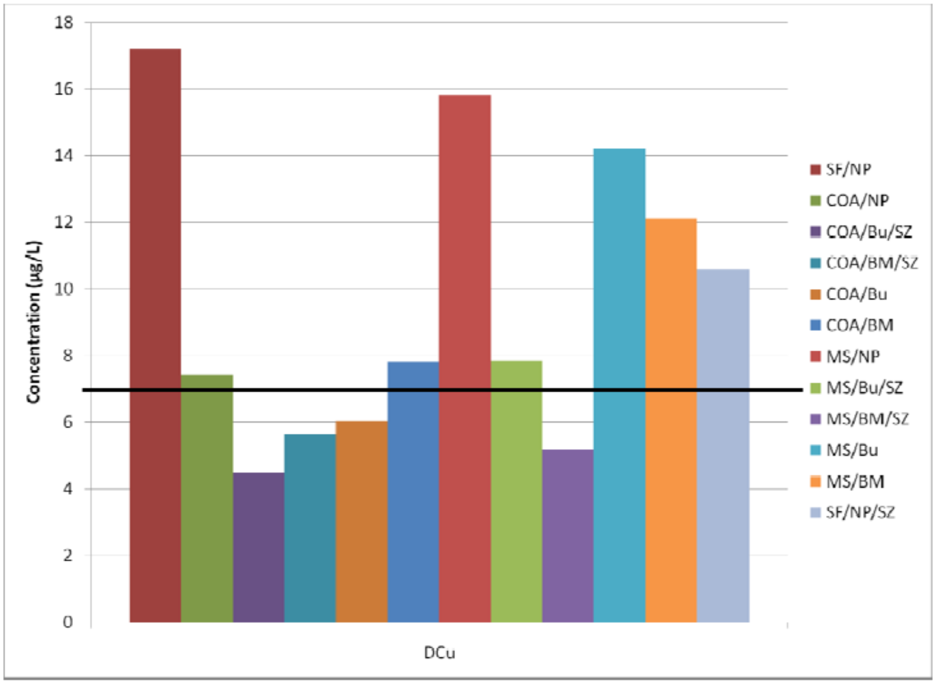

Figure 31 - DCu influent and effluent concentrations for the real stormwater experiment

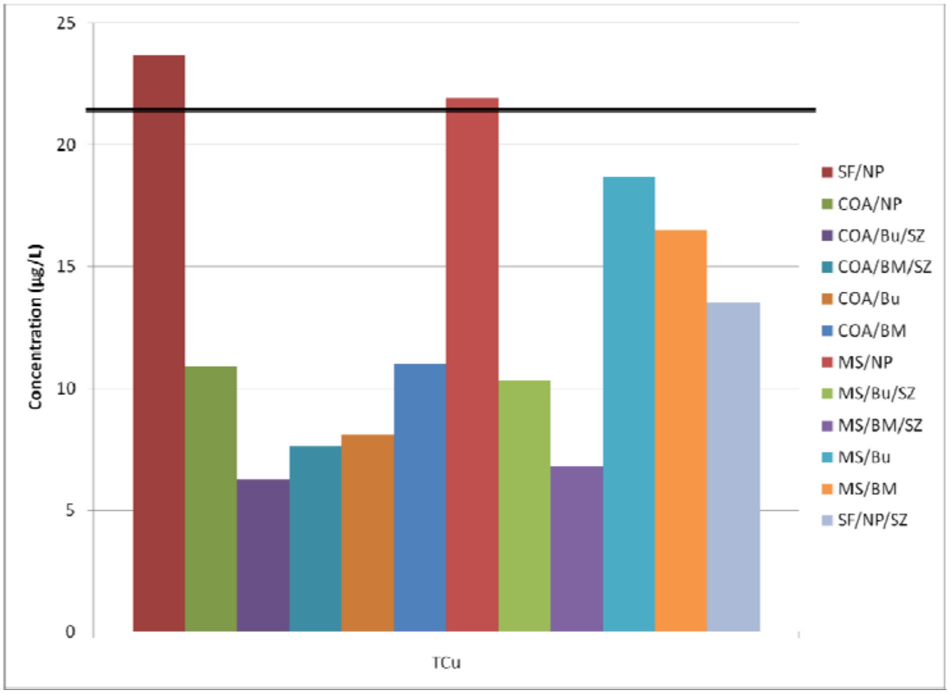

Figure 32 - TCu influent and effluent concentrations for the real stormwater experiment

The TCu effluent concentrations were higher than the influent concentration for two columns in the experiment with real stormwater. This result was not expected. It is possible that lower pH in the actual stormwater compared to the usual synthetic stormwater pH could have caused this Cu export. The main interest is the performance of the vegetated columns and they showed a significant, but smaller, TCu removal than in the synthetic stormwater experiments.

The influent and effluent concentrations for TZn and TPb for the experiment with actual stormwater are presented in Figure 33 and Figure 34. Removals of these constituents were still very good for all the columns and not substantially different than the experiments with synthetic stormwater.

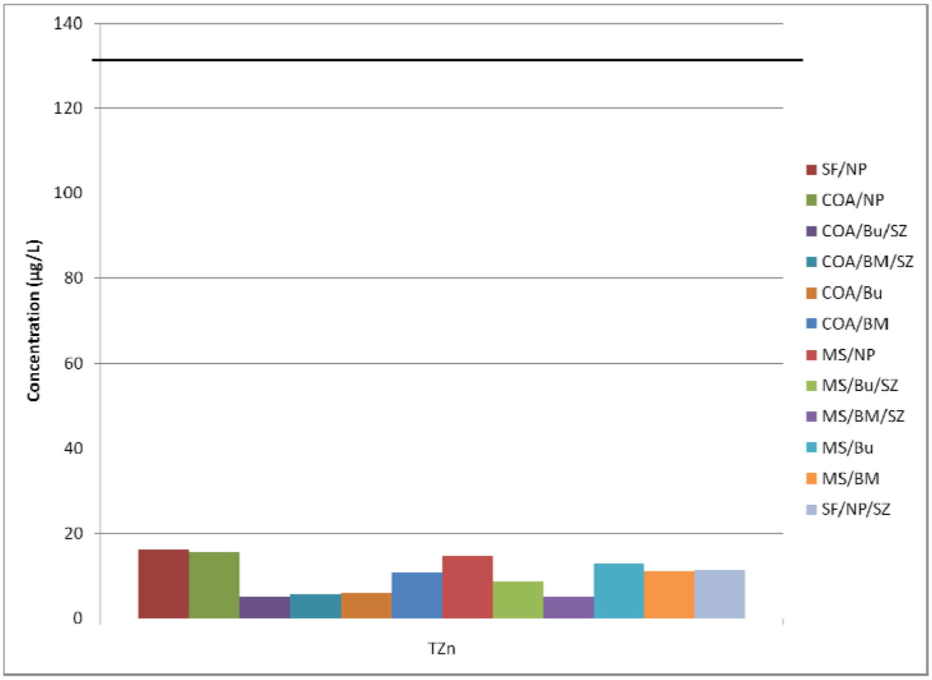

Figure 33 - TZn influent and effluent concentrations for the real stormwater experiment

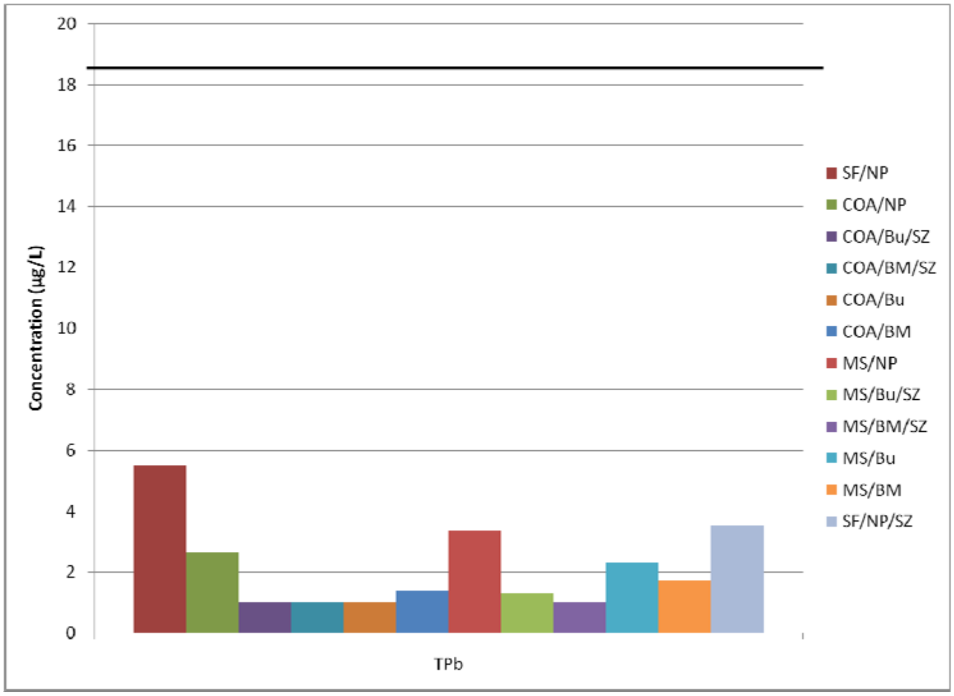

Figure 34 - TPb influent and effluent concentrations for the real stormwater experiment

4.7.3 Discussion

All metals results were comparable to what has been reported in the literature. Every laboratory study has shown metals removals around 95% (e.g., Hatt (2008) had 95% TCu removal, 97% TZn removal and 98% TPb removal). However, these removals exceed what would be expected in a real facility, based on the experiment with actual stormwater and a comparison with Austin sand filters field monitoring. Cu appeared in our study to be the most variable and the least efficiently removed of the three metals. Bratieres (2008) already observed that the removal of Cu was slightly lower than for Zn and Pb and had a higher coefficient of variation. We can see that for both synthetic and real stormwater experiments and for the three metals studied, the COA medium performed better than MS, which performed better than the SF medium, likely the result of their particle size distribution.

4.8 CHEMICAL OXYGEN DEMAND (COD)

4.8.1 Synthetic stormwater results

Figure 35 shows the COD concentrations observed for the synthetic stormwater experiments. The influent concentrations varied more for this constituent than for the others in this set of experiments. This variation is likely the result of fluctuation in the organic content of the sediment used to create the TSS. No temporal trend in the effluent concentrations was evident.

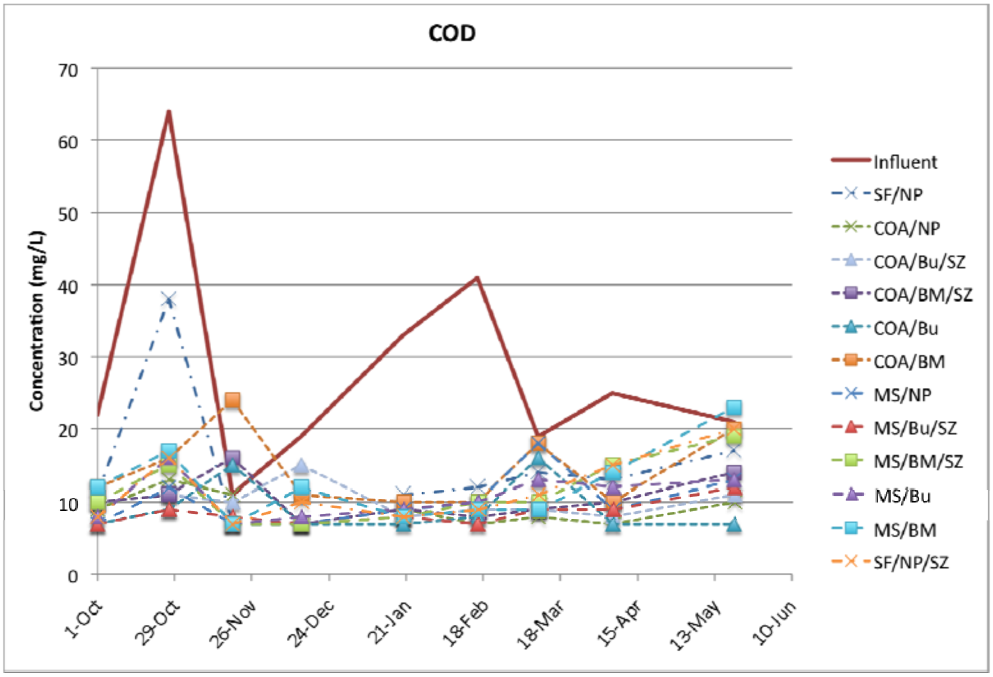

Figure 35 - COD influent and effluent concentrations for synthetic stormwater experiments

Table 20 presents the average concentrations and removal efficiencies observed for COD. The effluent concentrations were normally distributed for nine of twelve configurations; consequently, the observed data were used in the statistical analysis. Non-vegetated columns showed a better performance with COA and MS media than with the SF medium, but were not significantly different from each other. The plants (presence and type), the type of medium (between COA and MS) and the saturated zone did not appear to have a significant influence on COD removal.

Table 20 - Average COD influent and effluent concentrations and removals over time for each column

Column	Concentration (mg/L)	Removal
Influent	**28.3**	
SF/NP	15.4	46%
COA/NP	9.3	67%
COA/Bu/SZ	10.1	64%
COA/BM/SZ	10.4	63%
COA/Bu	9.2	67%
COA/BM	14.6	49%
MS/NP	10.2	64%
MS/Bu/SZ	8.4	70%
MS/BM/SZ	11.2	60%
MS/Bu	10.7	62%
MS/BM	12.3	56%
SF/NP/SZ	11.6	59%

4.8.2 Real stormwater results

Figure 36 shows the results for the real stormwater experiment for COD. The average removal for COD in the real stormwater experiment was 88%, so it is consistent with what was observed in the synthetic stormwater experiments.

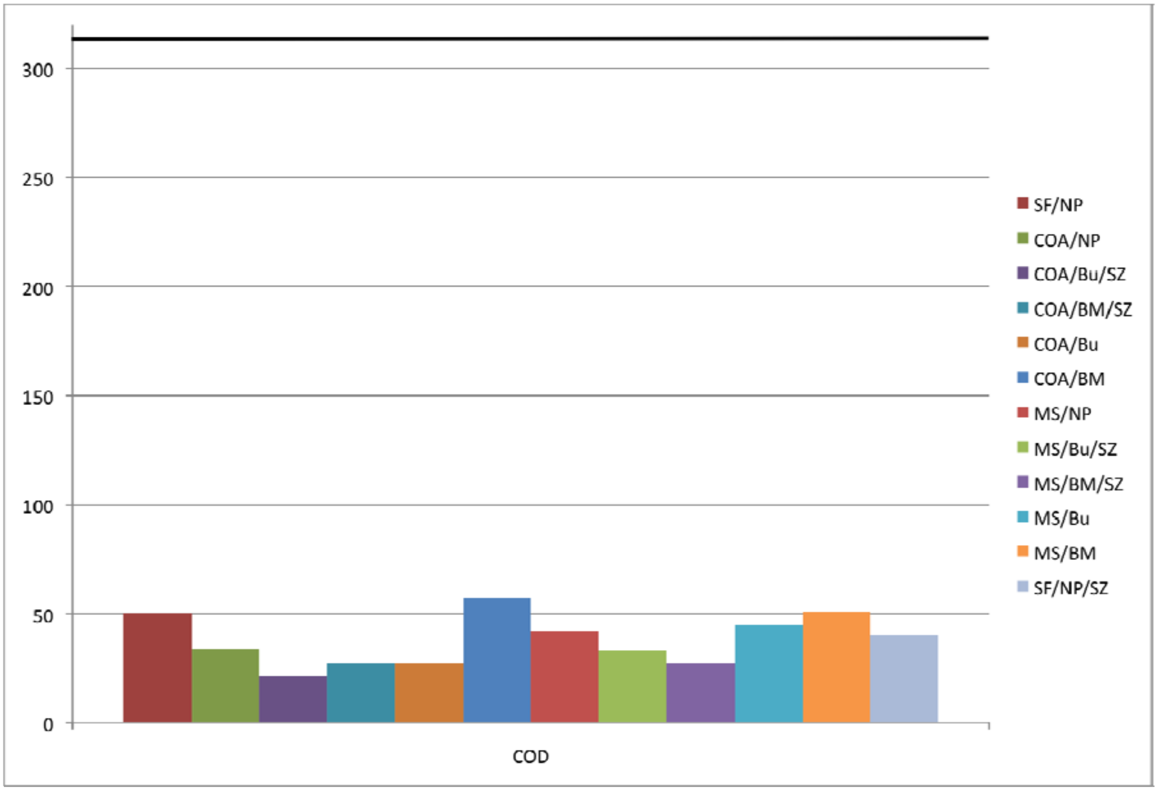

Figure 36 - COD influent and effluent concentrations for the real stormwater experiment

4.8.3 Discussion

COD removal in the SF/NP configuration was comparable to what has been reported from the Austin Sand Filters. The field studies of sand filters documented influent concentrations between 12 and 78 mg/L and effluent concentrations of between 9 and 26 mg/L, resulting in a removal of between 25% and 68% (Barrett, 2010). The SF/NP column provided a 46% removal, which is within the range observed in the field. COD removal is similar in the synthetic and real stormwater experiments. No design parameter had a significant influence on COD removal. No previous studies reported COD concentrations in biofiltration system effluent.

4.9 BACTERIA

Elevated bacteria counts are a concern in many urban waterways; consequently, a need to determine the removal efficiency of these constituents in a biofiltration facility existed. Because of the logistics of adding bacteria to the synthetic stormwater, it was decided to do one experiment with real stormwater, with the specific goal of looking at their removal. Consequently, bacteria results are only available from the one experiment with actual stormwater. Two common bacteria indicators were tested: *E. coli* and fecal coliform.

4.9.1 *E. coli*

Table 21 shows the results for *E. coli* with the 95% confidence level. The value has a 95% chance to be in the interval represented by the upper and lower 95% concentrations. The COA medium performed better than the other two media for four of five configurations (except for COA/BM). The vegetation and the saturated zone did not appear to have an influence on *E. coli* removal. However, with only one experiment, it is hard to make definitive statements. Overall, *E. coli* removal was good with an average of 97.1%. FAWB (2008) showed a much greater improvement in the presence of a saturated zone than we saw here but, as stated previously, their saturated zone was bigger and one experiment is not enough to draw conclusions.

Table 21 - Average *E. coli* influent and effluent concentrations and removals over time for each column

Column	**Measured concentration (MPN/100mL)**	**Lower 95% concentration (MPN/100mL)**	**Upper 95% concentration (MPN/100mL)**	**Removal (%)**
Influent	**32600**	**20660**	**49810**	
SF/NP	816	566	1146	98
COA/NP	20	2	110	99.9
COA/Bu/SZ	10	1	55	99.97
COA/BM/SZ	173	103	282	99
COA/Bu	10	1	37	99.97
COA/BM	1920	1367	2645	94
MS/NP	2610	1709	3985	92
MS/Bu/SZ	583	405	806	98
MS/BM/SZ	315	206	457	99
MS/Bu	2030	1450	2764	94
MS/BM	2200	1612	2924	93
SF/NP/SZ	537	383	740	98

4.9.2 Fecal Coliform

Table 22 presents the results for Fecal Coliform. Results for fecal coliform were similar to the ones for *E. coli*; however, the overall removal was a little lower, with an average removal of 85%. The COA medium produced lower concentrations in the effluent for four out of five configurations.

Table 22 - Average Fecal Coliform influent and effluent concentrations and removals over time for each column

Column	Concentration (cfu/100mL)	Removal (%)
Influent	**30200**	
SF/NP	2500	92
COA/NP	300	99
COA/Bu/SZ	100	99.7
COA/BM/SZ	420	99
COA/Bu	20	99.9
COA/BM	11400	62
MS/NP	11400	62
MS/Bu/SZ	4640	85
MS/BM/SZ	940	97
MS/Bu	9150	70
MS/BM	13200	56
SF/NP/SZ	850	97

4.9.3 Discussion

The bacteria reduction in the SF/NP control configuration, shown in Table 22, was better than that observed in real Austin Sand Filters. The average removal observed in facilities monitored in the Austin area was only 27% (Barrett, 2010). Monitoring of fecal coliform was also done by the California Department of Transportation for Austin Sand Filters located in California (Caltrans, 2004). In this study, a removal efficiency of 72% was observed. Both of these are substantially lower than observed in the control column. Consequently, field results may be significantly worse than observed in this laboratory study.

In general, the columns had substantial removal of both bacteria indicators, although the performance for *E. coli* was better than that for fecal coliform. In addition, the COA medium had better removal for both bacteria indicators. The EPA water quality standards for contact recreation for a single grab sample recreation are 394 *E. coli*/100mL and 400 fecal coliform/100 mL. In these experiments, three (almost four) of the five COA columns were able to meet these criteria.

Hunt et al. (2008) conducted one of the only other studies reporting bacteria removals. He obtained a 69% Fecal Coliform removal and a 71% *E. coli* removal and had lower influent concentrations than our actual stormwater for both bacteria indicators. The laboratory columns had higher removal than has been observed in field studies, consequently, the data likely overstate the expected performance.

4.10 WATER BALANCE RESULTS

A potentially important process in biofiltration is reduction in runoff volume through evapotranspiration (ET). Consequently, volumes of influent and effluent were measured for all experiments where runoff was not submitted to the laboratory for analysis. In each run, 30 cm of water was poured in each column. Results are given in Figure 37, the abscissa being a time line and the ordinate giving the amount of water that was retained by the column for each experiment.

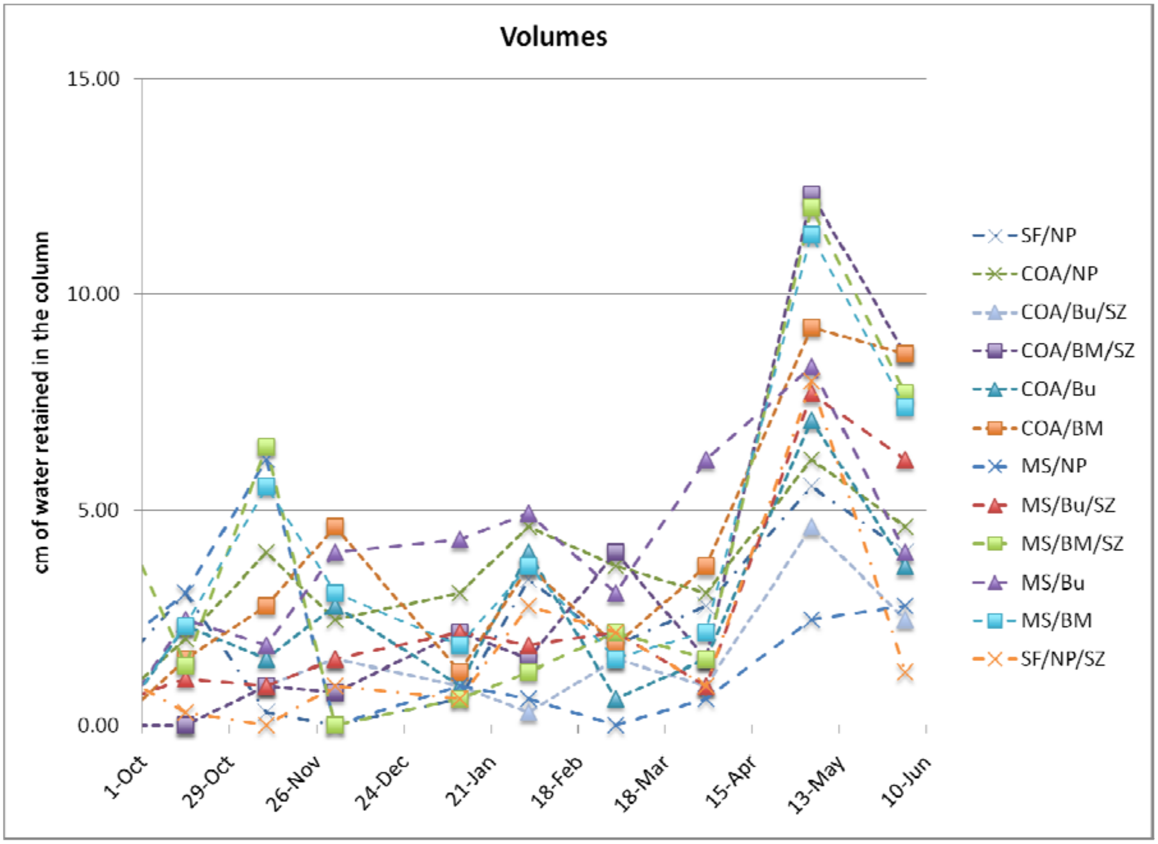

Figure 37 - Volumes measurements

The difference between the fall/winter/early spring season and the late spring/summer season, when ET was substantially higher, was clear. No obvious evapotranspiration was seen in the fall/winter/early spring season, when the plants were dormant, with more than 80% of the influent going out of the columns. When the ET was significant, for the last two experiments, Big Muhly seemed to reduce the runoff volume more than Buffalograss and more than non-vegetated columns. This can be explained by the size of the two plants. BM is bigger and has deeper roots, so it uses more water to survive. This observation could also partially explain why BM performs better than Bu in some cases. If it uptakes more water, it would be expected that it would also uptake more pollutants. The type of medium and the presence of a saturated zone did not appear to matter. One reason why the presence of the saturated zone may not have increased ET is that this zone was limited to the thickness of the gravel underdrain layer, so much of the water may not have been available to the plants.

Hunt et al. (2006) found that over a year, outflow volumes were less than 50% of the runoff volumes entering their facility, indicating the importance of ET and exfiltration, even without a submerged zone. We were not able to confirm these results but the larger size of the facility used by Hunt et al. (2006) and the fact that is was unlined likely explains the difference.

4.11 HYDRAULIC CONDUCTIVITY RESULTS

The hydraulic conductivity in the columns decreased initially, but then tended to stabilize through time or even increase slightly, as shown by the data in Figure 38. These results were similar to the ones presented by Le Coustumer (2008). None of the columns became completely clogged. Even after 10 months of operation, the hydraulic conductivity was still between 2 cm/h and 50 cm/h. Additional runs would be required to estimate the actual maintenance interval. The COA medium generally had the lowest hydraulic conductivity, which is consistent with its finer grain size.

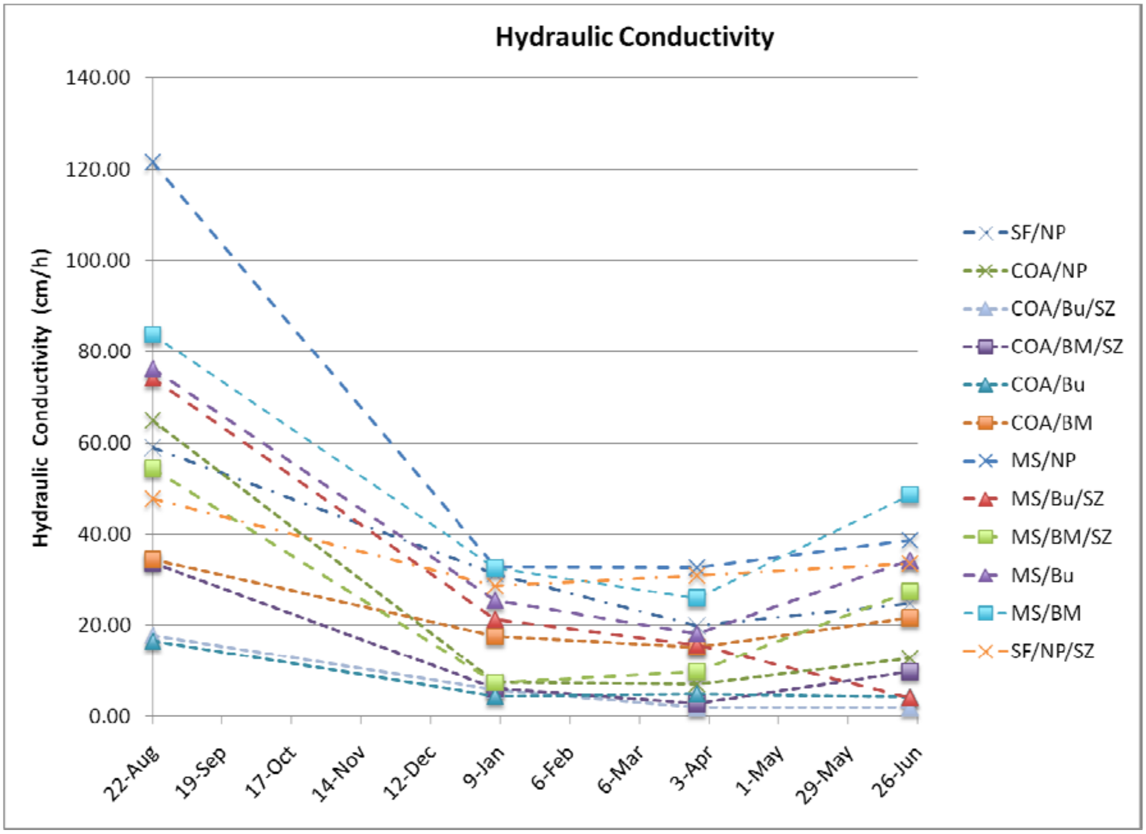

Figure 38 - Evolution of Hydraulic Conductivity for each column through time

Bu was found to have on average a slightly lower hydraulic conductivity than BM, which could be explained by two facts: 1) Bu was grown in sod that has a high clay content and low permeability, and 2) BM has thicker roots, which can help create macropores in the soil, as reported by Le Coustumer (2008) for Malaleuca. Moreover, four columns out of the six that showed a significant increase in hydraulic conductivity from the third to the fourth test are columns with Big Muhly, and the three columns that showed a decrease are columns with Buffalograss. Consequently, it appears that BM would be substantially better for preventing clogging. FAWB (2008) also observed a recovery in hydraulic conductivity after a year of operation due to plant growth. Hsieh and Davis (2005b) recommended a top mulch layer to prevent the medium from clogging but this study demonstrated that it is not necessary if plant growth can help preserve the hydraulic conductivity of the medium.

4.12 BEHAVIOR OF THE VEGETATION

Growing vegetation in a sandy soil could seem like a challenge, but it turned out that the vegetation, both Big Muhly and Buffalograss, grew well in both COA and MS media. Contrary to many recommendations, the plants did not actually need any organic matter in the soil to survive. Figure 39 is a comparison of the two plants in the two different media. It is clear that the appearance of the plants was the same in both media. Consequently, the media did not seem to have an effect on plant health.

Figure 39 – Comparison of both plants behavior in different media (from left to right: BM/MS, BM/COA, Bu/MS, Bu/COA)

Although ET did not seem to be increased by the presents of plants, the submerged zone seemed to help the plants stay green during warm weather, as shown in Figure 40. The plant growing in a column with a saturated zone was clearly greener than the one growing in a column without a saturated zone. Figure 40 shows this difference for Big Muhly with Masonry Sand but the same observation was made on columns with Buffalograss or with the COA medium.

Figure 40 – Influence of the presence of a saturated zone on BM/MS (top: with a saturated zone, bottom: without a saturated zone)

Chapter 5: Conclusions

5.1 SUMMARY

This project compared twelve different biofiltration designs in a laboratory study. Columns with different media, plants and design configurations were used to evaluate the importance of each parameter for stormwater pollutant removal, evapotranspiration and clogging. Nutrients were the main pollutants of concern because they are not well removed by sand filters. The goal of this study was to determine how the City of Austin should modify their sand filters to improve nutrient removal, without reducing their substantial TSS and metals removal. A summary of the experimental results are presented in Table 23. The results of the experiments conducted also allowed drawing the following conclusions and developing recommendations to the City of Austin for new biofiltration facilities.

5.2 CONCLUSIONS OF THE STUDY

The main objectives of this project were to answer the following questions:

1. How does the pollutant removal of filter medium meeting newly developed biofiltration criteria and a well documented mix used in Australia compare to pollutant removal observed using concrete sand (current standard filter medium)?
2. Which native plants will thrive in these conditions and produce the largest reduction in nitrogen and phosphorus concentrations?
3. Does the presence of a submerged, anaerobic zone with a carbon source promote denitrification?
4. Will the submerged zone increase the water available for evapotranspiration and support plants during the extended dry periods encountered in this climate?
5. Will biofiltration systems operate effectively long term with ponding depths as great as three feet (similar to sand filter design)?
6. Does water depth affect pollutant removal?

Table 23 - Summary of Pollutant Removal from Column Experiments

Column	**TSS**	**NOx**	**TKN**	**TN**	**DP**	**TP**	**DCu**	**TCu**	**DZn**	**DPb**	**TPb**	**COD**
SF/NP	88%	-165%	65%	18%	43%	58%	71%	89%	91%	34%	88%	46%
COA/NP	95%	-232%	83%	18%	68%	79%	89%	97%	91%	81%	98%	67%
COA/Bu/SZ	97%	-38%	84%	59%	88%	89%	90%	97%	91%	87%	99%	64%
COA/BM/SZ	97%	62%	83%	79%	94%	94%	90%	97%	91%	85%	99%	63%
COA/Bu	97%	3%	89%	72%	89%	92%	90%	97%	91%	87%	99%	67%
COA/BM	97%	44%	73%	67%	87%	87%	78%	94%	91%	35%	92%	49%
MS/NP	94%	-172%	72%	22%	75%	80%	81%	94%	91%	60%	95%	64%
MS/Bu/SZ	95%	32%	80%	70%	91%	90%	85%	96%	91%	80%	98%	70%
MS/BM/SZ	96%	56%	77%	72%	93%	93%	87%	96%	91%	69%	97%	60%
MS/Bu	90%	22%	76%	65%	83%	82%	82%	95%	91%	69%	96%	62%
MS/BM	96%	30%	74%	65%	71%	77%	68%	92%	91%	37%	92%	56%
SF/NP/SZ	94%	-149%	70%	25%	56%	68%	77%	94%	91%	62%	94%	59%

The answers to these questions are the following:

1. Both media, the one meeting newly developed biofiltration criteria (COA Biofiltration medium) and the well-documented mix used in Australia (masonry sand), had better pollutant removal than the current Austin sand filter medium (concrete sand medium). No organic matter is needed in the filter medium for nutrient removal, based on the observation that masonry sand performed very well and had no organic matter. The only significant differences between the two media were TSS effluent concentrations (TSS removal was positively correlated with the fineness of the filter medium) and hydraulic conductivity. COA Biofiltration mix had a lower TSS effluent concentration but a lower hydraulic conductivity than Masonry Sand. Nevertheless, the COA column with the lowest hydraulic conductivity (1.98 cm/hr) is still capable of draining a pond with a design water depth of 8 feet within 48 hours.

2. Plants provide a very substantial nutrient reduction (both nitrogen and phosphorus). Big Muhly grass produced a larger reduction in nitrogen concentrations than Buffalograss. However, both plants showed a significant improvement in removing most of the pollutants compared to non-vegetated columns. Periodic trimming of the vegetation and removal of the clippings may be required to optimize nutrient reduction. No silt, clay, or organic matter is needed in the medium to support vegetation. Both plant species demonstrated good growth in masonry sand.

3. The presence of a submerged zone with carbon source did not promote denitrification (probably because it was aerobic). However, the limestone gravel in this submerged zone apparently promoted phosphorus removal, possibly due to dissolved phosphorus precipitation.

4. The submerged zone did not seem to increase evapotranspiration, but plants in columns with a submerged zone looked greener than the ones in columns without a submerged zone in hot and dry weather. The saturated zone was probably too small to have a significant influence on ET.

5. The biofiltration systems operated effectively for as long as ten months and no clogging was observed. They functioned well with high solids loadings.

Maintenance was not required to maintain permeability and it appears that plant growth helped stabilize the permeability of the medium. A recovery in hydraulic conductivity was observed at the end of the study in selected columns, possibly due to plant growth for columns with Big Muhly.

6. The depth of water applied to the columns did not seem to substantially affect the pollutant removal.

5.3 RECOMMENDED DESIGN CHANGES

The recommendations to the City of Austin, based on the results of this research are to:

- Replace the current filter media by either their biofiltration media mix or masonry sand. Masonry sand is probably a better choice since it is more widely available and has a higher hydraulic conductivity, which will reduce maintenance needs. However, the COA Biofiltration might be preferred if the lowest possible TSS effluent concentration is desired.

- Raise the outlet of the filters by 300 mm to create a submerged zone. This will to improve pollutant removal, reduce the hydraulic gradient, and potentially create more ET by making the water more available to the plants. At this depth, the top of the filter medium should remain dry, which will reduce the growth of surface biofilms.

- Consider the use of crushed limestone in the underdrain to improve phosphorus removal.

- Either type of vegetation could be used depending on aesthetic and maintenance concerns. Big Muhly performed slightly better, but Buffalograss also resulted in a substantial improvement in pollutant removal compared to a conventional sand filter. Some questions remain about the optimum plant selection given the following options:

    - A native plant that is adapted to dry weather and nutrient poor soils but does not need or is able to use a large amounts of nutrients when they are available, and

    - A native or non-native plant that is adapted to wet conditions can use a large amount of nutrients, but which may have a hard time adapting to the dry Austin weather, especially during the establishment period.

5.4 RECOMMENDATIONS FOR FUTURE WORK

For future work on this topic, we would recommend:

- Continue doing the same experiments for a longer period of time to see if the increasing trend in some effluent concentrations at the end of this study would persist, stabilize or go back down,
- Continue hydraulic conductivity tests for a longer period of time in order to observe long-term clogging and to see how much recovery the Big Muhly grass brings,
- Do the same experiments with a larger submerged zone to determine if pollutant removal is improved and ET increased,
- Investigate further the survivability and establishment needs of various types of vegetation, depending on the weather and the time of the year.

Appendix A

Tables of data for each pollutant reporting influent and effluent concentrations for each column for each experimental run are presented. Grey cells indicate below detection limit concentrations.

TSS (mg/L)	Influent	SF/NP	COA/NP	COA/Bu/SZ	COA/BM/SZ	COA/Bu	COA/BM
1-Oct	70.6	14.7	3.5	2.1	4.4	4.2	3.2
27-Oct	249	32	4.4	2.2	3.5	4.6	4.1
19-Nov	54.4	13.2	13.4	13.2	9	8.3	5.2
14-Dec	98.8	11.3	8.9	2.8	2.2	2.1	2.3
20-Jan	95.6	3.4	7.1	4	7.5	1.2	3
16-Feb	157	7	1	1.3	2	2	2
10-Mar	114	13.6	7.6	5.4	4.2	3.4	3.2
6-Apr	148	17.2	3.6	1.4	1	1.1	2
20-May	155	20	5.1	2	2.4	2.1	8.8

TSS (mg/L)	Influent	FAWB/NP	FAWB/Bu/SZ	FAWB/BM/SZ	FAWB/Bu	FAWB/BM	SF/NP/SZ
1-Oct	70.6	7	5	4.9	12.3	5.5	6.3
27-Oct	249	11.1	4.3	7.3	50	10.8	10
19-Nov	54.4	7.1	13.2	7.4	15.3	5.6	6.6
14-Dec	98.8	5	3	2.1	3.2	1.9	4.4
20-Jan	95.6	6.3	9.5	7.7	3.7	4.3	2.8
16-Feb	157	4.6	2.8	1.1	2.5	1	4.1
10-Mar	114	11.4	9.6	4.4	11.4	4.9	10
6-Apr	148	10.6	3.9	2.4	9.3	3	10.3
20-May	155	9.3	3.2	6.8	11.5	10.7	10.2

NO$_x$ (mg/L)	Influent	SF/NP	COA/NP	COA/Bu/SZ	COA/BM/SZ	COA/Bu	COA/BM
1-Oct	0.623	1.61	1.8	0.21	0.168	0.324	0.403
27-Oct	0.862	1.74	2.23	0.383	0.407	0.385	0.512
19-Nov	0.762	1.12	1.24	0.538	0.416	0.52	0.41
14-Dec	0.853	1.93	1.96	0.584	0.39	0.488	0.454
20-Jan	0.829	0.906	1.14	0.647	0.478	0.512	0.415
16-Feb	0.833	1.62	2.52	0.826	0.373	0.567	0.397
10-Mar	0.791	1.63	1.94	0.951	0.393	0.931	0.377
6-Apr	0.801	3.46	4.03	2.16	0.02	1.57	0.351
20-May	0.779	4.9	6.82	3.54	0.046	1.59	0.699

NO_x (mg/L)	Influent	FAWB/NP	FAWB/Bu/SZ	FAWB/BM/SZ	FAWB/Bu	FAWB/BM	SF/NP/SZ
1-Oct	0.623	1.83	0.231	0.316	0.482	0.452	1.47
27-Oct	0.862	1.8	0.266	0.293	0.391	0.684	1.82
19-Nov	0.762	1.08	0.539	0.42	0.591	0.537	1.82
14-Dec	0.853	1.79	0.387	0.287	0.537	0.407	1.52
20-Jan	0.829	0.943	0.689	0.424	0.738	0.621	0.915
16-Feb	0.833	1.7	0.572	0.353	0.595	0.421	1.49
10-Mar	0.791	1.88	0.784	0.312	0.769	0.484	1.67
6-Apr	0.801	3.72	0.627	0.233	1.01	0.533	2.88
20-May	0.779	4.68	0.777	0.514	0.47	0.886	4.16

TKN (mg/L)	Influent	SF/NP	COA/NP	COA/Bu/SZ	COA/BM/SZ	COA/Bu	COA/BM
1-Oct	1.63	0.482	0.425	0.551	0.649	0.607	0.814
27-Oct	2.88	0.751	0.355	0.505	0.601	0.485	1.06
19-Nov	1.64	0.812	0.544	0.555	0.563	0.24	0.751
14-Dec	2.06	0.908	0.692	0.654	0.473	0.225	0.633
20-Jan	2.17	1.34	0.598	0.281	0.463	0.16	0.514
16-Feb	3.49	1.25	0.429	0.593	0.591	0.283	0.678
10-Mar	4.57	1.66	0.378	0.273	0.459	0.264	0.802
6-Apr	4.97	1.06	0.549	0.401	0.301	0.349	0.805
20-May	4.35	1.34	0.819	0.586	0.532	0.349	1.47

TKN (mg/L)	Influent	FAWB/NP	FAWB/Bu/SZ	FAWB/BM/SZ	FAWB/Bu	FAWB/BM	SF/NP/SZ
1-Oct	1.63	0.482	0.425	0.551	0.649	0.607	0.814
27-Oct	2.88	0.751	0.355	0.505	0.601	0.485	1.06
19-Nov	1.64	0.812	0.544	0.555	0.563	0.24	0.751
14-Dec	2.06	0.908	0.692	0.654	0.473	0.225	0.633
20-Jan	2.17	1.34	0.598	0.281	0.463	0.16	0.514
16-Feb	3.49	1.25	0.429	0.593	0.591	0.283	0.678
10-Mar	4.57	1.66	0.378	0.273	0.459	0.264	0.802
6-Apr	4.97	1.06	0.549	0.401	0.301	0.349	0.805
20-May	4.35	1.34	0.819	0.586	0.532	0.349	1.47

TN (mg/L)	Influent	SF/NP	COA/NP	COA/Bu/SZ	COA/BM/SZ	COA/Bu	COA/BM
1-Oct	2.253	2.092	2.225	0.761	0.817	0.931	1.217
27-Oct	3.742	2.491	2.585	0.888	1.008	0.87	1.572
19-Nov	2.402	1.932	1.784	1.093	0.979	0.76	1.161
14-Dec	2.913	2.838	2.652	1.238	0.863	0.713	1.087
20-Jan	2.999	2.246	1.738	0.928	0.941	0.672	0.929
16-Feb	4.323	2.87	2.949	1.419	0.964	0.85	1.075
10-Mar	5.361	3.29	2.318	1.224	0.852	1.195	1.179
6-Apr	5.771	4.52	4.579	2.561	0.321	1.919	1.156
20-May	5.129	6.24	7.639	4.126	0.578	1.939	2.169

TN (mg/L)	Influent	FAWB/NP	FAWB/Bu/SZ	FAWB/BM/SZ	FAWB/Bu	FAWB/BM	SF/NP/SZ
1-Oct	2.253	2.346	0.64	0.903	1.043	1.179	1.865
27-Oct	3.742	2.384	0.631	0.779	1.013	1.427	2.33
19-Nov	2.402	1.652	1.058	1.076	1.182	1.286	2.406
14-Dec	2.913	2.369	0.878	0.814	1.225	0.992	2.041
20-Jan	2.999	1.929	1.317	1.039	1.406	1.324	2.005
16-Feb	4.323	3.23	1.105	0.839	1.233	1.079	2.89
10-Mar	5.361	2.96	1.754	1.035	1.829	1.267	3.25
6-Apr	5.771	4.458	1.315	1.168	1.809	1.392	3.72
20-May	5.129	5.87	1.602	1.994	1.372	2.376	5.49

DP (mg/L)	Influent	SF/NP	COA/NP	COA/Bu/SZ	COA/BM/SZ	COA/Bu	COA/BM
1-Oct	0.303	0.023	0.053	0.02	0.02	0.02	0.031
27-Oct	0.336	0.037	0.06	0.02	0.02	0.02	0.02
19-Nov	0.363	0.204	0.063	0.058	0.029	0.046	0.034
14-Dec	0.369			0.036	0.02	0.041	0.056
20-Jan	0.362	0.354	0.129	0.066	0.025	0.049	0.088
16-Feb	0.477	0.172	0.123	0.04	0.026	0.041	0.062
10-Mar	0.398	0.307	0.216	0.084	0.02	0.061	0.076
6-Apr	0.34	0.304	0.161	0.037	0.02	0.02	0.033
20-May	0.314	0.249	0.135	0.024	0.02	0.068	0.03

DP (mg/L)	Influent	FAWB/NP	FAWB/Bu/SZ	FAWB/BM/SZ	FAWB/Bu	FAWB/BM	SF/NP/SZ
1-Oct	0.303	0.02	0.02	0.02	0.02	0.02	0.02
27-Oct	0.336	0.02	0.02	0.02	0.02	0.029	0.032
19-Nov	0.363	0.02	0.02	0.02	0.047	0.082	0.118
14-Dec	0.369	0.044	0.022	0.02	0.048	0.12	0.174
20-Jan	0.362	0.159	0.036	0.056	0.11	0.254	0.292
16-Feb	0.477	0.08	0.06	0.037	0.099	0.148	0.158
10-Mar	0.398	0.189	0.073	0.031	0.126	0.175	0.295
6-Apr	0.34	0.15	0.02	0.02	0.05	0.06	0.239
20-May	0.314	0.149	0.02	0.02	0.035	0.073	0.11

TP (mg/L)	Influent	SF/NP	COA/NP	COA/Bu/SZ	COA/BM/SZ	COA/Bu	COA/BM
1-Oct	0.579	0.066	0.082	0.064	0.031	0.051	0.073
27-Oct	0.86	0.136	0.075	0.028	0.061	0.042	0.075
19-Nov	0.525	0.266	0.129	0.079	0.038	0.103	0.09
14-Dec	0.638	0.221	0.123	0.06	0.026	0.048	0.064
20-Jan	0.754	0.45	0.192	0.102	0.06	0.059	0.142
16-Feb	0.793	0.222	0.114	0.066	0.032	0.046	0.068
10-Mar	0.559	0.418	0.216	0.118	0.041	0.061	0.108
6-Apr	0.615	0.387	0.175	0.066	0.02	0.02	0.076
20-May	0.63	0.338	0.142	0.089	0.02	0.068	0.1

TP (mg/L)	Influent	FAWB/NP	FAWB/Bu/SZ	FAWB/BM/SZ	FAWB/Bu	FAWB/BM	SF/NP/SZ
1-Oct	0.579	0.043	0.02	0.028	0.054	0.063	0.045
27-Oct	0.86	0.048	0.022	0.022	0.145	0.075	0.072
19-Nov	0.525	0.071	0.085	0.05	0.088	0.115	0.181
14-Dec	0.638	0.056	0.038	0.021	0.062	0.135	0.192
20-Jan	0.754	0.209	0.105	0.11	0.176	0.303	0.355
16-Feb	0.793	0.133	0.078	0.044	0.116	0.158	0.206
10-Mar	0.559	0.252	0.142	0.058	0.197	0.241	0.391
6-Apr	0.615	0.2	0.052	0.027	0.114	0.107	0.283
20-May	0.63	0.164	0.032	0.057	0.105	0.172	0.187

DCu (µg/L)	Influent	SF/NP	COA/NP	COA/Bu/SZ	COA/BM/SZ	COA/Bu	COA/BM
1-Oct	3.12	1.02	1.02	1.02	1.02	1.02	1.43
27-Oct	3.76	1.78	1.11	1.02	1.02	1.02	2.19
19-Nov	4.4	1.44	1.06	1.61	1.06	1.09	1.48
14-Dec	27.3			1.02	1.02	1.02	1.02
20-Jan	8.93	1.84	1.02	1.02	1.02	1.02	1.02
16-Feb	7.87	1.46	1.02	1.02	1.02	1.02	1.02
10-Mar	9.56	2.08	1.45	1.49	1.57	1.77	1.79
6-Apr	30.7	8.1	1.58	1.17	1.05	1.49	2.71
20-May	18.2	11.9	3	1.9	2.8	2.3	12.8

DCu (µg/L)	Influent	FAWB/NP	FAWB/Bu/SZ	FAWB/BM/SZ	FAWB/Bu	FAWB/BM	SF/NP/SZ
1-Oct	3.12	1.02	1.02	1.02	1.02	1.67	1.02
27-Oct	3.76	1.02	1.02	1.03	1.02	2.76	1.75
19-Nov	4.4	1.02	1.27	1.1	1.44	2.06	1.67
14-Dec	27.3	1.02	1.17	1.02	1.02	1.48	1.61
20-Jan	8.93	1.02	1.33	1.02	1.3	1.42	1.06
16-Feb	7.87	1.02	1.02	1.02	1.03	1.07	1.63
10-Mar	9.56	1.82	1.96	1.61	1.94	2.32	1.99
6-Apr	30.7	5.48	2.59	1.48	5.28	5.85	6.47
20-May	18.2	7.9	5.7	5.5	6.9	17.7	9.2

TCu (µg/L)	Influent	SF/NP	COA/NP	COA/Bu/SZ	COA/BM/SZ	COA/Bu	COA/BM
1-Oct	72.5	3.03	2.71	2	2	2	2.61
27-Oct	82.9	9.32	2	2	2	2	2.8
19-Nov	77.1	3.7	2.93	2	2	2	2
14-Dec	65.5			2	2	2	2
20-Jan	83.5	3.92	2	2	5.04	2	2
16-Feb	75	2	2	2	2	2	2
10-Mar	64.1	4.16	2	2.3	2	2.44	2.25
6-Apr	75.2	16.4	2	2	2	2	3.92
20-May	76.4	21.3	4.12	2.21	3.17	2.75	17.7

TCu (µg/L)	Influent	FAWB/NP	FAWB/Bu/SZ	FAWB/BM/SZ	FAWB/Bu	FAWB/BM	SF/NP/SZ
1-Oct	72.5	2	2	2	2.3	3.3	2.22
27-Oct	82.9	2	2	2	3.21	3.83	3.83
19-Nov	77.1	2.16	2.39	2	2.44	3.26	3.56
14-Dec	65.5	2	2	2	2	2.28	2.62
20-Jan	83.5	2.19	2.08	2	2.23	2.03	2.25
16-Feb	75	2	2	2	2	2	2
10-Mar	64.1	3.61	3.85	2.23	2.75	2.72	3.23
6-Apr	75.2	10.7	3.68	2.15	7.97	7.89	10.4
20-May	76.4	11.5	7.11	7.16	10.2	25.1	13.2

DZn (µg/L)	Influent	SF/NP	COA/NP	COA/Bu/SZ	COA/BM/SZ	COA/Bu	COA/BM
1-Oct	43.7	4.08	4.08	4.08	4.08	4.08	4.08
27-Oct	15.6	4.08	4.08	4.08	4.08	4.08	4.08
19-Nov	54.8	4.08	4.08	4.08	4.08	4.08	4.08
14-Dec	57.2			4.08	4.08	4.08	4.08
20-Jan	50	4.08	4.08	4.08	4.08	4.08	4.08
16-Feb	61.2	4.08	4.08	4.08	4.08	4.08	4.08
10-Mar	51.4	4.08	4.08	4.08	4.08	4.08	4.08
6-Apr	34.1	4.08	4.08	4.08	4.08	4.08	4.08
20-May	40.6	4.08	4.08	4.08	4.08	4.08	4.08

DZn (µg/L)	Influent	FAWB/NP	FAWB/Bu/SZ	FAWB/BM/SZ	FAWB/Bu	FAWB/BM	SF/NP/SZ
1-Oct	43.7	4.08	4.08	4.08	4.08	4.08	4.08
27-Oct	15.6	4.08	4.08	4.41	4.08	4.08	4.08
19-Nov	54.8	4.08	4.08	4.08	4.08	4.08	4.57
14-Dec	57.2	4.08	4.08	4.08	4.08	4.08	4.08
20-Jan	50	4.08	4.08	4.08	4.08	4.08	4.08
16-Feb	61.2	4.08	4.08	4.08	4.08	4.08	4.08
10-Mar	51.4	4.08	4.08	4.08	4.08	4.08	4.08
6-Apr	34.1	4.08	4.08	4.08	4.08	4.08	4.08
20-May	40.6	4.08	4.08	4.08	4.08	4.08	4.08

TZn (µg/L)	Influent	SF/NP	COA/NP	COA/Bu/SZ	COA/BM/SZ	COA/Bu	COA/BM
1-Oct	167	8.1	5	5	5	5	5
27-Oct	187	26.7	5	5	5	5	5
19-Nov	171	8.02	7.82	5	5	5	5
14-Dec	170			5	5	5	5
20-Jan	214	10.6	6.11	5	10.8	5	5
16-Feb	193	5	5	5	5	5	5
10-Mar	137	10.6	5	5	5	5	5
6-Apr	142	8.92	5	5	5	5	5
20-May	169	8.23	5	5	5	5	5

TZn (µg/L)	Influent	FAWB/NP	FAWB/Bu/SZ	FAWB/BM/SZ	FAWB/Bu	FAWB/BM	SF/NP/SZ
1-Oct	167	5	5	5	5	5	5
27-Oct	187	5	5	5	9.87	5	8.88
19-Nov	171	6.34	7.02	5	6.48	5	9.64
14-Dec	170	5	5	5	5	5	6.4
20-Jan	214	5.76	5.07	5	5	5	5.45
16-Feb	193	5	5	5	5	5	5
10-Mar	137	8.11	9.6	5	5	5	7.88
6-Apr	142	8.63	5	5	5	5	6.57
20-May	169	5	5	5	5	5	5

DPb (µg/L)	Influent	SF/NP	COA/NP	COA/Bu/SZ	COA/BM/SZ	COA/Bu	COA/BM
1-Oct	1.02	1.02	1.02	1.02	1.02	1.02	1.02
27-Oct	1.2	1.02	1.02	1.02	1.02	1.02	1.02
19-Nov	1.72	1.02	1.02	1.02	1.02	1.02	1.02
14-Dec	1.03			1.02	1.02	1.02	1.02
20-Jan	1.49	1.02	1.02	1.02	1.02	1.02	1.02
16-Feb	1.32	1.02	1.02	1.02	1.02	1.02	1.02
10-Mar	1.72	1.02	1.02	1.02	1.02	1.02	1.02
6-Apr	3.51	1.02	1.02	1.02	1.02	1.02	1.02
20-May	58.7	35	4.8	1.02	2.4	1.02	38.1

DPb (µg/L)	Influent	FAWB/NP	FAWB/Bu/SZ	FAWB/BM/SZ	FAWB/Bu	FAWB/BM	SF/NP/SZ
1-Oct	1.02	1.02	1.02	1.02	1.02	1.02	1.02
27-Oct	1.2	1.02	1.02	1.02	1.02	1.02	1.02
19-Nov	1.72	1.02	1.02	1.02	1.02	1.02	1.02
14-Dec	1.03	1.02	1.02	1.02	1.02	1.02	1.02
20-Jan	1.49	1.02	1.02	1.02	1.02	1.02	1.02
16-Feb	1.32	1.02	1.02	1.02	1.02	1.02	1.02
10-Mar	1.72	1.02	1.02	1.02	1.02	1.02	1.02
6-Apr	3.51	1.02	1.02	1.02	1.02	1.02	1.02
20-May	58.7	20.4	6.1	13.8	14.2	36.7	19.4

TPb (µg/L)	Influent	SF/NP	COA/NP	COA/Bu/SZ	COA/BM/SZ	COA/Bu	COA/BM
1-Oct	121	3.9	1	1	1	1	1
27-Oct	140	16.4	1	1	1	1	1
19-Nov	109	4.81	1.73	1	1	1	1
14-Dec	89.3			1	1	1	1
20-Jan	122	5.42	1	1	1	1	1
16-Feb	134	1	1	1	1	1	1
10-Mar	85	4.29	1	1	1	1	1
6-Apr	101	4.14	1	1	1	1	1
20-May	153	73.8	10.7	1	4.59	1	75.6

TPb (µg/L)	Influent	FAWB/NP	FAWB/Bu/SZ	FAWB/BM/SZ	FAWB/Bu	FAWB/BM	SF/NP/SZ
1-Oct	121	1	1	1	1	1	1.43
27-Oct	140	1	1	1	1.9	1.28	5.19
19-Nov	109	2.53	1.5	1	2.01	1.15	4.75
14-Dec	89.3	1	1	1	1	1	2.04
20-Jan	122	2.63	1	1	1	1	2.65
16-Feb	134	1	1	1	1	1	1
10-Mar	85	2.76	1	1	1	1	3.13
6-Apr	101	1.8	1	1	1	1	2.59
20-May	153	39.7	15.8	27.2	31.7	73.2	45.5

Appendix B

PARTICLE SIZE DISTRIBUTION FUNCTIONS AND VOLUME DISTRIBUTION FUNCTIONS OF THE RUNOFF SAMPLES OF CITY OF AUSTIN BIOFILTER PROJECT

LIST OF FIGURES

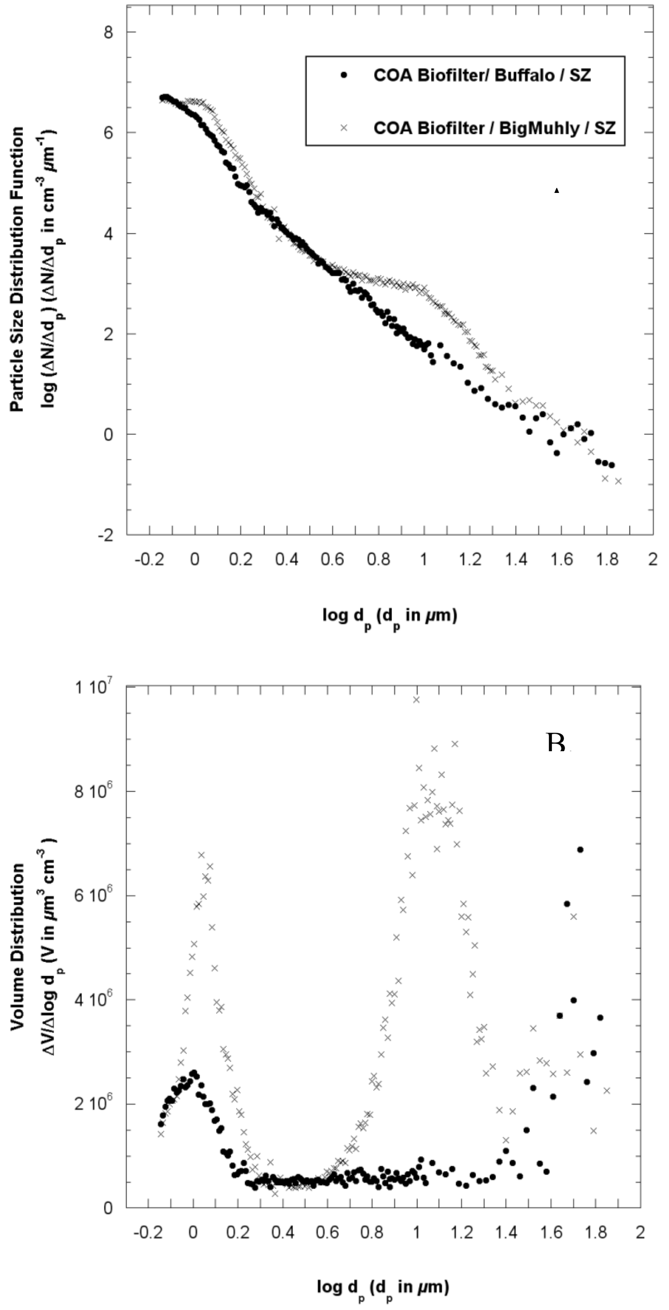

Figure C-1 Comparison of (A) Particle size distribution function, (B) volume distribution of COA Biofilter with different plants with saturated zone in Experiment 2.

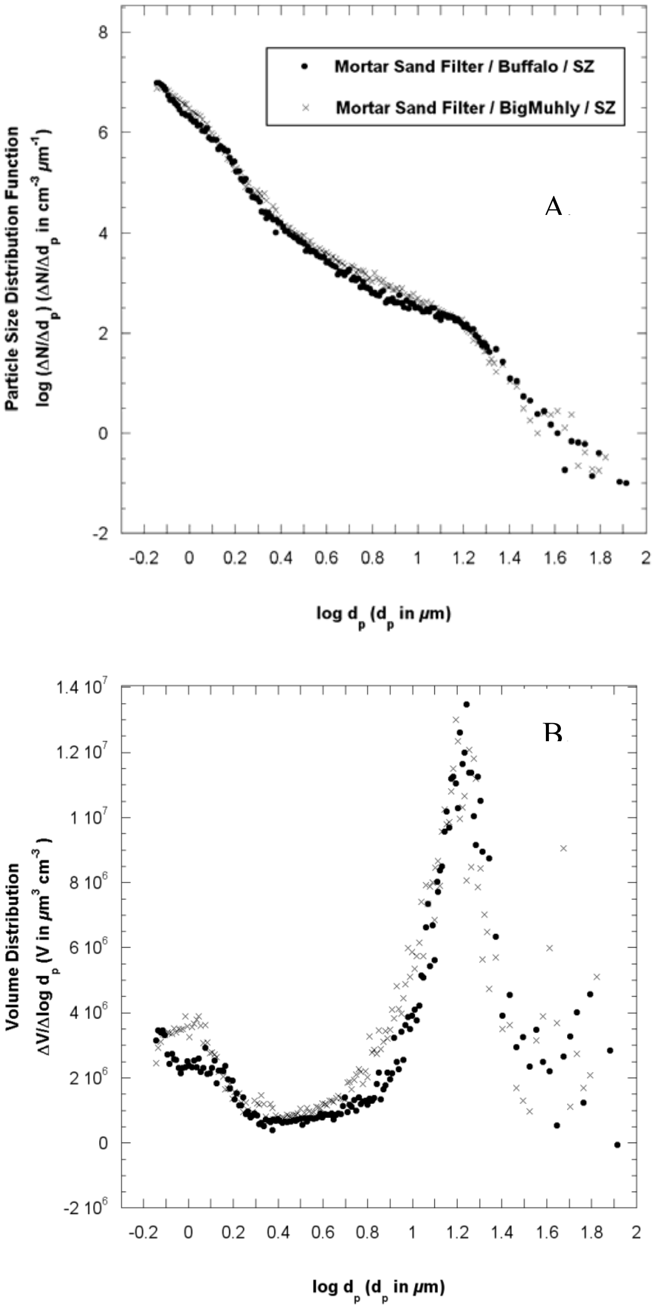

Figure C-2 Comparison of (A) Particle size distribution function, (B) volume distribution of Mortar sand filter with different plants with saturated zone in Experiment 2.

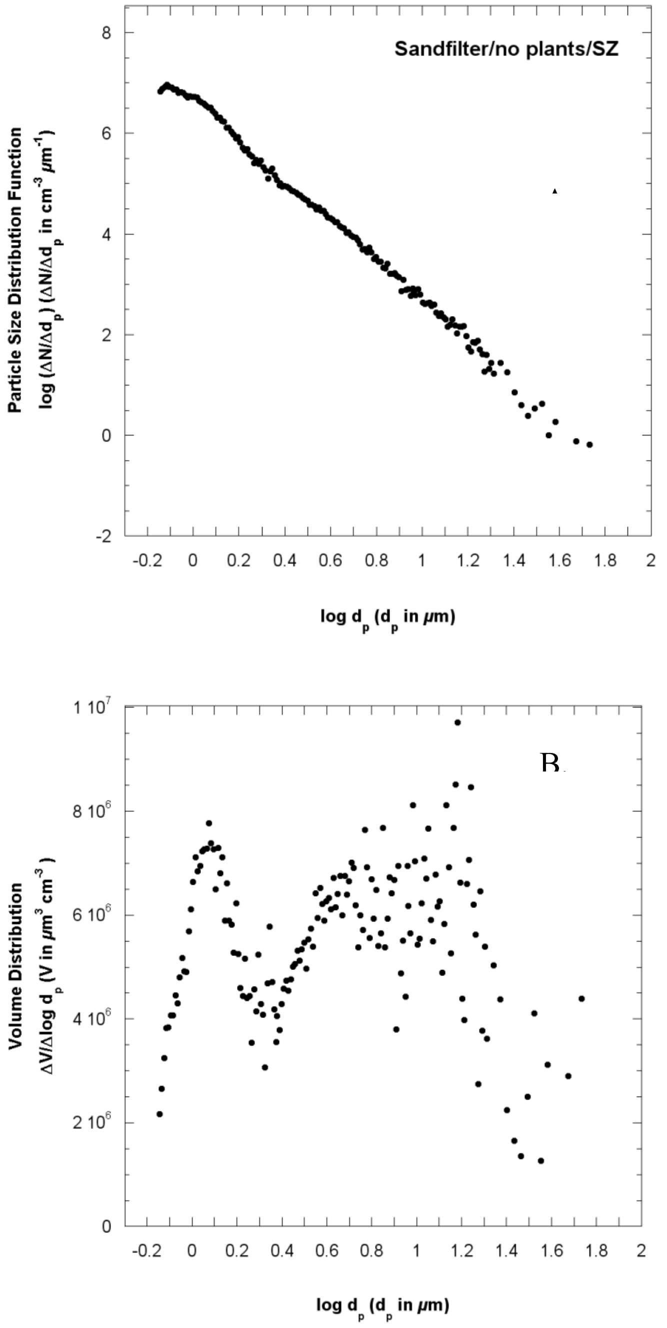

Figure C-3 (A) Particle size distribution function, (B) volume distribution of COA Sand filter with saturated zone in Experiment 2.

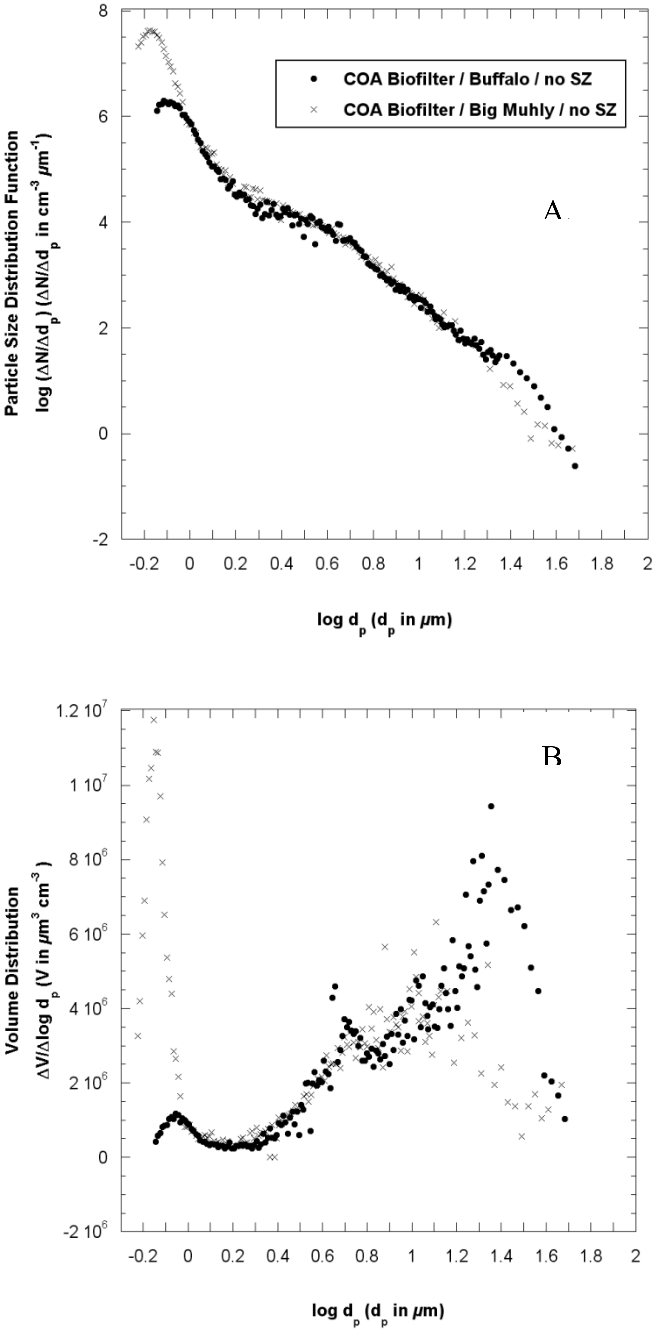

Figure C-4 Comparison of (A) Particle size distribution function, (B) volume distribution COA Biofilter with different plants in the absence of saturated zone in Experiment 3.

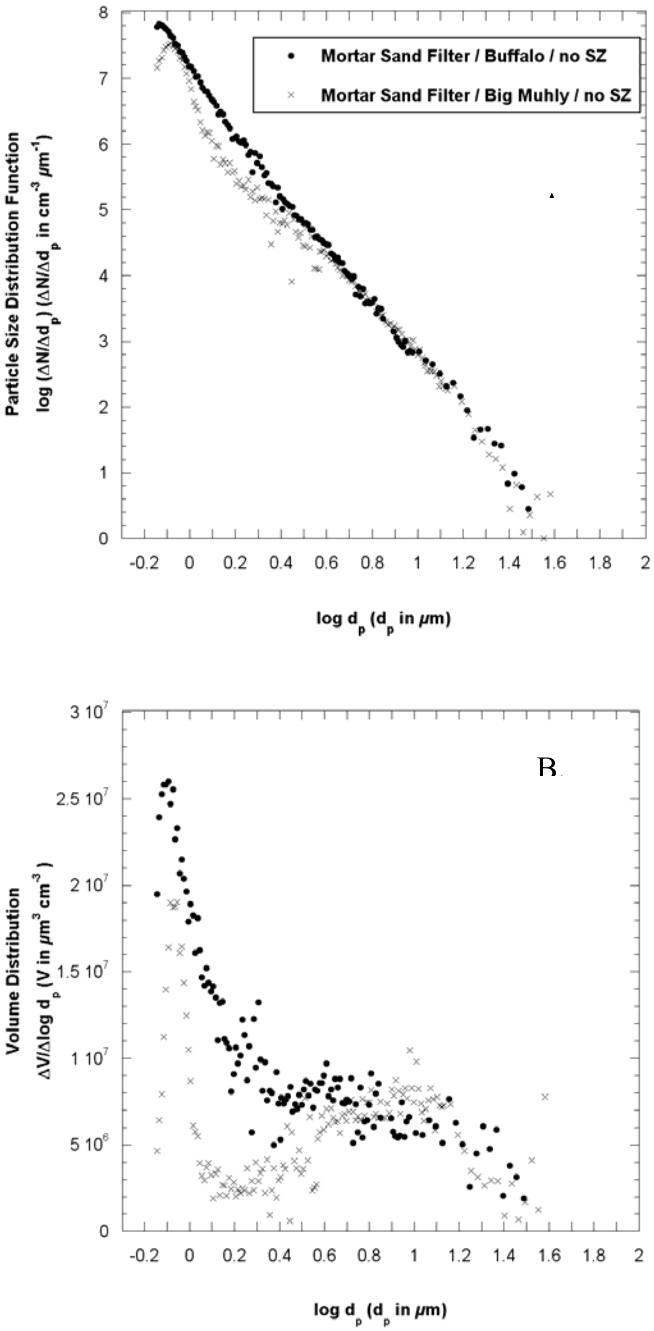

Figure C-5 Comparison of (A) Particle size distribution function, (B) volume distribution of Mortar sand filter with different plants in the absence of saturated zone in Experiment 3.

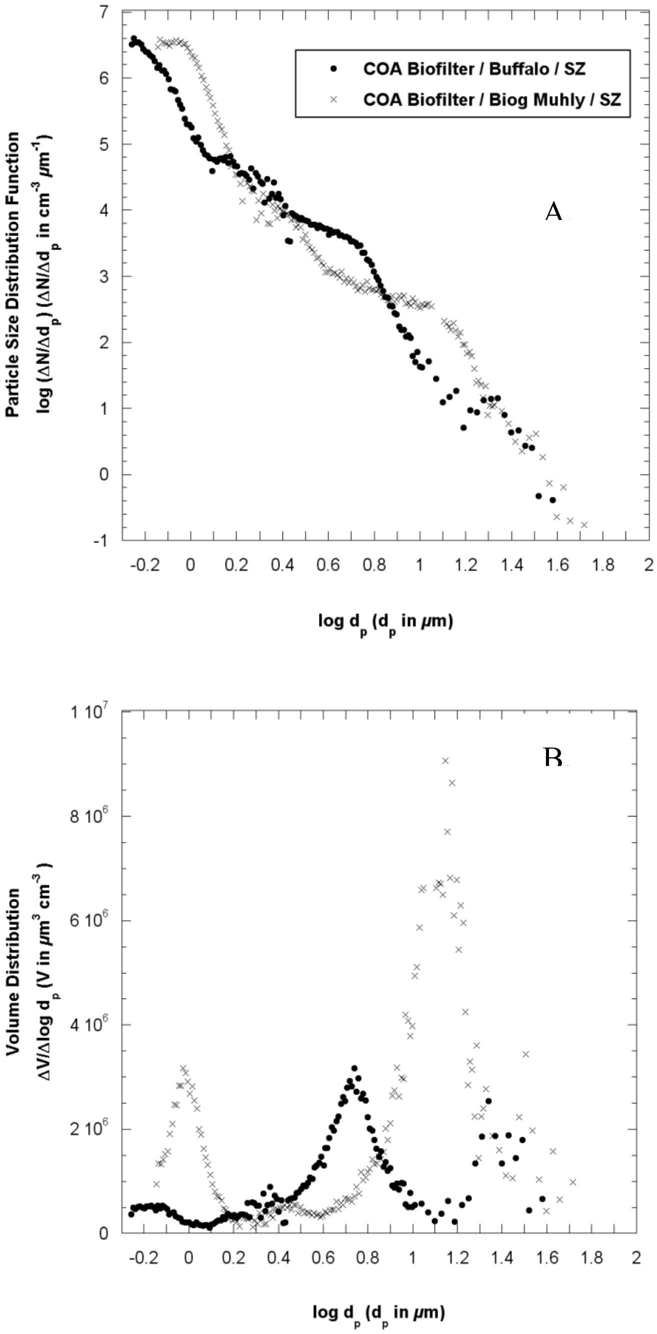

Figure C-6 Comparison of (A) Particle size distribution function, (B) volume distribution of COA Biofilter with different plants and with saturated zone in Experiment 3.

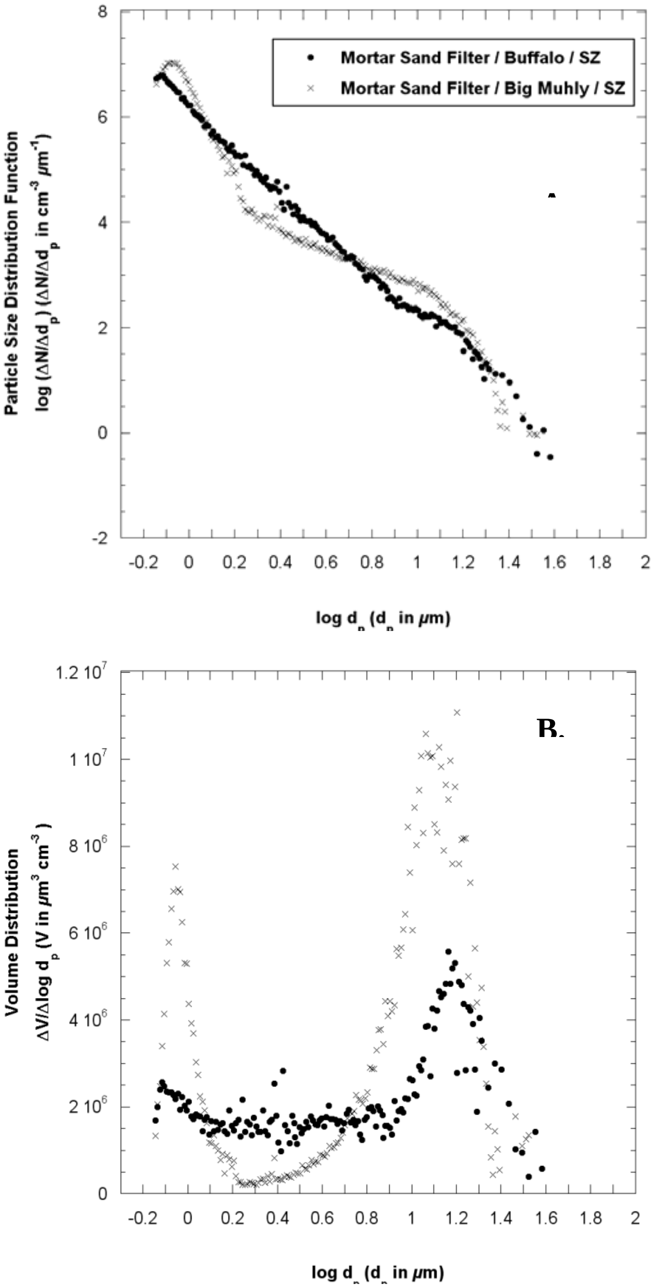

Figure C-7 Comparison of (A) Particle size distribution function, (B) volume distribution Mortar sand filter with different plants and with saturated zone in Experiment 3.

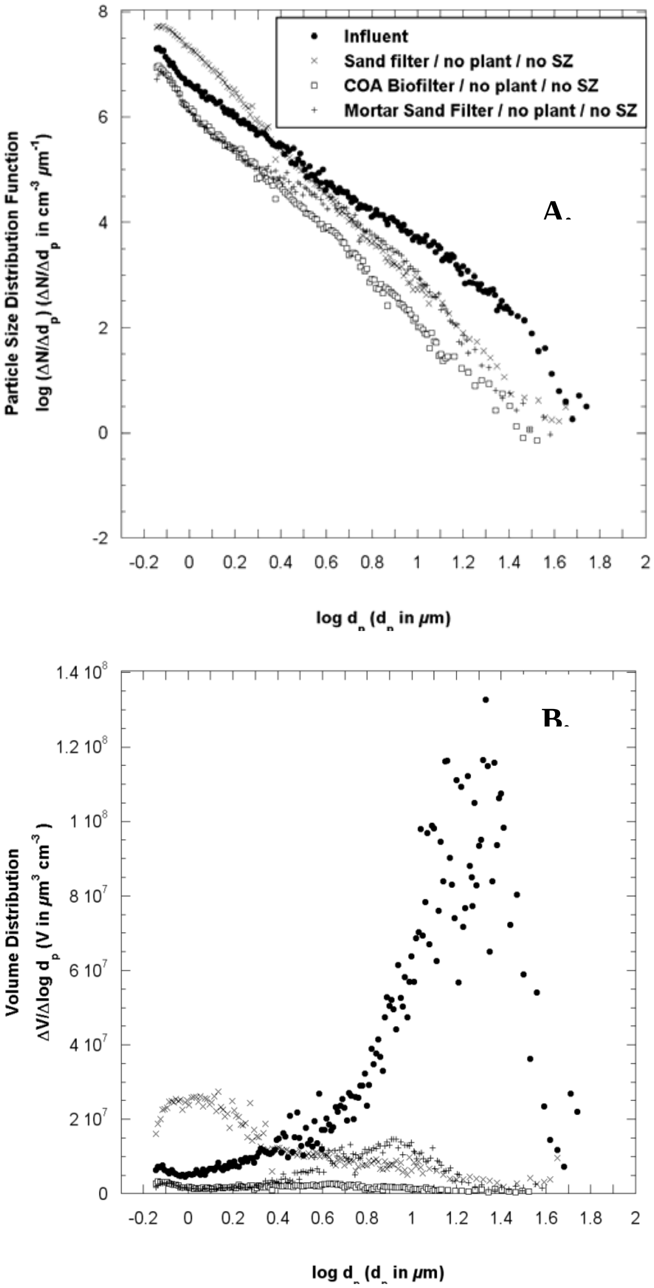

Figure C-8 Comparison of (A) Particle size distribution function, (B) volume distribution of COA Sand filter, COA Biofilter, and Mortar sand filter in the absence of plants and saturated zone in Experiment 3.

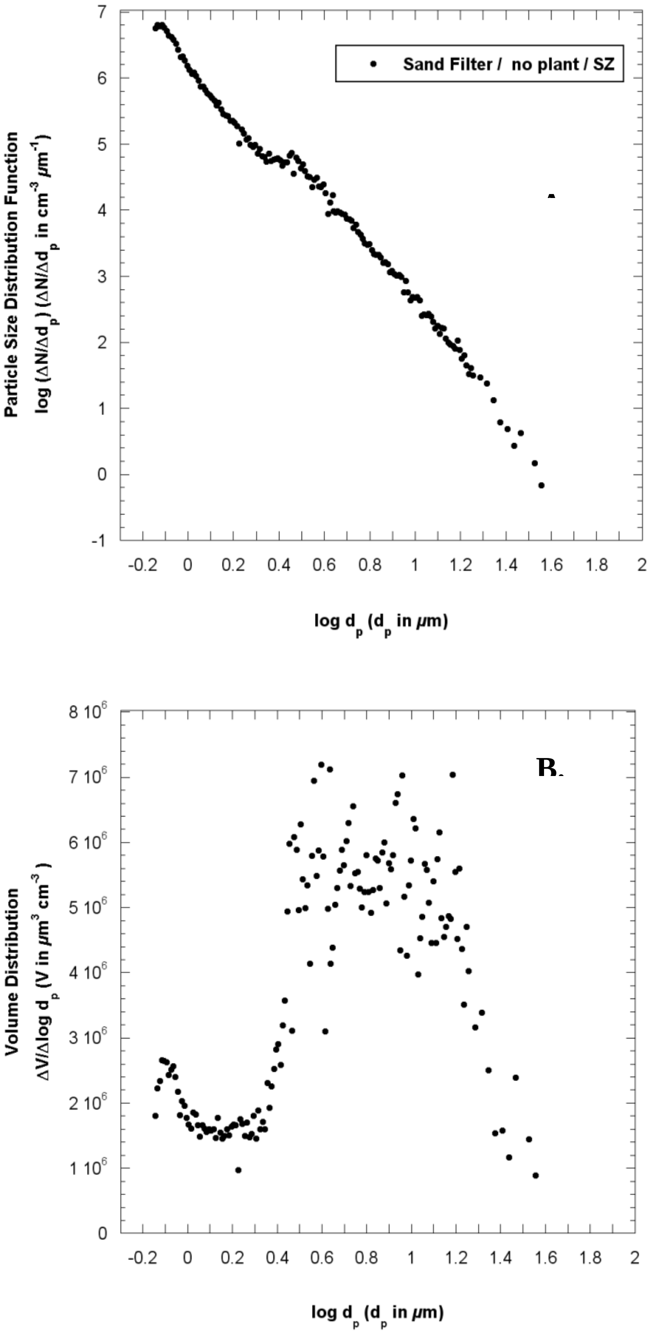

Figure C-9 (A) Particle size distribution function, (B) volume distribution of COA Sand filter with saturated zone in Experiment 3.

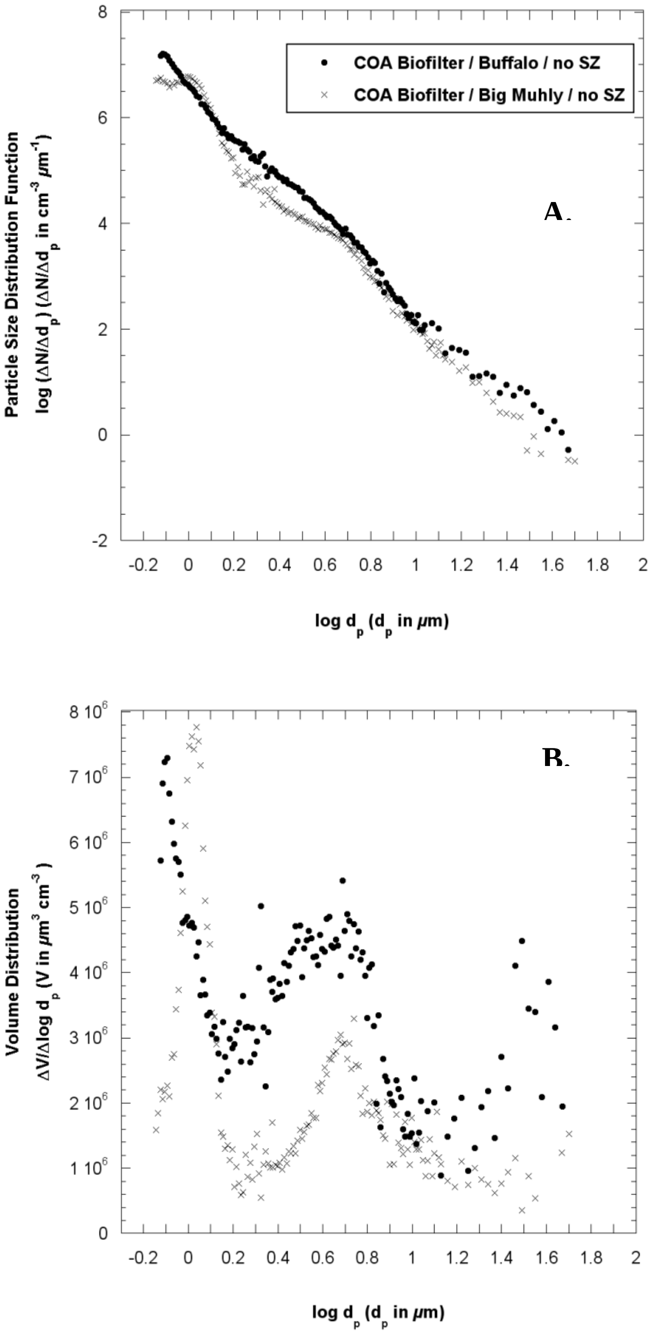

Figure C-10 Comparison of (A) Particle size distribution function, (B) volume distribution of COA Biofilter with different plants in the absence of saturated zone in Experiment 4.

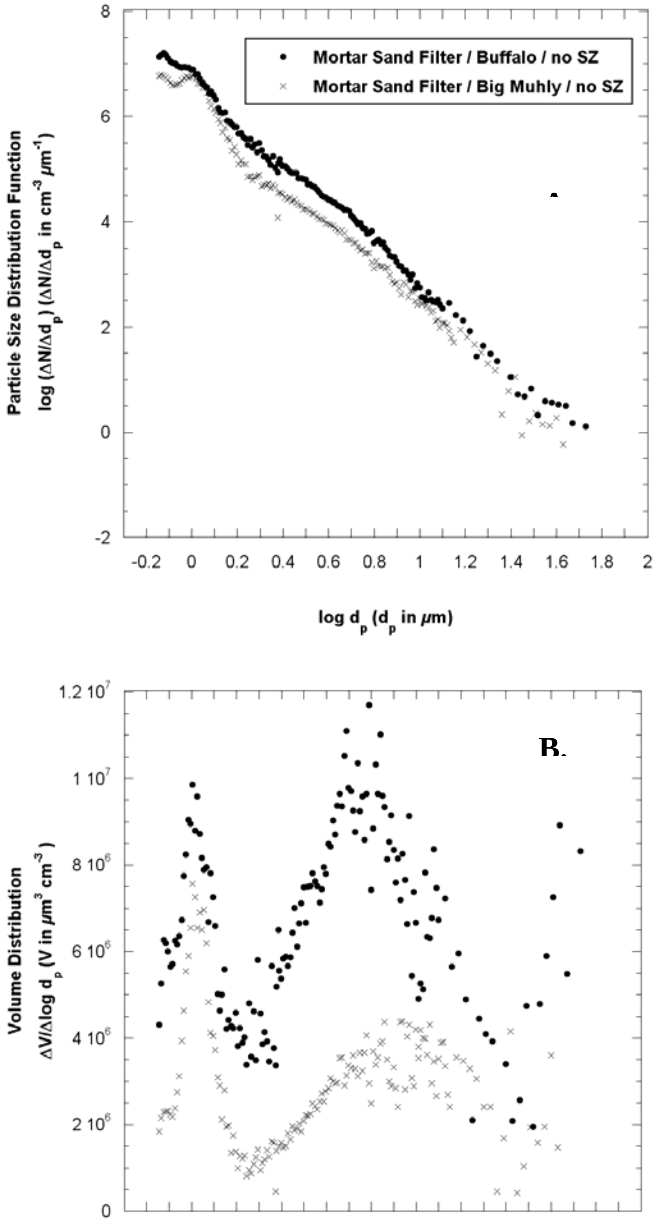

Figure C-11 Comparison of (A) Particle size distribution function, (B) volume distribution of Mortar sand filter with different plants in the absence of saturated zone in Experiment 4.

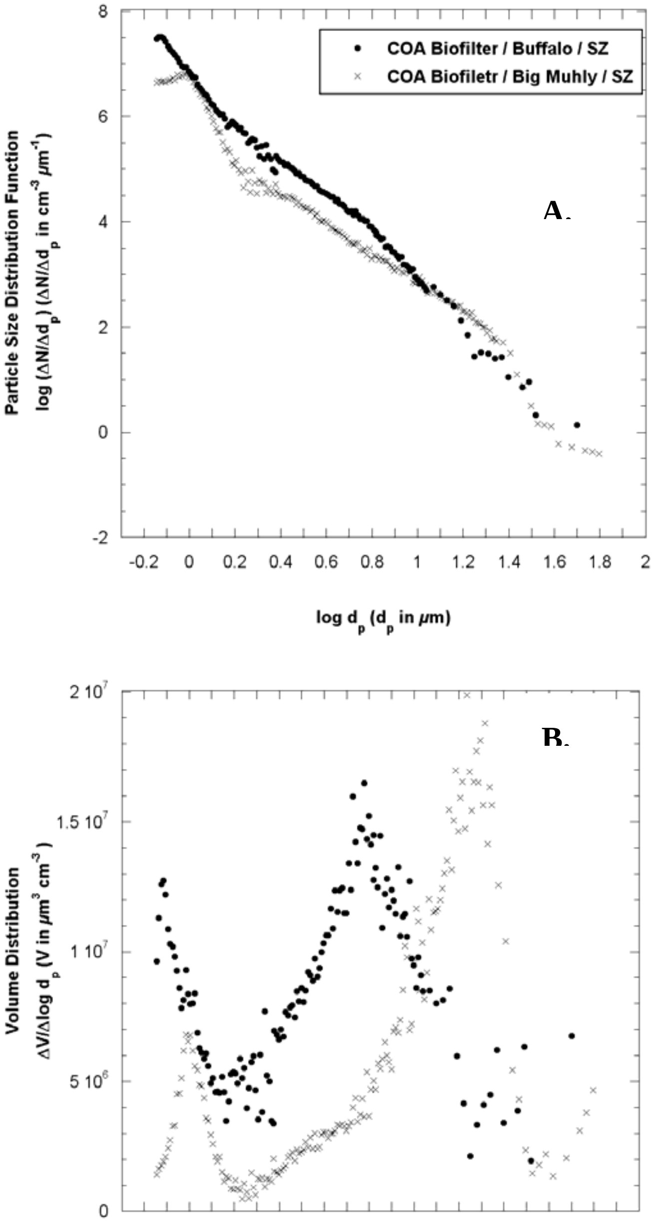

Figure C-12 Comparison of (A) Particle size distribution function, (B) volume distribution of COA Biofilter with different plants and with saturated zone in Experiment 4.

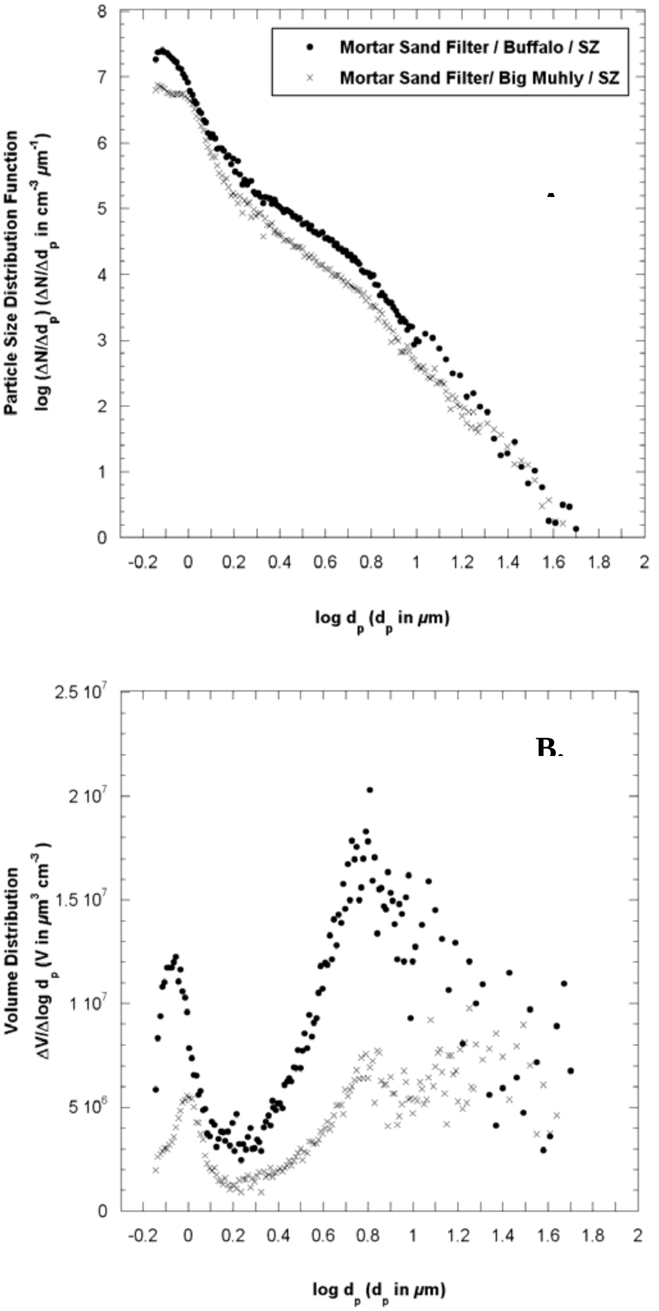

Figure C-13 Comparison of (A) Particle size distribution function, (B) volume distribution of Mortar sand filter with different plants and with saturated zone in Experiment 4.

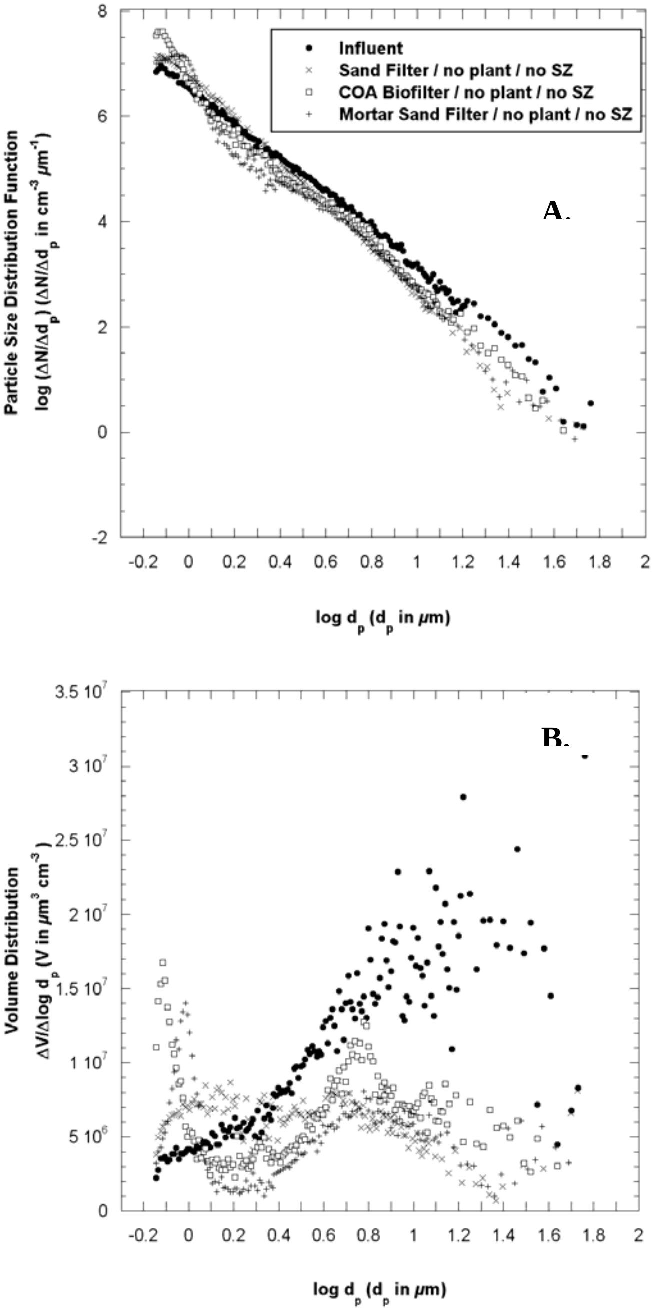

Figure C-14 Comparison of (A) Particle size distribution function, (B) volume distribution of COA Sand filter, COA Biofilter, and Mortar sand filter in the absence of plants and saturated zone in Experiment 4.

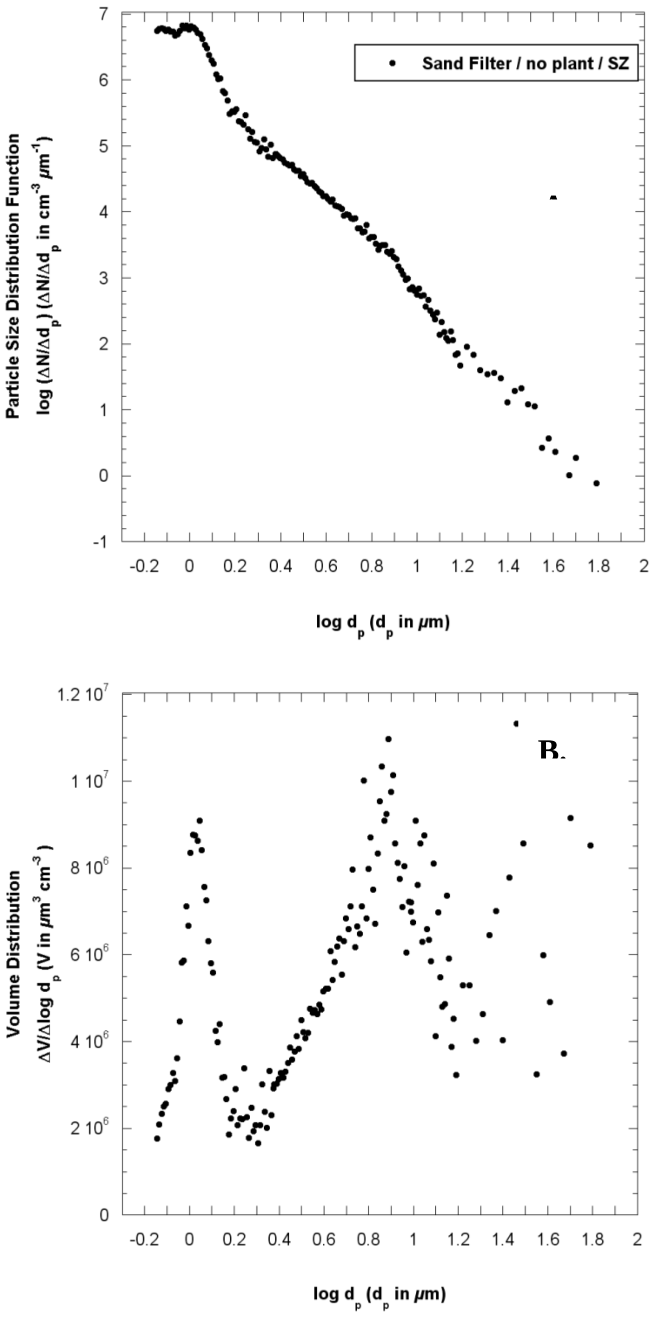

Figure C-15 (A) (A) Particle size distribution function, (B) volume distribution of COA Sand filter with saturated zone in Experiment 4.

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