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16. Abstract
This final report summarizes five years' worth of work in evaluating the applicability and performance of bioretention best management practices (BMPs) for highway environments in Texas. Within the five-year time frame, the research team did a literature review, conducted pilot experiments, and constructed a field demonstration site. The field site was tested with two different designs: (1) dry (or non-internal water storage [IWS]) and (2) internal water storage types. The field site is near the intersection of SH 21 and SH 6 in Bryan, Texas. The site includes a water hydrant for irrigation and synthetic runoff tests. The report includes introduction, research methods, test results, discussion, drawing examples, designs and maintenance guidelines, a special specification, a planting plan guide, a summary of the site selection process, and test data.

In summary, bioretention BMPs can reduce peak flow and increase detention time. Non-IWS design moderately removed suspended solids, less effectively removed copper and zinc, less effectively removed total nitrogen, and moderately removed total phosphorus. The IWS layer significantly improved all performances, including hydraulic and water quality.

The significance of this research project is that bioretention BMPs are a promising method for highway application in hot, semi-arid areas. Furthermore, the IWS layer is a viable application to improve bioretention performances.

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BIORETENTION FOR HIGHWAY STORMWATER QUALITY IMPROVEMENT IN TEXAS: FINAL REPORT

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Dr. Ming-Han Li, P.E., #91045.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear here solely because these are considered essential to the object of this report.

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CHAPTER 1:
INTRODUCTION

Bioretention is a best management practice (BMP) that consists of an engineered soil, vegetation filter, and optional underdrain system for treating stormwater runoff. Pollutant removal mechanisms include physical, chemical, and biological activity (Davis et al., 2001; Hunt, 2003). Plant uptake and soil microorganism activities during intermittent storm events then permanently remove these captured pollutants (Davis et al., 2001; Henderson et al., 2007; Lucas and Greenway, 2008). Since its invention in the early 1990s in Prince George's County (PGC), Maryland (Prince George's County, 2002), bioretention has been applied to diverse environments, including residential gardens (Dietz and Clausen, 2005), parking lots (Davis, 2007; Hunt et al., 2006; Passeport et al., 2009), and urban streets and highways (Hatt et al., 2009; Chapman and Horner, 2010; Li et al., 2011; Trowsdale and Simcock, 2011; Li et al., 2012).

Many studies report the effective performance of bioretention methods in removing various pollutants from stormwater runoff, including metals (Davis et al., 2003), nitrogen and phosphorus (Davis et al., 2006), oil and grease (Hong et al., 2006), polycyclic aromatic hydrocarbons (Diblasi et al., 2009), *Escherichia coli* (Zhang et al., 2010), and thermal waste (Jones and Hunt, 2009). However, only a few have evaluated its performance in large-scale highway applications (Li et al., 2011; Li et al., 2012).

A highway is a significant source of non-point source pollutants. Based on the fact that the water quality of stormwater runoff varies widely by contributing drainage areas, even by different transportation facilities (Li et al., 2008), an evaluation of the feasibility of bioretention in treating highway runoff is necessary (Li et al., 2011). Li et al. (2008) demonstrated that a bioretention system effectively removed metals, total suspended solids (TSS), and *E. coli* from highway runoff, but poorly removed nitrogen (N) and phosphorus (P). Leaching of N and P is a particular concern because of eutrophication in a receiving water body.

In 2003, The Texas Commission on Environmental Quality (TCEQ) became the permitting authority for stormwater runoff from construction facilities and mandated that the Texas Department of Transportation (TxDOT) prepare a Storm Water Pollution Prevention Plan (SWPPP) for construction activities that disturb more than 1 ac of soil (TXR150000). The Texas Pollutant Discharge Elimination System (TPDES) is the means by which TxDOT meets its obligations as prescribed by Section 402 of the Federal Clean Water Act, administered by the

TCEQ. Long-term plans that affect small municipal separate storm sewer systems are called for in the TXR040000.

Bioretention can be a good alternative to treat runoff for a relatively long period because vegetation continuously removes pollutants from a soil filter. Despite its performance and longevity, bioretention has not been included in current TxDOT stormwater management guidelines or design manuals, for instance, the *Stormwater Management Guidelines for Construction Activities* (TxDOT, 2002), the *Hydraulic Design Manual* (TxDOT, 2004), and the *Landscape and Aesthetics Design Manual* (TxDOT, 2007a). Existing bioretention manuals may not be directly applicable to TxDOT rights-of-way and other facilities because these were based on studies in northern states where the climate is significantly different from Texas (e.g., Prince George's County, 2002; Wisconsin Department of Natural Resources, 2003; Puget Sound Action Team, 2005). Considering the hot and arid/semi-arid climate in Texas, design specifications—such as the types of vegetation, the depth and property of soil filter media, and managerial schemes—must be revised.

This project aimed to develop a bioretention design guideline for treating stormwater runoff from TxDOT highways. This project consisted of three major tasks: reviewing existing literature, conducting pilot-scale laboratory experiments, and constructing and monitoring a field-scale bioretention facility in a real TxDOT highway environment. The previous report described results of the pilot-scale laboratory experiments (Li et al., 2010b). This report includes the literature review, a brief summary of the pilot-scale laboratory experiments conducted in the second year, complete findings of the pilot-scale laboratory experiments conducted in the third year, and the findings from the field bioretention demonstration project to August 2012. Additional experiments were conducted to examine the effect of an internal water storage (IWS) zone on pollutant removal. Based on these findings, this report developed a draft design guideline for treating stormwater runoff in Texas highways with detailed computer-aided design (CAD) illustrations.

CHAPTER 2:
LITERATURE REVIEW

REGULATORY SUMMARY

TxDOT is in charge of managing stormwater runoff from 1.1 million acres of rights-of-way (ROWs; TxDOT, 2007b). Pursuant to the Phase II regulation of the National Pollutant Discharge Elimination System (NPDES), the State of Texas recently promulgated a new state stormwater permit system that extends its authority to small construction activities disturbing soil areas of 1 acre or greater (TPDES general permit No. TXR150000). Under this rule, any permanent controls that are installed during construction must be described. Regulated MS4s must be compliant with the MS4 permit. Housekeeping measures (TXR040000, Part III §A, 2007) and BMPs (which may include new or existing structural or non-structural controls) must be identified and either continued or implemented with the goal of preventing or reducing pollutant runoff from municipal operations. Examples of municipal operations and municipally owned areas include but are not limited to:

- Park and open space maintenance.
- Street, road, or highway maintenance.
- Fleet and building maintenance.
- Stormwater system maintenance.
- New construction and land disturbances.
- Municipal parking lots.
- Vehicle and equipment maintenance and storage yards.
- Waste transfer stations.
- Salt/sand storage locations.

According to the TCEQ, operators of such activities “must develop and implement a SWPPP according to the requirements of this permit” (TXR050000, Part II §C, 2011), and one of the requirements is the physical structure “to reduce pollutants in stormwater discharges” (TXR050000, Part III §A.6[a]). The performance of stormwater BMP is particularly important when working under an industrial permit. Industrial permits, unlike construction permits, enumerate effluent limitations for hazardous metals in the stormwater runoff. Tables 1 and 2 show the numerical limitations of stormwater runoff to inland water and tidal water, respectively.

Table 1. Numeric Limitations for Discharges of Stormwater to Inland Waters.

(TXR050000, Part III §D.1[a])

Hazardous Metal (Total)	Daily Average (mg/L)	Daily Composite (mg/L)	Daily Maximum (mg/L)	Monitoring Frequency
Arsenic	0.1	0.2	0.3	1/yr
Barium	1.0	2.0	4.0	1/yr
Cadmium	0.05	0.1	0.2	1/yr
Chromium	0.5	1.0	5.0	1/yr
Copper (Cu)	0.5	1.0	2.0	1/yr
Lead (Pb)	0.5	1.0	1.5	1/yr
Manganese	1.0	2.0	3.0	1/yr
Mercury	0.005	0.005	0.01	1/yr
Nickel	1.0	2.0	3.0	1/yr
Selenium	0.05	0.1	0.2	1/yr
Silver	0.05	0.1	0.2	1/yr
Zinc (Zn)	1.0	2.0	6.0	1/yr

Table 2. Numeric Limitations for Discharges of Stormwater to Tidal Waters.

(TXR050000, Part III §D.1[b])

Hazardous Metal (Total)	Daily Average (mg/L)	Daily Composite (mg/L)	Daily Maximum (mg/L)	Monitoring Frequency
Arsenic	0.1	0.2	0.3	1/yr
Barium	1.0	2.0	4.0	1/yr
Cadmium	0.1	0.2	0.3	1/yr
Chromium	0.5	1.0	5.0	1/yr
Copper (Cu)	0.5	1.0	2.0	1/yr
Lead (Pb)	0.5	1.0	1.5	1/yr
Manganese	1.0	2.0	3.0	1/yr
Mercury	0.005	0.005	0.01	1/yr
Nickel	1.0	2.0	3.0	1/yr
Selenium	0.1	0.2	0.3	1/yr
Silver	0.05	0.1	0.2	1/yr
Zinc (Zn)	1.0	2.0	6.0	1/yr

Besides two general TPDES permits, TxDOT is also responsible for managing stormwater that degrades specific water resources protected by separate state codes. The Edwards Aquifer rule of 2005 (30 TAC Chapter 213) lists the construction of roads as one of the regulated activities and requires inclusion of the temporary and permanent BMPs in a construction plan. According to this rule, the permanent BMPs must remove "80 percent of the increase in the annual mass loading of total suspended solids from the site” (30 TAC §213.5[b][4][D][ii][I]) and “any spill of hydrocarbons or hazardous substances such as on a roadway” (30 TAC §213.5[b][4][G][ii][I]).

As regulatory requirements become more complex and stringent, TxDOT needs to research more state-of-the-art technology on treating stormwater from its facilities. Bioretention can be an alternative measure for TxDOT because of its effective performance of pollutant removal and wide applicability.

CHARACTERISTICS OF HIGHWAY RUNOFF

Highway runoff washes off pollutants generated by traffic activities including fluid leakage, pavement degradation, mechanical abrasion, and atmospheric deposition (Han et al., 2006). Thus, the primary pollutants for highway runoff are heavy metals, oil and grease (O&G), and TSS. Table 3 compares recently monitored stormwater quality data from two Texas highways with other national data.

Table 3. Comparison of Median Event Mean Concentrations (EMCs) for Texas Highway Runoff with National Data.

	Li et al. (2008)		Barrett et al. (1998)		Kayhanian et al. (2007)**		FHWA (1990)	
	College Station	Austin	Austin Urban	Austin Suburb	CA Urban	CA Rural	Urban	Rural
ADT	>50,000	35,000	58,150	8,780	>100,000	<30,000	>30,000	<30,000
Pollutants*								
TSS	84	84	129	91	158.9	69.9	142	41
TKN	1.990	1.670	-	-	2.5	1.5	1.83	0.87
NO_{3+2}-N	0.375	0.220	1.07	0.71	1.6	0.6	0.76	0.46
Total P	0.183	0.120	0.33	0.11	0.3 (NO_3-N)	0.2 (NO_3-N)	0.4 (PO_4-P)	0.16 (PO_4-P)
Cu	0.014	0.019	0.037	0.007	0.050	0.012	0.054	0.022
Pb	0.006	0.008	0.053	0.015	0.075	0.017	0.400	0.080
Zn	0.122	0.125	0.222	0.044	0.261	0.076	0.329	0.080
COD	72	86	130	39	-	-	114	49
O&G	-	-	4.2	1.4	-	-	-	-

*Unit: mg/L.
**Data show mean EMCs. Median EMCs were not available for this study.
ADT = average daily traffic, TKN = total kjeldahl nitrogen, COD = chemical oxygen demand, NO_{3+2}-N = nitrate + nitrite nitrogen, NO_3-N = nitrate-nitrogen, PO_4-P = phosphate phosphorus.

One of the characteristics of highway runoff is the first flush effect, in which the initial runoff of the storm carries more pollutants than the rest (Marsh, 2005; Han et al., 2006). Despite various threshold volumes reported, the first 0.5 inch of runoff is generally referred to as the first flush. Barrett et al. (1998) also observed a similar result in Texas highways. They found the concentrations of most pollutants in the first flush (3 to 5 mm) are higher than the event mean concentrations at two of three sampled highways in the Austin area.

Several studies discuss the impact of the antecedent dry period (ADP) on stormwater quality. The conventional theory suggests that the runoff quality is more degraded after long dry days because more pollutants have accumulated on the paved surface. For instance, Kayhanian et al. (2007) found a positive correlation between the ADP and 17 of 18 pollutant concentrations in highway runoff. Based on this result, they concluded that the ADP is a very consistent predictor for the quality of highway runoff. On the contrary, Li and Barrett (2008) found that the ADP is negatively related to stormwater runoff quality on highways with no curbs. Although they did not clearly understand the detailed mechanism, they speculated that the pollutant buildup in pavement mainly occurs after the storm event when the surface is still wet. Once the surface becomes dry, the turbulence of motor vehicles blows out the pollutants on the road surface, where roadside vegetation then degrades these. Thus, pollutant concentrations in highway runoff decrease after a longer ADP. This phenomenon is not observed at curbed highways where curb structure blocks pollutants' pathways during dry periods and they accumulate along the edge of pavement.

Traffic volume is another factor that determines the quality of highway runoff. The Federal Highway Administration (1990) reported that pollutant concentration is generally higher in runoff from urban highways than rural highways. Barrett et al. (1998) also found that, controlling other factors, runoff from highways with large average daily traffic (ADT) is contaminated more than runoff from those highways with smaller ADT. However, some biological pollutant concentrations, such as ammonia (NH_3-N) and TSS, were higher in rural sites. Kayhanian et al. (2003) argued that the atmospheric deposition of pollutants from nearby agricultural land may contribute to the EMCs of those pollutants in rural highway runoff.

All of the characteristics discussed above should be considered in bioretention design for treating highway runoff because bioretention has specific structural requirements depending on the type and concentration of stormwater runoff.

UNDERLYING PRINCIPLES

Bioretention systems use biomass to retain nutrients and other pollutants, and rely on the natural cleansing processes that occur in the soil-mulch-plant matrix. They also mitigate stormwater runoff close to the generation point, allowing local water tables to be naturally replenished. Pollutant removal includes physical, chemical, and biological processes. Removal mechanisms include filtration and sedimentation (physical), adsorption (chemical) by the soil media, and absorption (biological) through plant uptake and microbial activity (Hunt, 2003; Davis et al., 2001; Marsh, 2005).

Bioretention cells appear to have two advantages that detention and retention ponds do not have, regardless of vegetation. These cells have greater mass and surface area for sedimentation, filtration, and sorption; and the ability to physically suspend (trap) pollutants near their pollutant removal mechanisms, allowing for chemical and biological removal.

The chemical aspect involves *adsorption* (Rusciano and Obropta, 2007; Davis et al., 2001), which is "the process by which molecules of a substance, such as a gas or a liquid, collect on the surface of another substance, such as a solid. The molecules are attracted to the surface but do not enter the solid's minute spaces as in absorption" (Free Online Dictionary; "Adsorption," 2011). As mentioned in the *North Carolina Department of Environment and Natural Resources (NCDENR, 2005) Stormwater BMP Manual*, "A filter media with an organic or clay content, high cation exchange capacity (CEC), and a neutral to alkaline pH, has the highest adsorption potential, as well as, storage capacity." Clay, however, has a much slower percolation rate, and organic material may contain undesirable nutrients (pollutants) such as nitrogen (Li et al., 2010). Although sand allows for greater and more rapid percolation, its adsorption capacity is much less than clay, as it has less overall surface area. The low CEC also means sand has a low nutrient retention capacity.

It is presumed that since adsorption is the process by which molecules of a substance collect on the surface of another substance (Free Online Dictionary; "Adsorption." 2011), a saturation capacity of pollutants will occur at some point, which is currently unknown. Also, since sand has low water retention capacity, it is also limited in its ability to provide biological treatment of pollutants (Austin City Connection, 2011).

As mentioned, bioretention uses biological mechanisms for pollutant removal (plants use heavy metals and other runoff elements as nutrients); harvesting the plants could make the process perpetual, as would, perhaps, the intermittent replacement of sorptive soil media. This process has also been called phytoremediation: the use of plants to remediate contamination by the uptake of contaminated water by plants. Plants can be used to contain, remove, or degrade contaminants (Prince George's County, 2002).

Finally, an anoxic zone encourages denitrification (Kim et al., 2003), which can be a perpetual process if the IWS zone is maintained and there is sufficient organic matter and warm temperatures present (NCDENR, 2005). One study in a wetland (similar to an IWS zone) revealed that the planted wetland removed only 4–11 percent of nitrogen through vegetation uptake, whereas denitrification accounted for 89–96 percent (Lin et al., 2002).

HYDRAULIC PERFORMANCE

Similar to conventional detention basins, bioretention cells decrease the peak discharge by temporarily holding runoff water during a storm event. Figure 1 shows the typical hydrographs at the inlet and the outlet of the bioretention.

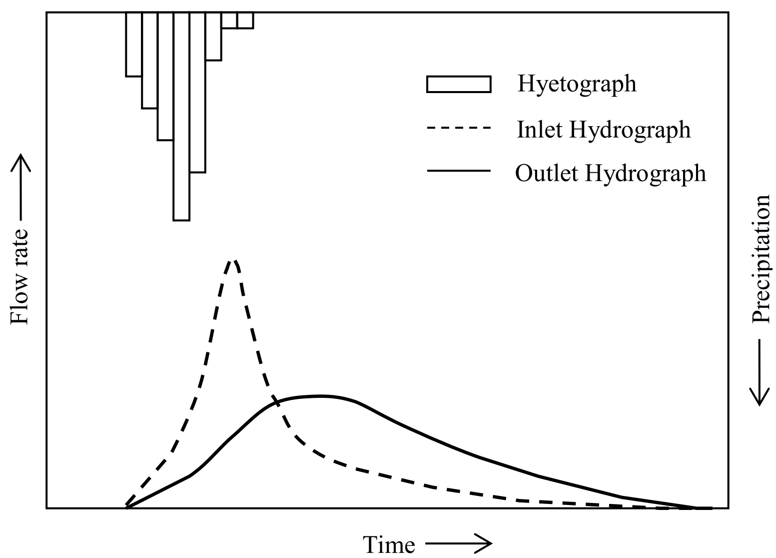


Figure 1. Hydraulic Effect of Bioretention.
(Modified from Dietz and Clausen, 2006)

In a field demonstration study, Hunt et al. (2007) found that bioretention reduced the magnitude of peak discharges by 96 percent. If no impermeable liner is installed in the bioretention cell, detained runoff can further infiltrate into the ground. By analyzing the water balance in the bioretention system, Sharkey and Hunt (2005) estimated that an unlined bioretention cell in North Carolina removed surface runoff by 93 percent during summer and 44 percent during winter. Although little research or documentation has been done on Non-IWS Cell detention time, a similar study on wetland microcosms found that residence time was indeed a factor in pollution removal rates (Ingersoll and Baker, 1998), and if long detention times are required, it may increase the volume requirement inside the bioretention area dedicated to the anaerobic zone (Hunt, 2003).

Unfortunately, little research has been done comparing detention pond residence time to bioretention residence time in Texas. However, Table 4 (Davis and McCuen, 2005) estimates the infiltration rates that could be applied to both stormwater mitigation techniques. This table can be used to compare a preconstruction infiltration rate (the main variable in detention time along with size and dimension) to a post-construction bioretention cell rate. If a clay site is replaced with a bioretention site, infiltration initially increases rapidly, but after the runoff reaches the underlying clay, the initial infiltration rate must be reapplied. Bioretention soils should have an infiltration rate from 1.5 to 4 (sand/loamy sand) inches per hour (Davis and McCuen, 2005).

Table 4. Ultimate Infiltration Rates (f_c) (Davis and McCuen, 2005).

(f_c) in/hr	**(f_c)**
5.0	Sand
1.5	Loamy sand
0.8	Sandy loam
0.4	Sandy clay loam
0.4	Loam
0.25	Clay loam
0.20	Silty loam
0.15	Sandy clay
0.15	Silt
0.08	Silty clay loam
0.04	Silty clay
0.02	Clay

WATER QUALITY PERFORMANCE

Although the removal performance varies by design and site conditions, bioretention is generally effective for heavy metals, oil and grease, and fecal coliform, and moderately effective for nutrient pollutants. Table 5 summarizes pollutant removal efficiencies reported previously. Table 6 was recently added to update the literate review since this project was ongoing.

Soluble forms of nutrients, such as nitrate (NO_3-N) and nitrite (NO_2-N), are difficult to separate from water by physical filtering processes. Nutrients can leach from various sources of organic matter in the bioretention cell, including vegetation, mulch, and soil. As a result, negative nutrient removal rate, i.e., increase in nutrients in effluents, could occur. Organic material, however, is essential for vegetation growth and microbial activities, which permanently remove nutrients filtered in soil media. Currently, there is no standard for the proper amount of organic material. It should be determined based on site conditions.

The performance of bioretention for N removal is unclear. NO_3-N and NH_3-N removal rates range from 0 to 95 percent and −1 to 85 percent, respectively, summarized from many field monitoring studies. Even in cases where bioretention showed a higher removal rate of either NO_3-N or NH_3-N, the mass of total nitrogen (TN) in effluent did not significantly change, suggesting that bioretention simply changes the chemical species from one to another. For instance, Hunt et al. (2006) monitored performances of two bioretention cells. One showed a high removal rate for NO_3-N (75 percent) but a low rate for NH_3-N (−1 percent), while the other had a high removal rate for NH_3-N (86 percent) but a low rate for NO_3-N (13 percent). TN removal rate, however, was low in both cells (around 40 percent). Other studies also reported relatively low TN removal rates (50 percent on average).

Denitrification, occurring in saturated soils, is known to be a pathway of soil N removal. In the absence of oxygen (O_2), denitrifying bacteria use nitrate as an electron acceptor for respiration. The process converts nitrate into nitrous oxide (N_2O) and finally to nitrogen gas (N_2). When nitrogen exists in ammonium (NH_4-N) or ammonia (NH_3-N) form, it must first be converted to nitrite and then nitrate by nitrification for denitrification to then occur. The reactions often appear simultaneous and proceed rapidly to the nitrate form; therefore, nitrite levels usually appear low.

Kim et al. (2003) first installed an internal wet zone at the bottom of a bioretention cell. Since then, many studies have applied this approach to create an anaerobic environment to promote the denitrification process. However, only a few studies have shown that the wet zone had a positive effect. The lack of a positive effect of the internal wet zone might be due to the short retention time of stormwater, which does not allow denitrification to take place. For instance, Kim et al. (2003) found that if water remained more than a week in the wet zone, NO_3-N was almost completely removed from the water. No significant removal by the wet zone was observed if the residence time was less than a day. These findings imply that a wet zone will not result in additional N removal in practice because stormwater needs to be discharged from the bioretention cell within a day.

Because soil media is easily saturated by P, the removal rate of P depends on the initial concentration of P in the soil media (Hunt et al., 2006). Half of the literature reported elevated P concentration in effluent from bioretention facilities. The removal rate for total phosphorus (TP) varies from –240 percent to 87 percent. To improve the performance of bioretention, Zhang et al. (2006) added fly ash to the soil to provide cations that precipitate phosphate (PO_4-P) into solid, such as calcium phosphate ($CaPO_4$). However, fly ash rapidly decreases the soil infiltration rate, so they recommended limiting fly ash to no more than 5 percent of the soil media. Media mixed with 5 percent fly ash removed 85 percent of TP, compared to 2 percent without fly ash amendment. In a study, Mortula and Gagnona (2007) indicated that phosphorus removal using oven-dried alum residual solids was effective and comparable to granular activated carbon; however, increased aluminum leaching was seen.

Bioretention very effectively removes heavy metals. Removal rates of copper (Cu), zinc (Zn), and lead (Pb) range from 43 to 99 percent, 31 to 99 percent, and 54 to 99 percent by mass, respectively. The mulch layer adsorbs most metals. Dietz and Clausen (2006) found that 98 percent of Cu, 16 percent of Zn, and 36 percent of Pb of total mass removed by bioretention are adsorbed on mulch.

Bioretention also removes oil and grease effectively. This ability of bioretention is particularly useful for applications to highway runoff. In a laboratory study, Hong et al. (2006) reported that 1.2 inches of mulch layer removed 80 percent of oil and grease. A field demonstration study also showed similar results. Hsieh and Davis (2005) found that bioretention removed 99 percent of oil and grease from parking lot runoff. Soil microbial activity permanently decomposes hydrocarbons filtered on soil particles.

The performance of TSS removal is an important criterion for selecting BMPs to treat runoff from construction sites. Bioretention methods show a relatively good removal of TSS. Removal rate is between 60 and 90 percent, but some literature shows that suspended solids may increase when the bioretention cell is newly constructed. Fine particles in media are washed off with effluent (Hunt et al., 2006). Leaching of suspended solids gradually decreases as the soils stabilize. Bioretention effectively removes fecal coliform and *E. coli*. Laboratory experiments showed a 96 percent removal rate for fecal coliform (Rusciano and Obropta, 2007). Kim et al. (2012) also reported positive *E. coli* removals using large-scale laboratory experiments. Hunt et al. (2007) reported in a field demonstration study that bioretention removes 69 percent of fecal coliform and 71 percent of *E. coli*.

Table 5. Percent Mass Removal Efficiencies from 2001–2007 for Various Pollutants.

(Adapted from Aitkenhead-Peterson and Volder, 2010, pp. 422–423)

	Experiment	TSS	Fecal coliform	*E. coli*	Cu	Pb	Zn	Fe	O&G
Davis et al. (2001)	Lab				>99	>99	>99		
Davis et al. (2003)	Field				43~97	54~70	64~>95		
Kim et al. (2003)	Lab (IWS)								
Hsieh and Davis (2005)	Lab	2 ~ >96				66~>98		>96	>96
	Field (without IWS, with liner)	−103				>94		>99	>99
	Field (with IWS, with liner)	10				>95		>99	>99
Davis et al. (2006)	Lab								
	Field								
Hong et al. (2006)	Lab (mulch only)							80	80
Hsieh et al. (2007)	Lab	>94							
Davis (2007)	Field (without IWS)	54			77	84	69		
	Field (with IWS)	59			83	88	27		
Dietz and Clausen (2005)	Field								
Dietz and Clausen (2006)	Field (without IWS)								
	Field (with IWS)								
Sharkey and Hunt (2005)	Field (without IWS, without liner)								
	Field (without IWS, with liner)								
	Field (with IWS)								
Hunt et al. (2006)	Field (without IWS, low P-index soil)								
	Field (without IWS, high P-index soil)	−170			99	81	98		
Hunt et al. (2007)*	Field (with IWS, medium P-index soil)	60	69	71	54	31	77	−330	
Culbertson and Hutchinson (2004)	Lab (bare ground)								
	Lab (daylily planted)								
	Lab (switchgrass planted)								
Zhang et al. (2006)	Lab (sand only)								
	Lab (5% fly ash)								
Dougherty et al. (2007)	Field (without IWS)								
	Field (with IWS)								
Rusciano and Obropta (2007)*	Lab	91.6	95.9						

*Only report the EMCs.

Table 5. Percent Mass Removal Efficiencies from 2001–2007 for Various Pollutants. (Continued)

	Experiment type	NO_3-N	NH_3-N	TKN	Organic N	TN	TP	BOD-5
Davis et al. (2001)	Lab	24	79	68		68	81	
Davis et al. (2003)	Field							
Kim et al. (2003)	Lab (IWS)	70~90						
Hsieh and Davis (2005)	Lab	1~43	2~26				4~85	
	Field (without IWS, with liner)	31	37				0	
	Field (with IWS, with liner)	0.1	44					
Davis et al. (2006)	Lab	96		94		96	92	
	Field	15~16		52~67		49~59	65~87	
Hong et al. (2006)	Lab (mulch only)							
Hsieh et al. (2007)	Lab						47~68	
Davis (2007)	Field (without IWS)	95					77	
	Field (with IWS)	90					79	
Dietz and Clausen (2005)	Field	35.4	84.6	31.2	21.3	32	−110.6	
Dietz and Clausen (2006)	Field (without IWS)	81	86	22	6	68	−104	
	Field (with IWS)	87	69	5	−9	69	−98	
	Field (without IWS, without liner)	26	77	27		27~52	38	
Sharkey and Hunt (2005)	Field (without IWS, with liner)	0.52	84	57		60	53	
	Field (with IWS)					52	25	
Hunt et al. (2006)	Field (without IWS, low P-index soil)	13	86	45		40	65	
	Field (without IWS, high P-index soil)	75	−0.99	−4.9		40	−240	
Hunt et al. (2007)*	Field (with IWS, medium P-index soil)	−5	73	44		32	31	63
Culbertson and Hutchinson (2004)	Lab (bare ground)	−200					−700	
	Lab (daylily planted)	−155					−867	
	Lab (switchgrass planted)	−37					−400	
Zhang et al. (2006)	Lab (sand only)						2	
	Lab (5% fly ash)						85	
Dougherty et al. (2007)	Field (without IWS)					32~71	32~71	
	Field (with IWS)					14~30	15~30	
Rusciano and Obropta (2007)*	Lab							

*Only report the EMCs.
BOD-5 = 5-day biological oxygen demand.

Table 6. Percent Mass Removal Efficiencies from 2008–2011 for Various Pollutants.

	Experiment	TSS	Fecal coliform	*E. coli*	Cu	Pb	Zn	Fe	O&G
Li and Davis (2009)	Field	96	95	94	65	83	92		
	Field	99	100	100	96	100	99		
Jaber and Guzik (2009)	Field				100		83		
Line and Hunt (2009)	Field (0.79 m sand and soil mixture)	~79			−50	64	82		
Hatt et al. (2009)	Field								
Greene et al. (2009)	Field (silt-loam with vegetation)	−94			−171				
	Field (silt-loam with earthworms)	77			−124				
	Field (silt-loam with veg. and earthworms)	28			62				
	Field (silt-loam control)	95			93				
Li et al. (2009)	Field (0.5–0.8 m sandy loam)	88	0	57	31	55	78		
	Field (0.9 m sandy clay loam)	88	50	0	0	0	80		
Yang et al. (2009)*	Field IWS Biphasic 1				~100%	~100%	~100%		
	Field IWS Biphasic 1								
Brown and Hunt (2010)	Field (undersized cells, 0.6 m media)	71							
	Field (undersized cells, 0.9 m media)	84							
	Field (repaired cells, 0.6 m media)	79							
	Field (repaired cells, 0.9 m media)	89							
Chapman & Horner (2010)	Field (street side)	87			80	86	80		92
Luell et al. (2010)	Field IWS (51 cm depth w 0.6 m–small)	55							
	Field IWS (51 cm depth w 0.6 m–big)	63							
Brown and Hunt (2011)	Field 0.6-m Media Post-Repair Period	77							
	Field 0.9-m Media Post-Repair Period	88							
	Field IWS (Sandy-clay-loam) 1 m depth	95							
	Field IWS (Sand) 1 m depth	99							
Debusk et al. (2011)*	Field IWS (sand-clay + compost)	~100%							
Trowsdale & Simcock (2011)	Field (sand, subsoil and topsoil–1.15 m)	High			Low	High	High		

Only report the EMCs.
* No or low effluent so calculated as 100% "Absorption"

Table 6. Percent Mass Removal Efficiencies from 2008–2011 for Various Pollutants (Continued)

	Experiment type	NO_3-N	NH_3-N	TKN	Organic N	TN	TP	BOD-5
Li and Davis (2009)	Field	−108		25		−3	−36	
	Field	99		87		97	100	
Jaber and Guzik (2009)	Field	83					65	
Line and Hunt (2009)	Field (0.79 m sand and soil mixture)			28		−3	44	
Hatt et al. (2009)	Field		54			0.1		
Greene et al. (2009)	Field (silt-loam with vegetation)					−1205	85	
	Field (silt-loam with earthworms)					−1541	84	
	Field (silt-loam with veg. and earthworms)					−2590	85	
	Field (silt-loam control)					−736	96	
Li et al. (2009)	Field (0.5–0.8 m sandy loam)	−170		−11		−53	−200	
	Field (0.9 m sandy clay loam)	86		−30		−0	0	
Yang et al. (2009)	Field IWS Biphasic 1	Low					~100%	
	Field IWS Biphasic 1							
Brown and Hunt (2010)	Field (undersized cells, 0.6 m media)		78			12	5	
	Field (undersized cells, 0.9 m media)		79			13	44	
	Field (repaired cells, 0.6 m media)		78			35	12	
	Field (repaired cells, 0.9 m media)		87			32	19	
Chapman & Horner (2010)	Field (street side)	23~73				63	67	
Luell et al. (2010)	Field IWS (51 cm depth w 0.6 m–small)		67	35		45	−4	
	Field IWS (51 cm depth w 0.6 m–big)		77	48		56	−5	
Brown and Hunt (2011)	Field 0.6-m media post-repair period					31	11	
	Field 0.9-m media post-repair period					26	26	
	Field IWS (sandy-clay-loam) 1 m depth					88	85	
	Field IWS (sand) 1 m depth					99	99	
Debusk et al. (2011)	Field IWS (sand-clay + compost)					99*	99*	
Trowsdale & Simcock (2011)	Field (sand, subsoil and topsoil–1.15 m)							

Only report the EMCs.

* no or low effluent so calculated as 100% “Absorption”

DESIGN CONSIDERATIONS

Unlike other BMPs, survival of vegetation under specific climate conditions is an important consideration factor in the design of a bioretention facility. Since bioretention collects water from the surrounding areas, plants in the bioretention cell suffer from frequent inundation, which creates anoxic conditions in the root zone. Thus, the Prince George's County (2002) manual recommends water pooling on the surface to be discharged within 12 hrs (preferably 6 hrs). To ensure this discharge rate, PGC's manual further recommends that soil used for bioretention should have a minimal infiltration rate of 1 inch/hr and the depth of the surface water pool above soil layer should be less than 1 ft.

Due to its aesthetic benefit, bioretention is particularly suitable for urban areas. Considering its shallow water pooling depth and the high land price usually encountered in urban areas, the bioretention facility size is often designed to treat the first flush only. Typical size needed for this volume is 5 percent of the watershed area. Runoff exceeding this capacity is bypassed via an emergency spillway.

A bioretention cell typically includes three to four layers of different materials. Figure 2 illustrates the vertical profile of a bioretention cell. The top layer is vegetation. Several bioretention manuals including those of PGC (2002), Wisconsin Department of Natural Resources (2003), and Puget Sound Action Team (2005) provide lists of vegetation suitable for their climates. A surface layer is mulch, which physically absorbs pollutants as well as provides nutrients for vegetation. However, thick mulch may interrupt the exchange of air between atmosphere and soil, which could result in suffocation of plant roots. In addition, mulch is a source of nutrients and might cause high N and P concentrations in the effluent. Accordingly, PGC's (2002) manual recommends the mulch layer be a maximum 2 to 3 inches.

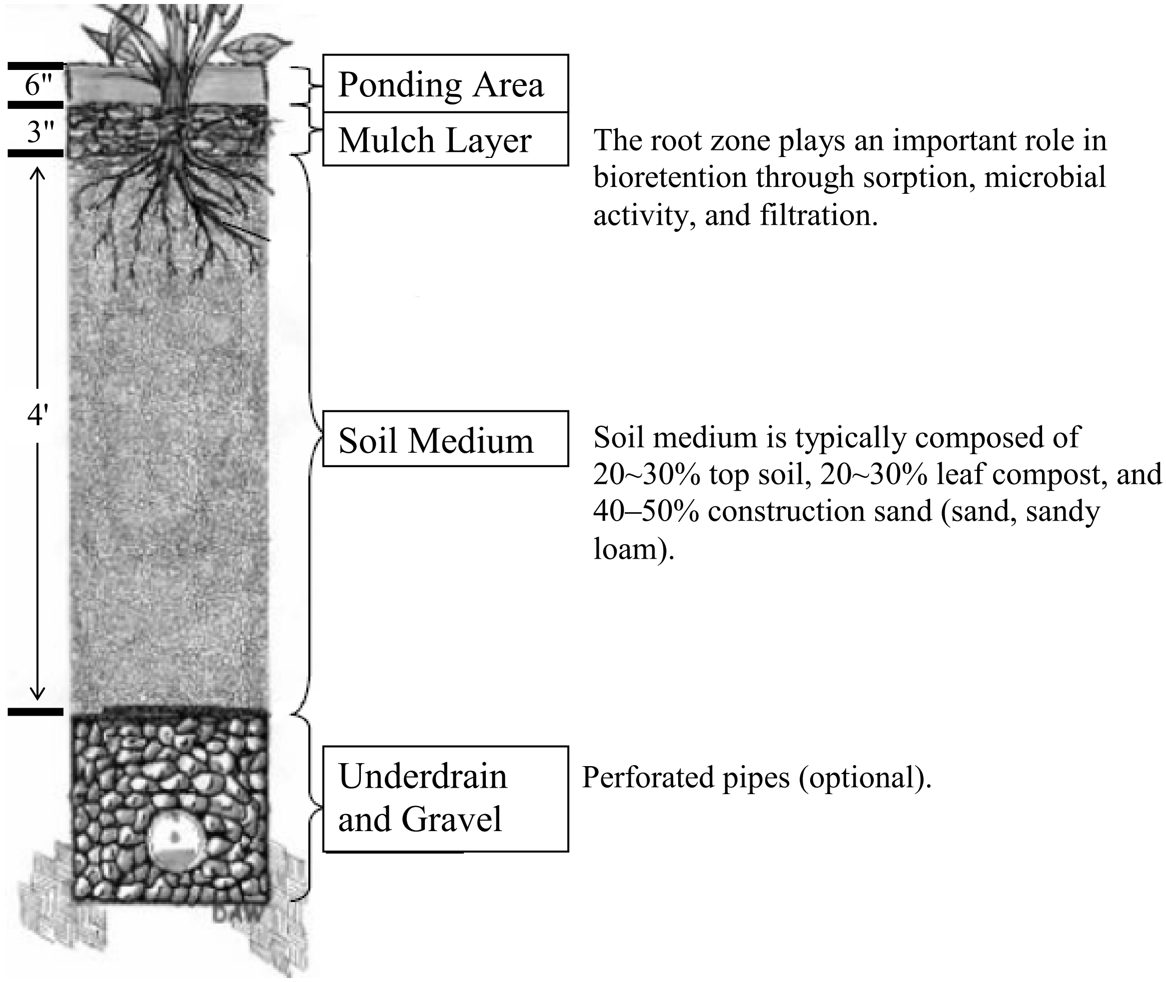


Figure 2. Vertical Profile of a Bioretention Cell.
(Modified from PGC, 2002, pp. 1–16)

A key component of bioretention is the soil media. PGC's (2002) manual suggests a soil texture of 50–60 percent sand, 20–30 percent compost, and 20–30 percent topsoil. Hsieh and Davis (2005) also found that 1.8~2.5 ft of sand and sandy loam (infiltration rate of 1.5 inch/hr) shows the best pollutant removal performance. They recommended clay content not to exceed 5 percent because not only does excessive clay decrease the infiltration rate, but it also creates preferential paths for runoff (Hsieh and Davis, 2005). Pollutants quickly saturate soil particles along the preferential paths. As a result, the pollutant removal effectiveness decreases shortly after the installation.

An underdrain pipe may or may not be installed, depending on the site drainage condition. If *in-situ* soil contains too much clay content and/or groundwater is too shallow, the bioretention facility needs the underdrain pipe to ensure proper discharge of the filtered water. PGC's manual also advises using an underdrain pipe if *in-situ* soil has infiltration rates greater than 1 inch/hr and if the water table is within 2 ft below the bottom of the bioretention cell. If the bioretention cell includes the underdrain pipe, it should be covered either by pea gravel (3-9 inches thick) or geotextile fabric to prevent pipe clogging from soil particles. A plastic liner can be added at the bottom of the bioretention cell if groundwater contamination is a concern.

Applicability

While the construction cost of bioretention per acreage is higher than other stormwater BMPs, such as detention ponds, the bioretention method has a lower treatment cost per pollutant because it requires a relatively small area of land. Wossink and Hunt (2003) found that the construction cost of a bioretention cell was approximately $5,000 per 1000 ft^2 in 2001. At a site where the land price is high and watershed size is less than 10 ac, the estimated cost per acre treated by bioretention is two to six times lower than other BMPs (Wossink and Hunt, 2003). Noting that this cost does not include aesthetic benefit, bioretention is best applicable in urban areas. Also, curbs and gutters often bound urban highways, and shield the dissipated pollutants from vehicle turbulence. Since these structures may result in generally higher pollutant concentrations in runoff, urban stormwater BMPs are required to treat runoff with higher pollutant concentrations.

For rural highways where runoff quality is not as degraded as urban counterparts, however, BMPs with less engineered structures, e.g., stormwater wetlands, seem more cost-effective. Bioretention may be an overinvestment because it requires more engineering cost. Economies of scale further lower the cost per acre for stormwater wetland as the watershed size increases. As such, bioretention is less cost-effective for rural highways that often have large watersheds and less polluted runoff.

Characteristics of pollutants in runoff are another consideration when selecting BMPs. Bioretention shows the best performance for TSS and heavy metals, and performs moderately for 18 nutrients. In small watersheds, the estimated costs per percent removal of TSS and heavy metals are one to three times lower than those of other BMPs (Wossink and Hunt, 2003). However, the costs per percent nutrient removal are higher for bioretention. As mentioned, the concern of highway runoff, especially in urban areas with a large traffic volume, is not nutrients.

Thus, researchers weighed the removal cost of heavy metals more than the cost of nutrient removal. For rural highways in which agricultural pollutants are air-deposited, other BMPs that more efficiently remove nutrients are more cost-effective.

Given that the size of transportation facilities rarely exceeds 10 ac and the primary pollutants are not nutrients, researchers concluded that bioretention can be the most cost-effective stormwater BMP, especially in urban and suburban areas. Particularly, bioretention is best applicable to roadside medians and maintenance yards but is less applicable to large rural interchanges. Table 7 summarizes the applicability of bioretention to three different TxDOT ROWs (interchange, roadside median, maintenance yard) by taking into account watershed size, land availability, and pollutant removal efficiency.

Table 7. Applicability of Stormwater BMPs to Various TxDOT Facilities.

	Rural	**Urban**
Interchange (>10 ac)	SW	SW
Interchange (≤9 ac)	B, SW	B
Urban Roadside Median	-	B
Rural Roadside with No Curb	SW, DP	-
Maintenance Yard	B, SW	B

SW : Stormwater wetland.
B : Bioretention.
DP : Detention/retention pond.

Watershed and Storm Design

According to the PGC (2002) manual, "The strategic, uniform distribution of bioretention facilities across a development site results in smaller, more manageable subwatersheds, and thus, will help in controlling runoff close to the source where it is generated." Yu and Langan (1999) further emphasized the watershed scale approach when constructing roads or other facilities "near or within watersheds supplying drinking water reservoirs." Bioretention is ideal in smaller watersheds since approximately 5 percent of the watershed should be dedicated to the bioretention cell (Sharkey and Hunt, 2005) to greatly enhance the stormwater effluent quality of the first flush. However, a larger bioretention cell may be needed if controlling stormwater quantity is also an objective.

An approximate design storm is required to have an idea about what size of bioretention facility is needed for a particular watershed. For the City of Austin (Austin City Connection, 1.6.2., 2011), "The primary control strategy for water quality basins is to capture and isolate at least a minimum volume of stormwater runoff for treatment, and to release the treated volume in forty-eight (48) hours or as specified. The minimum volume is the first one-half (0.5) inch of runoff plus an (0.1) inch for each ten (10) percent increase of impervious cover over twenty (20) percent within the drainage area to the control. This depth of runoff from the contributing drainage area to the control [is] referred to as the 'Water Quality Volume,' [which] must consist of runoff from all impervious surfaces such as roadways, parking areas and rooftops, and all developed pervious areas." Once again, though, the size of the bioretention cell depends on the overall objective as much as the flow; designers must assess early on whether stormwater quality, quantity, or both are to be addressed. The size of the bioretention cell is directly related to the answer to this question.

Soil Media

The contrasting properties of filtration and sorption are issues with soil media. Sand allows for effective and rapid filtration but retains less sediment and pollutants. Clay is difficult to permeate but has a very high sediment and pollutant sorption rate. It is recommended that clay content be less than 5 percent to "allow surface ponding to completely drain within three 3–4 hours" (Huber et al., 2006; Davis and McCuen, 2005). The City of Austin (Austin City Connection, 2011) has the following criteria for soil media (see Table 8).

Table 8. Soil Media Criteria.

[Adapted from Austin City Connection (2011)]

Properties	Recommended level
Porosity	0.45
Saturated Hydraulic Conductivity	2 inch/hr
Percent Organic Matter (by weight)	1–4%
Cation Exchange Capacity	10 meq/100 g
Texture Analysis (Sand, clay, & sand + clay)	(70–90%, 2–10%, 25%)

A uniformly mixed soil media, free of foreign seed material, with a pH between 5.5 and 6.5 is ideal. Although the City of Austin recommends 2 inches/hr hydraulic conductivity, other literature recommendations list 1–1.5 inches/hr, with approximately 80 percent compaction

(Huber et al., 2006). Although many sources recommend compost and organic matter (1.5–3 percent), further research suggests this may increase nutrient N and P (and K) leaching (Huber et al., 2006; Li et al., 2010). It also may imbalance the C:N ratio, as most forms of organic matter (mulch, wood chips, newspapers, etc.) are high in carbon, which demands an increase in nitrogen for biological processes in the plants to occur. Imported soil should be free of weed seed.

Vegetation

Plants contribute to pollutant removal directly by degradation and consumption of certain pollutants as nutrients and necessary minerals (metals), and indirectly as they interact with the soil rhizosphere and soil microbial communities through organic matter input, modifying water retention, and altering the pH (Schnoor et al., 1995; Salt et al., 1998).

Vegetation is expected to extend the longevity of the bioretention cell by uptake of nutrients and heavy metals captured in soil media. Davis et al. (2001) discovered that the concentrations of Cu, Pb, and Zn in plant tissues increased by a factor of 6.3, 7.7, and 8.1, respectively, after 31 synthetic stormwater runoff experiments. From the results, they estimated that, in the long run, vegetation uptakes 90 percent of N filtered by soil media (Davis et al., 2006).

Another role of vegetation is to enhance the water and pollutant removal performances by root systems. Culbertson and Hutchinson (2004) compared the performances of bioretention with and without vegetation and found that the addition of vegetation enhances both water and NO_3-N removal rates by up to a factor of 2 and 3, respectively. Vegetation also provides shade and dissipates heat by increasing evapotranspiration and, therefore, decreases effluent temperature (Jones et al., 2007). Vegetation, as it dies, also provides organic matter, which increases sorption as well as provides a food source for anaerobic bacteria in the case of denitrification in IWS zones (NCDENR, 2005).

Culbertson and Hutchinson (2004) examined different species of vegetation in the Midwest climate, which revealed that switchgrass (*Panicum virgatum*) and daylily (*hemerocallis spp.*) successfully established in a bioretention environment. However, there is still much that is unknown about which plants are most appropriate for bioretention in Texas. The field testing chapter “Discussion-Vegetation” includes updated details on vegetation considerations. Appendix A also includes a recommended list of bioretention cell vegetation species.

CHAPTER 3: LARGE-SCALE PILOT EXPERIMENT

INTRODUCTION

As the combination of physical, chemical, and biological processes within the separate layers of a bioretention cell remove pollutants, the removal efficiencies of different pollutants by bioretention vary widely depending on soil mixtures, plant materials, and other site conditions. To evaluate the performance of bioretention under such complexity, previous studies have employed various test methodologies including batch tests, column tests, pilot tests, and field tests. Details of these testing methods can be found in the previous technical report (Li et al., 2010b). The test method used in this project was a pilot test, which is a large-scale experiment in a laboratory setting. This type of test constructs a microcosm of bioretention, which allows not only vertical but also horizontal movement of water.

MATERIALS AND METHODS

Researchers used synthetic stormwater runoff to test the bioretention designs with and without IWS layers. The synthetic runoff simulated the quantity and quality of stormwater runoff from Texas highways. The water quality of the synthetic runoff mimicked the pollutant concentrations of highway runoff that Li et al. (2008) measured. Chemicals described in Table 9 were mixed with tap water and continuously agitated during a 3-hr experiment. To simulate varying storm intensity within a storm event, flow rates changed hourly. The hourly flow rates were calculated by assuming that (1) the drainage area was 334.5 m^2 (3,600 ft^2), which is 100 times larger than the surface area of the bioretention box; (2) the runoff coefficient of the drainage area was 0.9; (3) the design storm was the mean 3-hr storm for Brazos County, Texas; and (4) the design storm followed a Soil Conservation Service (SCS) Type III rainfall pattern (Asquith et al., 2006). A water pump regulated the target flow rates.

Influent was grab-sampled every hour to verify that the chemicals were uniformly mixed with the tap water. Effluent was sampled every 30 min until it became negligible. Effluent flow rate was measured in 1 min intervals using a Teledyne ISCO 730 bubbler flow module attached to a 22.5° V-notch weir box. Before each experiment, soil moisture contents were measured at a

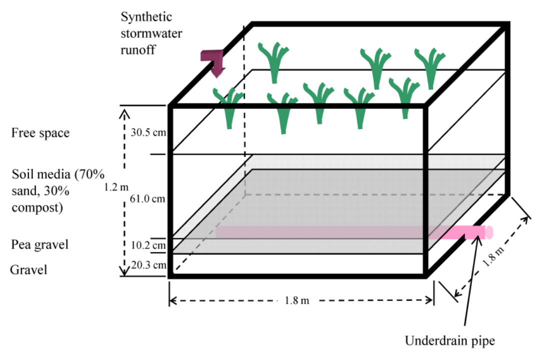
6 cm (2.4 inches) depth from the surface at five randomly selected locations using Delta-T Devices ThetaProbe Type ML2x.

Water samples collected at influent and effluent locations were transported to the Environmental Biotechnology Laboratory (EBL) at Texas A&M University and refrigerated at 4°C until analysis. For TSS, 300 mL subsamples taken from original grab samples were agitated using a magnetic stir bar. Then, 100 mL subsamples were passed through a 0.47 mm Whatmann glass fiber filter. The weight change of the filter after addition of TSS was measured. For other analyses, samples were filtered using a 0.22 μm pore size membrane filter. For metal analysis, the filtrates were acidified with nitric acid (HNO_3, trace metal grade) to pH 2. Analyzed pollutants were Cu, Zn, Pb, TSS, TN, and TP. Table 9 describes the analysis methods.

The five bioretention cells were identical in size and filling materials but varied in vegetation types. The boxes measured 1.8 m (6 ft) long, 1.8 m (6 ft) wide, and 1.2 m (4 ft) deep and were made from steel garbage dumpsters. These were coated with truck-bed spray liner (40 percent polyurethane and 60 percent polyurea) to prevent corrosion and then filled (from the bottom) with a 10.2 cm (4 inches) diameter perforated polyvinyl chloride (PVC) pipe for the underdrain, a 20.3 cm (8 inches) deep gravel layer, a 10.2 cm (4 inches) deep pea gravel layer, a 61.0 cm (2 ft) deep soil media, and a 30.5 cm (1 ft) deep free space for water ponding (see Figure 3). The gravel and pea gravel layers prevented clogging of the underdrain pipes by fine sediments. The soil media consisted of 70 percent sand and 30 percent compost by volumetric ratio (see Table 10). The depth of the wet zone in the soil media was 1 ft. The boxes were continuously irrigated to maintain the water level because water was lost via evapotranspiration and leakage through the bottom of the boxes. The infiltration rate of the sand/compost soil media was 24.8 cm/hr (9.75 inches/hr). Table 10 also shows the physicochemical properties of the soil media. Researchers planted each of the five boxes with different species compositions (three grass mixes, one shrub mix, and one without vegetation; see Table 11). The four vegetated boxes were left unmaintained, while the unvegetated one was continuously maintained by removing weeds. To simulate real-world conditions, the vegetation communities were not managed except the control box, which had all vegetation removed once every two weeks.

The boxes were first used for testing the design without an IWS layer and later converted to the other design with an IWS layer for comparison. Researchers converted the boxes to include an IWS layer by inverting the outlets of the underdrain pipes by 61.0 cm (2 ft) upward from the bottom of the boxes (see Figure 3). Because the bottom 30.5 cm (1 ft) of the boxes was gravel and pea gravel layers, this modification created 30.5 cm (1 ft) deep IWS layers in the soil media. During the experiment period, a water depth of 61.0 cm (2 ft) in the IWS layer was maintained by adding water into the inverted pipe regularly (see Figure 3).

(a) Schematic view of a bioretention box



(b) Bioretention boxes with vegetation (1 yr after planting)

(*c*) Illustration of IWS layer

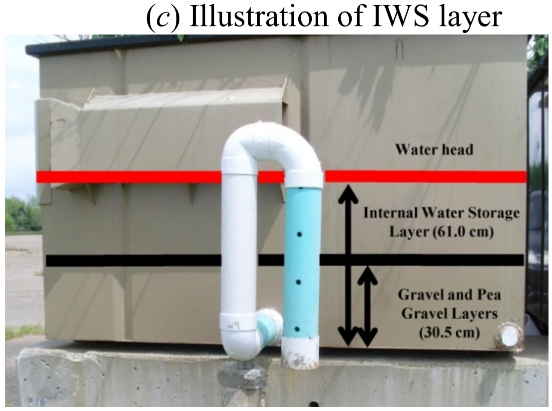


Figure 3. Pilot Test Bioretention Boxes (Photos adapted from Li et al., 2012).

Table 9. Water Quality of Synthetic Stormwater Runoff.

Pollutants	Target concentrations*	Chemicals used to make synthetic runoff	Analytical methods for water samples**
Cu	0.02 mg/L	$CuSO_4 \cdot H_2O$	ICP-MS
Zn	0.13 mg/L	$ZnSO_4 \cdot H_2O$	ICP-MS
Pb	0.08 mg/L	$Pb (NO_3)_2$	ICP-MS
TSS	98.17 mg/L	Silica	Filtering/oven drying
Phosphorus (TP, HPO_4)	0.17 mg/L	Na_2HPO_4	Ascorbic acid method, IC
Nitrogen (TN, NH_4-N, NO_3-N, NO_2-N)	1.84 mg/L	0.15 mg/L $NaNO_2$, 0.15 mg/L $NaNO_3$, 0.77 mg/L NH_4Cl	Persulfate digestion method, Phenate method, IC

*Data from (20).
**Data from (26).
ICP-MS = inductively coupled plasma–mass spectroscopy, IC = ion chromatography.

Table 10. Physiochemical Properties of the Soil Media.

Physicochemical property	Contents
pH	7.6
NO_3-N	14 ppm
P	191 ppm
K	190 ppm
Ca	4900 ppm
Mg	183 ppm
S	21 ppm
Na	147 ppm
Fe	11.5 ppm
Zn	9.24 ppm
Mn	7.09 ppm
Cu	1.16 ppm
Organic matter	2.90%
Sandy loam	81% sand, 2% silt, 17% clay

Table 11. Vegetation Species Planted in Five Bioretention Boxes.

Box	Species		Planting/seeding rates (kg/ha)
	Scientific name	Common name	
Shrub	*Ilex vomitoria*	Stroke Dwarf Yaupon Holly	3 counts
	Morella cerifera	Wax Myrtle	3 counts
	Leucophyllum frutescens	Texas Sage (Cenizo)	3 counts
TxDOT Seed mix for sandy soil (Bryan District)	*Cynodon dactylon*	Bermudagrass	1.7
	Eragrostis curvula	Weeping Lovegrass (Ermello)	0.7
	Eragrostis trichodes	Sand Lovegrass	0.7
	Leptochloa dubia	Green Sprangletop	0.3
	Paspalum notatum	Bahia grass (Pensacola)	8.4
	Coreopsis lanceolata	Lance Leaf Coreopsis	1.1
Native grass seed mix	*Bouteloua curtipendula*	Sideoats Grama	11.2
	Leptochloa dubia	Green Sprangletop	5.6
	Schizachyrium scoparium	Little Bluestem	5.6
	Eragrostis trichodes	Sand Lovegrass	5.6
	Desmanthus illinoensis	Illinois Bundleflower	7.9
	Chamaecrista fasciculata	Partridge Pea	5.6
Bermudagrass	*Cynodon dactylon*	Bermudagrass	18.6
Unvegetated	-	-	-

DATA ANALYSIS

To examine peak discharge reduction by the bioretention boxes, the stormwater runoff detention times were estimated using the centroid method (Haan et al., 1994):

Equation 1

$$Detention\ time = T_{out} - T_{in}$$

where T_{in} and T_{out} are the centroids of influent and effluent hydrographs, respectively. T_{in} and T_{out} were calculated by:

Equation 2

$$T_{in} = \sum \left(influent_t \times storm\,duration_t \right) / \sum influent_t$$

$$T_{out} = \sum \left(effluent_t \times storm\,duration_t \right) / \sum effluent_t$$

where $influent_t$ and $effluent_t$ are influent and effluent flow rates at time *t* in L/min, respectively, and $storm\,duration_t$ is the time in minutes since the beginning of the experiment.

Pollutant removal efficiencies were estimated by the difference in total masses of a pollutant between influent and effluent:

Equation 3

$$Removal\,efficiency = 1 - \left[\sum_{\forall t} C_{out,t} \times effluent_t \times \Delta t \Big/ \sum_{\forall t} C_{in,avg} \times Influent_t \times \Delta t \right]$$

where $C_{in,avg}$ is an average concentration of influent samples of the bioretention box in mg/L, $C_{out,t}$ is an effluent concentration at time *t* in mg/L, and Δt is the time interval of the hydrograph, i.e., 1 min.

NON-IWS CELL TESTING

Hydraulic Performance

Figure 4 shows influent and effluent hydrographs of the five pilot boxes and the detention times for the first experiments (July 14–19, 2009). The result indicates that all boxes reduced the peak flow, but the degree of reduction varied. The control box had better performance in flow reduction than the four vegetated boxes. In these boxes, surface ponding occurred only during the second hour, when the influent flow rate reached 10.25 gpm, and quickly disappeared once the flow rate decreased to 1.95 gpm. Effluents were also quickly reduced and merely dripped 1 hr after the influent ceased (see Figures 4[a]–4[d]).

In contrast, the control box showed water ponding immediately after the influent began. During the second hour, ponding depth exceeded 1 ft and overflowed over the pilot box. Overflow occurred between 80 and 124 min. Effluent lasted for 4 hrs after influent ceased, i.e., 7 hrs after the beginning of the experiment (Figure 4[e]). Detention times showed that the control box retained the runoff much longer than the four vegetated boxes. No significant difference in the flow reduction performances among the four vegetation types was observed. Hydrographs for the second experiments showed similar patterns (see Figure 4).

Water Quality Performance

Metals

All pilot boxes effectively removed Zn and Pb from the synthetic runoff. On average, removals of Zn and Pb were 61.6 percent and 79.4 percent, respectively. The removal efficiencies were similar between the four vegetated boxes and control box. On the other hand, the pilot boxes showed poor Cu removal. Negative removal efficiencies for the vegetated boxes suggest that Cu leached out of the pilot boxes. Only the control box had positive removal of Cu.

Suspended Solids

Suspended solids were also effectively removed by all the pilot boxes, except the native grass box (−6.0 percent). The mean TSS removal was 42.9 percent. The control box (unvegetated) had the highest TSS removal (80.5 percent), which was approximately twice as high as the average TSS removal of the five boxes. The researchers suspect that roots of vegetation significantly increased the infiltration rate of the soil media. In turn, the increased infiltration rate reduced the detention time of stormwater runoff, resulting in less TSS removal for vegetated boxes.

Nitrogen

Higher NH_3-N removal was observed for the four vegetated boxes (>81.2 percent) when compared to that of the control box (77.2 percent). NO_2-N concentrations were below detection limits in all influent and effluent samples, suggesting that NO_2-N was rapidly converted to NO_3-N before samples were analyzed in the laboratory. This can also explain why NO_3-N concentrations were higher in the influent samples than the target concentrations. The measured NO_3-N concentrations in the influents were approximately equal to the sum of the target concentrations of NO_2-N and NO_3-N. High NO_3-N concentrations were observed in effluent samples. Removal of NO_3-N was −1896 percent on average. Leaching NO_3-N was the most serious in the control box. The NO_3-N removal by the control box was −4139 percent. TN removal by the control box (−480 percent) was less than those by the four vegetated boxes (ranging from −438 to −23 percent), once again supporting that vegetation mitigates the problem of leaching N out of bioretention.

Phosphorus

None of the pilot boxes removed P effectively. The average TP removal was −1873 percent, suggesting that P was leaching from soil media. Unlike TN removal, when compared to the performance of the control (−954 percent), the presence of vegetation resulted in higher P leaching from the soil media.

Pathogens

The pilot boxes very effectively removed the *E. coli*, and the removal efficiencies were more than 70 percent for all pilot boxes. Although the control box had the highest removal, the difference between the five boxes was not significant. Note that the removal efficiencies were calculated after excluding one outlier of influent samples because the concentration of this sample was four orders of magnitude higher than the mean influent concentrations.

IWS TESTING

In the previous report (Li et al., 2010b), the researchers showed that bioretention effectively removed TSS, metals, and pathogens, but poorly removed N and P. Leaching of N and P is a particular concern because of eutrophication in a receiving water body. N concentrations even increased while synthetic runoff passed through the pilot boxes, which indicated that N was exported from the pilot boxes. Compost mixed in the soil media could be a major source that increased N concentrations in the effluents.

Although P removal is largely dependent on plant uptake, N removal can occur through plant uptake or by creating an IWS layer at the bottom of a bioretention system. An IWS layer facilitates denitrification—anaerobic respiration of soil microorganisms that converts nitrate to nitrogen gases. The effect of the IWS layer on N removal has been proven theoretically and in indoor experiments (Kim et al., 2003), but evidence is controversial in field-scale experiments. Some studies found a statistically significant difference in N removal between conventional and IWS designs (Dietz and Clausen, 2006), while others did not (Hunt et al., 2006; Hsieh and Davis, 2005).

Furthermore, an IWS may be a potential solution to two other problems in Texas bioretention: that of red imported fire ants (RIFAs) and that of a lack of water due to the hot, dry Texas summers.

RIFAs prefer sandy soils and hot conditions such as those that exist in a bioretention cell, and tend to burrow holes in it, creating channels for water to bypass the filtering process and negate the water quality and quantity control effect of bioretention. However, an IWS creates a permanently wet zone that may deter RIFAs. Ants may be prevented from burrowing deeper, but it is not known if an IWS deters them from the site entirely.

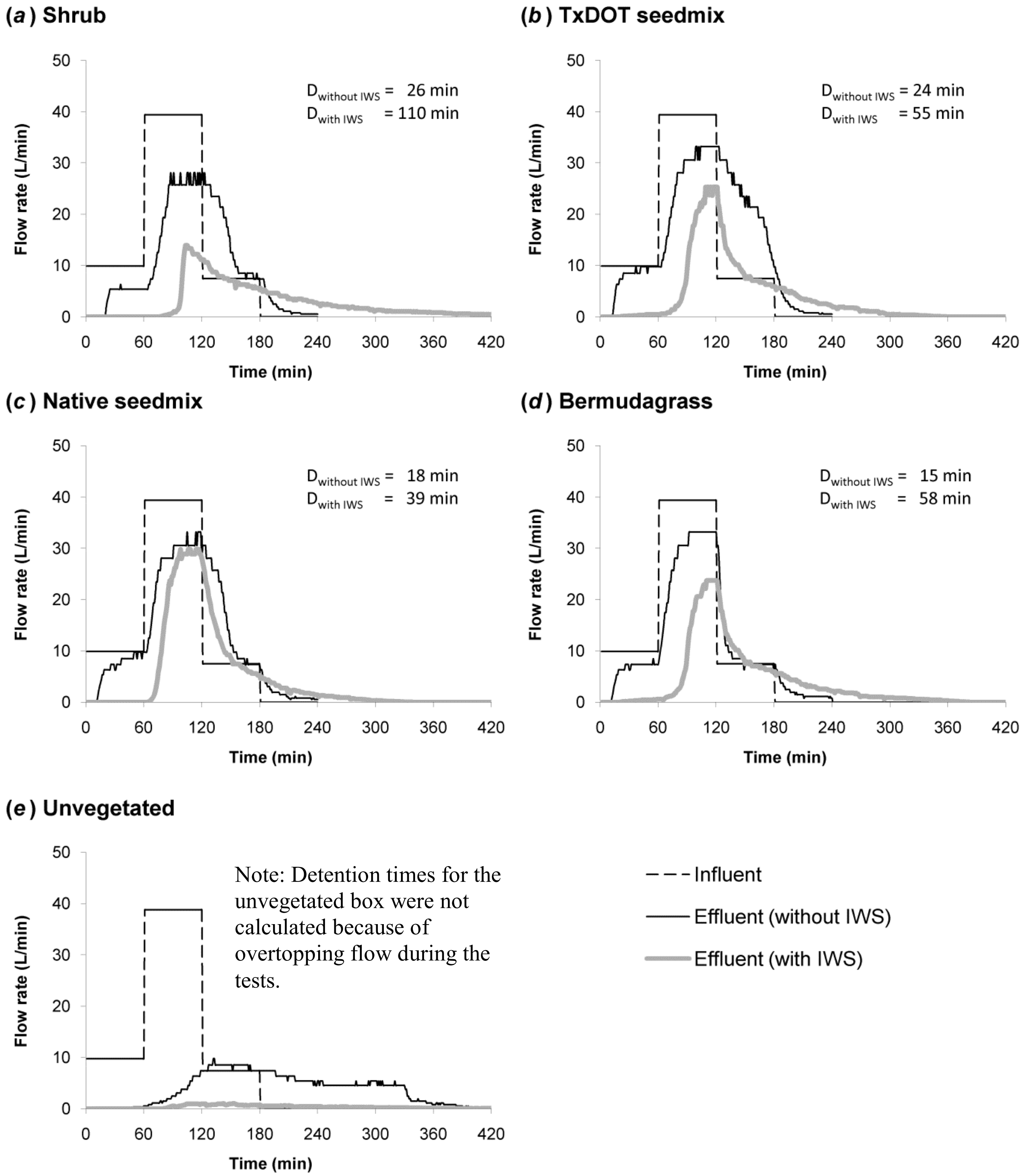
The second problem of dry, hot Texas summers appears to find a solution in an IWS system, as it can be a continual source of water for the vegetation in bioretention cells. What is not known is how this affects the growth, root condition, or disease tendency of some plants being considered for bioretention.

An IWS was installed in five pilot-scale bioretention boxes located at the TxDOT/Texas A&M Transportation Institute (TTI) Hydraulics, Sedimentation, and Erosion Control Laboratory (HSECL) at the Texas A&M University Riverside Campus on July 7, 2010. As mentioned, the IWS was installed by inverting the outlet pipe upward by 2 ft from the bottom of the boxes (see Figure 3). The thickness of sand layer was reduced from 2 ft to 18 inches.

The research team conducted synthetic stormwater runoff experiments simulating the water quantity and quality of highway runoff, then compared peak discharge reduction and pollutant removal efficiencies between the two designs.

Hydraulic Performance Results

Figure 4 exhibits influent and effluent flow rates of the synthetic runoff experiments with and without the IWS layers. The five boxes significantly reduced the peak discharge of the synthetic runoff. Without the IWS layer, the four vegetated boxes detained the synthetic runoff for an average of 21 min. The unvegetated box was more effective for peak discharge reduction than the four vegetated ones. This is probably because the roots elevated the soil infiltration rate of vegetated boxes while the control box remained unchanged and detained runoff most effectively. Effluent from the unvegetated box was so small that detained runoff overflowed the top of the box during the 80th and 114th minutes when water ponding exceeded 30.5 cm (1 ft) of free space above the soil media. The IWS layer further reduced peak discharge in all boxes. With the IWS layers, the detention times increased by approximately three times (from 21 to 65 minutes) in the four vegetated boxes. The researchers attributed such increase to the longer flow path from the soil surface to the exit of the upturned drain by the IWS design. The IWS layer also significantly reduced peak discharge in the unvegetated box. Because the unvegetated box slowly discharged the synthetic runoff, most synthetic runoff spilled out of the box via overbank flow occurring during the 81st and 193rd minutes.



Note: $D_{with\ IWS}$ and $D_{without\ IWS}$ indicate detention time with and without an IWS layer, respectively.

Figure 4. Influent and Effluent Hydrographs for Five Bioretention Boxes (Adapted from Li et al., 2012).

Water Quality Performance Results

Figure 5 shows that the design with the IWS layers had either similar or higher removal efficiencies than that without the IWS layers. As expected, the IWS layers significantly increased N removal. Without the IWS layer, however, the bioretention boxes poorly removed the N. A removal efficiency of TN was −186 percent on average for the four vegetated boxes, suggesting that a large amount of N leached out of the boxes. After installing the IWS layers, removal efficiency of TN became 35 percent on average for the four vegetated boxes. With the IWS layer, none of the boxes had negative removal efficiency for N. The IWS layer also significantly improved TN removal (from −434 to 96 percent), but these values did not represent the true removal efficiencies because a large amount of N was lost with overbank flow. In addition to TN removal, the IWS layers also had positive effects on TSS and Cu removal. The IWS layers increased TSS removal by 56 percent (from 36 to 92 percent) and Cu removal by 88 percent (from −26 to 62 percent) in the four vegetated boxes. There was no clear pattern in the change in Zn, Pb, and TP removal before and after installing the IWS layer.

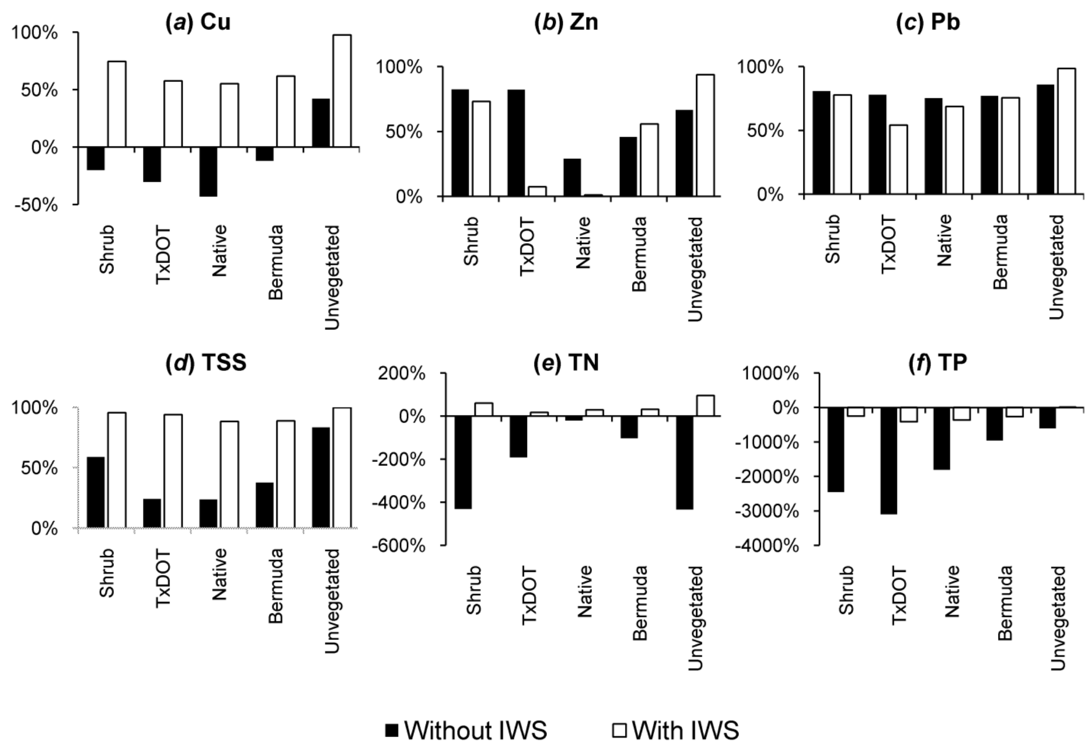


Figure 5. Comparison of Pollutant Removal with and without an IWS Layer.

CHAPTER 4: FIELD DEMONSTRATION CONSTRUCTION AND EXPERIMENT

In addition to the pilot-scale test, a field-scale bioretention cell was constructed to treat stormwater from a real TxDOT right-of-way. Construction of the cell occurred on September 1, 2010, but the vegetation was not planted until March 8, 2011. The field test is a full-scale bioretention test that includes design, construction, and monitoring procedures. Because field tests require land, have higher costs, involve longer periods of time for monitoring, and include more variables that are difficult to control, fewer field-scale tests than pilot tests exist in the literature. Most field monitoring studies have been conducted in eastern states with a temperate climate (Davis et al., 2003; Dietz and Clausen, 2005; Hsieh and Davis, 2005; Davis et al., 2006; Davis, 2007; Hunt et al., 2006; Jones et al., 2007) or in Australia (Bratieres et al., 2008; Read et al., 2008) with very different soil regimes and soil chemistries. Therefore, local studies are needed to examine different soil media and vegetation performances in a hot, semi-arid climate. Furthermore, Passeport et al. (2009) revealed that the best nutrient removal efficiencies occurred during warm seasons; this alludes to potentially higher pollutant removal efficiencies in a warmer climate.

SITE SELECTION

Researchers considered five sites for this project: Interchange 45 + 130 (Austin), a TxTag site (Austin), a TTI site (College Station), Interchange 21 + 6 (Bryan), and SH 6 + Harvey Road (Bryan). Appendix B contains more details on the site selection process, yet it should be noted that cost, proximity, adequate pollutant load, and site-specific conditions providing a ponding area and drainage area were all considered (see Figure 8). The estimated construction costs ranged from $8,851 to $64,988. To meet the budget limit and provide a design with a high probability of success, the research team chose the Interchange 21 + 6 (Bryan) site, as it had the lowest construction and maintenance cost, as well as the close-by convenience for them. The site was constructed in TxDOT ROWs where SH 21 crosses a service road (SH 6 frontage), in Bryan, Texas (see Figures 6 and 7).

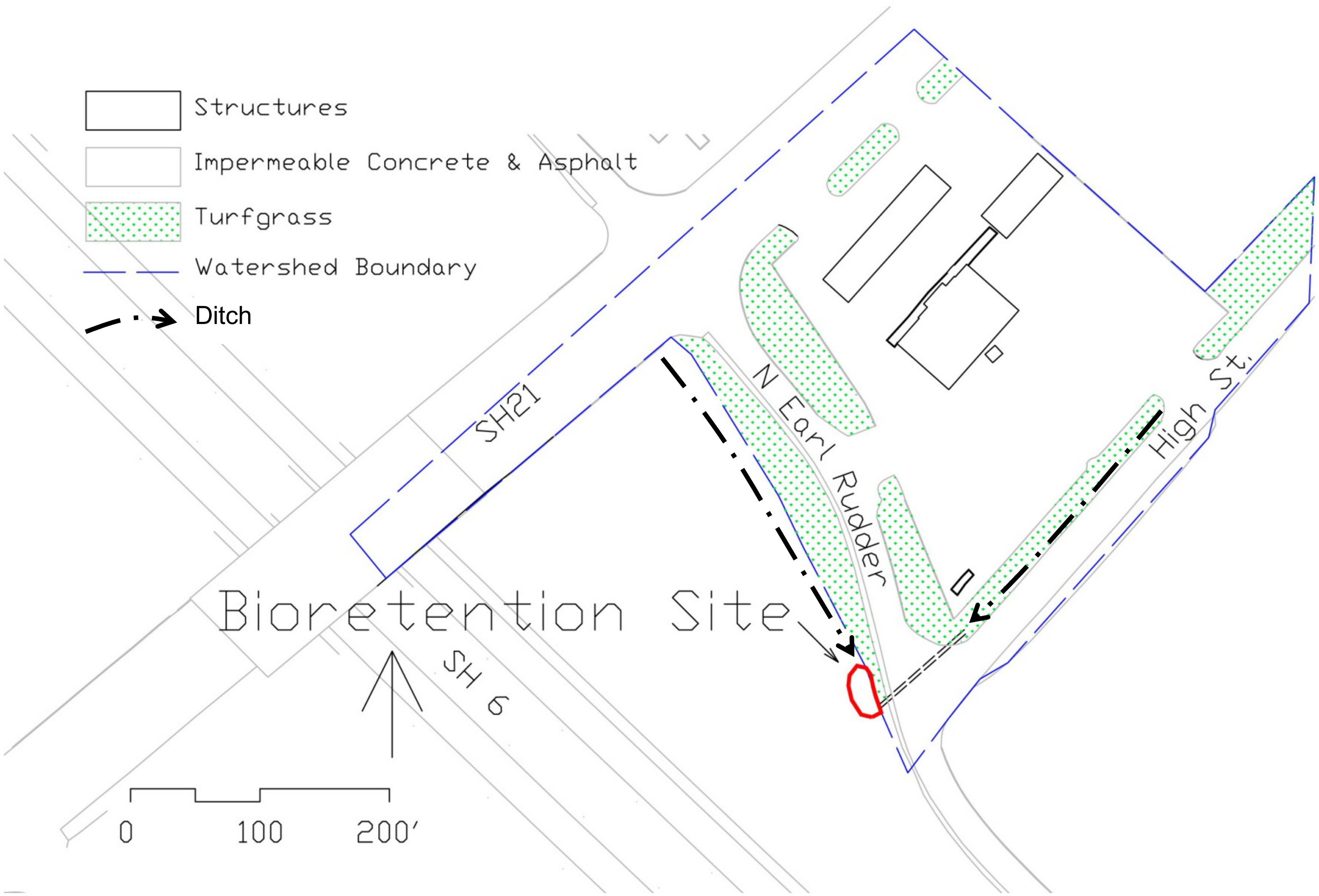


Figure 6. Location of Bioretention Cell in Bryan, Texas.

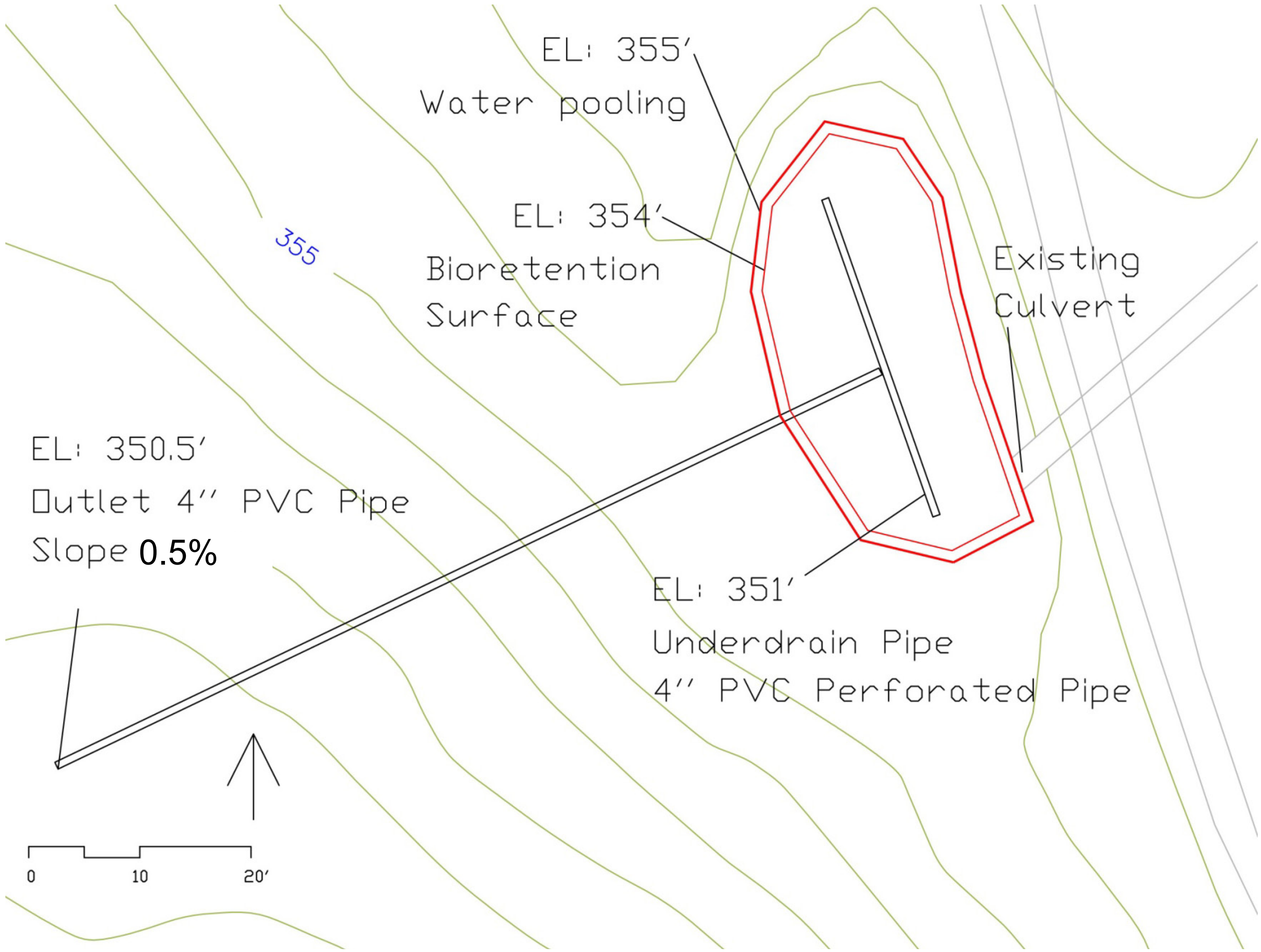


Figure 7. Site Setup of the Bioretention Cell in Bryan, Texas.

Figure 8. Flood Irrigation of Bioretention Cell (Photo Taken in June 2011).

SITE PROPERTIES

As mentioned, the site was located where SH 21 crosses SH 6 frontage near a very busy gas station. The surrounding land use was suburban highway, gas station parking where many 18-wheelers were a major user group, and light commercial. The watershed is mentioned in the next section.

MATERIALS AND METHODS

Watershed

The drainage basin (or watershed) includes runoff from the gas station parking lot, highway and bridge deck, and surrounding light industrial with minimal strips of native and turf grasses. Most of the site is impermeable concrete and asphalt. The full-scale bioretention facility has approximately 670 ft^2 of surface area that was designed to store mean 3 hr storms (0.779 inch) falling on 2.0 acres of drainage area. The storm intensity follows the Soil Conservation Service Type III rainfall pattern. The impermeable area consists of 1.5 ac of paved surface, including a highway bridge (at SH 21), service roads (SH 6 frontage), and a gas station with minimal vegetation area. The composite runoff coefficient was estimated at 0.9, slightly on the conservative side. Two earthen ditches collected stormwater runoff and conveyed them into the bioretention cell (see Figure 6). One ditch collected runoff from the highway bridge and the other from the gas station. A concrete culvert is installed where one of the ditches passes under the frontage road. The two ditches join before runoff entering the bioretention area. An emergency spillway was installed to bypass stormwater runoff greater than the first flush of one inch. This cell, whose footprint is 1 percent of the drainage basin, is designed at the lower end of the average 2 percent–7 percent and the common 5 percent (McNett et al., 2011) suggested in the literature. Appendix F (Design Example) gives more details of the watershed.

Dimensions

The full-scale bioretention cell was a 670 ft^2 (approximately 35 ft × 20 ft) area with rounded edges. The cell had a similar vertical profile as the pilot design. The vertical profile was 30 inches deep (8 inches of gravel, 4 inches of pea gravel, and 18 inches of sandy clay) with a

6-inch surface storage design below the overflow. Appendix C (Drawing Examples) includes CAD drawings of non-IWS and IWS bioretention designs.

Drainage Material

Figure 7 shows a 4-inch perforated PVC pipe was placed in a T form along the length of the cell to allow for full drainage. The slope of the PVC pipe was roughly 0.5 percent. PVC pipes were covered by 1 to 1.5 inches diameter gravel (8 inches in depth) and then by 0.375-inch diameter pea gravel (4 inches in depth). The researchers then put 18 inches of soil media above the gravel and pea gravel layers. H-flumes were placed at the inflow and outflow sources to measure the stormwater properties and removal efficiencies of the bioretention cell. The H-flumes (see Figure 9 and Figure 10) were calibrated to 0.75 ft (9 inches) for the 6712 ISCO water samplers. Appendix D is a draft bioretention special specification that details the materials to be used, including soil, gravel, pea gravel, PVC pipes, etc.

Figure 9. H-Flume at the Influent Location to Measure Flow.

Figure 10. H-Flume Installed at the Effluent Location to Measure Flow.

IWS Modification

The cell was first configured for testing without an IWS layer. Non-IWS tests were performed from April 26, 2011, until February 2, 2012, when the cell was modified to include an IWS layer. The IWS modification was made by installing an upturned pipe at the underdrain pipe (see Figure 11). The modification created a depth of 0.5 m (21 inches) for IWS. The highest elevation of IWS is 0.23 m (9 inches) below the bioretention soil surface. During the IWS experiment period, the IWS level and rainfall were monitored with a second ISCO 6712 water sampler (see Figures 11 and 12). On February 17, a third Teledyne ISCO 6712 sampler was set up to measure fluctuations within the IWS cell. Measurements were taken at 15 minutes and later (February 29) at 5-minute intervals from February 17 to August 7.

Figure 11. Modification of Effluent Discharge to Create IWS Layer.

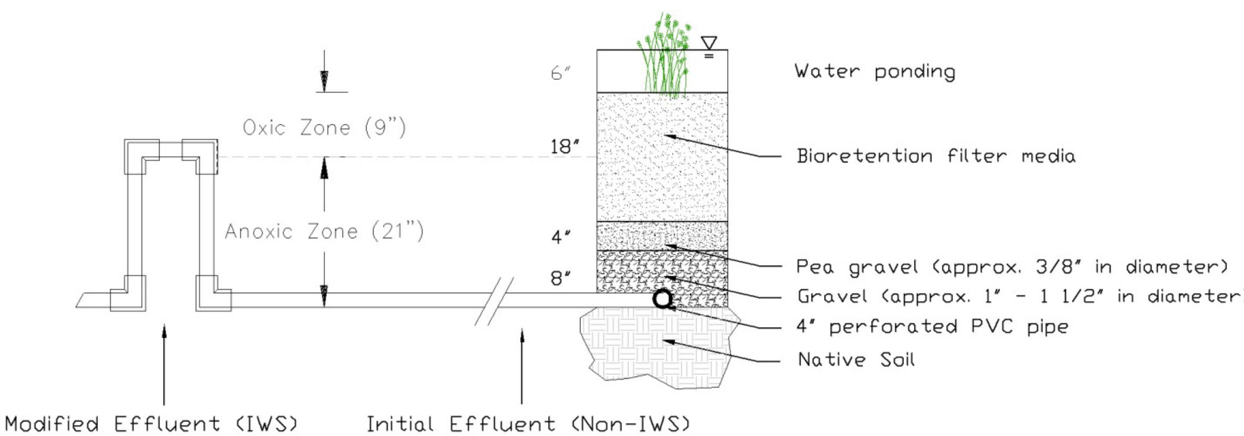


Figure 12. Schematic Drawing of IWS Layer.

Soil Media

The bioretention cell was filled with imported soil media with a texture of 94 percent sand, 0 percent silt, and 6 percent clay. Table 12 describes the upper and lower layer soil properties of the post-construction site. Chapter 5 (Discussion) gives more details.

Table 12. Post-Construction Soil Media Properties of Bioretention Site (Analyzed in October 2010).

	(Upper layer)	(Lower Layer)		
Analysis	**Results**	**Results**	**Units**	**Fertilizer Recommended**
pH	8.8	8.8	-	
Conductivity	23	38	µmho/cm	
Nitrate-N	3	3	ppm	1.3 lb N/1000 ft^2
Phosphorus	1	1	ppm	2.9 lb P_2O_5/1000 ft^2
Potassium	16	15	ppm	3.6 lb K_2O/1000 ft^2
Calcium	25,753	24,870	ppm	0 lb Ca/1000 ft^2
Magnesium	139	140	ppm	0 lb Mg/1000 ft^2
Sulfur	25	23	ppm	0 lb S/1000 ft^2
Sodium	109	90	ppm	
Iron	1.92	3.92	ppm	
Zinc	0.06	0.49	ppm	
Manganese	0.45	1.33	ppm	
Copper	0.03	0.22	ppm	

Vegetation

Leucophyllum frutescens 'Green Cloud' (Cenizo or Texas Sage; see Figure 13) was planted on March 8, 2011, as the vegetative filter, since it had the best survival rate of any of the plants from previous laboratory pilot-scale box testing. Two years after the pilot testing was finished and after the summer 2011 drought, this shrub appeared in decent shape (see Figure14). Several factors are attributed to its success; these are mentioned in Chapter 5 of this report. The impermeable surface drains into a grass swale lined with *Cynodon dactylon* (Bermudagrass) leading into a culvert (see Figure 15), which then enters the bioretention cell.

Figure 13. On-Site *Leucophyllum frutescens* (Texas Sage/Cenizo).

Figure 14. *Leucophyllum frutescens* Condition Two Years after Pilot Test.

Synthetic and Natural Stormwater

Stormwater runoff is the product of precipitation flowing over various types of permeable and impermeable surfaces but is unable to infiltrate into the surface. This runoff can contain pollutants, nutrients, pathogens, and other compounds that it accumulates as it moves over the permeable and impermeable surfaces.

In 2011, which was the first summer of the field experiment period (2011–2012), Texas experienced an exceptional drought condition. In the midpoint of the period, the researchers anticipated that they could not collect natural rain samples before the end of the budgeted year and decided to use synthetic runoff to test the demonstration site. They prepared the synthetic runoff by following the procedure that Li et al. (2010b) described. The main water supply came from a fire hydrant (see Figure 15) adjacent to the demonstration site. To mimic the concentration levels of various compounds in stormwater, various reagents commonly found in stormwater were added to tap water, mixed, and used as synthetic runoff, subsequently undergoing filtration in the bioretention cells. Table 13 outlines the mass, target concentration, and source for all the constituents (mixed in deionized water) of synthetic stormwater used during the experiment. In the Environmental Biotechnology Laboratory (EBL) at Texas A&M University, the research team mixed the constituents with deionized water, using a magnetic stir bar on a stir plate until the elements were completely dissolved. They transported the solutions to the site where these were placed in a 500-gal (1,893-liter) hydroseeder mixing tank (see Figure 15) with hydrant water.

To simulate varying storm intensities within a storm event, influent flow rates were changed hourly. The hourly flow rates were calculated by assuming that:

- The drainage area was 6243 m^2 (67200 ft^2) which is 100 times larger than the surface area of the cell.
- The runoff coefficient of the drainage area was 0.9.
- The design storm was the mean 3-hour storm for Brazos County, Texas.
- The design storm followed a Soil Conservation Service Type III rainfall pattern(Asquith et al., 2006).

Therefore, the synthetic runoff tests used approximately 151 liters/min (40 gpm), 757 liters/min (200 gpm) and 151 liters/min (40 gpm) flow rates for the first, second, and third hours, respectively. The second synthetic runoff test (for both non-IWS and IWS) then used approximately half of the flow rate for each respective hour to test a smaller storm.

TxDOT also approved to extend the research for one more year (until August 2012) so that natural rainfall samples could be collected. For natural rainfall tests, the researchers used battery-powered equipment to collect samples, and measure rainfalls and influent/effluent flow rates. They determined valid samples based on onsite assessments soon after the rain event. Discrete rainfalls were assumed to be any event with an antecedent dry period of 6 hours (Li et al., 2009). Collected samples were transported to the EBL for processing within 24 hours.

Figure 15. Fire Hydrant and Hydro-Seeder near Grass Swale Inlet.

Table 13. Pollutant Target Concentrations in Synthetic Stormwater.

Constituent	Concentration (mg/L)*	Source
Total Suspended Solid	98.167	Silica
Lead	0.08	Pb $(NO_3)_2$
Zinc	0.132	$ZnSO_4 \cdot 7H_2O$
Copper	0.02	$CuSO_4 \cdot 5H_2O$
Nitrate	0.148	$NaNO_3$
Nitrite	0.148	$NaNO_2$
Ammonia	0.77	NH_4Cl
Organic Nitrogen	0.77	Glycine
Total Phosphorus	0.173	Na_2HPO_4

*Based on Li et al. (2008).

Sampling Method

Researchers collected inflow samples before entering the bioretention cells and outflow samples after permeating through the bioretention cells in 0.5 L bags at 30-min influent and 1-hr effluent time intervals. Influent and effluents were grab-sampled for the first two synthetic tests. The team took all other samples automatically with a Teledyne ISCO 6712 water sampler, which was calibrated to enable at 5 gpm influent and 2 gpm effluent. They also measured flow using the same water sampler. Flow rate was measured at 1-min intervals using a 0.75 ft H-flume. After collection, researchers brought samples to the EBL and then refrigerated these at 4°C until filtering (i.e., pretreatment) and TSS analysis could be completed. TSS analysis was completed the day after sample collection.

TSS Analysis. Each sample collected at the time intervals was analyzed for TSS concentration using a modified version of TSS dried at 103°–105°C (Eaton et al., 1995). A 300 mL sample from the collection bag was stirred using a magnetic stir bar on a magnetic stirring plate . A wide-bore pipette was used to collect a 100 mL subsample from mid-depth and midway between the beaker's wall and the vortex created by stirring at a speed of 600 to 700 rpm (Kayhanian et al., 2008). A filter/aluminum dish was assigned to each sample. The 100 mL subsample was filtered using a 0.47 mm Whatmann glass fiber filter. The filter was placed in the aluminum dish and dried in an oven at 103°–105°C. The filter and dish were weighed after drying.

TSS Concentration Calculation

The TSS concentration was calculated as follows:

Equation 4

$$TSS\ (mg/L) = ((B - A) \times 1000)/(C)$$

where, A = mass of weighing dish and filter before filtering takes place (g).

B = mass of weighing dish and filter after filtering and drying (g).

C = sample volume filtered (mL).

Ammonia Detection (Phenate Method). After collection, samples were brought to the EBL, where 5 mL of each sample was filtered using a 0.2 μm pore-diameter membrane filter. The sample was stored at–20°C until analysis.

Apparatus and Methods

Ammonia analysis used the phenate method (Eaton et al., 1995). The reaction between ammonia, hypochlorite, and phenol, catalyzed by sodium nitroprusside, resulted in the creation of the intense blue compound indophenol. The color intensity depends on the concentration of ammonia in the sample. The standard curve was composed of a dilution series of five standards of known ammonia concentrations, ranging from 0.01 ppm to 5 ppm. The color intensity of the standards and samples was measured using an Agilent spectrophotometer at a wavelength of 640 nm. A calibration curve was plotted using the standard's absorbance values versus the standard's concentration. R-squared values were better than 0.990 for correlations of standard concentrations (mg/L) and spectrophotometer readings (au). The line of best fit resulting from the data allowed correlation of the absorbance readings of the samples to a concentration. The analysis of the samples was performed in triplicate. The detection limit was 0.01 ppm.

Nitrate, Nitrite, and Phosphate Detection (Ion Chromatographic Method). After collection, samples were brought to the EBL, where 10 mL samples were vacuum filtered using a plastic filtering device through a 0.2 μm pore-diameter membrane filter. Filtrates were then stored at –20°C until IC analysis could be completed.

To determine nitrate, nitrite, and phosphate influent and effluent concentrations, researchers used a DX-180 ion chromatograph IC (Dionex Corporation, Sunnyvale, California) equipped with an IonPac AS14A-5μm analytical column (3 mm × 150 mm) for anion separation. The eluent solution was composed of 0.16 M Na_2CO_3 and 0.02 M $NaHCO_3$. The regeneration solution was 70 mL N H_2SO_4. Flow rates were 1 mL/min. The sample size used for IC analysis was 5 mL. Standard solutions for nitrate, nitrite, and phosphate ranged from 10 ppb to 5 ppm. The standard solutions underwent the same analytical process as the sample solutions. The detection limit was 10 ppb for nitrate, nitrite, and phosphate.

Metal (Zn, Cu, Pb) Detection (Inductively Coupled Plasma Analysis). After collection, samples were brought to the EBL, where 20 mL samples were vacuum filtered using a plastic filtering device through a 0.2 μm pore-diameter membrane filter. Filtrates were then acidified to pH 2 with concentrated HNO_3 (trace metal grade) and stored at 4°C for ICP-MS analysis.

Researchers analyzed various metals (Zn, Cu, Pb) by ICP-MS using a Perkin Elmer DRCII ICP-MS system. The ICP-MS is a sensitive multi-element analytical method with potential to make trace determinations at the ppb levels and below. The spectrometer is quadrupole based and incorporates the latest dynamic reaction cell (DRC) technology to minimize the effects of interferences from molecular ions present in the system (Eaton et al., 1995). A series of standard metal solutions with an optimum concentration range of 2–200 ppb was used as calibration standards. The method detection limits (MDL) for metals were ppb level.

TN and TP Analysis. Researchers brought the collected samples to the EBL, where 15 mL samples were vacuum filtered using a plastic filtering device through a 0.2 μm pore-diameter membrane filter. The filtrates were then stored at –20°C for TN and TP analysis. TN samples were measured using a commercial kit TNT 826 and 827, which modifies the persulfate digestion method. The method determines total nitrogen by oxidation of all nitrogenous compounds to nitrate (Hach, Product Number TNT826 and TNT827). TP samples were determined using a commercial kit TNT 843 and 845, which modifies the ascorbic acid method (Hach, Product Number TNT843 and TNT845; Eaton et al., 1995).

NON-IWS CELL TESTING

Hydraulic Performance Results

Figure 16 shows the hydrographs for the six tests conducted without an IWS layer. The four events where natural rainfall was tested also include a hyetograph within the hydrograph. Table 14 presents the rainfall and flow details for each event. For the non-IWS testing, the volume of rainfall events varied from 9.4 mm (0.37 inch) to 26.1 mm (1.03 inch), representing low/moderate fall season rains in the study area. The two non-IWS synthetic tests (April 26 and July 5) had a peak flow reduction of 50 percent–64 percent with corresponding detention times of 26–37 min. Other non-IWS rainfall events revealed a peak discharge reduction of 68 percent–95 percent with corresponding detention times of 15 to 43+ min. The H-flume used in this study has a capacity of 1628 liters/min (430 gpm). The capacity was exceeded for a number of times during natural rainfall monitoring, including the November 15 AM and January 24 rains. The hydraulic performance during these two days is less accurate.

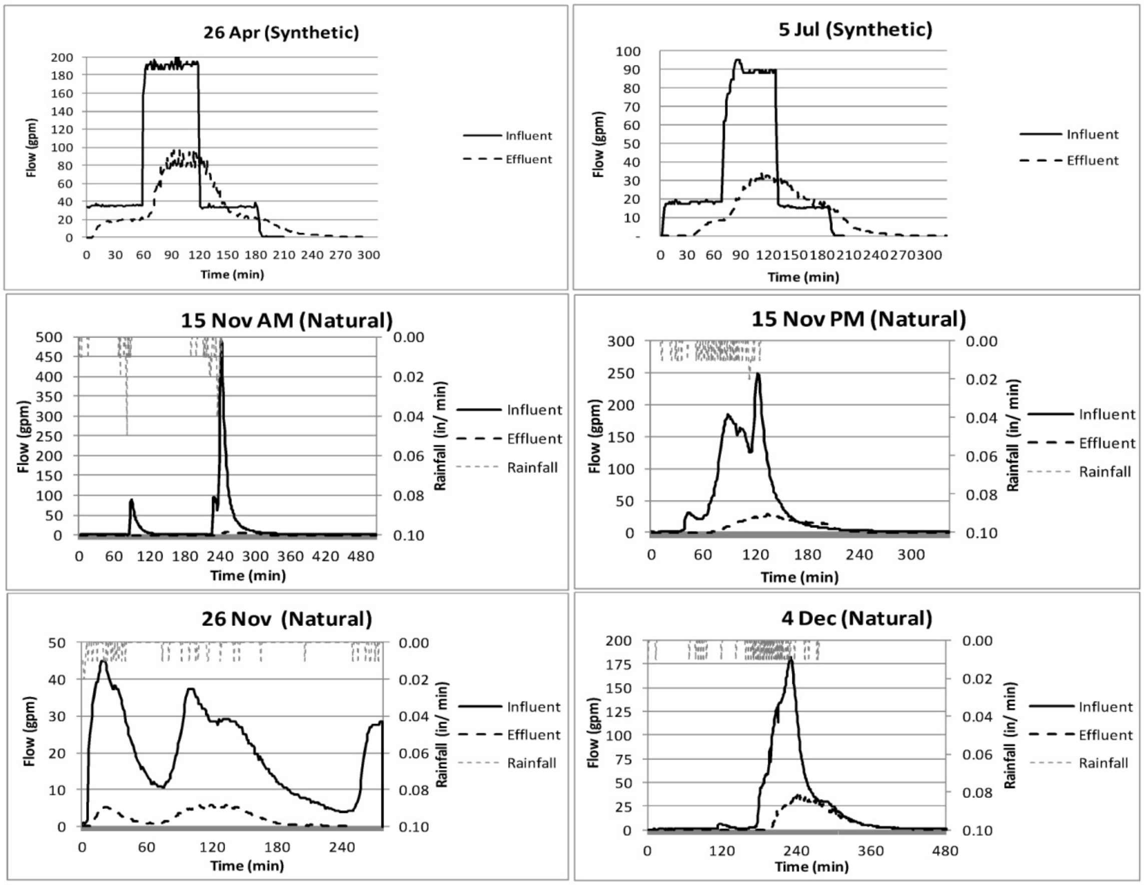


Figure 16. Hydro-Hyetographs for Non-IWS Field Testing.

Table 14. Rainfall and Flow Data for Non-IWS Cell Field Testing.

Event	Rainfall				Flow						
	Length	Intensity (in)			Inflow		Outflow		Difference[b]	Performance	
	Total (min)	6 min	1 hr	Total	Total In-flow (gal)	Peak In-Flow (gpm)	Total Out-flow (gal)	Peak Out-Flow (gpm)	Inflow-Outflow (gal)	Peak Flow Reduction	Det. Time[c] (min)
Apr 26	180	synthetic			16656	204	8327	97	8329	50%	26
July 5	180	synthetic			7366	95	3376	35	3990	64%	37
Nov 15[a]	240	.15	.32	.53	8821	491	398	8	8330	95%	43
Nov 15[a]	113	.07	.30	.42	13250	249	2535	29	10715	80%	35
Nov 26	266	.06	.18	.37	5530	45	633	6	4897	89%	15
Dec 4	275	.04	.28	.49	11327	182	3483	37	7844	68%	34
Jan 24[d]	95	.40	.62	1.03	34268	1025	4521	33	29747	87%	54

[a] November 15 includes two separate rainfall events; the first in the morning (AM) and the second in the afternoon (PM)
[b] Difference is composed of bypass spillway, filtration and evapotranspiration
[c] Detention time
[d] Excessive runoff exited spillway

Water Quality Performance Results

Table 15 presents the results of pollutant removal efficiency for the Non-IWS testing. The first sample of effluent was excluded in the Non-IWS testing because it was believed that residual sediment offsets the initial effluent. Details of the results are described in the following paragraphs.

Total Suspended Solids (TSS)

TSS removal of the non-IWS design was low to moderate (25 percent~65 percent). The low removal efficiency of the July 5 test may be attributed to the low influent TSS concentrations (36~100 mg/L) injected into the cell, compared to the TSS influent concentrations in the first test on April 26 (156~243 mg/L).

The TSS removal efficiencies from natural rainfalls seemed to vary greatly (from −92 percent to 66 percent). The negative value on the November 15 PM could be due to insufficient detention time for TSS to settle after the morning rain on the same day.

Metals

The non-IWS design removed Cu, Zn, and Pb very effectively in the synthetic runoff testing but not as positively in the natural rainfall testing. The comparison of the influent water quality reveals that natural runoffs carried less metal concentrations than synthetic runoffs. Cu, Zn, and Pb concentrations in the influents of the synthetic runoff testing had a range of 0.09~1.39 mg/L, not detectable~1.83 mg/L, and 0.02~0.55 mg/L, respectively; whereas their concentrations in the natural runoff entering the cell ranged from 0.04~0.17 mg/L, not detectable~4.2 mg/L, and not detectable~0.06 mg/L, respectively. The low metal concentration in the natural runoff testing could have contributed to the varying removal performance.

Nitrogen

Non-IWS design showed mixed results for TN and NO_3-N removals but an overall positive NH_3-N removal. Negative NO_3-N removal might be due to leaching from the cell or the oxidation of other nitrogen sources to NO_3-N. The positive NO_3-N removal in the natural runoff testing can be attributed to the high NO_3-N concentration as well as low TN and NH_3-N concentrations in the influents (i.e., less conversion to NO_3-N).

Phosphorus

Except for the synthetic runoff test on July 5, TP and HPO_4-P were removed at moderately high levels in all non-IWS designs.

Table 15. Non-IWS Cell Pollutant Removal Efficiencies (%).

Event	TSS	Cu	Zn	Pb	TN	NH_3-N	NO_3-N	TP	HPO_4-P
Non-IWS Cell Testing[a]									
4/26/2012 (synthetic)	65	100	100	99	21	75	(-16)	32	50
7/05/2012 (synthetic)	25	100	99	98	21[b]	86	(-341)	(-49)	(-238)
11/15/2012 (natural)[c]	41	(-14)	(-103)	(-99)	(-1872)	63	51	60	100
11/15/2012(natural)[c]	(-92)	(-6)	10	5	100	38	30	54	88
11/26/2012 (natural)	66	(-9)	54	100	ND[d]	ND	23	58	79
12/4/2012 (natural)	16	17	(-13)	100	22	77	28	51	70

Note #1: The cell received 1 lb/25 plants of 14-14-14 N-P-K Osmocote fertilizer on November 3, 2011
[a] The first effluent sample was excluded from EMC calculation
[b] One outlier was removed
[c] The morning test was separated from the afternoon test
[d] ND: Not detected (lower than detection limit)

IWS CELL TESTING

Hydraulic Performance Results

Figure 17 shows the hydrographs for the six tests conducted without an IWS layer. The four events where natural rainfall was tested also include a hyetograph with the hydrograph. Table 16 presents the rainfall and flow details for each event.

Natural rainfall depth in the IWS testing varied from 12.2 mm (0.48 inch) to 67.8 mm (2.67 inches) (see Table 16), representing more intensive spring season rains than the fall season rains. The IWS natural rainfall tests all had high peak flows that exceeded the H-flume capacity at some point. Despite the H-flume limit, the IWS layer revealed a greater peak discharge reduction than the non-IWS layer. The two synthetic tests are comparable to each other (from 50 percent–64 percent to 59 percent–82 percent) and the detention times are similar. This is likely because the IWS cell's capacity to detain water is enhanced as the effluent level is raised but only until the effluent level is reached. Also, note that in the two IWS synthetic tests, the cell was topped off with regular hydrant water the evening or morning before the test for a conservative evaluation of the hydraulic performance.

Another limitation of the hydraulic performance evaluation results from discharges at the emergency spillway. As mentioned in the Chapter 4 section "Materials and Methods," the cell was designed to capture the first flush only; subsequent runoff is bypassed via the emergency spillway. As indicated in Tables 15 and 16, flow loss through the emergency spillway occurred on November 15 AM and January 24 for non-IWS testing; and on February 3, February 17, and May10 for IWS testing. Effluent was observed but not measured, which in turn affected the accuracy of the performance evaluation. Because of this limitation, distinguishing between spillway overflow, exfiltration (infiltration) and evapotranspiration (ET) is not possible. However, Li et al. (2009) revealed that a bioretention cell in North Carolina lost a total of 27 percent of influent to ET and exfiltration; 19 percent attributed to ET and 8 percent to exfiltration. The low exfiltration amount is attributed to the high clay content in the soils, just like the soils in this research. This 19 percent ET, however, can be expected to be even greater in hot, semi-arid areas like Texas.

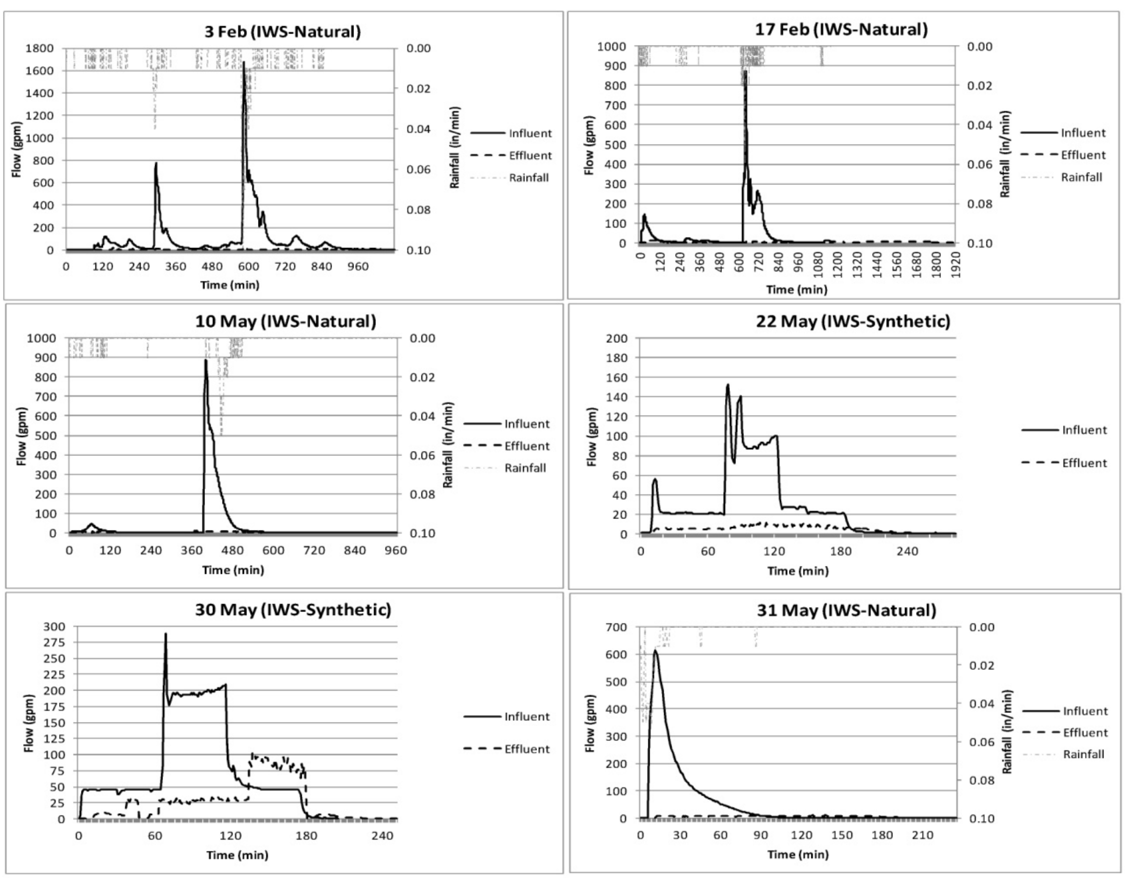


Figure 17. Hydro-Hyetographs for IWS Field Testing.

Table 16. Rainfall and Flow Data for IWS Field Testing.

Event	Rainfall				Flow						
	Length	Intensity (in)			Inflow		Outflow		Difference[a] (In-Out)	Performance	
	Total (min)	6 min	1 hr	Total	Total In-Flow (gal)	Peak In-Flow (gpm)	Total Out-Flow (gal)	Peak Out-Flow (gpm)	Spillway Infiltration Evap.-Tran.	Peak Flow Reduction	Det. Time[b] (min)
Feb 3[c]	846	.38	1.41	2.67	93353	1675	6860	22	86493	92%	93
Feb 17[c]	1708	.26	.65	1.33	51058	874	8102	13	42956	84%	316
May 10[c]	507	.25	.85	1.07	32872	888	2358	11	30514	93%	17
May 22	180	synthetic			7921	152	1440	11	6481	82%	23
May 30	180	synthetic			16115	289	6603	106	9512	59%	39
May 31[c]	86	.26	.47	.48	13034	616	1553	11	11481	88%	79

[a] Difference is composed of bypass spillway, filtration and evapotranspiration
[b] Detention time
[c] Excessive runoff exited spillway

Water Quality Performance Results

Table 17 presents the results of pollutant removal efficiency for the IWS testing. Details of the results are described in the following paragraphs.

Total Suspended Solids (TSS)

For the IWS cell, the average influent concentration of TSS in natural rains was 87 mg/L, similar to that in natural rains for the non-IWS tests. The TSS removal efficiencies with IWS were very effective (overall > 88 percent) and much higher than those without IWS (see Figure 18).

Brown and Hunt (2010) reported the improvement of TSS removal by IWS, in which 77 percent~88 percent of TSS removal with the non-IWS design was increased to95 percent~99 percent with IWS. In non-IWS design, the soil media gets cracked and increases in porosity during extended dry periods. This causes the formation of preferential flow paths with macropores, which allow particles to move through faster (Blecken et al. 2010, Lintern et al. 2011). In the IWS design, the low TSS concentration in effluent is likely because TSS was settled and could not be easily elevated as high as the effluent pipe.

Metals

The IWS design further enhanced metal removal performance in both synthetic and natural runoff testing. The degree of varying efficiencies in the natural runoff testing was reduced (see Table 17). Similar to the non-IWS testing, the influent concentrations of metals in the natural runoffs were lower than those in the synthetic runoff, yet such a condition seemed to affect the Pb removal only. Furthermore, Pb effluent concentrations were so low in many natural rain studies that removal efficiencies do not give a fair assessment of the cell's removal capacity; the synthetic tests, however, all revealed high Pb removals.

In their study, Blecken et al. (2010) also observed the improvement of Cu and Zn removals. The heavy metals mobilize in the environment by oxidizing the anoxic sediments (Förstner et al., 1989). The IWS design provides a more stable moisture regime or at least partially anoxic conditions (Goonetilleke et al., 2011) that prevents or minimizes oxidation and hinders the transport of heavy metals to the effluent (Blecken et al., 2010). The application of IWS enhances the growth of plants, one of the factors for improved water quality. However, since heavy metals are not as important a growth factor as other nutrients, the uptake by plants is not a dominant mechanism for heavy metal removal. Therefore, Blecken et al. (2010) recommended not applying an IWS layer if heavy metals are the main targeted contaminants.

Nitrogen

IWS design exhibited a more consistent, positive removal performance of nitrogen sources, and outperformed non-IWS design in TN and NO_3-N removals. The NH_3-N removal was similar in both designs. The improvement of TN and NO_3-N removals indicates that the IWS design provided a stable anaerobic denitrification environment, as Brown and Hunt (2010) also reported. In addition, the IWS could reduce the stress that plants might undergo during the dry season and promote greater plant growth and nutrient uptake (Zhang et al., 2011).

Phosphorus

Except for the synthetic runoff test on July 5, TP and HPO_4-P were removed in both non IWS and IWS designs. Note that the concentrations of TP and HPO_4-P in both influents of synthetic and natural runoff testing were similar. Also, IWS design enhanced both TP and HPO_4-P removals. Brown and Hunt (2010) also observed improvement of TP removal with the construction of IWS.

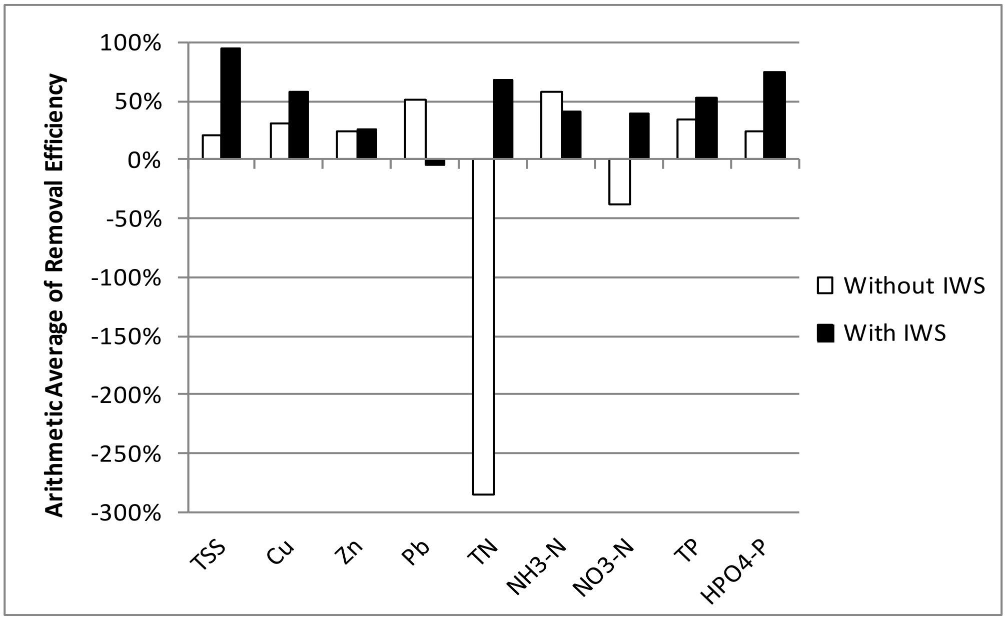


Figure 18. Non-IWS and IWS Removal Efficiencies.

Table 17. IWS Cell Pollutant Removal Efficiencies (%).

Event	TSS	Cu	Zn	Pb	TN	NH_3-N	NO_3-N	TP	HPO_4-P
IWS Design									
5/22/2012 (synthetic)	96	93	99	87	76	96	88	72	98
5/30/2012 (synthetic)	96	76	60	86	55	71	29	23	44
2/3/2012 (natural)	94	42	(−171)	(−198)	100	(−77)	18	69	82
2/17/2012 (natural)	100	56	68	41	100	84	(−10)	62	77
5/10/2012 (natural)	92	64	31	(−27)	43	29	74	66	100
5/31/2012 (natural)	88	16	70	(−20)	34	43	39	20	45

IWS Level and Precipitation Monitoring

Researchers monitored the IWS level and precipitation from February 17 to August 7. The cell first went dry on April 24 at 7:20 PM. The antecedent rainfall leading to this includes 1.13 inches on March 28, 0.35 inch on March 29, and 0.39 inch on April 3. Insignificant rainfall was measured on April 15 (0.03 inch), April 16 (0.01 inch), and April 20 (0.07 inch). Therefore, after a rainfall of 1.48 inches on March 28 and 29 with a small recharge 5 days later on April 3 (0.39 inch), the IWS level held water above the drainage pipe for 21 days (3 weeks). However, on July 7 the level nearly went dry (0.11 decimal feet) until it started to rain. The IWS level held water again (although synthetic testing occurred) until it went dry on August 5 at 7:55 PM.

Although this water storage is significant, whether or not this is sufficient to mitigate droughts is debatable.

Figure 19 presents the IWS level monitoring and all natural precipitation from February 17 to August 7. It should be noted that the cell was irrigated on May 3 with 4,000 gallons since the cell had been dry for several days. Also on May 22 and May 30 (the dates of the synthetic tests) the cell was topped off with water, either the evening before or morning of the test, to ensure immediate outflow. The quantity of this water ranged from 800 to 2,000 gallons. The synthetic tests were ran and the effluent loads were 7,921 gallons (May 22) and 16,115 gallons (May 30). Aside from these three exceptions, the one irrigation and two synthetic tests, the cell's level is a result of natural rainfall. The cell went dry only twice in this six-month period (see Figure 19). Total rainfall was recorded at 20.20 inches from February 17 to August 7.

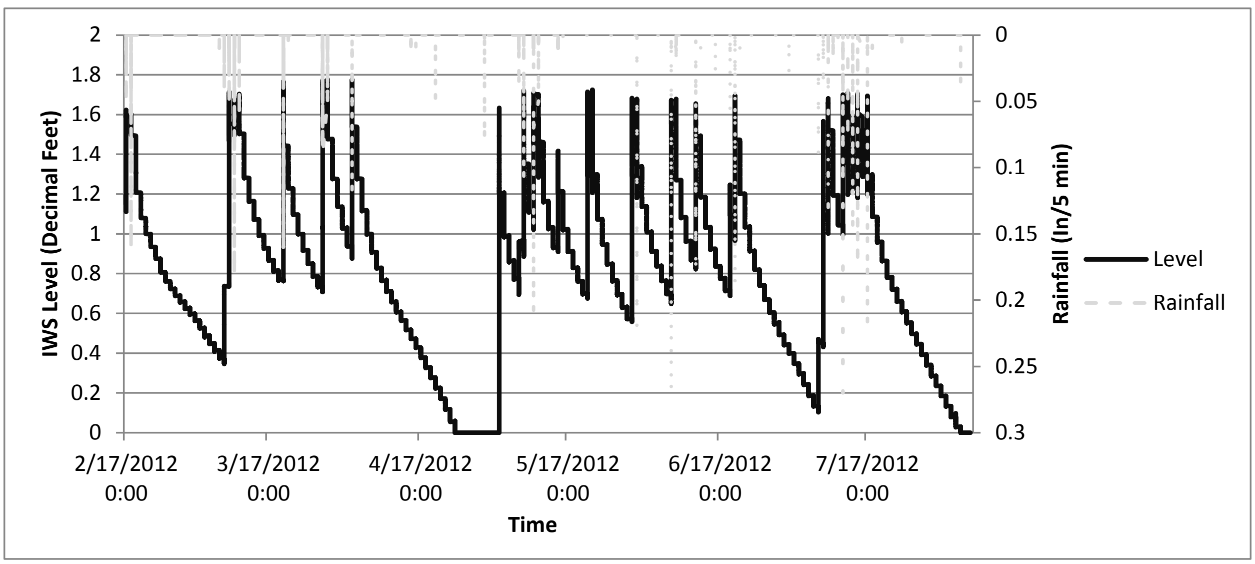


Figure 19. Rainfall and IWS Level (February 17, 2012–August 7, 2012).

CHAPTER 5: DISCUSSION

PILOT BOX TESTING

The laboratory pilot box testing found that an IWS layer improves the water quality and hydraulic performances of bioretention in treating highway runoff. In particular, the IWS layer significantly enhances TN removal. The soil media used in the pilot testing had a high initial NO_3-N concentration (see Table 10). Researchers observed a large amount of N leaching from the soil media during the synthetic runoff experiments for the design without the IWS layer. The IWS layer reduced N leaching because anaerobic conditions can facilitate denitrification, which in turn decreases NO_3-N concentrations in the soil media.

This pilot testing also found a significant effect of the IWS layer on metal removal. An anaerobic condition may have increased sorption of Cu to soil media (Blecken et al., 2009). Unlike Cu, Zn and Pb were effectively removed in the design without the IWS layer, which can explain the insignificant effect of the IWS layer on Zn and Pb removal.

The five boxes (with or without the IWS layer) significantly reduced the peak discharge of the synthetic runoff. The IWS layer further reduced peak discharge in all boxes. The researchers deemed that the IWS layer served as a reservoir that extended the runoff residence time and reduced the peak flow.

In addition to the benefits of peak discharge reduction and water quality improvement, the IWS layer can mitigate drought stress to plants. Most design references suggest sandy soil for filter media and the use of an underdrain because effective drainage is essential for plant survival. However, these engineered drainage systems create a Non-IWS environment during intermittent storm events. A gravel layer or a landscape fabric commonly placed under the soil media, which prevents roots from accessing moisture stored in deeper soil horizons, also causes drought stress to the vegetation (Li et al., 2011). This suggests that drought must be taken into consideration in bioretention cell design, particularly for applications in hot and arid areas. An IWS layer can be an alternative design element to mitigate drought stress.

The results of this study are limited and cannot be directly used to support the drought mitigation effect of an IWS layer. As mentioned earlier, water was regularly supplemented to maintain the 61 cm (2 ft) deep IWS layer. Previous studies also report notable water loss via evapotranspiration and infiltration through the bottom of bioretention cells (Davis, 2008; Emerson and Traver, 2008; Hatt et al., 2009; Chapman and Horner, 2010).

The difficulty in holding water in the IWS layer may also explain inconsistent effects of the IWS layer reported in previous studies. For instance, Hsieh and Davis (2005) and Hunt et al. (2006) did not find a statistically significant effect of an IWS layer. Bioretention systems used in those studies did not have an impermeable liner, and a large amount of stormwater might have been lost via infiltration. Because denitrification occurs slowly in anaerobic environments, losing water in the IWS layer due to infiltration means losing the anaerobic environment. The true removal mechanism of N by the IWS layer is not the direct removal of NO_3-N from runoff but a long-term reduction of N concentration in soil media (Yang et al., 2009). Therefore, inconsistent effects of the IWS layer that previous studies reported may be attributed to infiltration, which made the bioretention unsaturated most of the time. Unlike the other studies, Dietz and Clausen (2006) found a statistically significant difference in N removal between conventional and IWS designs. They used an impermeable liner to seal the bottom of the bioretention system. This design allowed a long-term saturation condition, exemplified by a low redox potential in soil media, and thus removed N from the soil media.

Although maintaining water level is critical for the success of the IWS design, certain factors need to be considered when selecting a permeable or impermeable liner for bioretention. Lowering the groundwater table has been a serious problem in urban areas where impervious surfaces impede stormwater infiltration (Sung and Li, 2010; Sung et al., 2011). Recent stormwater management practices, such as low-impact development, no longer rely on engineered drainage systems but rather aim to increase on-site infiltration (Li et al., 2010a). Therefore, a high infiltration rate is desirable from an eco-hydrological viewpoint.

On the other hand, if groundwater contamination is a concern, an impermeable liner for the bioretention cell is necessary. A small bioretention cell with an IWS can remove a sufficient quantity of nutrients without removing excessive water. However, if the cell is expanded to a larger area (for greater pollutant removal), the lack of water available to percolate may create a significant decrease in groundwater storage levels.

FIELD TESTING

Field testing revealed many insights that pilot box testing did not, as well as, confirm and explain much of the pilot testing results. Similar to the pilot testing, an IWS layer has a positive effect on peak discharge reduction, increased detention time and removal of pollutants from highway runoff. The difficulty of controlling variables at a field scale were made obvious early on in this experiment, as was the challenge of using natural rainstorm for influent measurement. However, this experiment revealed several key points that are discussed in the following sections: hydraulic performance, water quality performance, soil media, vegetation, irrigation, Red Imported Fire Ants and maintenance.

Hydraulic Performance

The cell (with or without the IWS layer) significantly reduced the peak discharge of the synthetic runoff. The IWS cell's capacity to detain more water is enhanced as the effluent level is raised, but only when the water level in the IWS layer stays low after a dry period. Nevertheless, the IWS layer extended the runoff residence time and reduced the peak flow. The overall average of non-IWS peak discharge reduction was 76 percent and IWS 83 percent averaging to 80 percent overall. The overall average of non-IWS detention time is 32 minutes, whereas in an IWS design, it approaches 50 minutes. These numbers reveal data in a cell with a native sandy clay loam (50 percent sand, 20 percent silt, and 30 percent clay) underlay that acts as a semi-permeable layer more than a permeable sandy layer. Furthermore, although effluent was observed when possible over the emergency spillway, it was not measured so distinguishing between spillway overflow, exfiltration (infiltration), and evapotranspiration (ET) was not possible. However, Li et al. (2009) revealed that a bioretention cell in North Carolina lost a total of 27 percent of influent to ET and exfiltration: 19 percent attributed to ET and 8 percent to exfiltration. The low exfiltration amount is attributed to the high clay content in the soils, just like the soils in this study in Bryan, Texas. This 19 percent ET can be expected to be even greater in hot, semi-arid areas like Texas.

However, many of the IWS rainfall tests occurred during intense spring rains and caused a great deal of overflow through the emergency spillway. If more runoff beyond the first flush is to be detained, a larger cell should be designed. A larger cell would also increase pollutant removal. This cell's surface area is 1 percent of the runoff area of 67,200 ft^2(6,243 m^2), which creates a storage capacity for approximately 7,734 gallons (see Equation 5). This amount is adequate for many storms within the Bryan, Texas area but a larger bioretention cell (comprising near 5 percent of the drainage basin) is recommended for greater water storage.

Equation 5

Bioretention cell 35 ft × 20 ft ≈ 670 SF
670 × 8 inches (0.66 ft.) of gravel at 0.55 porosity = 246 CF
670 × 4 inches (0.33 ft.) of pea gravel at 0.45 porosity = 101 CF
670 × 18 inches (1.5 ft.) of sand at 0.35 porosity = 352 CF
670 × 6 in (0.5 ft.) of surface ponding = 335 CF

Total volume of runoff at the capacity: 246 + 101 + 352 + 335 = 1034 CF = 7,734 gallons.

Water Quality Performance

The field testing confirmed the pilot testing results that an IWS layer improves the performance of pollutant removal in treating highway runoff. In particular, TSS and TN removal was greatly increased. However, TP removal also increased as did the metals Cu and Zn. Pb did not reveal a higher removal efficiency in the IWS layer, which can be attributed to the low concentration in the influent. Each pollutant is discussed separately in the following paragraphs. Table 18 gives combined non-IWS and IWS removal efficiencies, and Table 19 shows the flow weighted EMC of pollutants in effluents. Figure 19 further shows the data.

Brown and Hunt (2010) also reported the improvement of TSS removal, in which 77 percent~88 percent of TSS removal with the non-IWS design was increased to 95 percent~99 percent with the IWS design. In non-IWS design, the soil media gets cracked and increases in porosity during extended dry periods. This causes the formation of preferential flow paths with macropores, which allow particles to move through faster (Blecken et al. 2010; Lintern et al. 2011). Another contributing factor is that the low TSS concentration in effluent is likely because TSS was settled and could not be easily elevated as high as the effluent pipe.

The improvement of Cu and Zn removals in the IWS layer was also observed in the study of Blecken et al. (2010). The heavy metals mobilize in the environment by oxidizing the anoxic sediments (Förstner et al., 1989). The IWS design provides a more stable moisture regime or at least partially anoxic conditions (Goonetilleke et al., 2011), which prevents or minimizes oxidation and hinders the transport of heavy metals to the effluent (Blecken et al., 2010). The application of IWS could enhance the growth of plants, one of the factors for improved water quality. However, since heavy metals are not as important a growth factor as other nutrients, the uptake by plants is not a dominant mechanism for heavy metal removal. Therefore, Blecken et al. (2010) recommended not applying an IWS layer if heavy metals are the main targeted contaminants.

As previously mentioned, the pilot box testing revealed N leaching in the effluent due to compost in the soil mix. Therefore, the field study excluded compost. The non-IWS field tests revealed some N removal but this was significantly enhanced with the addition of an IWS layer. The improvement of TN and NO_3-N removals indicates that the IWS design provided a stable anaerobic denitrification environment, as Brown and Hunt (2010) also reported. In addition, the IWS layer could reduce the stress that plants might undergo during the dry season and promote greater plant growth and nutrient uptake. Zhang et al. (2011) recognized that IWS cells had 9 percent–18 percent more plant biomass than non-IWS cells. P and particularly N are contributing factors to plant biomass composition.

Although the non-IWS design revealed an overall positive removal for P, the IWS design enhanced both TP and HPO_4-P removals. Brown and Hunt (2010) also observed improvement of TP removal with the construction of IWS. Mildly stressed vegetation also uses more P as well. Furthermore, harvesting herbaceous vegetation (grass species) stresses plants, thereby encouraging extra P (and N) uptake and, hence, removal. Appendix E includes more details on design guidelines that target specific pollutants. Harvesting is expensive, however, and harvested material must be dumped offsite or left on site, which would return some P back into the system. A bonus to leaving organic matter on site, however, would be providing a carbon source for a denitrification zone (N removal). Mixing fly ash in the soil media has also proven to reduce P levels up to 85 percent (Zhang et al., 2006).

Table 18 Combined Non-IWS and IWS Removal Efficiencies (%).

Event	TSS	Cu	Zn	Pb	TN	NH_3-N	NO_3-N	TP	HPO_4-P
Non-IWS Design[a]									
4/26/2012 (synthetic)	65	100	100	99	21	75	(−16)	32	50
7/05/2012 (synthetic)	25	100	99	98	21[b]	86	(−341)	(-49)	(−238)
11/15/2012 (natural)[c]	41	(−14)	(−103)	(−99)	(−1872)	63	51	60	100
11/15/2012(natural)[c]	(−92)	(−6)	10	5	100	38	30	54	88
11/26/2012 (natural)	66	(−9)	54	100	ND[d]	ND	23	58	79
12/4/2012 (natural)	16	17	(−13)	100	22	77	28	51	70
IWS Design									
5/22/2012 (synthetic)	96	93	99	87	76	96	88	72	98
5/30/2012 (synthetic)	96	76	60	86	55	71	29	23	44
2/3/2012 (natural)	94	42	(−171)	(−198)	100	(−77)	18	69	82
2/17/2012 (natural)	100	56	68	41	100	84	(−10)	62	77
5/10/2012 (natural)	92	64	31	(−27)	43	29	74	66	100
5/31/2012 (natural)	88	16	70	(−20)	34	43	39	20	45

Note #1: The cell received 1 lb/25 plants of 14-14-14 N-P-K Osmocote fertilizer on November 3, 2011
[a] The first effluent sample was excluded from EMC calculation
[b] The outlier was removed
[c] The morning test was separated from the afternoon test
[d] ND: Not detected (lower than detection limit)

Table 19. Flow Weighted Even Mean Concentrations of Pollutants in Effluents (mg/L).

Event	TSS	Cu	Zn	Pb	TN	NH_3-N	NO_3-N	TP	HPO_4-P
Non-IWS Design[a]									
4/26/2012 (synthetic)	79	0.00	0.00	0.00	3.16	0.35	0.33	0.92	0.12
7/05/2012 (synthetic)	58	0.00	0.00	0.00	1.43[b]	0.14	0.53	0.99	0.08
11/15/2012 (natural)[c]	91	0.15	1.04	0.02	3.39	0.01	0.01	0.35	0.00
11/15/2012(natural)[c]	60	0.10	0.36	0.01	0.00	0.01	0.42	0.63	0.04
11/26/2012 (natural)	3	0.06	0.07	0.00	N/D	N/D	0.31	0.33	0.04
12/4/2012 (natural)	17	0.06	0.38	0.00	0.51	0.02	0.44	0.44	0.10
IWS Design									
5/22/2012 (synthetic)	4	0.03	0.01	0.02	1.00	0.05	0.02	0.29	0.00
5/30/2012 (synthetic)	17	0.08	0.11	0.03	1.51	0.24	0.09	0.65	0.06
2/3/2012 (natural)	2	0.05	0.57	0.02	0.00	0.03	0.29	0.23	0.03
2/17/2012 (natural)	0	0.03	0.49	0.01	0.00	0.01	0.37	0.19	0.02
5/10/2012 (natural)	6	0.03	0.44	0.03	2.00	0.06	0.24	0.21	0.00
5/31/2012 (natural)	35	0.09	0.08	0.02	2.78	0.09	0.72	0.89	0.08

Note #1: The cell received 1 lb/25 plants of 14-14-14 N-P-K Osmocote fertilizer on November 3, 2011
[a] The first effluent sample was excluded from EMC calculation
[b] The outlier was removed
[c] The morning test was separated from the afternoon test

Soil Media

The native soil is composed of 50 percent sand, 20 percent silt, and 30 percent clay. The imported bioretention soil media is 94 percent sand, 0 percent silt, and 6 percent clay. Table 20 gives a detailed soil analysis of the native and imported soil media. The results indicate that the native soil contained higher nitrogen and phosphorus concentrations than the soil media in the cell. The nitrogen and phosphorus concentrations of the soil media did not change with time; nitrogen and phosphorous levels remained very low. In the early fall of 2011, the plants appeared to be highly stressed. It was determined to be a soil-induced N deficiency because new growth was dark green and old growth an unhealthy yellow. Appendix G shows the chronology of photographs of the site's vegetation. A soil sample was taken on October 7, 2011 (see Table 20) and the cell was fertilized on November 3 at a rate of 1 lb of 14-14-14 Osmocote per 25 plants. Although N and P levels remained low, the final soil sample revealed an increase in iron, Zn, manganese, and Cu concentrations over time as more runoff drained into the cell. The bioretention special specifications in Appendix D recommend avoiding compost to reduce N and P leaching. Although the N and P natural stormwater influent concentrations were moderate or even high, considering this site does not include runoff from residential communities with fertilized grass lawns or agriculture fields, the call of Limozin et al. (2011) to avoid all compost in bioretention is perhaps debatable. In this study, much of the N was nearly completely absorbed in the first flush and both N and P effluents were much cleaner. This is particularly true of the IWS layer.

Perhaps a compromise for this dilemma would be increasing the content of silt or clay in the soil media a small amount. Silt and clay has better CEC than sand and can retain more of the N and P going through the soil. In regards to soil media, both hydraulic performance and water quality must be considered. After conducting 18 experiments to evaluate various bioretention media, Hsieh and Davis (2005) recommended a blend of coarse sand and sandy loam in the filtration area. Limouzin et al. (2011) indicated that masonry sand appeared to be the best soil media used, with a special blend of City of Austin bioretention medium (concrete sand and sandy loam which may contain up to 25 percent silt and clay). Avellaneda et al. (2010) revealed that pure sand provides better TSS removal but solely because clay and silt can be washed out more readily due to their smaller pore sizes. Although clay soil media has a higher cation exchange capacity, a higher absorption potential and a greater storage capacity which aids in vegetation health, it has a much slower filtration rate. Therefore, one must consider the pollutant load and desired filtration velocity and then choose a soil media mix and corresponding plant palette.

Table 20. Soil Property Fluctuations (Soil, Water, and Forage Testing Lab TAMU).

Analysis	Native Soil	Bioretention Cell Soil Media			Units
		Sept. 2010, soon after construction	Oct. 2011, 13 months after construction	June 2012, 22 months after construction	
pH	8.1	8.8	9.6	8.5	-
Conductivity	204	23	78	56	µmho/cm
Nitrate-N	6	3	2	0	ppm
Phosphorus	15	1	1	0	ppm
Potassium	195	16	20	23	ppm
Calcium	4,513	25,753	32,260	20,126	ppm
Magnesium	345	139	163	132	ppm
Sulfur	4	25	27	20	ppm
Sodium	64	109	146	33	ppm
Iron	6.79	1.92	2.66	3.68	ppm
Zinc	3.84	0.06	0.55	3.93	ppm
Manganese	1.37	0.45	1.08	1.69	ppm
Copper	0.92	0.03	0.12	0.58	ppm

1 lb of 14-14-14 Osmocote applied (25 plants)

Vegetation

Since vegetation is an important part of bioretention, observations of plant material in Texas bioretention systems is vital to display the performance levels of various vegetation species. *Leucophylum frutescens* (Cenizo or Texas Sage) thrived in this experiment under the very harsh Texas summer conditions with its roots placed in sand, which retains very little water. The long-term health of the plant in sandy soils (with low CEC) is debatable. As mentioned earlier in the vegetation section of materials and methods, the Cenizo that was left over from the box experiment appeared leggy but healthy two years after artificial irrigation ceased (see Figure 14). However, the vegetation in this cell struggled throughout the experiment likely from the drought (the summer of 2011 required intermittent irrigation, which is discussed under Irrigation) and the lack of nutrients, mainly N. Researchers applied synthetic fertilizer on November 3 at a rate of 1lb/25 plants of 14-14-14 N-P-K. Whether or not the vegetation would have remained healthy enough through another year without further fertilizer is unknown. It is supposed, however, that vegetation be considered temporary in such soil media extremes and be replaced intermittently. Also, future tests should study the nutrient levels of N & P in the vegetation leaves, for example, to examine the soil to plant interactions.

Aside from a potential nutrient deficiency attributed to the soil media, Cenizo has several characteristics ideal for bioretention:

- It appears to withstand periodic droughts and inundation.
- It tolerates both heat and cold (down to 5°F/−15°C) and is a perennial evergreen (it can remove nutrients from the soil during all seasons of the year, although it slows down in the winter).
- It thrives in full sun (typical of bioretention sites) and alkaline soils. However, if it is planted in acidic soils, dolomitic limestone should be added (Aggie Horticulture, 2011).
- It is a medium to slow grower, meaning it grows fast enough to remove nutrients but slow enough to not require frequent maintenance/pruning.
- It has low overall water use, although as with any shrub or tree, the first year requires regular deep watering for successful root establishment. After establishment, however, no fertilization, minimal irrigation beyond average rainfall, and minimal maintenance are required (University of Texas at Austin, 2009).
- It is not susceptible to pests or diseases other than cotton root rot, which well-drained soil will discourage (Aggie Horticulture, 2011). Although the IWS zone could irrigate the roots in years of frequent and consistent rainfall, root rot is a potential problem but was not noticed in this experiment. A bonus of this particular plant is that it often blooms right before or after rainfall (when humidity levels rise), giving it the common name of barometer bush (University of Texas at Austin, 2009).

Furthermore, it should be mentioned that volunteer *Cynodon dactylon* (Bermudagrass), which has become naturalized in central Texas, encroached and began to cover the cell's surface in the fall of 2011 after the drought ended. By spring 2012, the site was partially covered with *C. dactylon;* by summer 2012, this grass had seriously threatened *L. frutescens* (see Appendix G for chronological photographs). For this reason *Cynodon dactylon* (Bermudagrass) should be considered in the plant palette as well to decrease maintenance costs. Another consideration for vegetated bioretention cells is the C:N ratio. Ingersol and Baker (1998) noted that the limiting C:N ratio is about 5:1. Net nitrate removal efficiencies increase as the C:N ratio increases to 5:1, although previous literature may reveal higher ratios, closer to 20:1. Therefore, in Ingersol and

Baker's (1998) study, "net nitrate removal efficiencies at each hydraulic loading rate increased with increasing carbon addition rates." This ratio may be a reason to periodically test for a site's C:N ratio to either increase or decrease C; it may be more ecologically sound and cheaper to do this as well as opposed to adding N.

With regard to herbaceous plants such as grasses, a separate strategy can be considered to aid in pollutant removal: mowing and/or harvesting. As mentioned under the water quality section within the discussion of N and P removal, mildly stressing a plant may force it to take up more nutrients. Mowing can create this stress. Furthermore, harvesting the vegetation removes the pollutants off site.

As a record-keeping strategy, and as a potential list of native and adapted plants to be studied in future field tests, the following list is given. All of these species grew naturally without any added irrigation in or near the bioretention cell until the extreme drought of the summer of 2011 occurred. The list includes:

- *Brassica nigra* (Black Mustard).
- *Coreopsis tinctoria* (Plains Coreopsis).
- *Erigeron spp.* (Fleabane).
- *E. modesta* (perennial) or *E. geiseri* (annual).
- *Lupinus texensis* (Texas Bluebonnet).
- *Monarda citriodora* (Lemon Beebalm).
- Triticum spp. (Wheat).
- *Vicia villosa* (Winter Vetch).
- *C. dactylon* (Bermudagrass).
- Sorghum halepense (Johnsongrass).

Most of these plants are either annuals or eventually withered in the drought and summer heat of 2011. It is possible, however, that some would survive a typical (no drought) summer. As mentioned, Bermudagrass grew naturally on the site, was successful in pilot testing, and therefore is highly recommended for future IWS testing. Bermudagrass (as many grasses) has a very adaptable water usage regime: when there is water, the grass takes up and thrives, but when there is none, the grass slows down and goes dormant but rarely dies.

Finally, because several years have passed since the beginning of the pilot and field tests, recent updates in the literature on the pollutant removal capacities of various vegetation species are now available. Fortunately, for dry semi-arid climates, Australia (Read et al., 2008; Bratieres et al., 2008 and Read et al., 2008 and 2009) and Austin, Texas (Limouzin et al., 2011) are included in these tests. The Read et al. (2008 and 2009) and Bratieres et al. (2008) research took place in Melbourne, Australia, where the Australia hardiness zone of 3 is roughly equivalent to the United States Department of Agriculture (USDA) zone of 9 (close to the 8b in Bryan/College Station, Texas). However, other climatic variations exist such as the low macronutrient levels common in Australia soils. Although this information aids in understanding which pollutants are targeted by certain native species, it does not necessarily mean that they are adapted or can adapt to a non-IWS or IWS roadside bioretention cell. This is because these studies are columnar ones that occur in a controlled environment usually with synthetic stormwater.

The Limouzin et al. study (2011) compared buffalo grass and Big Muhly, revealing excellent and moderate removal efficiencies for Big Muhly and buffalo grass, respectively, but only these two species were tested. Why Big Muhly performed so well is somewhat unknown. Although specific characteristics affecting pollutant removal are not completely understood, Read et al. (2008) revealed that (in Australia) "*Carex*, *Melaleuca*, and *Juncus spp.* appear to be particularly effective at reducing concentrations of some pollutants per unit root mass. Other species in the Read et al. (2008) study such as *Leucophyta*, *Microlaena*, and *Acacia* are specifically less effective. Although these genera are also native to Texas, the species are different, and so a correlation cannot necessarily be made. Furthermore, according to Read et al. (2008), "Species were not universally effective at removing pollutants"; *Juncus spp.* "were relatively effective at retention of N and P, but not Pb."

For Cu, however, there is relatively little difference in effluent concentration between any plant species and the control. Although the reason why these species are effective is still unclear, Read et al. (2008) believed that "for nitrogen and phosphorus species (but not metals, which are generally effectively removed by any soil-based filter media), some of this variation (20–37 percent) could be explained by plant size. However, there was still marked variation among plant species in pollutant removal per unit plant mass. We expect that some of this variation in pollutant removal will be due to differences among species in root architecture and physiology, leading to variation in uptake of pollutants as well as varying effects on soil physicochemistry and the associated microbial community." For example, the particularly dense root architecture of the Carex sedge (with numerous and very fine root hairs) supplies more surface area per volume for plant uptake of nutrients (Bratieres et al. 2008). More specifically, a microscopic analysis shows that the *Carex* plants possess very high numbers of microscopic root hairs, which greatly increase the area of soil exploitable by the plant. Therefore, further studies of ideal species and their related soil mix requirements (for plant health, soil microbial activity and filtration rate) should take all this into consideration.

More species taken from the planting plan guidelines (Appendix A) need to be studied for Texas (semi-arid climate) roadside bioretention cells. Furthermore, the researchers believe that plants with increased water efficiency such as Facultative CAM (*Sedum spp.*), C4 (*C. dactylon*), and other hardy, woody shrubs like *L. frutescens* should be targeted in future bioretention cell research. These plants are common in green roof contexts which share similar extremes in heat, limited soil media options and rainfall fluctuations. Read et al. (2009) developed a list of physiologic patterns of effective plant attributes most effective in removing specific pollutants. The adapted Table 21 below lists these traits.

Table 21. Plant Traits that Enhance Pollutant Removal.

Adapted from Read et al. (2009)

Pollutant	Traits Showing significant correlations
TSS	--
Cu	--
Zn	--
Pb	--
Mn	Root soil depth, leaf area
TN	Longest root, root mass, root soil depth, percent root mass, ULR, RGR, root length
NH_4+-N	Longest root, root soil depth, root mass, total mass, percent root mass, ULR, root length, RGR
NOx-N_L	Longest root, root soil depth, percent root mass, root mass, ULR, RGR, total mass, root length
TDN	Longest root, root soil depth, root mass, ULR,RGR, percent root mass, root length
TP	Longest root, percent root mass, root mass, root soil depth, root length
TDP	Root length, percent root mass, longest root, root soil depth, root mass, RGR, total mass, fine roots, ULR, SRL
FRP	Percent root mass, longest root, root mass, root length

TDN, total dissolved N;TDP, total dissolved P; FRP, filterable reactive P; ULR, unit leaf rate; RGR, relative growth URL=specific root length

Table 22 shows the criteria recommended for Non-IWS bioretention cell plant selection. Appendix A lists the specie recommendations.

Table 22. Plant Recommendations.

Dry
• Heat and full sun tolerant. • Drought tolerant. • Ability to thrive in well-drained soils. • Ability to withstand periodic inundation. • Low maintenance requirements. • Perennial and/or evergreen (for continued removal and reduced maintenance). • Moderate (for adequate nutrient uptake) to fast growth (for harvesting).

Irrigation

As previously mentioned, 2011 experienced a record drought with a very low annual rainfall of 19.97 inches, which is half the yearly average of 40.06 inches that is based on 30 years' worth of average rainfall (http://www.srh.noaa.gov). This unusually dry weather made analyzing typical irrigation requirements difficult. However, researchers can state that in the spring of 2011, the plants were irrigated (by bucket) once a week when rainfall did not occur. This is partially due to the drought and partially due to the vegetation being in the establishment phase. Beginning around June, the plants were lightly irrigated with the fire hydrant and a fire hose (see Figure 15) biweekly, but in August that was reduced to weekly irrigation. Anywhere from 1,700 to 4,200 (usually about 3,000) gallons were used to flood irrigate. For the first year (2011), precipitation data for the site was taken from College Station Easterwood Airport, Station #1889 (Asquith et al., 2006), which is located approximately 15 mi from the bioretention site. The month of April (2011) recorded no rainfall; and May, June, July, and August received 3.37, 2.87, 0.10, and 0.29 inches, respectively, although this usually came in spurts and not intermittently.

It started raining regularly in September 2011 with a monthly total of 2.25 inches, and supplemental irrigation was not continued. The reduced heat in the fall and winter and the increased rainfall from that point allowed the site to be self-sufficient until it was finally irrigated for the first time in 2012 on May 3 with 4,000 gallons. In retrospect, this irrigation was perhaps unnecessary as it rained a few days later and a total of 1.91 inches was recorded between May 5 and May 11.

Furthermore, it is likely the Cenizo vegetation could have survived with much less irrigation as the Cenizo plant in the pilot box test survived, but the researchers wanted to ensure the plants were healthy for testing. Furthermore, the Cenizo shrub in the box test was planted with a soil media including more clay and compost that aids in nutrient retention.

The IWS layer did appear to reduce the need for irrigation but the IWS layer is still dependent on intermittent rain as it only holds water for up to 3 weeks (see Section IWS Level and Rainfall Monitoring). A lining underneath the IWS layer would likely increase the residence time of water even further but this may negatively expose some plant roots to diseases such as root rots.

Therefore, a light weekly irrigation schedule is recommended in the summer during weeks without rainfall, particularly during the first growing season. Proper vegetation selection is very important to reducing irrigation costs. As mentioned in the vegetation section, plants with increased water efficiency should be further explored in bioretention cells as irrigation costs can be high if done manually in arid areas and in areas where travel time is required. Also, designers and engineers should identify a site-specific need—e.g., pollutant removal, stormwater infiltration, or groundwater concern—before making specifications as to type (non-IWS or IWS), size, depth, soil media, and vegetation as all these elements affect the irrigation potential for a bioretention cell.

Red Imported Fire Ants

Red imported fire ants (*Solenopsis invicta*) are a major problem in hot, sandy soils. Therefore, bioretention sites in Texas are ideal for them. RIFA were encountered on site, but instances were scarce and appeared temporary during 2011. However, in the spring of 2012, more RIFA populations were observed. It is believed that this is mainly due to increased rainfall (to its regular level). The RIFA mounds were found on the berm of the cell but not particularly noticed inside the cell. RIFA mounds seemed to like the increased humidity near the site but did not like the frequent inundations of being on the cell's surface.

Maintenance

Regular maintenance was minimal aside from irrigation, which should be the main maintenance consideration. The vegetation (*Leucophyllum frutescens*) required no regular maintenance. Researchers mowed the volunteer Bermudagrass around the effluent and effluent

H-flumes (*Cynodon dactylon*) once over the course of each summer (2011 and 2012), but this was just to prevent the highway mowing contractors from not seeing the setup and damaging the influent or effluent. Debris (garbage) was regularly removed from the site with special attention to the influent to ensure that no clogging occurred. Although the site was fertilized, the researchers do not recommend this. The site was fertilized only to monitor if the lack of N and P was the problem with the vegetation, which it appeared to be. Therefore, if a site has a proper soil media and vegetation mix, the vegetation should not need heavy maintenance unless it is a herbaceous grass that requires mowing or there are aesthetic concerns. Even mowing within the cell is discouraged unless it is for the specific purpose of lightly stressing the plant to increase the N and P uptake.

It is important to note that soil media does reach a pollution maximum removal efficiency capacity in which the sediment and pollutants have begun to saturate the soil media. In Austin, for example, this is about every 5 months (or roughly 15 inches of accumulated rain). Limouzin et al. (2011) recommended that the top 10 cm (4 inches) be removed and replaced twice a year. It is believed that in the practice of disking (as done in Austin Sand filters), the top 8 inches of soil media would provide a similar function and could occur on Bermudagrass without any permanent damages to the grass. Eventually, (in 1–2 years) the top layer would need to be removed. Whether the packing of the soil media by a tractor would negatively affect infiltration or pollutant removal is unknown. Vegetation does help loosen up the soil as plant roots may be able to mitigate the clogging of pores, which occurs from various reasons in bioretention cells.

CHAPTER 6: CONCLUSION AND CHALLENGES

From the pilot and field testing, the researchers drew the following conclusions:

- Bioretention can be a method of reducing peak flow and increasing detention time.
- The non-IWS bioretention cell moderately removed suspended solids.
- The non-IWS bioretention cell removed Cu and Zn to varying degrees and did not demonstrate strong enough removal performance.
- The non-IWS bioretention cell did not show a promising Pb removal, which is attributed to a low concentration in influents used in testing.
- The non-IWS removed minimal TN.
- The non-IWS bioretention removed moderate amounts of TP.
- The IWS bioretention cell removed nearly all suspended solids.
- The IWS bioretention cell improved Cu, Zn, and maybe Pb removals, and the performance is deemed moderate to effective.
- The IWS modification greatly enhanced TN removal and moderately enhanced TP removal.
- The IWS modification appeared to create a denitrifaction zone and enhance the available water content to increase plant vigor and biomass.
- Very sandy soils may incur N and P deficiencies in the vegetation.
- *Leucophyllum frutescens* and *Cynodon dactylon* survive well in semi-arid subtropical climate of Texas but volunteer *Cynodon dactylon* can overtake the existing vegetation of a cell.
- Irrigation is needed during establishment and during extreme droughts.
- The maintenance of the cell was minimal with the exception of irrigation.
- RIFA control can be an issue but was not a problem in the field bioretention cell.
- Knowing the goal of infiltration and its related groundwater issues is necessary before designing a bioretention system.

- An understanding of the site-specific properties of runoff (pollutant type and quantity) is necessary before designing a bioretention system.
- Oil and grease influents and effluents were not measured in this study but this information would be very pertinent.

REFERENCES

Aggie Horticulture (2011). *Texas Sage*. Retrieved October 8, 2012 from http://aggie-horticulture.tamu.edu/ornamentals/nativeshrubs/leucophyllumfrutes.htm.

Aitkenhead-Peterson, J. and A. Volder (2010). *Urban Ecosystem Ecology*. American Society of Agronomy Inc. (Agronomy Monograph 55).

Arnold, M. A. (2008). *Landscape Plants for Texas and Environs* (3rd ed.). Champaign, IL – Stipes Publishing LLC.

Asquith, W. H., M. C. Roussel, T. G. Cleveland, X. Fang, and D. B. Thompson (2006). *Statistical Characteristics of Storm Interevent Time, Depth, and Duration for Eastern New Mexico, Oklahoma, and Texas* (No. Professional Paper 1725). Austin, TX – U.S. Geological Survey.

Austin City Connection: American Legal Publishing Co. (2011). *Section 1: Water Quality Management.* Retrieved July 21, 2011, from http://austintech.amlegal.com/nxt/gateway.dll/Texas/environ/cityofaustintexasenvironmentalcriteriama?f=templates$fn=default.htm$3.0$vid=amlegal:austin_environment$anc=

Avellaneda, P., T. Ballestero, R. Roseen, and J. Houle (2010). Modeling Urban Storm-Water Quality Treatment: Model Development and Application to a Surface Sand Filter. *Journal of Environmental Engineering*, 136, pp. 68–77.

Barrett, M. E., L. B. Irish, Jr., J. F. Malina, Jr., and R. J. Charbeneau (1998). Characterization of Highway Runoff in Austin, Texas, Area. *Journal of Environmental Engineering*, 124, pp. 131–137.

Blecken, G.-T., Y. Zinger, A. Deletic, T. D. Fletcher, and M. Viklander (2009). Impact of a Submerged Zone and a Carbon Source on Heavy Metal Removal in Stormwater Biofilters. *Ecological Engineering*, 35, pp. 769–778.

Blecken, G.-T., Y. Zinger, A. Deletic, T. D. Fletcher, and M. Viklander (2010). *Effect of Retrofitting a Saturated Zone on the Performance of Biofiltration for Heavy Metal Removal: Preliminary Results of a Laboratory Study.* Paper presented at the 7th International Conference on Sustainable Techniques and Strategies in Urban Water Management, Lyon, France.

Bratieres, K., T. Fletcher, A. Deltic, and Y. Zinger (2008). Nutrient and Sediment Removal by Stormwater Biofilters: A large-scale design optimisation study. *Water Research*, 42, pp. 3930–3940.

Brown, R. A. and W. F. Hunt (2010). Impact of Maintenance and (Im)Properly Sizing Bioretention on Hydrological and Water Quality Performance. Paper presented at the ASCE 2010 International Low Impact Development Conference Redefining Water in the City, April 11-14.

Brown, R. A. and W. F. Hunt (2011). Evaluating Media Depth, Surface Storage Volume, and Presence of an Internal Water Storage Zone on Four Sets of Bioretention Cells in North Carolina. Paper presented at the ASCE 2011 World Environmental and Water Resources Congress, May 22-26.

Chapman, C. and R. R. Horner (2010). Performance Assessment of a Street-Drainage Bioretention System. *Water Environment Research*, 82, pp. 109–119.

Culbertson, T. L. and S. L. Hutchinson (2004). *Assessing Bioretention Cell Function in a Midwest Continental Climate.* Paper presented at the ASAE/CSAE Annual International Meeting, Ottawa, Ontario, Canada.

Davis, A. P., M. Shokouhian, H. Sharma, and C. Minami (2001). Laboratory Study of Biological Retention for Urban Stormwater Management. *Water Environment Research*, 73, pp. 5–14.

Davis, A. P., M. Shokouhian, H. Sharma, C. Minami, and D. Winogradoff (2003). Water Quality Improvement through Bioretention: Lead, Copper, and Zinc Removal. *Water Environment Research*, 75, pp. 7–82.

Davis, A. P. and R. H. McCuen (2005). *Stormwater Management for Smart Growth*. New York - Springer Science + Business Media Inc.

Davis, A. P., M. Shokouhian, H. Sharma, and C. Minami (2006). Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal. *Water Environment Research*, 78, pp. 284–293.

Davis, A. P. (2007). Field Performance of Bioretention: Water Quality. *Environmental Engineering Science*, 24, pp. 1048–1064.

Davis, A. P. (2008). Field Performance of Bioretention: Hydrology Impacts. *Journal of Environmental Engineering*, 13, pp. 90–95.

Diblasi, C. J., H. Li, A. P. Davis, and U. Ghosh (2009). Removal and Fate of Polycyclic Aromtic Hydrocarbon Pollutants in an Urban Stormwater Bioretention Facility. *Environmental Science & Technology*, 43, pp. 494–502.

Dietz, M. E. and J. C. Clausen (2005). A Field Evaluation of Rain Garden Flow and Pollutant Treatment. *Water, Air, and Soil Pollution*, 167, pp. 123–138.

Dietz, M. E. and J. C. Clausen (2006). Saturation to Improve Pollutant Retention in a Rain Garden. *Environmental Science & Technology*, 40, pp. 1335–1340.

Dougherty, M., C. LeBleu, E. Brantley, and C. Francis (2007). *Evaluation of Bioretention Nutrient Removal in a Rain Garden with an Internal Water Storage (IWS) Layer.* Paper presented at the ASABE Annual International Meeting, Minneapolis, MN.

Eaton, A. D., L. S. Clesceri, and A. E. Greenberg (1995). *Standard Methods for the Examination of Water and Wastewater* (19th ed.). Washington, DC – American Public Health Association.

Emerson, C. H. and R. G. Traver (2008). Multiyear and Seasonal Variation of Infiltration from Stormwater Best Management Practices. *Journal of Irrigation and Drainage Engineering*, 134, pp. 598–605.

Federal Highway Administration. (1990). *Pollutant Loadings and Impacts from Highway Stormwater Runoff Volume III: Analytical Investigation and Research Report* (No. FHWA-RD-88-008). McLean, VA.

Förstner, U., W. Ahlf, and W. Calmano (1989). Studies on the Transfer of Heavy Metals between Sedimentary Phases with a Multi-Chamber Device: Combined effects of salinity and redox variation. *Marine Chemistry*, 28, pp. 145–158.

Free Online Dictionary. (2011). *Adsorption*. Retrieved July 12, 2011, from http://www.thefreedictionary.com/adsorption.

Goonetilleke, A., P. Egodawatta, and A. Liu (2011). *Enhancing Water-Sensitive Urban Design (WSUD) Practices to Mitigate Urban Stormwater Pollution and Reuse Potential.* Paper presented at the International Conference on Sustainable Water Resource Management and Treatment Technologies, at NEERI, Nagpur, India. CD ROM Publication.

Haan, C. T., B. J. Barfield, and J. C. Hayes (1994). *Design Hydrology and Sedimentology for Small Catchments*. San Diego, CA – Academic Press, Inc.

Han, Y., S.-L. Lau, M. Kayhanian, and M. K. Stenstrom (2006). Characteristics of Highway Stormwater Runoff. *Water Environment Research*, 78, pp. 2377–2388.

Hatt, B. E., T. D. Fletcher, and A. Deletic (2009). Hydrologic and Pollutant Removal Performance of Stormwater Biofiltration Systems at the Field Scale. *Journal of Hydrology*, 365, pp. 310–321.

Henderson, C., M. Greenway, and I. Phillips (2007). Removal of Dissolved Nitrogen, Phosphorus, and Carbon from Stormwater by Biofiltration Mesocosms. *Water Science & Technology*, 55, pp. 183–191.

Hong, E., E. A. Seagren, and A. P. Davis (2006). Sustainable Oil and Grease Removal from Synthetic Stormwater Runoff Using Bench-Scale Bioretention Studies. *Water Environment Research*, 78, pp. 141–155.

Hsieh, C.-H. and A. P. Davis (2005). Evaluation and Optimization of Bioretention Media for Treatment of Urban Storm Water Runoff. *Journal of Environmental Engineering*, 131, pp. 1521–1531.

Hsieh, C.-H., A. P. Davis, and B. A. Needelman (2007). Bioretention Column Studies of Phosphorus Removal from Urban Stormwater Runoff. *Water Environment Research*, 79, pp. 177–184.

Huber, W. C., J. P. Heaney, E. W. Strecker, and N. Weinstein (2006). *Evaluation of Best Management Practices for Highway Runoff Control*. The Low Impact Development Center Inc., National Cooperative Highway Research Program Report 565, pp. 28–42.

Hunt, W. F. (2003). *Pollutant Removal Evaluation and Hydraulic Characterization for Bioretention Stormwater Treatment Devices*. (Doctoral dissertation). The Pennsylvania State University, University Park, PA.

Hunt, W. F., A. R. Jarrett, J. T. Smith, and L. J. Sharkey (2006). Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. *Journal of Irrigation and Drainage Engineering*, 132, pp. 600–608.

Hunt, W. F., J. T. Smith, and J. Hathaway (2007). *Hall Marshall Bioretention: Final report*. Charlotte, NC: Storm Water Services, City of Charlotte.

Ingersoll, T. L. and L. A. Baker (1998). Nitrate Removal in Wetland Microcosms. *Journal of Water Research*, 32 (3), pp. 677–684.

Jones, M. P., W. F. Hunt, and J. T. Smith (2007). *The Effect of Urban Stormwater BMPs on Runoff Temperature in Trout Sensitive Waters*. Paper presented at the ASABE Annual International Meeting, Minneapolis, MN.

Jones, M. P. and W. F. Hunt (2009). Bioretention Impact on Runoff Temperature in Trout Sensitive Waters. *Journal of Environmental Engineering*, 135, pp. 577–585.

Kayhanian, M., A. Singh, C. Suverkropp, and S. Borroum (2003). Impact of Annual Average Daily Traffic on Highway Runoff Pollutant Concentrations. *Journal of Environmental Engineering*, 129, pp. 975–990.

Kayhanian, M., C. Suverkropp, A. Ruby, and. K. Tsay (2007). Characterization and Prediction of Highway Runoff Constituent Event Mean Concentration. *Journal of Environmental Management*, 85, pp. 279–295.

Kim, H., E. A. Seagren, and A. P. Davis (2003). Engineered Bioretention for Removal of Nitrate from Stormwater Runoff. *Water Environment Research*, 75 pp. 355–367.

Kim, M. H., C. Y. Sung, M.-H. Li, and K.-H. Chu (2012). Bioretention for stormwater quality improvement in Texas: Removal effectiveness of Escherichia coli. *Separation and Purification Technology*, 84, pp. 120–124.

Li, H., L. J. Sharkey, W. F. Hunt, and A. P. Davis (2009). Mitigation of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland. *Journal of Hydrological Engineering*, pp. 407–415.

Li, M.-H., M. E. Barrett, P. Rammonhan, F. Olivera, and H. C. Landphair (2008). Documenting Stormwater Quality on Texas Highways and Adjacent Vegetated Roadsides. *Journal of Environmental Engineering*, 134, pp. 48–59.

Li, M.-H. and M. E. Barrett (2008). Relationship between Antecedent Non-IWS Period and Highway Pollutant: Conceptual Models of Buildup and Removal Processes. *Water Environment Research*, 80, pp. 740–747.

Li, M.-H., B. Dvorak, and C. Y. Sung (2010a). *Bioretention, Low Impact Development, and Stormwater Management*. In J. Aitkenhead-Peterson, V. Astrid (Eds.), *Urban Ecosystem Ecology* (pp.413-430). Madison, WI – American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Li, M.-H., C. Y. Sung, M. H. Kim, and K.-H. Chu (2010b). *Bioretention for Stormwater Quality Improvement in Texas: Pilot Experiments* (FHWA/TX-10/0-5949-2). College Station, TX – Texas Transportation Institute.

Li, M.-H., C. Y. Sung, M. H. Kim, and K.-H. Chu (2011). Assessing Performance of Bioretention Boxes in Hot and Semi-Arid Regions: A Highway Application Pilot Study. *Transportation Research Record*, 2262, pp. 155–163.

Li, M.-H., C. Y. Sung, M. H. Kim, and K.-H. Chu (2012). Performance of Bioretention System in Treating Urban Highway Runoff: A Comparison Study of Designs with and without an Internal Water Storage Layer. *Landscape Architecture*, pp. 140–147.

Limouzin, M., D. Lawler, and M. Barrett (2011). *Performance Comparison of Stormwater Biofiltration Designs* (CRWR Online Report 10-05). Austin, TX – Center for Research in Water Resources, The University of Texas at Austin.

Lin, Y.-F., S. R. Jing, and D.-Y. Lee, (2002). Effects of Macrophytes and External Carbon Sources on Nitrate Removal from Groundwater in Constructed Wetlands. *Environmental Pollution*, 119 (3), pp. 413–420.

Lintern, A., E. Daly, H. Duncan, B. E. Hatt, T. D. Fletcher, and A. Deletic (September 2011). *Key Design Characteristics That Influence the Performance of Stormwater Biofilters.* Paper presented at the 12th International Conference on Urban Drainage, Porto Alegre, Brazil.

Lucas, W. C. and M. Greenway (2008). Nutrient Retention in Vegetated and Non-Vegetated Bioretention Mesocosms. *Journal of Irrigation and Drainage Engineering*, 134, pp. 613–623.

Marsh, W. M. (2005). *Landscape Planning Environmental Applications* (4th ed.). John Wiley & Sons, Inc.

McNett, J. K., W. F. Hunt, and A. P. Davis (2011). Influent Pollutant Concentrations as Predictors of Effluent Pollutant Concentrations for Mid-Atlantic Bioretention. *Journal of Environmental Engineering,* 137, pp. 790–799.

Mortula, M. M. and G. A. Gagnona (2007). Phosphorus Adsorption and Oven Dried Alum Residual Solids in Fixed Bed Column Experiments. *Journal of Environmental Engineering and Science*, 6(6), pp. 623–628.

North Carolina Department of Environment and Natural Resources (NCDENR). (2005). *Stormwater BMP "Updated Draft Manual of Stormwater Best Management Practices"*. North Carolina Division of Water Quality.

Passeport, E., W. F. Hunt, D. E. Line, R. A. Smith, and R. A. Brown (2009). Field Study of the Ability of Two Grassed Bioretention Cells to Reduce Storm-Water Runoff Pollutant. *Journal of Irrigation and Drainage Engineering*, 135, pp. 505–510.

Prince George's County. (2002). *Bioretention Manual*. Landover, MD – Department of Environmental Resources, Watershed Protection Branch, Prince George's County, MD.

Puget Sound Action Team. (2005). *Low Impact Development: Technical Guidance Manual for Puget Sound* (No. PSAT 05-03). Olympia, WA – Washington State University.

Read, J., T. Wevill, T. Fletcher, and A. Deletic (2008). Variation among Plant Species in Pollutant Removal from Stormwater in Biofiltration Systems. *Water Research*, 42, pp. 893–902.

Read, J., T. Fletcher, T. Wevill, and A. Deletic (2009). Plant Traits that Enhance Pollutant Removal from Stormwater in Biofiltration Systems. *International Journal of Phytoremediation*, 12(1), pp. 34–53.

Rusciano, G. M. and C. C. Obropta (2007). Bioretention Column Study: Fecal Coliform and Total Suspended Solids Reductions. *Transactions of the ASABE*, 50(4), pp. 1261–1269.

Salt, D. E., R. D. Smith, and I. Raskin (1998). Phytoremediation. *Plant Physiology and Plant Molecular Biology*, 49, pp. 643–668.

Schnoor, J. L., L. A. Licht, S. C. McCutcheon, N. L. Wolfe, and L. H. Carreira (1995). Phytoremediation of Organic and Nutrient Contaminants. *Environmental Science Technology*, 29, pp. 318–323.

Sharkey, L. J. and W. F. Hunt (2005). *Design Implications on Bioretention Performance as a Stormwater BMP: Water Quality and Quantity*. Paper presented at the ASAE Annual International Meeting, Tampa, FL.

Sung, C. Y. and M.-H. Li (2010). The Effect of Urbanization on Stream Hydrology in Hillslope Watersheds in Central Texas. *Hydrological Processes*, 24, pp. 3706–3717.

Sung, C. Y., M.-H. Li, G. O. Rogers, A. Volder, and Z. Wang (2011). Investigating Alien Plant Invasion in Urban Riparian Forests in a Hot and Semi-Arid Region. *Landscape and Urban Planning*, 100, pp. 278–286.

Texas Commission of Environmental Quality. (2007). *Stormwater Discharges Associated with Small Municipal Separate Storm Sewer Systems* (TPDES General Permit Number TXR040000). Austin, TX – U.S. Government Printing Office.

Texas Commission of Environmental Quality. (2008). *Stormwater Discharges Associated with Construction Activities* (TPDES General Permit Number TXR150000). Austin, TX – U.S. Government Printing Office.

Texas Commission of Environmental Quality. (2011). Multi-Sector General (TPDES General Permit Number TXR050000). Austin, TX – U.S. Government Printing Office.

Texas Department of Transportation. (2002). *Stormwater Management Guidelines for Construction Activities*. Retrieved October 8, 2012, from http://ftp.dot.state.tx.us/pub/txdot-info/library/pubs/bus/storm_water/1introtoc.pdf.

Texas Department of Transportation. (2004). *Hydraulic Design Manual*. Retrieved October 8, 2012, from http://onlinemanuals.txdot.gov/txdotmanuals/hyd/hyd.pdf.

Texas Department of Transportation. (2007a). *Landscape and Aesthetics Design Manual*. Retrieved October 8, 2012, from http://onlinemanuals.txdot.gov/txdotmanuals/lad/lad.pdf.

Texas Department of Transportation. (2007b). *Texas Department of Transportation Pocket Facts*. Retrieved from ftp://ftp.dot.state.tx.us/pub/txdot-info/pio/pfacts/pf_2007.pdf.

Trowsdale, S. A. and R. Simcock (2011). Urban Stormwater Treatment Using Bioretention. *Journal of Hydrology*, 397, pp. 167–174.

University of Texas at Austin. (2009). *Native Plant Database*. TWC Staff, GDG. Retrieved July 04, 2011, from http://www.wildflower.org/plants/result.php?id_plant=LEFR3.

Weiss, P. T., J. S. Gulliver, and A. J. Erickson (2007). Cost and Pollutant Removal of Storm-Water Treatment Practices. *Journal of Water Resources Planning and Management*, pp. 218–229.

Wisconsin Department of Natural Resources (2003). *Rain Gardens: A How-to Manual for Homeowners* (No. PUB-WT-776). Madison, WI – City of Wisconsin.

Wossink, A. and B. Hunt (2003). *The Economics of Structural Stormwater BMPs in North Carolina*. N.C. Urban Water Consortium, Stormwater Group, Water Resources Research Institute of the University of North Carolina.

Yang, H., D. C. Florence, E. L. McCoy, W. A. Dick, and P. S. Grewal (2009). Design and Hydraulic Characteristics of a Field-Scale Bi-Phasic Bioretention Rain Garden System for Storm Water Management. *Water Science & Technology*, 59, pp. 1863–1872.

Yu, S. and T. Langan (1999). *Controlling Highway Runoff Pollution in Drinking Water Supply Reservoir Watersheds*. Charlottesville, VA – Virginia Transportation Research Council.

Zhang, L., E. A. Seagren, A. P. Davis, and J. S. Karns (2010). The Capture and Destruction of Escherichia coli from Simulated Urban Runoff using Conventional Bioretention media and Iron Oxide-Coated Sand. *Water Environment Research*, 82, pp. 701–714.

Zhang, W., G. O. Brown, and D. E. Storm (2006). *Enhancement of Phosphorus Removal in Bioretention Cells by Soil Amendment*. Paper presented at the ASABE Annual International Meeting, Portland, OR.

Zhang, Z., Z. Rengel, T. Liaghati, T. Antoniette, and K. Meney (2011). Influence of Plant Species and Submerged Zone with Carbon Addition on Nutrient Removal in Stormwater Biofilter. *Ecological Engineering*, 37, pp. 1833–1841.

APPENDIX A: PLANTING PLAN GUIDELINES

Table 23 below includes a list of plants that appear to meet the vegetation criteria in Chapter 5 (although further testing is recommended) and that are often commercially available in south-central Texas. Further information on these plant recommendations can be found in the following references: (1) University of Texas at Austin-Ladybird Johnson Wildflower Center (2009), (2) Aggie Horticulture (2011), or (3) Arnold (2008). These plants are mainly for south-central Texas. In northern and western Texas, verify cold-hardiness; in western and eastern Texas, verify moisture requirements. Also, be sure to select seed with local provenance. Carefully consider the moisture requirements as you specify plants in either Non-IWS or IWS bioretention cells.

Table 23. Bioretention Plant Recommendations.

Botanical Name	Common Name	Evergreen	Height	Sun	Moisture
Leucophyllum frutescens	Texas Sage (Cenizo)	E	4′–8′	yes	dry
Schizachyrium scoparium	Little Bluestem		2′–4′	yes	dry
Nassella tenuissima	Mexican Feathergrass	SE	1′–2′	yes	dry
Sedum spectabile	Sedum (Stonecrop)	E	1′–2′	yes	dry
Carex texensis	Texas Sedge		0.5′	yes	dry
Salvia texana	Texas Sage		1′–3′	yes	dry
Echinacea purpurea	Purple Coneflower		1′–3′	yes	dry
Salvia greggii	Autumn/Cherry Sage	E	2′–5′	yes	dry
Dalea frutescens	Black Dalea	SE	1′–3′	yes	dry
Dalea greggii	Gregg Dalea	E	2′–4′	yes	dry
Chrysactinia Mexicana	Damianita	E	1′	yes	dry
Penstemon baccharifolius	Rock Penstemon	SE/E	1′–2′	yes	dry
Ratibida columnifera	Mexican Hat		1′–3′	yes	dry/moist
Monarda fistulosa	Beebalm		2’–5’	yes	dry/moist
Uniola paniculata	Sea Oats	SE	3′–5′	yes	dry/moist
Liatris pycnostachya	Prairie Blazing Star		2′–5′	yes	dry/moist
Rudbeckia hirta var. *pulcherrima*	Black-eyed Susan		1′–3′	yes	dry/moist
Buchloe dactyloides	Buffalo grass		1.5’	yes	dry/moist
Cynodon dactylon	Bermudagrass		0.75′	yes	dry/moist
Gaura lindheimeri	Gaura		2′–3′	yes	dry/moist
Muhlenbergia lindheimeri	Big Muhly	SE	2′–5′	yes	dry/moist
Panicum virgatum	Switchgrass		3′–6′	yes	dry/moist
Helianthus maximiliani	Maximilian Sunflower		3′–6′	yes	moist/dry
Muhlenbergia rigens	Deer Muhly		3′–4′	yes	moist/dry
Muhlenbergia capillaris	Gulf Coast Muhly		2′–3′	yes	moist
Chasmanthium latifolium	Inland Sea Oats		2′–4′	partial	moist
Andropogon gerardii	Big Bluestem		4′–8′	yes	wet/moist
Equisetum hyemale	Horsetail	E	3′	yes	wet/moist

APPENDIX B:
SUMMARY OF SITE SELECTION PROCESS

This memorandum summarizes the site visits and design process of the field demonstration project for TxDOT 0-5949, "Bioretention for Stormwater Improvement in Texas." After analyzing seven candidate sites, we concluded that four sites—two in the Austin District, one in the Bryan District, and one at the TTI facility—were best applicable to conduct the field demonstration for bioretention.

Task 2.2 Contacting TxDOT for Selecting Candidate Sites

We contacted several TxDOT and TTI personnel, and identified seven sites at which bioretention could be constructed. Site conditions and photos were described in Attachment A. The following list summarizes the contacts.

1. November 12, 2007
TxDOT personnel: David Bruno, P.E., Transportation Engineer, Bryan District
Project: FM 2818 and Wellborn intersection
Meeting (minutes available): November 12, 2007, with presence of David Bruno, Ming-Han Li, Kung-Hui Chu, Chan Yong Sung, and Myunghee Kim
Status: Preliminary design of a linear roadside bioretention was proposed with material quantity estimated following TxDOT's specifications. Due to the delay of the project in TxDOT, Bruno suggested not to proceed with this option.

2. February 2008
TxDOT personnel: Steven Ligon (PD), Environmental Division
Email solicitation: An email with an overview of bioretention slide show was sent to TxDOT personnel.

3. July 14, 2008
Personnel: Ming-Han Li (RS), TTI, Holly Crenshaw, TTI
Meeting: Two consecutive meetings: (1) September 8, 2008, with Holly Crenshaw, Tom Woodfin, and Che-Chia; and (2) September 25, 2008, with Holly Crenshaw and BRW architects, Texas A&M Physical Plant.
Status: Hydraulic study was conducted to retrofit the existing detention pond to bioretention. The study is under review by TTI facility manager.

4. July 2008
Personnel: Ming-Han Li (RS), TTI
Email solicitation: Emails were sent to several TxDOT district landscape architects, including Betsy Pittman, Kerry Blackmon, Ethan Beeson, Dana Cote, Maury Jacob, and Patrick Haigh.
Status: Two field trips: (1) August 14, 2008, for three interchanges on SH 130 and for TxTag parking lot in Austin District; and (2) September 10, 2008, for two interchanges on SH 6 in the Bryan District. Preliminary designs for two candidate sites in the Austin District were proposed to Jon Geiselbrecht.

Task 4.1 Designing Demonstration Projects

Of seven sites identified in Task 2.2, we concluded that four sites were suitable for the field demonstration project.

- Existing detention pond at the interchange on SH 130/SH 45 in the TxDOT Austin District.
- Existing detention pond at TxTag parking lot in the TxDOT Austin District.
- Interchange on SH 6/SH 21 in the TxDOT Bryan District.
- Existing detention pond at the TTI Gilchrist building.

1. Two candidate sites in the TxDOT Austin District were designed and sent to Jon Geiselbrecht for review on October 24, 2008. We contacted Jon Geiselbrecht to check the status of the projects on December 5, 2008. Attachment B is a memorandum describing the proposed designs of two bioretentions in the Austin District.

2. After contacting John Moravec, David Bruno, and Maury Jacob on October 29, 2008, and on November 10, 2008, one candidate site in the TxDOT Bryan District was designed and sent to them on December 19, 2008. A subsequent meeting was held on January 7, 2009, to discuss the construction details of the bioretention. Attachment C is a memorandum describing the proposed design for one bioretention in Bryan District.

3. One candidate site retrofits an existing detention pond at the TTI Gilchrist building. We conducted a hydraulic study for the existing detention ponds at the TTI Gilchrist building to evaluate the site suitability for bioretention. Based on the study, we found that the proposed bioretention could have a storage volume to treat stormwater runoff from the adjacent parking lot. We also designed the details of bioretention for this site. Attachment D describes the result of the hydraulic study. We contacted Holly Crenshaw on October 6, 2008, and December 5, 2008.

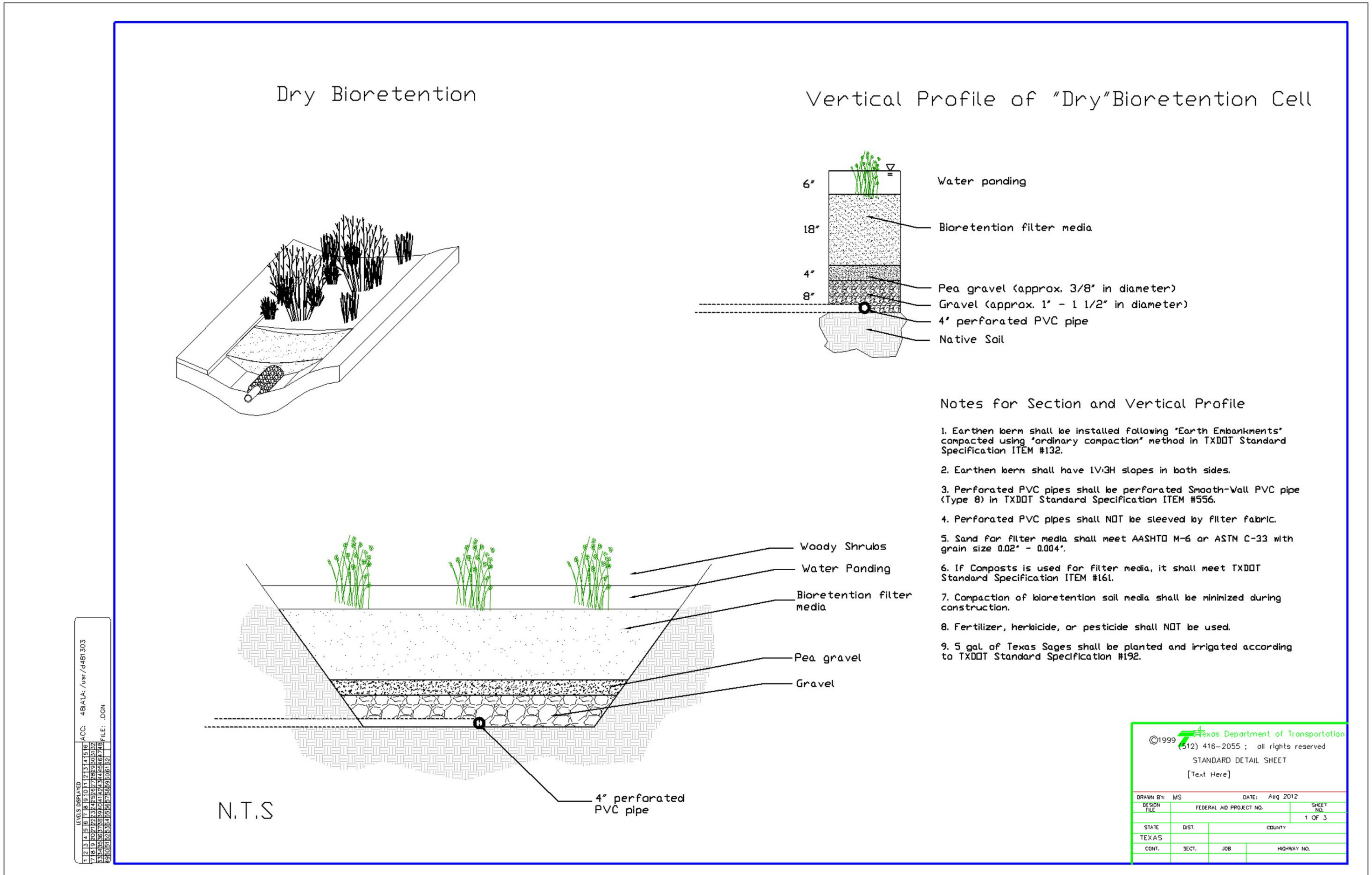


Figure 20. Vertical Profile of Non-IWS Bioretention Media.

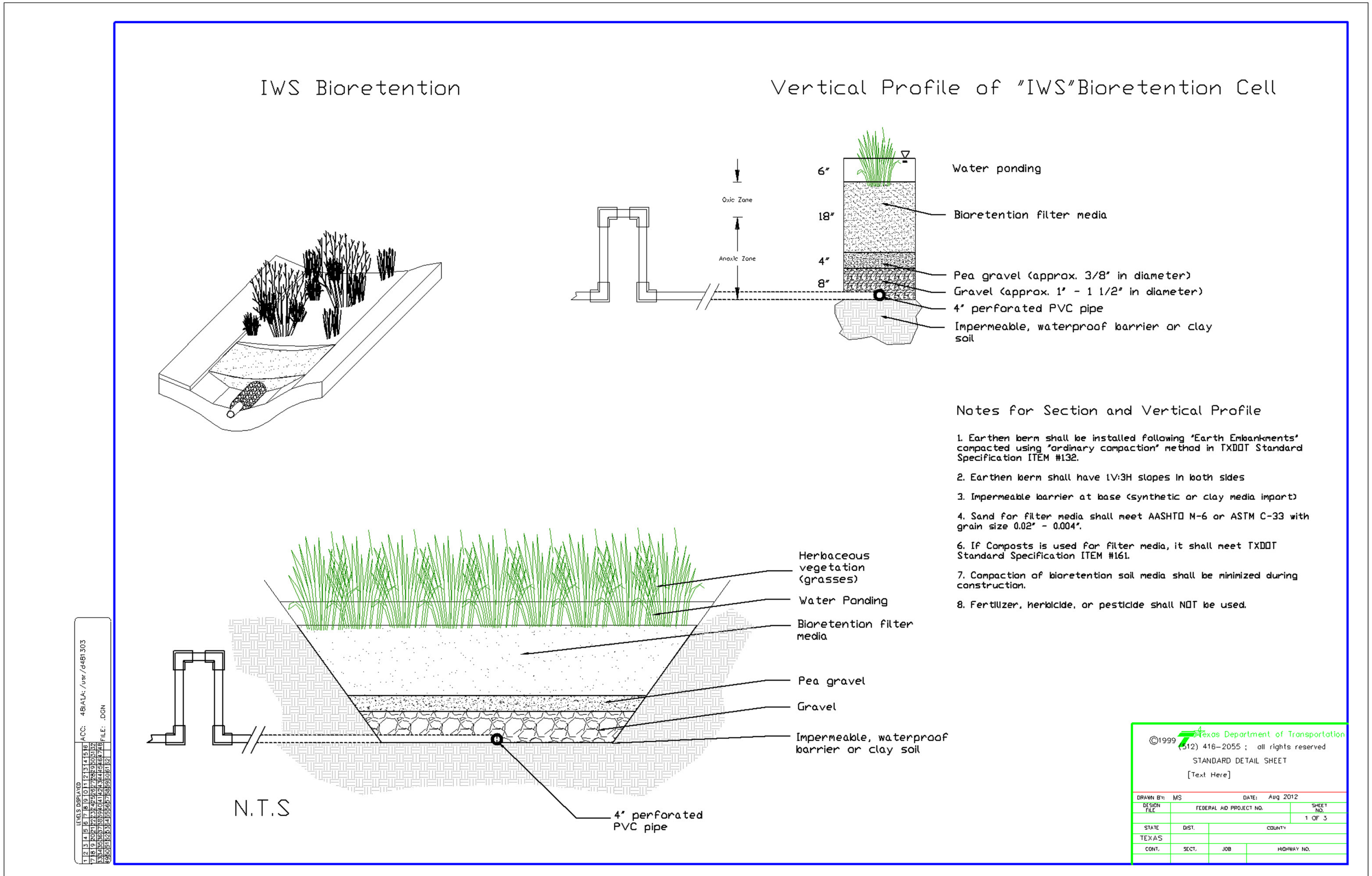


Figure 21. Vertical Profile of IWS Bioretention Media.

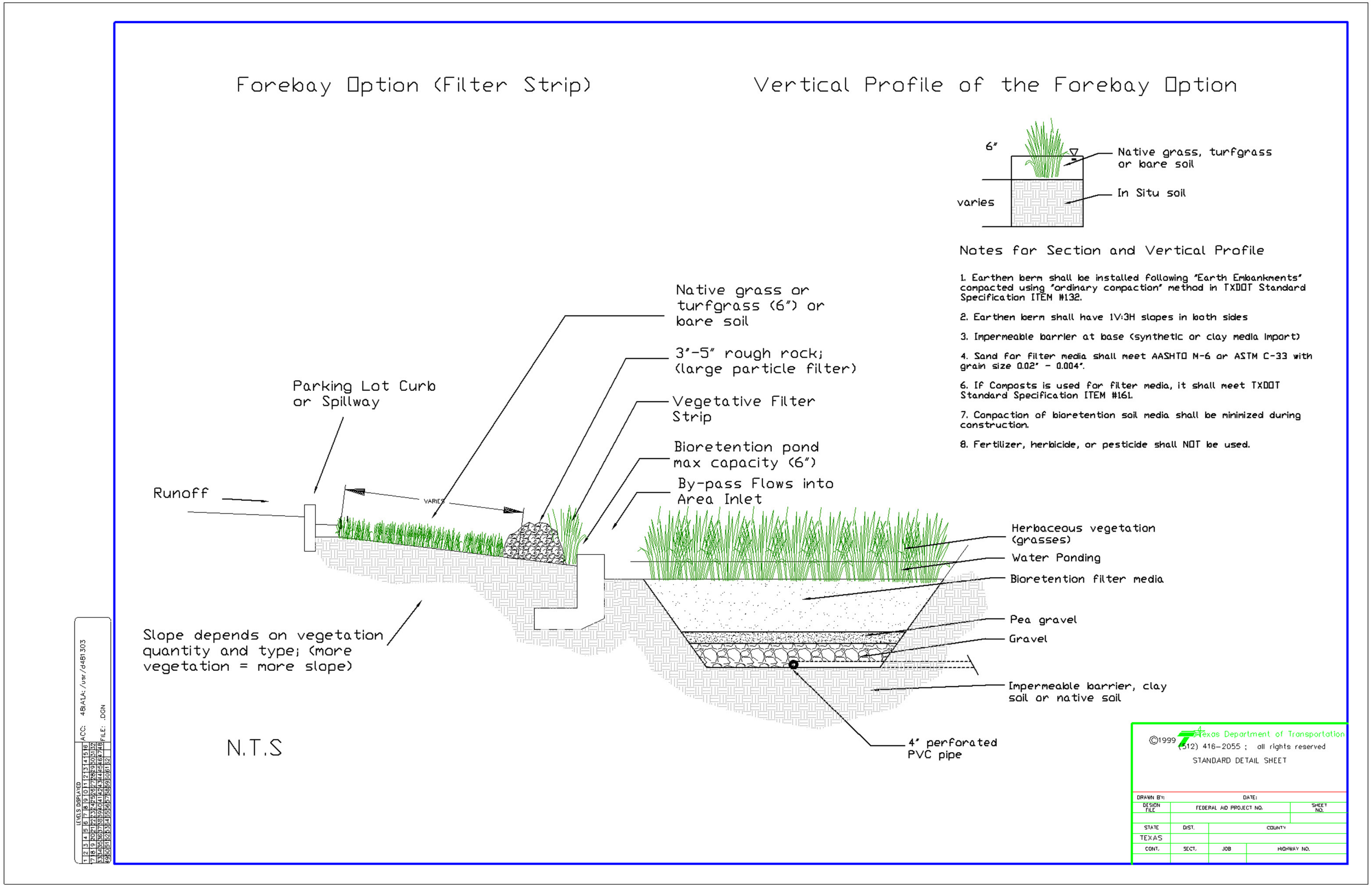


Figure 22. Vertical Profile of Forebay.

APPENDIX D:
BIORETENTION SPECIAL SPECIFICATION

1. DESCRIPTION. A bioretention cell is a stormwater best management practice that includes a vertical profile starting from the bottom: a drainage layer, a soil filtration media layer, an optional mulch layer and planting. The cell can manage both stormwater quantity and quality but must be designed according to the site-specific conditions, including soil, climate, hydrology, pollutant characteristics, etc.

2. MATERIALS.

A. **Soil Media.** Sand, silt, and clay: maximum sand quantity is 94 percent and a minimum 80 percent, and maximum clay content is the reciprocal 6–20 percent. Pollutant quantity and desired filtration rate must be carefully considered before these percentages are finalized. The soil media must have the following properties: minimum 32 ppm of magnesium, less than 69 ppm phosphorus (P_2O_5), minimum of 78 ppm of potassium (K_2O), and less than 500 ppm salts. Soil media must be free of weed seed initially and remain free during stockpiling, transport, and installation. The existing soil in the location of the bioretention area must be tested to determine the particle size and to classify the percentage of sand, silt or loam, and clay.

B. **Gravel.** The pea gravel should be 0.375 inch in diameter, and the underlay gravel size should be a minimum of 0.5 inch and a maximum of 1 inch.

C. **Organic Matter.** Mulch is not recommended unless the area has low N and P influent. Herbaceous plants eventually add to the organic matter. Organic matter is to be mixed with the upper portion of soil media where plant roots can reach it.

D. **PVC Pipe.** A 4-inch minimum standard (schedule 40) PVC pipe is recommended in small- to medium-sized (1,000 to 10,000 ft^2) cells, but a properly designed French drain would also work depending on the infiltration time, i.e., soils and runoff quantity.

E. Live Plant Materials. Only species tested hot and semi-arid bioretention cells or the recommended species in this report should be used. Careful consideration should be taken in choosing non-IWS and IWS cell vegetation. Dimensions depend on the vegetation. Plants should be in good health and of local provenance. Plants should be inspected at the nursery and after transportation for quality control. These should be planted the same day unless there is available irrigation. Spring is the ideal time for establishing new vegetation. It is recommend not to establish vegetation in the summer due to the increased heat and the common decrease in rainfall.

3. CONSTRUCTION METHODS.

A. Excavation (Item 110). Ensure no underground pipelines or wires exist (call utility company). After the designated area has been marked, begin excavation. The cell shall be excavated to the dimensions, side slopes, and elevations as shown in the drawing examples. Excavators and backhoes should avoid driving directly on the bioretention cell when possible.

B. Embankment; Earth Embankment (Item 132).

C. Level Bottom. Leveling should be in accordance with the precision requirements for drainage (usually ±0.5 percent). Compaction is not required or even preferred unless a hardened or impermeable layer is being created and/or lined with a synthetic fabric to prevent infiltration below, which prevents sub layer infiltration and promotes denitrification.

D. Install Perforated Pipe. If perforated pipes were to be installed, follow all material and installation instructions on the construction documents. The pipe should have a minimum slope of 0.5 percent and should extend the length of the bioretention cell. Ensure 2 inches of gravel are placed both above and below.

E. Apply Gravel. The gravel layer should be 8 inches thick in most cases.

F. Apply Pea Gravel. Apply 2 inches of pea gravel first. Smooth the surface and then apply the remaining 2 inches of pea gravel (should be 4 inches thick in most cases).

G. Apply Soil Media. Soil media should be previously mixed off site and should be applied evenly throughout the cell. The soil media shall be placed and graded using low ground-contact pressure equipment, or by excavators or backhoes operating on the ground adjacent to the bioretention facility. It should not be packed any more than necessary in installation, as this may damage the permeability and root expansion capacity. Final grading shall be performed after a 24 hr settling period. Final elevation shall be within 1 inch of the elevation shown on the plans. During the installation, care should be taken to avoid damage to existing components such as influent or effluent devices or the perforated pipe.

H. Level Surface. Be sure the soil media is leveled upon completion before the plant materials are installed. Be sure the overflow/emergency spillway height is correct before rocks are placed over it.

I. Apply Rip-Rap. Apply coarse rocks on top of formed cells and spillway to prevent erosion. An erosion mat may be applied as well.

J. Plant Shrubs/Grass. Follow all nursery instructions for plant materials. Most important is to plant the crown at ground level (2 inches above or below can kill it). Do not add extra potting soil.

K. Watering. Watering shall conform to the pertinent requirements of Item 168, Vegetative Watering. After the completion of the work, a watering schedule will be produced in accordance with the plant palette and soil media of the cell. This schedule may need to be changed during times of drought. Drought is defined as 28 consecutive days without measurable rainfall (0.1 inch in depth). The rate of watering shall be slow enough to ensure that no significant runoff occurs at the emergency spillway. An estimation of irrigation needs for plants with a dry soil moisture regime is 3 gallons per ft^2 of bioretention surface area (e.g., 670 ft^2 = 2,010 gallons). This process shall be repeated weekly if it is summer until measurable rainfall occurs.

L. Measurement. Soil, gravel, and mulch are to be measured by the square foot (SF), square yard (SY), or total pounds. Pipe is to be measured by the foot or yard. Plants are measured individually and purchased in bulk when possible.

M. Payment. The work performed and materials furnished in accordance with this item and measured as provided under "Measurement" will be paid for at the unit price in the measurements listed above and work to be done by the hour or site, depending on the specific contract. This price shall be full compensation for necessary earthwork, leveling, hauling, and placing live plant materials, soil, water and for all labor, tools, equipment, and incidentals necessary to complete the work.

APPENDIX E:
DESIGN AND MAINTENANCE GUIDELINE

Knowing the goal of stormwater quality improvement, groundwater issues and the site-specific properties of runoff (pollutant type such as TSS, metals, nutrients, oil and grease, etc. and quantity) is necessary before designing a bioretention system. Included in this guideline are site-specific scenarios that can be studied to solve design and maintenance questions for bioretention. Remember that both stormwater quality and quantity parameters will affect the size (length, width, height) and type (non-IWS or IWS) of the cell.

1. **Forebay Option**

   A forebay can be very useful for areas with excessive pollutants or in smaller spaces where time or space is limited and yet pollutant removal is crucial. The forebay will require periodic maintenance and removal of large debris but decreases the costs on maintaining the larger cell. Vegetation is recommended in the forebay but this may consist of volunteer grasses.

2. **Non-IWS Bioretention**

   A general bioretention cell with the proper soil mix and appropriate vegetation is sometimes sufficient. Appendix C includes three construction drawings for bioretention systems, one of which is a typical non-IWS bioretention cell. If no alterations are necessary from a unique landscape context or pollutant influent, then the standard specs should be applied.

3. **IWS Bioretention**

   The IWS layer is recommended for areas where N effluent is a concern, where greater detention time and peak discharge reduction is desired, and where water shortages or drought are a concern. IWS bioretention cells will require plants that can handle permanent or temporary inundation, which creates anoxic conditions for roots and soil microbes. The depth of the IWS layer should be considered with the plant palette in mind as well. Root length and type plays an important role in IWS success.

4. **Harvesting/Mowing Bioretention Vegetation**

   If the cell will be harvested (for extra pollutant removal, visual corridor, etc.), a schedule must be made *before* the planting plan is developed. Different grass species will have different growth patterns. Fluctuations in annual rainfall patterns will also affect this schedule. The general concept with mowing or harvesting is that stressed plants absorb more nutrients and water. When mowing herbaceous vegetation, care should be taken to avoid excess compaction of the vegetation and soil media.

5. **Pollutant Concentrations**

- **Oil and Grease Removal**

  A general bioretention cell with the proper soil mix and appropriate vegetation is believed to be sufficient.

- **Fecal Coliform Removal**

  A general bioretention cell with the proper soil mix and appropriate vegetation is believed to be sufficient.

- **Heavy Metal (Cu, Zn, and Pb) Removal**

  A general bioretention cell with the proper soil mix and appropriate vegetation is believed to be sufficient for moderate heavy metal removal. However, the addition of an IWS layer further reduces most metals.

- **Phosphorus Removal**

  A general bioretention cell with the proper soil mix and appropriate vegetation is believed to be sufficient for moderate P removal. However, the addition of an IWS layer does enhance P removal Furthermore, dense vegetation is recommended. Also, Zhang et al. (2006) revealed that adding fly ash to the mix increased P removal.

- **Nitrogen Removal**

  An IWS layer with dense vegetation is highly recommended for N removal as this creates a denitrification zone and enhances plant vigor and biomass, all of which increase N removal from stormwater. Be sure to exclude nitrogen-containing compost in the bioretention cell if N removal is your goal. If N removal is not your goal, however, consider the N needs of the plant.

6. **Groundwater Contamination**

   When groundwater contamination is an issue, more clay and less sand should be specified in the mix, as this prevents or slows water from infiltrating to the sublayer. Furthermore, a basin lining of clay or a waterproof barrier is recommended. However, this will decrease your overall water retention.

7. **Climate Variations**

- **East Texas**

  East Texas should consider the average annual high quantity of rainfall and design for rapid infiltration and find plants that are adapted to the wet, humid climate.

- **West Texas**

  West Texas should consider the average annual low quantity of rainfall and design for medium infiltration (desert storms often have a high peak discharge). An IWS is recommended, where possible, to store water between rainfalls and increase its availability to vegetation.

- **North Texas**

  North Texas (particularly the Panhandle area) should consider the average annual rainfall but also consider the colder winter climate and choose an appropriate plant palette. Also, in areas with average annual snowfall requiring deicing, the plant palette must also be resistant to excessive salt. A forebay may filter some of the salt in a first flush.

- **South Texas**

  South Texas should consider the local rainfall but also consider the very hot (and often humid) climate and choose an appropriate plant palette. In coastal areas, know that any water that is not properly filtered may contaminate oceanic waters. This is particularly dangerous with nutrients such as P and N, as algae growth is spurred (eutrophication). As these organisms die, dissolved oxygen is taken from the water body and can injure or kill aquatic life, such as fish, that are dependent upon it.

8. Maintenance Guideline

Table 24 summarizes maintenance guideline.

Table 24. Maintenance Guideline.

	Forebay	Non-IWS	IWS
Remove Trash & Debris	yes	yes	yes
Annual Soil Replacement (top 4″)	unknown but likely	yes	yes
Vegetation (Woody)	--	depends*	depends*
Vegetation (Herbaceous)	varies	varies	varies
Irrigation	--	yes	usually not
Inspect & Repair Spillway	--	yes	yes
Effluent Pipe Maintenance	--	no	no

* Woody vegetation (Cenizo) did not need any maintenance unless you consider removing the encroaching vegetation, which in the study was Bermudagrass.

APPENDIX F:
DESIGN EXAMPLE

As mentioned, a bioretention cell must be designed according to the site-specific conditions, including runoff quantity and quality and groundwater sensitivity. Included is an example rationale for siting and sizing a bioretention cell.

Site Selection

SH 6/21, Bryan, TX (near a very busy Texaco gas station)

Source: Google Maps

Figure 23. Plan View of Site at SH 21 and SH 6—Bryan, TX.

Site Inventory

As seen in Figure 23, the site is located near a road crossing, a very busy gas station, and light industrial area. Stormwater runoff is contaminated with suspended sediments, oil and gas, metals (including Pb, Zn, and Cu), as well as some N and P. However, N and P influent would be greater near a residential or agricultural area where fertilizer is a common runoff pollutant. The runoff is gathered into grass swale, which leads to a culvert on the south corner of the site. Space is somewhat limited by topography and an existing tree as well, so maximizing land usage is a priority. Also, the budget is minimal so materials and design needed to be minimized.

Site Analysis

A cell with an IWS layer is recommended because there is a high sediment load in the effluent and many other pollutants including N. An IWS cell maximizes pollutant removal. Furthermore, since space and budget are limited a smaller cell is specified. An IWS layer detains runoff longer than a non-IWS layer in most cases of intermittent rain. The cell is near a busy utility road and so aesthetics are a concern. The IWS layer increases plant growth and vigor. Although this design specified a hardy woody shrub that fit all the requirements in the "Planting Plan Guidelines," herbaceous vegetation could also have been used. However, this site was meant to be as maintenance free as possible so a low maintenance woody shrub was used. An impermeable base layer is not used because there is not an immediate danger of infiltration into the groundwater below. Infiltration in the native sub layer is low, however, due to the high clay content.

Soil Media

The soil media will be 94 percent sand and 6 percent clay to ensure rapid drainage and yet still have pollutant removal capabilities. Also, on an average year in Bryan, Texas, 40 inches of rain will go through the cell, so effective filtration is necessary. The IWS layer will increase detention time and promote further pollutant removal.

Watershed and Design Storm

The watershed area is calculated to be 2 ac, 1.5 ac of which are impermeable. The goal was to store water for mean 3-hr storms (0.779 inch) falling on this 2.0 ac of drainage area. The storm intensity follows the Soil Conservation Service Type III rainfall pattern. The impermeable area consisted of paved surface including a highway bridge (at SH 21), service roads (SH 6 frontage), and a gas station with minimal vegetation area. The composite runoff coefficient is 0.85.

Bioretention Cell Sizing

The following equation gives the approximate surface area required for the filtration basin:

Equation 6.

$$A_f = D.A. \times (X\%) \times C$$

Where:
A_f = required surface area of the bioretention facility
D.A. = drainage area (SF)
X = percent of runoff area to be transformed into bioretention
C = runoff coefficient
The drainage area is known to be 2 ac (87,120 SF). The C is estimated from Table 25 by considering the site properties are typical of a Commercial-Shopping Center, which is 0.70–0.95. A mid-high range (0.85) was chosen because of the existing grass swale on the site. Also, since space and budget are both limiting a 1 percent ratio of drainage area to bioretention will be proposed. This number can be anywhere from 1 percent–10 percent depending on budget, space, and need.

Therefore:

A_f = D.A. × (X%) × C
A_f = 87,120 × 0.01 × 0.85
A_f = 740.52 (this number is close to the 'as built' dimension of 670 ft^2)

Table 25. Coefficients of Runoff for Selected Urban Areas.

Runoff Surface	Runoff Coefficient
Commercial	
Downtown	0.70–0.95
Shopping Center	0.70–0.95
Residential	
Single Family (5–7 houses/ac)	0.35–0.50
Attached Multi-family	0.60–0.75
Suburban (1–4 houses/ac)	0.20–0.40
Industrial	
Light	0.50–0.80
Heavy	0.60–0.75
Railroad yard	0.20–0.80
Parks, Cemetery	0.10–0.25
Playgrounds	0.20–0.40

APPENDIX G:
VEGETATION INVENTORY

June 2011

January 2012

March 2012

April 2012

May 2012

June 2012

Aug 2011

Oct 2011

Oct 2011 (close up)

Feb 2012

Feb 2012

May 2012

APPENDIX H:
POLLUTANT CONCENTRATIONS OF ALL INFLUENT AND EFFLUENT WATER SAMPLES

April 26, 2011 (NON-IWS SYNTHETIC RUNOFF TEST #1)

Sample	Time (hr)	Influent and Effluent Measurements (mg/L)									Time (hr)	Flow (gal)
		Solids	Metals			Nutrients						
		TSS	Cu	Zn	Pb	TN*	NO_3*	NH_3*	TP*	HPO_4*		
(Target)		**98.167**	**0.02**	**0.13**	**0.08**	**1.836**	**0.148**	**0.77**	**0.173**	**0.173**		
Influent												
1	0:00	187	0.06	0.15	0.02	5.41	0.43	1.77	2.09	0.42	0:00~1:00	2134
2	1:00	243	0.01	0.01	0.00	1.28	0.11	0.72	0.42	0.00	1:00~2:00	11305
3	2:00	223	0.06	0.13	0.01	6.56	0.43	1.90	2.14	0.41	2:00~3:00	2065
4	3:00	156	0.06	0.17	0.01	3.94	0.36	1.75	1.56	0.42		
Effluent												
1	0:00	1367	0.00	0.00	0.00	2.12	0.82	0.00	0.72	0.09	0:00~0:30	338
2	0:30	476	0.00	0.00	0.00	2.91	0.63	0.18	0.91	0.15	0:30~1:00	591
3	1:00	875	0.00	0.00	0.00	4.34	0.75	0.31	1.26	0.17	1:00~1:30	1547
4	1:30	223	0.00	0.00	0.00	3.21	0.44	0.25	0.81	0.13	1:30~2:00	2555
5	2:00	69	0.00	0.00	0.00	2.68	0.16	0.38	1.01	0.11	2:00~2:30	1809
6	2:30	70	0.00	0.00	0.00	14.62**	0.16	0.43	0.59	0.10	2:30~3:00	741
7	3:00	46	0.00	0.00	0.00	3.01	0.37	0.39	0.93	0.09	3:00~3:30	497
8	3:30	57	0.00	0.00	0.00	4.27	0.42	0.44	1.44	0.11	3:30~4:00	161
9	4:00	84	0.00	0.00	0.00	3.99	0.53	0.39	0.82	0.05	4:00~4:30	64
10	4:30	83	0.00	0.00	0.00	2.40	0.60	0.38	1.49	0.07	4:30~5:00	25
11	5:00	76	0.00	0.00	0.00	2.57	0.68	0.40	0.77	0.03		
		TSS	**Cu**	**Zn**	**Pb**	**TN***	**NO_3***	**NH_3***	**TP***	**HPO_4***		
Influent EMC		224.73	0.04	0.08	0.01	4.02	0.29	1.37	1.35	0.23		
Effluent EMC*		79.21	0.00	0.00	0.00	3.16	0.33	0.35	0.92	0.12		
EMC		65%	100%	100%	99%	21%	−16%	75%	32%	50%		

*Removal efficiencies exclude the first hour effluent
**Outlier

July 5, 2011 (NON-IWS SYNTHETIC RUNOFF TEST #2)

Sample	Time (hr)	Influent and Effluent Measurements (mg/L)									Time (hr)	Flow (gal)
		Solids	Metals			Nutrients						
		TSS	Cu	Zn	Pb	TN	NO_3	NH_3	TP	HPO_4		
(Target)		**98.167**	**0.02**	**0.13**	**0.08**	**1.836**	**0.148**	**0.77**	**0.173**	**0.173**		
Influent												
1	0:15	74	0.02	0.06	0.01	1.71	0.16	0.98	0.99	0.12	0:00~0:30	551
2	0:45	58	0.01	0.03	0.01	1.55	0.13	1.06	0.72	0.02	0:30~1:00	526
3	1:15	100	0.02	0.06	0.04	1.73	0.12	1.11	0.68	0.01	1:00~1:30	2267
4	1:45	78	0.02	0.08	0.05	1.77	0.12	1.08	0.65	0.02	1:30~2:00	2756
5	2:15	50	0.01	0.04	0.01	1.47	0.11	0.91	0.53	0.00	2:00~2:30	796
6	2:45	36	0.01	0.04	0.01	3.51	0.09	0.79	0.50	0.00	2:30~3:00	477
Effluent												
1	0:30	363	0.00	0.00	0.00	2.31	1.36	0.00	1.22	0.13	0:00~1:00	648
2	1:30	79	0.00	0.00	0.00	1.37	0.50	0.07	1.03	0.08	1:00~2:00	1773
3	2:30	20	0.00	0.00	0.00	1.62	0.60	0.26	0.92	0.08	2:00~3:00	900
4	3:30	31	0.00	0.00	0.00	0.68	0.32	0.35	0.88	0.06	3:00~4:00	92
5	4:30	24	0.00	0.00	0.00	1.50	0.50	0.27	0.85	0.03	4:00~5:00	13
6	5:30	20	0.00	0.00	0.00	0.54	0.67	0.23	0.80	0.01	5:00~6:00	2
		TSS	**Cu**	**Zn**	**Pb**	**TN**	**NO_3**	**NH_3**	**TP**	**HPO_4**		
Influent EMC		77.30	0.02	0.06	0.04	1.82	0.12	1.04	0.67	0.02		
Effluent EMC*		58.00	0.00	0.00	0.00	1.43	0.53	0.14	0.99	0.08		
EMC		25%	100%	99%	98%	21%	-341%	86%	-49%	-238%		

*Removal efficiencies exclude the first hour effluent

November 15 (AM), 2011 (NON-IWS NATURAL RUNOFF TEST #1)

Sample	Time (hr)	Influent and Effluent Measurements (mg/L)									Time (hr)	Flow (gal)
		Solids	Metals			Nutrients						
		TSS	Cu	Zn	Pb	TN*	NO_3*	NH_3*	TP*	HPO_4*		
Influent												
1	0:00	487	0.28	0.67	0.01	2.45	1.19	0.06	0.57	0.00	0:00~0:30	1022
2	0:30	223	0.13	0.58	0.00	0.00	0.46	0.02	0.46	0.01	0:30~1:00	5693
3	1:00	37	0.11	0.42	0.02	0.00	0.80	0.00	1.48	0.36	1:00~1:30	559
Effluent												
1	0:00	1261	0.30	0.89	0.02	0.69	1.63	0.01	0.92	0.00	0:00~1:00	350
2	1:00	182	0.15	1.04	0.02	6.79	0.63	0.01	0.70	0.00	1:00~2:00	45
		TSS	**Cu**	**Zn**	**Pb**	**TN***	**NO_3***	**NH_3***	**TP***	**HPO_4***		
Influent EMC		153.05	0.13	0.51	0.01	0.17	0.64	0.013	0.89	0.16		
Effluent EMC**		91.00	0.15	1.04	0.02	3.39	0.32	0.005	0.35	0.00		
EMC		41%	−14%	−103%	−99%	−1872%	51%	63%	60%	100%		

*On November 3, 2011 a 14-14-14 fertilizer mix was applied to the cell at a rate of 1 lb/ 25 plants (650 SF).
**Removal efficiencies exclude the first hour effluent

November 15 (PM), 2011 (NON-IWS NATURAL RUNOFF TEST #2)

Sample	Time (hr)	Solids TSS	Metals Cu	Zn	Pb	Nutrients TN*	NO_3*	NH_3*	TP*	HPO_4*	Time (hr)	Flow (gal)
Influent												
1	0:00	82	0.19	0.26	0.01	1.40	1.29	0.02	0.59	0.00	0:00~0:30	262
2	0:30	63	0.13	0.49	0.01	0.00	0.33	0.15	0.67	0.07	0:30~1:00	1058
3	1:00	39	0.10	0.57	0.01	0.00	0.61	0.00	1.51	0.41	1:00~1:30	4716
4	1:30	36	0.09	0.40	0.01	0.00	0.61	0.00	1.44	0.38	1:30~2:00	4998
5	2:00	15	0.10	0.33	0.01	0.00	0.72	0.00	1.66	0.45	2:00~2:30	1401
Effluent												
1	0:00	200	0.12	0.29	0.02	0.00	0.78	0.04	0.58	0.00	0:00~1:00	989
2	1:00	98	0.11	0.38	0.01	0.00	0.46	0.01	0.66	0.02	1:00~2:00	1207
3	2:00	42	0.11	0.42	0.01	0.00	0.47	0.00	0.74	0.07	2:00~3:00	313
		TSS	**Cu**	**Zn**	**Pb**	**TN***	**NO_3***	**NH_3***	**TP***	**HPO_4***		
Influent EMC		31.18	0.09	0.40	0.009	0.01	0.60	0.008	1.38	0.37		
Effluent EMC**		59.90	0.10	0.36	0.011	0.00	0.42	0.005	0.63	0.04		
EMC		-92%	-6%	10%	5%	0.00	30%	38%	54%	88%		

*On November 3, 2011 a 14-14-14 fertilizer mix was applied to the cell at a rate of 1 lb/ 25 plants (650 SF).
**Removal efficiencies exclude the first hour effluent

November 26, 2011 (NON-IWS NATURAL RUNOFF TEST #3)

Sample	Time (hr)	Solids TSS	Metals Cu	Zn	Pb	Nutrients TN*	NO_3*	NH_3*	TP*	HPO_4*	Time (hr)	Flow (gal)
Influent												
1	0:00	56	0.16	0.57	0.01	N/D	0.47	N/D	0.56	0.00	0:00~0:30	1171
2	0:30	12	0.01	0.00	0.00	N/D	0.24	N/D	0.48	0.10	0:30~1:00	589
3	1:00	0	0.08	0.25	0.00	N/D	0.25	N/D	0.64	0.15	1:00~1:30	522
4	1:30	4	0.00	0.00	0.00	N/D	0.38	N/D	0.50	0.09	1:30~2:00	973
5	2:00	1	0.01	0.00	0.00	N/D	0.45	N/D	0.99	0.28	2:00~2:30	814
6	2:30	0	0.09	0.24	0.01	N/D	0.51	N/D	1.19	0.34	2:30~3:00	473
7	3:00	0	0.10	0.29	0.00	N/D	0.69	N/D	1.58	0.42	3:00~3:30	248
Effluent												
1	0:00	28	0.07	0.26	0.00	N/D	0.11	N/D	0.16	0.00	0:00~1:00	161
2	1:00	3	0.00	0.00	0.00	N/D	0.29	N/D	0.30	0.04	1:00~2:00	259
3	2:00	3	0.08	0.10	0.00	N/D	0.25	N/D	0.31	0.03	2:00~3:00	172
4	3:00	5	0.09	0.11	0.00	N/D	0.47	N/D	0.43	0.07	3:00~4:00	21
		TSS	**Cu**	**Zn**	**Pb**	**TN***	**NO_3***	**NH_3***	**TP***	**HPO_4***		
Influent EMC		9.86	0.05	0.16	0.003	N/D	0.39	N/D	0.77	0.18		
Effluent EMC**		3.36	0.06	0.07	0.000	N/D	0.31	N/D	0.33	0.04		
EMC		66%	−9%	54%	100%	N/D	23%	N/D	58%	79%		

*On November 3, 2011 a 14-14-14 fertilizer mix was applied to the cell at a rate of 1 lb/ 25 plants (650 SF).
**Removal efficiencies exclude the first hour effluent

December 4, 2011 (NON-IWS NATURAL RUNOFF TEST #4)

Sample	Time (hr)	Influent and Effluent Measurements (mg/L)									Time (hr)	Flow (gal)
		Solids	Metals			Nutrients						
		TSS	Cu	Zn	Pb	TN*	NO_3*	NH_3*	TP*	HPO_4*		
Influent												
1	0:00	46	0.21	0.95	0.01	4.26	0.95	0.00	0.69	0.00	0:00~0:30	130
2	0:30	26	0.15	0.68	0.01	2.32	1.38	0.00	0.56	0.00	0:30~1:00	1704
3	1:00	36	0.06	0.34	0.00	0.13	0.47	0.00	0.41	0.07	1:00~1:30	4460
4	1:30	23	0.07	0.27	0.00	0.61	0.45	0.08	0.90	0.24	1:30~2:00	22511
5	2:00	13	0.08	0.38	0.00	0.67	0.79	0.16	1.07	0.52	2:00~2:30	951
6	2:30	15	0.09	0.39	0.00	1.30	0.58	0.12	1.05	0.26	2:30~3:00	569
Effluent												
1	0:00	94	0.08	0.89	0.00	1.07	0.58	0.01	0.25	0.26	0:00~1:00	1641
2	1:00	21	0.07	0.38	0.00	0.59	0.48	0.03	0.47	0.10	1:00~2:00	1315
3	2:00	17	0.07	0.45	0.00	0.55	0.49	0.02	0.51	0.12	2:00~3:00	330
		TSS	**Cu**	**Zn**	**Pb**	**TN***	**NO_3***	**NH_3***	**TP***	**HPO_4***		
Influent EMC		20.18	0.08	0.33	0.0003	0.65	0.61	0.10	0.90	0.32		
Effluent EMC**		16.89	0.06	0.38	0.0000	0.51	0.44	0.02	0.44	0.10		
EMC		16%	17%	−13%	100%	22%	28%	77%	51%	70%		

*On November 3, 2011 a 14-14-14 fertilizer mix was applied to the cell at a rate of 1 lb/ 25 plants (650 SF).

**Removal efficiencies exclude the first hour effluent

March 22, 2012 (IWS SYNTHETIC RUNOFF TEST #1)

Sample	Time (hr)	Influent and Effluent Measurements (mg/L)									Time (hr)	Flow (gal)
		Solids	Metals			Nutrients						
		TSS	Cu	Zn	Pb	TN	NO_3	NH_3	TP	HPO_4		
(Target)		**98.167**	**0.02**	**0.13**	**0.08**	**1.836**	**0.148**	**0.77**	**0.173**	**0.173**		
Influent												
1	0:00	81	0.14	0.07	0.02	1.24	0.00	0.29	0.38	0.00	0:00~0:30	797
2	0:30	75	0.43	0.65	0.14	3.73	0.17	0.82	0.99	0.17	0:30~1:00	621
3	1:00	70	0.41	0.85	0.15	3.89	0.17	1.08	0.97	0.18	1:00~1:30	2629
4	1:30	90	0.35	0.76	0.22	3.43	0.13	0.95	0.81	0.13	1:30~2:00	2414
5	2:00	149	0.79	1.83	0.05	6.63	0.36	1.66	1.63	0.40	2:00~2:30	760
6	2:30	78	0.42	0.95	0.25	3.97	0.17	1.09	0.99	0.18	2:30~3:00	
Effluent												
1	0:00	2	0.00	0.00	0.01	0.52	0.00	0.02	0.05	0.00	0:00~1:00	304
2	1:00	1	0.02	0.02	0.04	0.88	0.00	0.04	0.18	0.00	1:00~2:00	487
3	2:00	5	0.05	0.00	0.01	1.11	0.00	0.04	0.34	0.00	2:00~3:00	446
4	3:00	7	0.05	0.00	0.01	1.29	0.00	0.10	0.55	0.02	3:00~4:00	
		TSS	**Cu**	**Zn**	**Pb**	**TN**	**NO_3**	**NH_3**	**TP**	**HPO_4**		
Influent EMC		95.86	0.46	1.01	0.15	4.17	0.19	1.09	1.03	0.20		
Effluent EMC*		3.71	0.03	0.01	0.02	1.00	0.02	0.05	0.29	0.00		
EMC		96%	93%	99%	87%	76%	88%	96%	72%	98%		

March 30, 2012 (IWS SYNTHETIC RUNOFF TEST #2)

Sample	Time (hr)	Influent and Effluent Measurements (mg/L)									Time (hr)	Flow (gal)
		Solids	Metals			Nutrients						
		TSS	Cu	Zn	Pb	TN	NO_3	NH_3	TP	HPO_4		
(Target)		**98.167**	**0.02**	**0.13**	**0.08**	**1.836**	**0.148**	**0.77**	**0.173**	**0.173**		
Influent												
1	0:00	296	1.39	0.38	0.02	11.48	0.13	2.15	3.08	0.07	0:00~0:30	1331
2	0:30	39	0.26	0.01	0.04	1.99	0.28	0.73	0.68	0.23	0:30~1:00	1340
3	1:00	270	0.54	0.46	0.55	4.70	0.00	1.22	1.20	0.02	1:00~1:30	5213
4	1:30	854	0.09	0.00	0.03	2.66	0.12	0.47	0.49	0.07	1:30~2:00	5438
5	2:00	53	0.28	0.37	0.17	1.91	0.20	0.74	0.65	0.20	2:00~2:30	1583
6	2:30	51	0.46	1.19	0.22	3.83	0.00	1.14	1.00	0.00	2:30~3:00	
Effluent												
1	0:00	2	0.05	0.00	0.03	0.49	0.35	0.01	0.25	0.03	0:00~1:00	748
2	1:00	40	0.08	0.00	0.02	1.77	0.00	0.04	0.58	0.11	1:00~2:00	1703
3	2:00	17	0.08	0.00	0.02	1.33	0.13	0.25	0.70	0.08	2:00~3:00	3999
4	3:00	5	0.08	0.35	0.04	1.80	0.02	0.40	0.69	0.00	3:00~4:00	
		TSS	**Cu**	**Zn**	**Pb**	**TN**	**NO_3**	**NH_3**	**TP**	**HPO_4**		
Influent EMC		396.38	0.33	0.27	0.19	3.33	0.12	0.83	0.84	0.10		
Effluent EMC*		16.78	0.08	0.11	0.03	1.51	0.09	0.24	0.65	0.06		
EMC		96%	76%	60%	86%	55%	29%	71%	23%	44%		

February 3, 2012 (IWS NATURAL RUNOFF TEST #1)

Sample	Time (hr)	Influent and Effluent Measurements (mg/L)									Time (hr)	Flow (gal)
		Solids	Metals			Nutrients						
		TSS	Cu	Zn	Pb	TN	NO_3	NH_3	TP	HPO_4		
Influent												
1	0:00	141	0.13	0.08	0.01	0.00	0.00	0.00	0.30	0.02	0:00~0:30	1076
2	0:30	61	0.10	0.00	0.00	0.00	0.20	0.00	0.29	0.03	0:30~1:00	2684
3	1:00	18	0.08	0.00	0.00	2.44	0.45	0.00	0.86	0.19	1:00~1:30	1486
4	1:30	5	0.08	0.00	0.01	2.96	0.47	0.01	1.08	0.25	1:30~2:00	1523
5	2:00	33	0.06	0.51	0.01	0.00	0.32	0.01	0.69	0.15	2:00~2:30	1475
6	2:30	3	0.06	1.27	0.02	2.05	0.50	0.17	1.17	0.26	2:30~3:00	
Effluent												
1	0:00	15	0.04	0.00	0.00	0.00	0.10	0.05	0.00	0.00	0:00~1:00	488
2	1:00	1	0.05	0.00	0.00	0.00	0.34	0.00	0.15	0.00	1:00~2:00	363
3	2:00	0	0.04	0.00	0.00	0.00	0.32	0.00	0.23	0.02	2:00~3:00	460
4	3:00	0	0.06	2.22	0.03	0.00	0.35	0.10	0.33	0.04	3:00~4:00	346
5	4:00	0	0.05	0.00	0.00	0.00	0.27	0.00	0.30	0.05	4:00~5:00	429
6	5:00	0	0.04	1.41	0.12	0.00	0.25	0.09	0.31	0.06	5:00~6:00	
		TSS	**Cu**	**Zn**	**Pb**	**TN**	**NO_3**	**NH_3**	**TP**	**HPO_4**		
Influent EMC		34.84	0.08	0.21	0.01	1.34	0.35	0.02	0.73	0.15		
Effluent EMC		1.96	0.05	0.57	0.02	0.00	0.29	0.03	0.23	0.03		
EMC		94%	42%	−171%	−198%	100%	18%	−77%	69%	82%		

February 17, 2012 (IWS NATURAL RUNOFF TEST #2)

Sample	Time (hr)	Solids TSS	Metals Cu	Zn	Pb	Nutrients TN	NO_3	NH_3	TP	HPO_4	Time (hr)	Flow (gal)
Influent												
1	0:00	198	0.11	4.20	0.03	3.91	0.41	0.13	0.26	0.03	0:00~0:30	3089
2	0:30	75	0.06	1.34	0.01	0.00	0.33	0.10	0.44	0.09	0:30~1:00	2146
3	1:00	27	0.07	0.26	0.02	0.00	0.29	0.06	0.68	0.13	1:00~1:30	929
4	1:30	14	0.06	0.00	0.01	0.00	0.33	0.01	0.72	0.15	1:30~2:00	457
5	2:00	10	0.07	0.00	0.01	0.00	0.36	0.00	0.72	0.16	2:00~2:30	282
6	2:30	10	0.07	0.00	0.00	0.00	0.39	0.01	0.79	0.18	2:30~3:00	
Effluent												
1	0:00	0	0.03	1.93	0.03	0.00	0.48	0.04	0.13	0.00	0:00~1:00	591
2	1:00	0	0.03	0.00	0.00	0.00	0.40	0.00	0.15	0.02	1:00~2:00	443
3	2:00	0	0.03	0.48	0.01	0.00	0.35	0.02	0.23	0.02	2:00~3:00	198
4	3:00	0	0.04	0.00	0.01	0.00	0.31	0.00	0.24	0.03	3:00~4:00	213
5	4:00	0	0.03	0.00	0.00	0.00	0.30	0.01	0.22	0.04	4:00~5:00	227
6	5:00	0	0.05	0.82	0.02	0.00	0.30	0.03	0.26	0.03	5:00~6:00	
		TSS	**Cu**	**Zn**	**Pb**	**TN**	**NO_3**	**NH_3**	**TP**	**HPO_4**		
Influent EMC		80.91	0.07	1.51	0.016	0.88	0.34	0.08	0.50	0.10		
Effluent EMC		0.00	0.03	0.49	0.010	0.00	0.37	0.01	0.19	0.02		
EMC		100%	56%	68%	41%	100%	-10%	84%	62%	77%		

Influent and Effluent Measurements (mg/L)

May 10, 2012 (IWS NATURAL RUNOFF TEST #3)

Sample	Time (hr)	Solids TSS	Metals Cu	Zn	Pb	Nutrients TN	NO_3	NH_3	TP	HPO_4	Time (hr)	Flow (gal)
Influent												
1	0:00	138	0.17	0.01	0.00	5.05	2.44	0.08	0.69	0.04	0:00~0:30	238
2	0:30	55	0.13	0.49	0.02	7.97	1.44	0.09	0.56	0.04	0:30~1:00	781
3	1:00	58	0.06	0.00	0.00	1.67	0.55	0.01	0.43	0.06	1:00~1:30	790
4	1:30	19	0.06	1.54	0.04	2.48	0.61	0.15	0.70	0.14	1:30~2:00	286
5	2:00	13	0.07	1.47	0.06	3.30	1.03	0.17	1.00	0.24	2:00~2:30	532
6	2:30	263	0.08	0.00	0.02	2.24	0.89	0.01	0.67	0.11	2:30~3:00	
Effluent												
1	0:00	30	0.07	0.05	0.03	1.41	0.06	0.02	0.26	0.00	0:00~1:00	302
2	1:00	7	0.04	0.00	0.02	4.31	0.28	0.01	0.26	0.00	1:00~2:00	198
3	2:00	6	0.03	0.00	0.09	2.08	0.00	0.02	0.20	0.00	2:00~3:00	158
4	3:00	4	0.03	1.48	0.01	1.65	0.41	0.13	0.22	0.00	3:00~4:00	473
5	4:00	0	0.01	0.18	0.02	1.37	0.36	0.05	0.17	0.00	4:00~5:00	413
6	5:00	0	0.03	0.62	0.04	1.48	0.00	0.07	0.21	0.00	5:00~6:00	
		TSS	**Cu**	**Zn**	**Pb**	**TN**	**NO_3**	**NH_3**	**TP**	**HPO_4**		
Influent EMC		66.83	0.08	0.64	0.02	3.52	0.93	0.08	0.63	0.10		
Effluent EMC		5.57	0.03	0.44	0.03	2.00	0.24	0.06	0.21	0.00		
EMC		92%	64%	31%	−27%	43%	74%	29%	66%	100%		

Influent and Effluent Measurements (mg/L)

May 31, 2012 (IWS NATURAL RUNOFF TEST #4)

Sample	Time (hr)	Influent and Effluent Measurements (mg/L)*									Time (hr)	Flow (gal)
		Solids	Metals			Nutrients						
		TSS	Cu	Zn	Pb	TN	NO_3	NH_3	TP	HPO_4		
Influent												
1	0:00	693	0.14	0.00	0.01	4.84	1.10	0.18	0.86	0.00	0:00~0:30	9892
2	0:30	55	0.09	0.53	0.03	3.69	1.13	0.12	1.16	0.21	0:30~1:00	2322
3	1:00	16	0.10	0.00	0.01	4.40	1.53	0.21	1.64	0.36	1:00~1:30	606
4	1:30	10	0.11	0.13	0.02	4.79	1.79	0.21	1.59	0.33	1:30~2:00	
Effluent												
1	0:00	8	0.07	0.34	0.07	1.72	0.14	0.19	0.55	0.03	0:00~1:00	457
2	1:00	41	0.10	0.00	0.01	3.57	0.85	0.06	0.98	0.09	1:00~2:00	546
3	2:00	45	0.10	0.00	0.01	2.23	0.98	0.05	1.00	0.12	2:00~3:00	

	TSS	Cu	Zn	Pb	TN	NO_3	NH_3	TP	HPO_4
Influent EMC	295.65	0.11	0.26	0.020	4.24	1.18	0.15	1.11	0.15
Effluent EMC	34.57	0.09	0.08	0.024	2.78	0.72	0.09	0.89	0.08
EMC	88%	16%	70%	−20%	34%	39%	43%	20%	45%

*Influent samples were higher than average due to extra chemicals being dumped near effluent the day before from synthetic testing.