MULTIPLE-EVENT STUDY OF BIORETENTION FOR TREATMENT OF URBAN STORM WATER RUNOFF

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ABSTRACT

Bioretention is a novel best management practice for urban storm water, employed to minimize the impact of urban runoff during storm events. Bioretention consists of porous media layers that can remove pollutants from infiltrating runoff via mechanisms that include adsorption, precipitation, and filtration. However, the effectiveness of bioretention in treating repetitive inputs of runoff has not been investigated. In this study, a bioretention test column was set up and experiments proceeded once every week for a total of 12 tests. Through all twelve repetitions, the infiltration rate remained constant (0.35 cm/min). All twelve tests demonstrated excellent removal efficiency for TSS, oil/grease, and lead (>99%). For total phosphorus, the removal efficiency was about 47% for the first test, increasing to 68% by the twelfth test. For ammonium, the system removal efficiency ranged from 2.3% to 23%. Effluent nitrate concentration became higher than the influent concentration during the first 28 days and removal efficiency ranged from 9% to 20% afterward. Some degree of denitrification was apparently proceeding in the bioretention system. Overall, the top mulch layer filtered most of TSS in the runoff and prevented the bioretention media from clogging during 12 repetitions. Runoff quality was improved by the bioretention column.

KEYWORDS: Best management practices, bioretention, infiltration rate, repetition, storm water runoff

INTRODUCTION

Urban storm water runoff is an important water resource because of its abundant volume. However, the resulting runoff is also a concern as a growing pollution source for many receiving water bodies because of the greater volume from increased impervious surface and increased loading of toxic contaminants from urban areas. Non-point runoff is a leading impairment source for surveyed estuaries and the third largest pollution source for surveyed lakes in the U.S. (USEPA, 1997).

Bioretention (Figure 1) is a best management practice for urban storm water and a component of low impact development (LID), employing integrated and distributed micro-scale storm water retention areas. LID causes less land disturbance and performs in a more aesthetically pleasing way than traditional development. Bioretention is an alternative for runoff treatment before discharging into waterways. Engineered mixtures of highly-permeable natural media, which are usually mixes of soil, sand and organic matter, are generally employed in bioretention facilities for pollutant removal. Runoff is directed into the facility and the bioretention media can remove pollutants through several mechanisms, such as filtration, adsorption, and precipitation. The physico-chemical characteristics of natural and mixed media can be related to pollutant removal (Cheung and Venkitachalam, 2000; Sui and Thompson, 2000; Arias et al., 2001). Once the intensity of rainfall exceeds the media loading capacity, bioretention can temporally hold the extra runoff on the ponding surface. Bioretention can also contribute to ground water recharge.

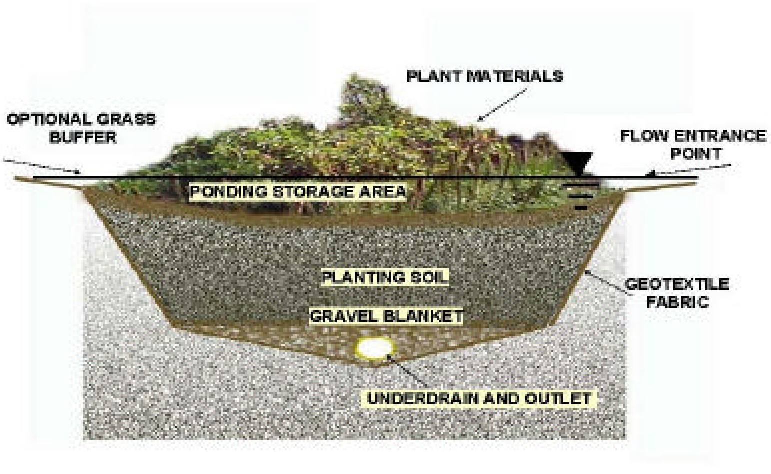

Figure 1. Typical bioretention facility for urban storm water management

The objectives of this study are to evaluate the long-term performance of an experimental bioretention column and to investigate the effects of filtered suspended solids on the infiltration rate of runoff. The input runoff target pollutants are oil/grease (O/G), total suspended solids (TSS), lead, total phosphorus (TP), nitrate, and ammonia. The media chemical characteristics were correlated with pollutant removals.

METHODS

In this study, all experiments used synthetic storm water runoff that was made up in the Environmental Engineering Laboratory, University of Maryland. The characteristics of this water are presented in Table 1 (Davis et al., 2001).

Table 1. Makeup of synthetic runoff used in this study (Davis et al., 2001)

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

A Plexiglas column with an inner diameter of 19.1 cm and a height of 110 cm was employed. The media used in the test include a top mulch layer (5 cm, 0.82 kg), a middle porous soil layer (15 cm, 8.17 kg), and a bottom sand layer (75 cm, 30.9 kg). Mulch used in the experiments was obtained from the College Park City Department of Public Works. It was produced from locally collected municipal leaves and grass clippings that were piled into long rows for composting. The soil was obtained from the Prince George's County Department of Public Works and Transportation and the sand was obtained from a local home supply store. Before the experiment started, the sand was washed using the Silica Sand Washing Procedure (Kunze and Dixon, 1989). Before and after the column tests, samples of the mulch, soil and sand were sent to the Soil Testing Laboratory of the Department of Agronomy, University of Maryland, College Park for analysis. Also, the particle-size distribution of all media on a mass basis was analyzed using dry-sieving techniques. The results are presented in Tables 2 and 3.

Table 2. Results of mechanical analysis of original bioretention media

	% Sand	*% Clay*	*% Silt*	*Classification*
Soil	66	19	15	Sandy Loam
Sand	95	3	2	Sand

Table 3. Results of media chemical analysis and grain size distribution

	pH	PO_4^{3-}	*Ca*	NO_3^-	*CEC*	*O.M*	d_{10}	d_{60}	d_{60} / d_{10}
			mg/kg-soil		meq/100g	%	mm	mm	
Mulch	7.1	560	>438	6000	34.36	29.8	0.15	2.31	15.4
Soil	7.8	120	>438	54	18.96	2.20	0.09	0.20	2.2
Sand	7.1	53	28	19	1.12	0.15	0.17	0.30	1.8

For each experiment, the simulated runoff was stored in a 200-L container with a large mixer. At the start of the experiment, runoff was pumped into the column from the top and the first sample was collected. Over a six-hr time period, samples were collected every hour from the bottom of the column and taken to calculate the flow rate and measure the pollutant concentration. The water head above the media surface was maintained constant at 15 cm by controlling the pumping rate during the experiment. The experiment proceeded once every week and totally, twelve tests were completed.

Analytical methods include TSS analysis (Section 2540D of Standard Methods, APHA 1995), oil and grease analysis (Lau and Stenstrom, 1997), phosphorus analysis (Section 4500-P of Standard Methods, APHA 1995), lead analysis (Section 3500-Pb of Standard Methods, APHA 1995), nitrate analysis, and ammonium analysis. Nitrate and ammonium were analyzed using a Dionex DX-100 ion chromatograph with a Dionex AS4 column and with a CS12 column, respectively. 1.3 mM Na_2CO_3/ 1.5 mM $NaHCO_3$ solution was employed as the eluent for nitrate analysis, and 22 mN H_2SO_4 solution was the eluent for ammonium analysis.

RESULTS AND DISCUSSION

The infiltration rate of runoff throughout all twelve repetitions remained constant at 0.35 cm/min. According to previous work employing identical column conditions (Hsieh and Davis, 2002), sand is more permeable (0.83 cm/min) than mulch (0.28 cm/min) or soil (0.28 cm/min). Therefore, less-permeable mulch and soil layer overlaid the high-permeability sand layer in this testing column. It was apparent that runoff infiltration was controlled by the top mulch and soil layers. Runoff did not enter the sand layer until the head was built up sufficiently.

Table 4 summarizes the total mass of input and output pollutants, which was calculated based on the runoff infiltration rate and concentration of pollutants in the influent and effluent samples for each repetition. Pollutant removal results for individual experiments are presented in Figure 2. O/G and lead were both removed very well (>99%) during the entire study. Except for the first 6-hr run, over 90% of TSS was filtered by the bioretention media. Visually, most of TSS was filtered by the top mulch layer. Although a total of 74.2 g of TSS was retained in the media, clogging did not happen and the runoff infiltration rate remained constant (0.35 cm/min) throughout all 12 repetitions. A fraction of TP was regularly removed and the removal efficiency ranged from 47% to 68%. The employed media in the bioretention column did not show good removal efficiency for nitrate (-64% to 19%) and ammonium (2% to 23%).

Table 4. Input and output mass of pollutants for twelve repetitive column experiments

	O/G	TSS	Lead	TP	NO_3^--N	NH_4^+-N
	g	g	mg	g	g	g
Input from runoff	9.76	87.4	51.4	1.62	1.60	1.26
Output in the effluent	<0.3	7.6	<1	0.60	1.85	1.10
% mass removal	>97	91	>98	63	-16	13

Table 5 summarizes the changes in chemical properties resulting from the twelve experiments. Large amounts of OM in the mulch leached out (decreasing from 55% to 10%). The capture of TSS may also decrease this percentage. Some fractions of the leaching OM were retained in the soil layer (increasing from 5% to 10%). Additionally, the Ca-content in both layers of sand increased, which might relate to the P sorption capacity of the media (Arias et al., 2001).

Table 5. Chemical properties of bioretention media before and after 12 runoff applications

	pH	NO_3^-	PO_4^{3-}	Ca	OM
MULCH		mg/kg-soil	mg/kg-soil	mg/kg-soil	%
Before testing	7.1	6000	560	>438	55
After testing	7.2	545	930	>438	10
SOIL I					
Before testing	7.8	54	120	>438	5
After testing	7.5	104	165	>438	10
SAND I					
Before testing	7.1	19	53	28	2
After testing (0-20 cm)	7.4	10	218	188	1
After testing (20-60 cm)	7.1	2	95	40	0.2

Comparing nitrate concentrations in the media, 91% of nitrate originally contained in the top mulch layer was lost. Some of the nitrate may have leached out to the soil and sand. This was supported by the increase of nitrate in the soil (93%) layer. Finally, nitrate washing out from the soil layer will flow through the sand layer and leach out of the column. Mass balances of nitrate and TP are calculated as

$$M_{added} = Ó\, Q_i C_{ii}(Ät) + Ó\, M_i L_{ii} \quad \text{(Eq. 1)}$$

$$M_{leached} = Ó\, Q_e C_{ie}(Ät) + Ó\, M_i L_{if} \quad \text{(Eq. 2)}$$

Where Q is the flow rate of infiltrating (i) and effluent (e) runoff, and C_{ii} and C_{ie} represent the nitrate or P concentrations in the influent and effluent, respectively. M_i is the mass of media employed and $L_{ii}$and L_{if} are the nitrate or P concentration in the origin media and after the runoff application. Results are shown in Table 6. The recovery of TP and nitrate was 102% and 71%, respectively. Totally, 1.06 g of TP was retained in the whole media, which confirmed the TP removal ability of bioretention media. 0.8 g of nitrate was lost from the system; this may be caused by microbial denitrification processes.

Table 6. Mass balance of TP and nitrate from twelve sequential events

	TP (g)	NO_3^-N (g)
Input from runoff	1.62	1.60
Loss from media	-1.06	1.02
Output in the effluent	0.60	1.85
Net	0.04	-0.77

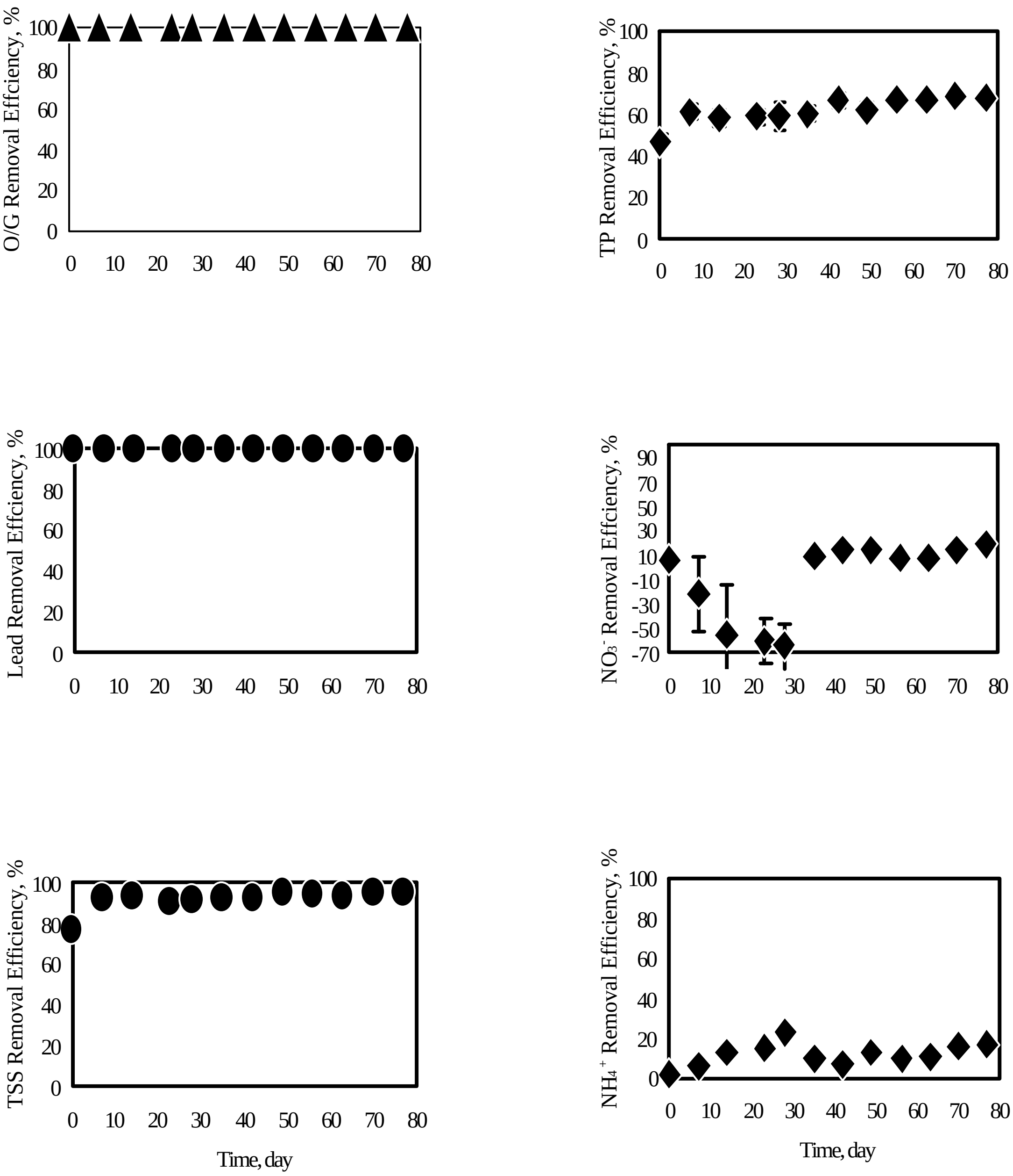

Figure 2. Removal efficiency of pollutants via bioretention column from twelve sequential events

CONCLUSIONS

Twelve consecutive experiments were completed. Bioretention performance, including runoff infiltration rate and pollutant removal efficiencies, were evaluated. The runoff infiltration rate remained constant during the testing period and most input SS was filtered by the top mulch layer. O/G and lead were efficiently (>99%) retained by bioretention media for all twelve repetitions. For TP, the removal efficiency ranged from 47% to 68% and may be related to the organic matter and Ca content in the media. Based on a mass balance analysis, some denitrification appeared to have occurred during the testing period. Overall, long-term effectiveness of a bioretention column employed for runoff quality improvement was confirmed.

REFERENCES

APHA, AWA, WPCF (1995). Standard Methods for the Examination of Water and Wastewater, 19 th Ed., Washington, D.C.

Arias, C. A., Bubba, M. D., and Brix, H. (2001), “Phosphorus Removal by Sands for Use as Media in Subsurface Flow Constructed Reed Beds,” Wat. Res., **35**, 1159-1168.

Cheung, K. C. and Venkitachalam, T. H. (2000), “Improving Phosphate Removal of Sand Infiltration System Using Alkaline Fly Ash,” Chemoshere, **41**, 243-249.

Davis, A.P., Shokouhian, M., Sharma, H., and Minami, C. (2001) "Laboratory Study of Biological Retention for Urban Stormwater Management," Water Environ. Res., **73**, 5.

Hsieh, C. -h. and Davis, A. P. (2002). " Engineering Bioretention for Treatment of Urban Storm Water Runoff," Watersheds 2002, Proceedings on CDROM Research Symposium, Session 15, Ft. Lauderdale, FL.

Kunze, G. W., and J. B. Dixon (1989) "Pretreatment for Mineralogical Analysis," Methods of Soil Analysis, **1**, 91-100.

Lau, S. L. and Stenstrom, M. K. (1997) "Solid-Phase Extraction for Oil and Grease Analysis," Water Environ. Res., **69**, 368.

Sui, Y. and Thompson, M. L. (2000), "Phosphorus Sorption, Desorption, and Buffering Capacity in a Biosolids-Amended Mollisol," Soil Sci. Am. J., **64**, 164-169.

U.S. EPA (1997), "Managing Urban Runoff," US Environmental Protection Agency, EPA 841-F-96-004G, Washington D.C.