Evaluation and Optimization of Bioretention Media for Treatment of Urban Storm Water Runoff

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Abstract: Bioretention is a relatively new urban storm water best management practice. The objective of this study is to provide insight on media characteristics that control bioretention water management behavior. Eighteen bioretention columns and six existing bioretention facilities were evaluated employing synthetic runoff. In columns, the runoff infiltration rate through different media mixtures ranged from 0.28 to 8.15 cm/min at a fixed 15 cm head. For pollutant removals, the results showed excellent removal for oil/grease (>96%). Total lead removal (from 66 to >98%) decreased when the total suspended solids level in the effluent increased (removed from 29 to >96%). The removal efficiency of total phosphorus ranged widely (4–99%), apparently due to preferential flow patterns, and both nitrate and ammonium were moderate to poorly removed, with removals ranging from 1 to 43% and from 2 to 49%, respectively. Two more on-site experiments were conducted during a rainfall event to compare with laboratory investigation. For bioretention design, two media design profiles are proposed; >96% TSS, >96% O/G, >98% lead, >70% TP, >9% nitrate, and >20% ammonium removals are expected with these designs

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Introduction

Due to increasing areas of impervious surfaces (roads, parking lots, and rooftops) in urbanized locations, a greater fraction of impinging precipitation cannot infiltrate into the soil and becomes runoff, mobilizing deposited pollutants. Without proper management, increases in the flow rate and volume of runoff result in high probabilities of streambed erosion and flooding. From the perspective of water quality, the effects of urban runoff on receiving waters are quite variable and site-specific (Hoffman et al. 2002). Nonetheless, urban runoff is designated as a leading impairment source for estuaries and the third largest pollution source for lakes (US EPA 1997). Increases in the variety and concentrations of pollutants mobilized in the runoff deleteriously impact water quality and the viability of surrounding ecosystems, in addition to increasing subsequent water treatment costs.

Urban storm water best management practices (BMPs) are technologies or combinations of practices that are designed to provide some degree of improvement to storm water runoff characteristics. Bioretention is an urban storm water BMP developed to reduce runoff quantity and improve quality in a natural, aesthetically pleasing manner. It is a component of the low impact development (LID) concept, which employs microscale storm water retention and infiltration tracts throughout developed areas. Bioretention generally consists of a porous media, supporting a vegetative layer, with a surface layer of hardwood mulch. A ponding area serves as reserve space for runoff storage and provides additional time for water to infiltrate into the media during and after rainfall events. Bioretention and other LID techniques are receiving increasing attention as municipalities struggle with ecological effects of urban growth.

Several studies to date have demonstrated the bioretention concept to be moderately to very effective in the removal of pollutants from infiltrating runoff. Pilot-scale box studies have demonstrated 60–80% removal of total Kjeldahl nitrogen (TKN), ammonium, and phosphorus (P) by bioretention media (Davis et al. 2001). For heavy metals, over 90% of copper (Cu), lead (Pb), and zinc (Zn) were captured by laboratory sandy-loam bioretention pilot-plant facilities under different pH, duration, intensity, and pollutant concentrations, supported by field-scale confirmation studies (Davis et al. 2003). Similar studies have demonstrated removals of 70–85% for P and 55–65% for TKN, but <20% for nitrate (Davis et al. 2005). Options to improve the removal efficiency for nitrate/nitrite by modifying the traditional bioretention design have been examined by Kim et al. (2003).

Physical–chemical treatments can be effective in reducing toxicity in storm water runoff (Pitt et al. 1995) and bioretention media remove pollutants from storm water through a variety of mechanisms, including sedimentation, filtration, sorption, and precipitation. Accordingly, different media compositions are expected to demonstrate different pollutant removal efficiencies because of the respective effects on pollutant capture mechanisms. For example, Pb, Cu, nickel (Ni), and Zn adsorption by and desorption from several soils were affected by the pH of the soil (Harter 1983). P retention and movement in soils is influenced by both influent and soil characteristics (Nagpal 1985). Sands with different calcium (Ca), iron (Fe), and aluminum (Al) contents

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resulted in about threefold differences in P removals in constructed reed bases (Arias et al. 2001).

Nonetheless, the hydraulic characteristics of bioretention media cannot be ignored. If bioretention is to be employed as an urban BMP, it must have a high hydraulic conductivity to infiltrate large water volumes directed from impervious areas. If permeability is low, a significant fraction of the runoff would simply bypass the bioretention, negating any possible delay of peak discharge and reduction of contaminants. The hydraulic conductivity of the media depends primarily on the size of conducting pores and, generally, larger pores conduct water more rapidly (Hillel 1998). Therefore, a sandy media is favored and high clay contents can be detrimental to infiltration; expanding clays tend to swell markedly after absorbing water and shrink as drying (Brady and Weil 2002). Since fine fractions in soils tend to be the most chemically active, however, a balance needs to be developed between the permeability of the media and pollutant removal characteristics. Consequently, design of the media profile is critical to determining bioretention performance characteristics.

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

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

Finally, although bioretention has been implemented at several urban and suburban areas throughout the United States, only a limited amount of research and performance data are available to assess the impact of this technology on ground and surface water quality. Evaluation of the performances of existing bioretention facilities will support findings from laboratory investigations and can serve as the basis for future design improvement, with a focus on media characteristics.

Materials and Methods

Eighteen 6 h bioretention columns with different media mixtures and configurations were employed to compare results on runoff infiltration rate and pollutant removal efficiencies. Also, 6 h on-site experiments were conducted on six existing bioretention facilities to evaluate their performances with respect to pollutant removal. In order to exclude effects resulting from variation in incoming runoff chemistry and flow (such as percent removals of pollutants being influenced by the influent concentrations), a synthetic runoff solution was made up and used in these experiments. The characteristics of the runoff were controlled and held constant. Two additional on-site experiments were conducted during an actual rainfall event for comparison with the simulated-runoff laboratory and field studies.

Table 1. Makeup of Synthetic Urban Runoff Used in this Study

Parameter	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 0.59 mm opening
Motor oil	20	Used oil from local garage

Storm Water Runoff

Synthetic storm water runoff was made up with tap water, dechlorinated with $NaHSO_3$, with target pollutant levels as presented in Table 1 (Davis et al. 2001). In order to investigate the phase distribution of each pollutant in the synthetic runoff (dissolved vis-à-vis particulate), a comparison sample with all pollutants added except suspended solids (SS) was collected first to quantify the initial total concentration for each specific pollutant. After adding SS into the synthetic runoff and mixing for 30 mins, another sample was collected and filtered through Pall Gelman GF/C filters (0.2 μm) to analyze the concentration of each pollutant dissolved (operationally) in the solution. By deducting the filtrate concentration from the initial concentration, the fraction of each pollutant adsorbed onto the SS was determined. Results indicated that 56% of input Pb and 3% of input P were sorbed onto the influent SS. Over 99% of nitrate and ammonium were in dissolved forms. In comparison to available runoff data, Sansalone and Buchberger (1997) reported that 55–82% of total input Pb was sorbed onto total suspended solids (TSS) in the runoff for five rainfall events in Cincinnati. Sorption of P by suspended sediment material during runoff transport has also been observed (Sharply et al. 1981; Uusitalo et al. 2000). The pollutant distribution is expected to play a major role in the removal of pollutants during filtration by the media.

Six Hour Bioretention Columns

Two types of sand and three types of soil with various physical and chemical properties were used in the laboratory studies to evaluate pollutant-removal properties. Both sands, with very different particle size distributions, were obtained from a local home supply store. Before packing into columns, sands were washed using the silica sand washing procedure (Kunze and Dixon 1989).

Two different soils were obtained locally from the Prince George's County (Md.) Department of Public Works and Transportation, whereas the third was obtained from the Low Impact Development Center (Beltsville, Md.). Mulch used in the experiments was obtained from the College Park (Md.) City Department of Public Works. The mulch was produced from locally collected municipal leaves and grass clippings that were piled into windrows for composting.

Media characterization was done by the Soil Testing Labora-

Table 2. Bioretention Column Media Chemical and Mechanical Analyses

Media	d_{10} (mm)	d_{60} (mm)	d_{60}/d_{10}	pH	Mg (mg/100 g soil)	P (mg/100 g soil)	K (mg/100 g soil)	Ca (mg/100 g soil)	O.M. (%)	CEC (meq/100 g soil)	Sand (%)	Clay (%)	Silt (%)	Classification
Sand (I)	0.17	0.30	1.8	7.1	9.5	5	3	2.8	0.15	1.1	95	3	2	Sand
Sand (II)	0.30	0.84	2.8	5.0	2.5	4	0.8	0.8	0.10	0.4	92	5	3	Sand
Soil (I)	0.09	0.20	2.2	7.8	29	12	21	>44	2.20	19	66	19	15	Sandy loam
Soil (II)	0.13	0.81	6.2	6.9	25	17	27	22	2.60	6.3	79	12	9	Sandy loam
Soil (III)	0.09	0.29	3.2	6.7	28	7.5	35	*	4.40	*	71	17	12	Sandy loam
Mulch	0.15	2.31	15.4	7.1	28	56	35	>44	29.8	34				

Note: *=no data collected.

tory, Department of Agronomy, University of Maryland, College Park, Md. The particle-size distribution of all media on a mass basis was determined using dry-sieving techniques. The results of these analyses are presented in Table 2.

The experimental Plexiglas column had an inner diameter of 19.1 cm and a height of 110 cm. Two types of bioretention column experiments were performed; one used a single medium to investigate the effects of specific media characteristics (including size distribution, silt/clay content, and chemical properties) on the runoff infiltration rate and pollutant removal. The second investigated the effects of different media layer configurations. The media used in these latter experiments included not only layers of the native media (e.g., sand, soil, and mulch), but also several media mixtures synthesized by homogeneously mixing native media (Synthetic Media I: mulch/Soil I/Sand I=1:2:2 mass basis; Synthetic Media II: Soil III/Sand II=4:1 mass basis; and Synthetic Media III: Soil III/Sand II=1:1 mass basis). All employed media were lightly packed into the bioretention column before experiments; degree of compaction is critical in controlling runoff infiltration rate (Pitt et al. 2002).

The simulated runoff was stored in a 200 L plastic container with a large mixer. At the start of each experiment, runoff was pumped into the column from the top and the first sample was collected. The water head in the column was maintained constant at 15 cm above the media surface, allowing different infiltration rates by the different media mixtures. Over a 6 h period, samples were collected every hour from the effluent of the column to calculate the flow rate and measure the pollutant concentrations. Media compositions used in the 18 column experiments are presented in Table 3.

Evaluation of Existing Bioretention Facilities

A total of six field experiments, one in Greenbelt, Md. (GB), two in Hyattsville, Md. (HV1 and HV2), and three in Landover, Md.

Table 3. Characteristics and Results of 6 h Bioretention Column Tests

Experiment number	Mass ratio (%)			Experimental set	Infiltration rate (cm/min)	Removal efficiency (%)					
	Mulch	Soil	Sand			TSS	O/G	Lead	TP	Nitrate	Ammonium
1[a]	0	0	100(I)	A,B	0.84±0.01	>96	>96	>98	85±1.5	11±16.7	8±3.4
2[a]	0	0	100(II)	A	8.15±0.18	>96	>96	96±0.7	10±3.1	1±0.7	15±0.8
3[a]	2	93(I)	5(I)	A,B	0.28±0.04	29±2.9	>96	>98	47±3.4	1±0.6	6±2.2
4[a]	2	93(II)	5(I)	A	0.95±0.01	88±0.9	>96	>98	41±4.5	14±2.2	24±0.8
5[a]	2	93(III)	5(II)	A	0.40±0.02	91±0.3	>96	>98	48±4.0	8±0.7	16±1.1
6[a]	91	0	9(I)	A	0.28±0.01	86±1.0	>96	75±2.0	4±4.5	43±3.2	16±1.9
7[a]	0	0	100(I)	—	0.81±0.02	—[e]	>96	66±7.0	84±1.3	13±6.4	5±1.7
8	3	0	97(I)	B	0.77±0.01	>96	>96	>98	61±4.5	9±0.4	9±2.0
9[b]	2	21(I)	77(I)	C-1	0.32±0.02	66±2.5	>96	>98	47±4.6	3±0.8	2±1.1
10[b]	8	26(I)	66(I)	C-1	0.31±0.01	94±0.6	>96	>98	50±3.8	4±0.7	7±1.0
11[b]	6	32(I)	62(I)	C-1	0.30±0.01	93±0.9	>96	>98	39±4.0	4±0.5	7±0.8
12[b]	0	24(I)	76(I)	C-1	0.30±0.01	93±0.5	>96	>98	39±3.5	2±0.5	5±2.2
13[c]	3	43(I)	54(I)	B,C-2	0.48±0.02	>96	>96	>98	83±1.4	13±59	26±2.6
14[c]	3	24(I)	73(I)	B,C-2	0.66±0.01	>96	>96	>98	57±2.7	24±2.9	17±2.1
15[c]	11	19(I)	70(I)	B,C-2	0.71±0.02	>96	>96	>98	54±2.7	27±1.1	20±1.2
16[d]	2	17(II)	81(II)	D	5.40±0.15	>96	>96	97±0.2	24±3.8	6±1.5	11±0.6
17[d]	2	72(III)	26(II)	D	1.15±0.02	92±0.3	>96	>98	72±0.8	9±0.9	19±0.6
18[d]	2	49(III)	49(II)	D	1.93±0.01	93±0.3	>96	>98	74±0.9	8±0.5	20±0.5

[a]Native media.
[b]Column with upper Soil I layer.
[c]Column with synthetic media I (mixture of Soil I/mulch/sand I).
[d]Column with upper Soil II or Soil III layer.
[e]Influent without suspended solids; (I),(II),(III): Different types of sands and soils—see Table 2.

Table 4. Results of Field Bioretention Media Chemical and Mechanical Analysis

Site (media depth)		pH	Mg (mg/100 g soil)	P (mg/100 g soil)	K (mg/100 g soil)	Ca (mg/100 g soil)	soluble salts (mg/100 g soil)	OM (%)	CEC (meq/100 g soil)	Sand (%)	Clay (%)	Silt (%)	Classification
GB (109 cm)	10–15 cm	7.1	29	16	16	*	*	3.4	*	66	21	13	Sandy clay loam
	15–40 cm	7.3	29	17	14	*	*	2.5	*	70	17	13	Sandy loam
LO1 (51 cm)	10–15 cm	7.3	29	18	13	>44	38	6.2	17	83	8	9	Loamy sand
	15–40 cm	6.8	23	9	7	>44	17	3.8	12	83	10	7	Loamy sand
LO2 (51 cm)	10–15 cm	7.0	29	28	43	37	17	2.1	10	89	9	2	Loamy sand
	15–40 cm	7.0	24	5	16	148	96	1.4	30	42	26	32	Loam
LO3 (51 cm)	10–15 cm	5.4	16	5	13	11	17	1.8	4	58	22	20	Sandy clay loam
	15–40 cm	5.4	18	5	10	11	17	2.0	5	48	28	24	Sandy clay loam
HV1 (76 cm)	10–15 cm	6.8	24	9	14	37	17	3.3	9	62	19	19	Sandy loam
	15–40 cm	7.6	25	7	9	67	17	1.0	14	78	14	8	Sandy loam
HV2 (64 cm)	10–15 cm	7.0	25	8	12	44	17	2.3	10	69	17	14	Sandy loam
	15–40 cm	7.7	18	10	2	15	17	0.1	4	93	6	1	Sand

Note: *=no data collected.

(LO1, LO2, and LO3), were completed. The GB site was constructed in 1993, whereas HV1 and HV2 were built in 1998; LO1, LO2, and LO3 were installed in 2001. The synthetic runoff was stored in six 200 L containers and transported to each site. An area about 5.3 m^2 (2.3 m × 2.3 m) within each bioretention facility was selected adjacent to a manhole. During the experiment, runoff was mixed and pumped into the selected area at 2.8 L/min (3.2 cm/h loading). Over a 6 h period, samples were collected from the facility underdrain outlet pipe in the manhole every half hour using acid-washed amber glass bottles, along with corresponding influent samples. All collected samples were transported to the Environmental Engineering Laboratory, University of Maryland, for measuring pollutant concentrations. Additionally, media samples were collected from each facility using a core sampler and were divided into two layers, 10–15 and 15–40 cm depth. Each layer sample was mixed homogeneously and sent to the Soil Testing Laboratory for characterization (Table 4).

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

Analytical Methods

Standard methods (APHA et al. 1995) were employed for the analysis of TSS (Section 2540D), total P (TP) (Section 4500-P), and Pb (Section 3500-Pb). Oil and grease (O/G) were analyzed by the method of Lau and Stenstrom (1997). 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 $NaHCO_3$ was employed as the eluent for nitrate analysis, and 1.1 mN H_2SO_4 as the eluent for ammonium measurement.

Results and Discussion

Six Hour Bioretention Column Experiments

Current design specifications for bioretention are based on simple texture composition for the media (limits on clay/silt/sand contents). Nonetheless, it is clear that various types of sands and soils resulted in different runoff infiltration rates in 6 h bioretention column experiments because of their wide range of particle sizes and textures (Table 3). Pollutant removal results are also summarized in Table 3. Clearly, different characteristics of the media components promoted variation in removal performance for several pollutants.

Performance of Different Media Components

The infiltration results for the six native media columns [Experiments 1–6 (Set A)] demonstrate that the rate through Sand II was nearly an order of magnitude faster than that through Sand I at 15 cm head. This is readily explained by the larger particle size of Sand II compared to Sand I. Similarly, the infiltration rate using Soil II as the dominant medium is much higher than that for Soil I or Soil III. Soil II has larger d_{10} and d_{60} (Table 2), and contains lower fractions of silt+clay than Soil I or Soil III. In addition, visual examination of Soil II shows large particles of organic material and sand. The d_{60}/d_{10} ratio is 6.2 for Soil II, much larger than for Soil I and Soil III. Larger pore sizes among media particles can result in a higher media permeability. All of these properties allow Soil II to be the most permeable soil among the three employed.

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

Turning to pollutant removals, both sands and all soils demonstrated excellent removal efficiencies for O/G and total Pb (Table 3). With mulch, O/G was removed >96% (Experiment 6), however, less Pb was removed using this medium as compared with the others. Very good TSS removal was noted in most of the native-media bioretention columns, except in the column in which Soil I was the dominant medium. Visually, it was apparent that some of the soil particulate matter washed out from the Soil I column during the testing period. This problem should disappear with subsequent runoff applications.

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

Each of the sands resulted in very different TP removals. In addition to physical filtration, TP removal by sand columns may relate not only to simple adsorption, but also to complex sorption/precipitation processes (Arias et al. 2001). All three soils removed just 41–48% of TP. In the column with 91% mulch, only small amounts of TP removal were found, indicating that mulch does not play an important role in TP removal. Although mulch is expected to retain P through complexation processes, these organic matter complexes may be in dissolved forms and can leach out.

The removal efficiency of nitrate by the native media ranged from 1 to 43%. The sands were mostly ineffective and the mulch-dominated medium removed nitrate most effectively. Biological activity, combined with a low infiltration rate, should have contributed to the mulch effectiveness. For ammonium removal, all types of media produced similar low removal efficiency.

Effect of Media Properties on the Performance of Bioretention

Since details on media properties are available, correlations of properties with pollutant removals by the six native media were examined. First, increased fractions of silt/clay in the medium lowered the runoff infiltration rate, as discussed previously. From Table 2, it is seen that the soils composed of higher silt/clay contents had higher cation (Mg/Ca/K) contents, organic matter (OM), and cation exchange capacity (CEC), which are expected to improve runoff pollutant removal efficiencies. Since both sand (for high infiltration) and soil (for pollutant uptake) are desired, mixtures of these media were evaluated. Columns employing different media (Sand I, Soil I, or Sand I/Soil I/mulch mixtures) with various clay+silt contents were studied (Set B, Table 3). The media layering of Experiments 13, 14, and 15 was: top mulch (5 cm), Synthetic Media I (25–82 cm), and Sand I (8–65 cm).

Again, excellent removal of input O/G, TSS, and Pb were found with all media (Table 3). Because these three pollutants are primarily removed through physical filtration, the treatment efficiency does not show any correlation with media chemical properties. TP retention by bioretention media, however, is expected to depend on media constituents. For example, TP removal by soil was positively correlated with soil OM content (Brejda 1998). Fe-bound P was positively correlated with soil CEC (Samadi and Gilkes 1999). Therefore, K+Mg, P, OM, and CEC of the soil (Table 2) all were individually correlated with TP removal efficiency of these six column tests using linear regression; no correlation, however, was found (R^2 ranged from 0.068 to 0.193). A reason for this lack of relationship may be that the runoff flow path in the column is affecting the fate of dissolved substances. Some degree of preferential flow may be allowing TP to bypass the bulk soil media (Kung et al. 2000). Therefore, even though media with higher silt/clay contents may have higher OM and cation levels to complex P from infiltrating runoff, dynamic processes apparently prevent the TP removal efficiency from correlating with OM content or CEC.

Nitrate and ammonium removals also did not correlate with silt/clay contents in the media. Generally, nitrate compounds are quite soluble and primarily removed through biological degradation (ASA and SSSA 1983). Ammonium can be adsorbed on exchange sites of contacting media or fixed within the clay or organic matrix (ASA and SSSA 1983; Brady and Weil 2002). Adsorption and desorption of ammonium have also been related to the contents of Ca and Mg in several sandy soils (Wang and Alva 2000). The removal efficiency of nitrate and ammonium for all column tests was moderate to poor (Table 3) and was not significantly affected by media properties in this study.

In order to combine the effects of both media permeability and pollutant reduction efficiency, the pollutant removals were also evaluated on a mass basis. Input, output, and removed mass of pollutants for different media during 6 h testing periods are calculated as

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

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

The results are summarized in Fig. 1. On a mass basis, Sand II removed much more of O/G, TSS, and Pb from the runoff than the other media because of the resulting high loading coupled with low output concentrations. Sand II therefore appears to be the best performer among these six media for O/G, TSS, and Pb removals. This analysis underscores the importance of particulate removal from urban storm water and the benefits of utilizing a sand filter as a BMP (Pell and Nyberg 1989; Schueler and Holland 2000), which is essentially what this single-media sand column represents. Sand filters, however, do not have a number of water quality and ecological advantages, as do bioretention facilities. Similar O/G, TSS, and Pb results are found for media mixes [Fig. 1(b)].

Sand I appears to be the better choice for TP treatment since significant mass was removed and a lower output TP concentration was obtained as compared with other media. The media mix with the smaller silt+clay fractions produced the higher runoff infiltration rate and greater TP mass removals during the 6 h testing period [Fig. 1(b)], percent TP removal, efficiency, however, varied. For nitrate and ammonium, none of the media performed exceptionally well and generally demonstrated minimal removal ability. Soil and mulch media demonstrated the greatest benefits seen in removal of nitrogen species.

Overall, these results emphasize the importance of a high infiltration rate. When employing sand in bioretention media, a high permeability is recommended, with d_{10} near 0.30 mm (such as Sand II). Because silt and clay generally contain more nutrient and water holding capacity than sands, soil is necessary for plant growth in the top media layer. The best performance with soils was also noted for that with high d_{10} and a value greater than 0.1 mm is recommended for bioretention soils. High d_{60}/d_{10} can result in high runoff infiltration rate and is desired. However, once the value of d_{60}/d_{10} is too high (such as the mulch used in this study, d_{60}/d_{10}=15.4), the small components among the media

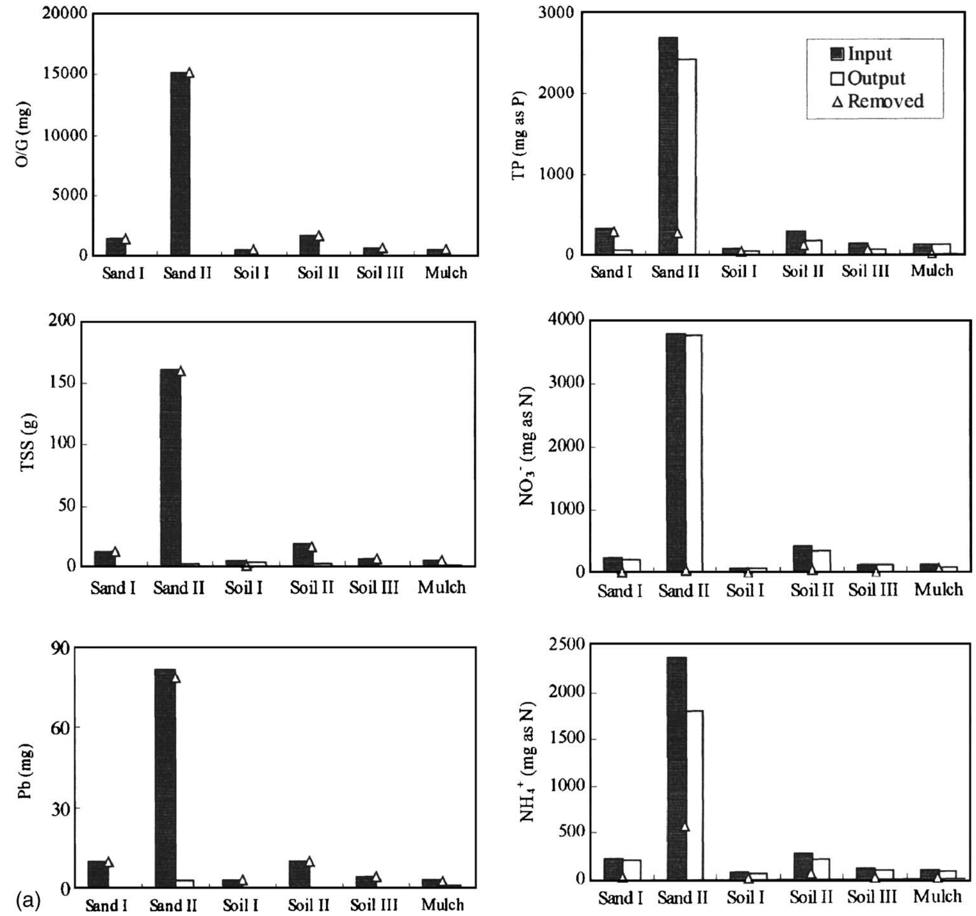

Fig. 1. Input, output, and removed mass of pollutants among different media for 6 h runoff treatment: (a) native media and (b) synthetic media mixtures

may disperse and be transported into media pores; consequently, the risk of clogging and reduction in runoff infiltration rate is increased.

Effect of Media Configuration on the Performance of Bioretention

Different media configurations (uniform vis-à-vis various layering) are expected to result in varied infiltration rates (Hillel 1998) and pollutant removal efficiencies from infiltrating runoff. Uniform coarse-textured sand, as demonstrated previously, is very efficient in promoting a high runoff infiltration rate and pollutant mass removal. Considering the vegetative and ecological aspects of bioretention, however, a certain depth of soil is necessary at the surface for plant growth. Also, coarse media may not be able to sustain pollutant removals over repetitive loadings and have less opportunity to support biological processes. Therefore, two series of layered columns were compared. In the first series of columns (Set C-1, Table 3), an upper Soil I layer (10–20 cm) sits on top of either a 65–75 cm Sand I layer, or 15 cm of Synthetic Media I with a layer of Sand I at the bottom. For the second group of columns (Set C-2, Table 3), the layering was: top mulch (5 cm), Synthetic Media I (25–82 cm), Sand I (8–65 cm).

In Set C-1, it was apparent that the runoff infiltration rate was limited by the less-permeable Soil I surface layer. All columns had identical rates of 0.30–0.32 cm/min. This rate was improved by mixing the Soil I surface layer with a fraction of Sand I, creating the C-2 series with higher infiltration rates. For O/G and Pb, both sets of layered columns resulted in excellent treatment. Some TSS washed from Experiment 9, which had a deeper (15 cm) soil I layer. Overall, columns with an upper Soil I layer (C-1) demonstrated lower removal efficiency for nutrients than the ones with the more-permeable Synthetic Media I surface layer (C-2). In less-permeable media, water usually infiltrates in the sublayer through preferential flow paths, concentrating at certain points rather than the entire layer (Hillel 1998). This channeling reduces the total contacting surfaces between infiltrating runoff and media, leading to less pollutant removal.

Pollutant mass removals for both types of layered columns are presented in Fig. 2. Because of the high permeability, combined with better pollutant removal, a permeable synthetic mixture layer (Experiments 13–15) performed better than the Soil I surface layer (Experiments 9–12). All of these results are also supported by Experiments 16–18 (Set D), which employed layers of mulch (5 cm), Synthetic Media II or III (85 cm) and Sand II (5 cm), which combined a high permeability sand with a sandy soil. Therefore, a layered medium with a permeable sand/soil mixture layer appears to provide the best treatment efficiency for bioretention.

Evaluation of Existing Bioretention Facilities

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

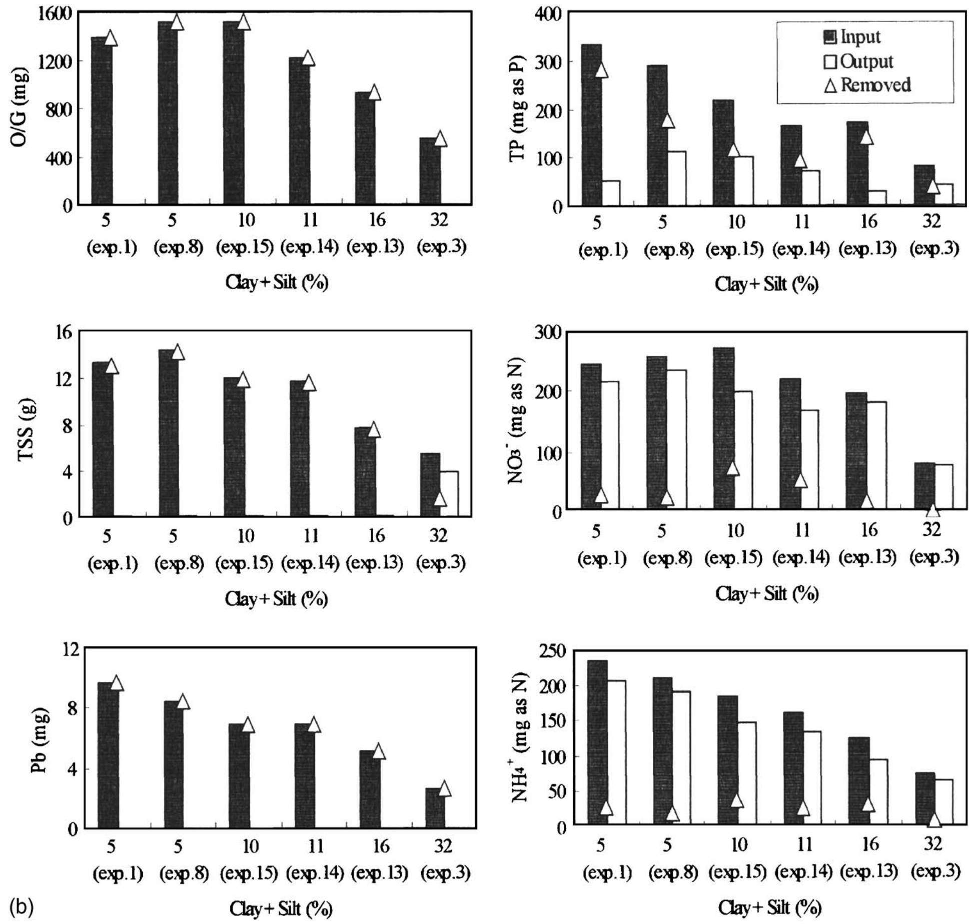

Fig. 1. (*Continued*).

Infiltration Aspects

The infiltration rate of runoff through a bioretention cell should relate directly to the textures of the media, as was demonstrated in the column studies. As shown in Table 4, the silt/clay content in the upper media layer is higher than that in the bottom for three of the six sites, either because of the initial design or subsequent TSS accumulation from incoming storm water runoff. Therefore, the less-permeable upper layer of these sites would limit the infiltration rate. Because of the low water loading (3.2 cm/h), pooling occurred only on two sites. Less than 5 cm pooling occurred at site HV1 after 35 min of pumping, and after 28 min for the LO3 site. Of the six, these two sites have the highest silt/clay contents in the upper media.

Water Quality Aspects

The water quality results from the first six field studies are presented in Fig. 3. The permeability of on-site bioretention media could not be determined because the influent pumping rate was insufficient to saturate the media in most cases. In addition, lateral flow is expected within the media. Therefore, pollutant concentration reduction is the only factor available to compare laboratory column experiments and field tests.

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

The most variability in the field sites was found in TP removal efficiencies, which ranged from 37 to 99%. Media depth and texture were correlated with TP removal, but no significant relationship was found. For example, although site GB is much deeper than the others, the removal efficiency of TP was not the best among these facilities. A good correlation between TP removal and OM content appears, which was not noted in laboratory studies. The highest OM was found at LO1, which demonstrated 93% TP removal. LO2 and HV2 have the lowest OM content and, correspondingly, the lowest TP removal.

For nitrate and ammonium, all six facilities produced similar low removal, as was found with column experiments. The exception was site LO1, in which 49% ammonium-N was removed. The reason for this remains unclear.

The results for two additional tests conducted during a rainfall event are summarized in Table 5. Because sample collection began 4 h after the beginning of the rain event, the water quality of inlet runoff samples should be better than those from first flush samples. Also, some pollutant loading from the parking lots was removed during transport through channels to the bioretention cells. Based on Table 5, TP was not found above the detection limit in all inlet and effluent samples, whereas TSS, Pb, nitrate

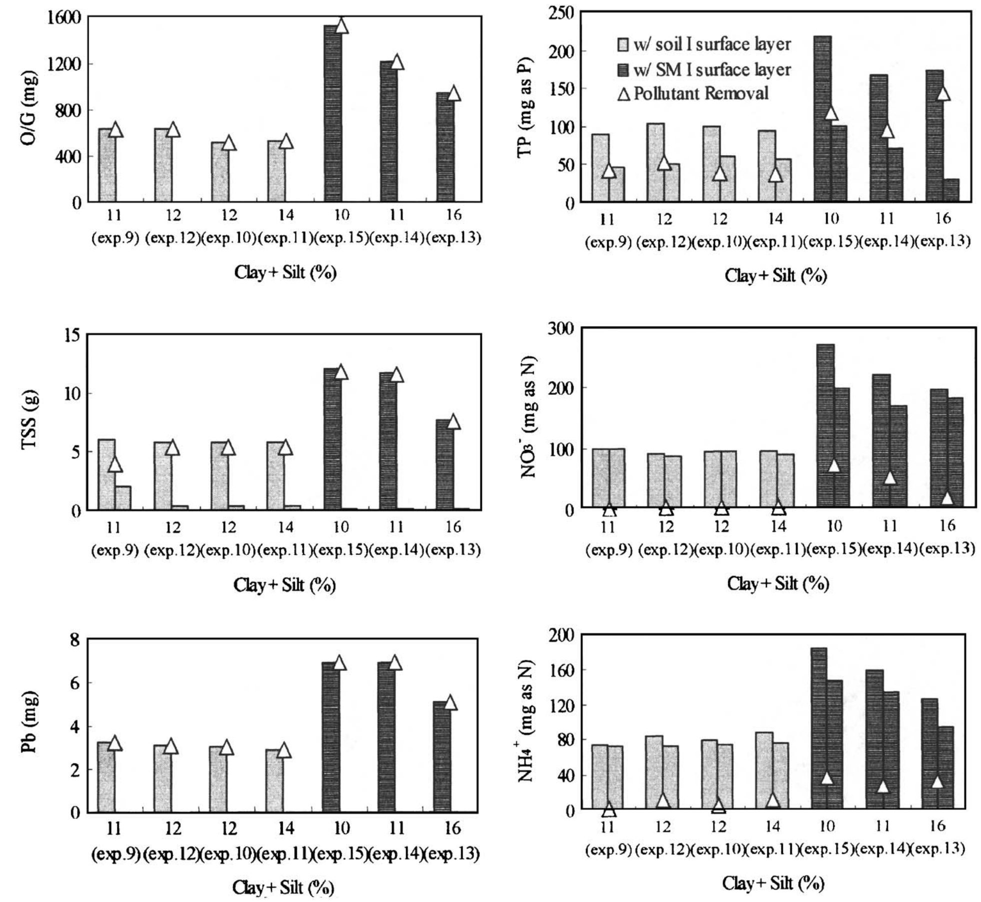

Fig. 2. Input, output, and removed mass of pollutants among different media layered configurations for 6 h runoff treatment

and ammonium input concentrations were smaller than in the synthetic runoff employed in this study. High concentrations of O/G appeared in the inlet samples, which should be attributed to the high vehicle activity in the parking lot being drained. In agreement with both laboratory and field studies, over 99% of O/G and 94% of Pb were removed by both bioretention facilities. Because

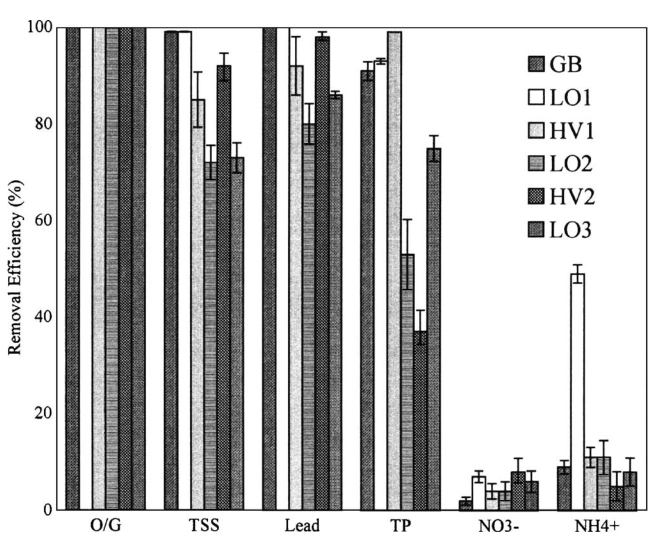

Fig. 3. Results of bioretention field studies for 6 h synthetic runoff treatment

these two sites had been just installed 3 months prior, the soil medium was still not stabilized and some TSS washed out, thus, negative removals were typically found.

More nitrate was removed by CP1 than by CP2, supporting the effectiveness of the CP1 denitrification layer. However, the hypothesis test of two means with a 20% level of significance does not conclude that the means of these two sets of samples are statistically different. Ammonium was removed to below the detection limit at both sites, but the input was relatively low.

Summary and Recommendations

Results from eighteen 6 h bioretention columns with different media mixtures, six on-site bioretention facilities employing synthetic runoff, and two others conducted during a rainfall event provide a comprehensive picture on bioretention behavior. Overall, all bioretention columns and on-site facilities demonstrated excellent removal for O/G and Pb. TSS removal was good in columns, but some washout of media particles was noted in field facilities, mostly from new installations. For nutrients treatment, the removal efficiency of TP ranged widely and appeared to be related not only to chemical properties of the media, but also to the flow behavior of runoff through the media. Unless special provisions were made, all media employed in this study were ineffective in removing nitrate and ammonium efficiently during a single 6 h experiment.

Based on the results of this study, two schematic profiles of

Table 5. Results of On-Site Evaluation during a Rainfall Event (Three Analytical Measurements/Sample)

Sample	Time (h)	O/G (mg/L)	TSS (mg/L)	Pb (μg/L)	NO_3^- (mg N/L)	NH_4^+ (mg N/L)	TP (mg P/L)
CP1							
Input	0	68±4	17±3	32±0	0.13±0.01	0.09±0.01	<0.05
Output	0	<0.5	46±5	<2	0.08±0.01	<0.05	<0.05
Removal (%)	0	>99	−174±43	>93	40±5	>44	—
Input	0.5	53±0	19±5	41±2	0.13±0.01	0.08±0.00	<0.05
Output	0.5	<0.5	33±0	<2	0.08±0.00	<0.05	<0.05
Removal (%)	0.5	>99	−78±37	>95	38±6	>37	—
Input	1	56±1	17±3	32±2	0.11±0.01	0.09±0.01	<0.05
Output	1	<0.5	41±4	<2	0.09±0.00	<0.05	<0.05
Removal (%)	1	>99	−145±39	>93	14±5	>44	
Input	1.5	67±3	23±4	28±0	0.13±0.00	0.09±0.01	<0.05
Output	1.5	<0.5	27±0	<2	0.09±0.00	<0.05	<0.05
Removal (%)	1.5	>99	−15±13	>92	31±0	>44	—
Mean input		61±7	19±4	33±5	0.12±0.01	0.08±0.01	<0.05
Mean output		<0.5	37±8	<2	0.08±0.01	<0.05	<0.05
Mean removal (%)		>99	−103±71	>94	31±12	>37	—
CP2							
Input	0	65±2	20±0	36±0	0.12±0.01	0.08±0.00	<0.05
Output	0	<0.5	14±1	<2	0.12±0.00	<0.05	<0.05
Removal (%)	0	>99	34±3	>94	−5±5	>37	—
Input	0.5	58±0	21±1	52±2	0.12±0.00	0.08±0.01	<0.05
Output	0.5	<0.5	15±3	<2	0.10±0.01	<0.05	<0.05
Removal (%)	0.5	>99	27±11	>96	17±10	>37	—
Input	1	56±4	16±1	36±2	0.09±0.00	0.09±0.01	<0.05
Output	1	<0.5	18±2	<2	0.08±0.00	<0.05	<0.05
Removal (%)	1	>99	−12±11	>93	11±0	>44	—
Input	1.5	67±3	23±4	28±0	0.13±0.00	0.09±0.01	<0.05
Output	1.5	<0.5	27±0	<2	0.09±0.00	<0.05	<0.05
Removal (%)	1.5	>99	−7±12	>92	17±16	>44	—
Mean input		63±7	18±2	39±8	0.11±0.01	0.09±0.01	<0.05
Mean output		<0.5	16±2	<2	0.10±0.02	<0.05	<0.05
Mean removal (%)		>99	10±23	>95	10±10	>44	—

bioretention media are presented in Fig. 4 as design recommendations. The permeability of the composted mulch used in this study was low and could limit runoff infiltration. Design of pretreatment for TSS removal from storm water is important to extend the lifetime of infiltration practices. Nonetheless, a fixed TSS loading is expected to bioretention facilities, especially when the volume of runoff is high. A top mulch layer can filter incoming TSS and prevent the underlying media from clogging. In addition, a mulch layer can assist in maintaining soil moisture during dry weather and can provide nutrients for future vegetation. Therefore, mulch with TSS filtering ability, high permeability ($d_{10}>0.1$ mm), and appropriate uniformity (a d_{60}/d_{10} value less than 4) is recommended as the top media layer in both designs.

The differences between the two design recommendations are the components of the bulk filtration layers. From the perspectives of construction and maintenance, a uniform profile is a more cost-effective alternative than multilayer media. Therefore, Fig. 4(a) is proposed which includes a combined filtration and vegetative layer. As mentioned, this upper media layer is critical to bioretention performance because runoff will begin to pond on the bioretention surface once the runoff loading is higher than the infiltration rate into the top media layer. An impervious upper layer would limit the overall infiltration rate (e.g., Set C-1, Table 3), even though lower layers may be highly permeable. With respect to pollutant removal, storing runoff temporally in the upper media layer is better than having it pond on the surface. In this manner, pollutants contained in the runoff can be sorbed onto the media or assimilated by microorganisms present in the media. Column studies showed that a Sand II/Soil III mixture produced a high runoff infiltration rate (Set D, Table 3) and very good pollutant mass removal. Therefore, a media layer created by mixing coarse sand (e.g., $d_{10}>0.30$ mm) with a sandy soil (sandy loam texture), where the soil ratio (20–70% by mass) depends on the requirements for the plant species to be employed is recommended. The suggested depth is 55–75 cm. With this design, the initial runoff infiltration rate is expected at 1.2–5.4 cm/min at 15 cm water head (Set D, Table 3), which is 4–6 times faster than that through a sandy loam soil (Experiment 3, 0.28 cm/min). For pollutant removal, >96% of TSS, >96% of O/G, >98% of Pb, from 24 to >70% of TP, 6–9% of nitrate and 11–20% of ammonium are expected to be removed from the infiltrating runoff.

The second design contains separate vegetation and filter layers. The vegetation layer is employed to optimize vegetation survival, whereas the filter layer is optimized for pollutant removal. Bioretention plants provide several natural functions to the facility and can also uptake some nutrients and heavy metals from the

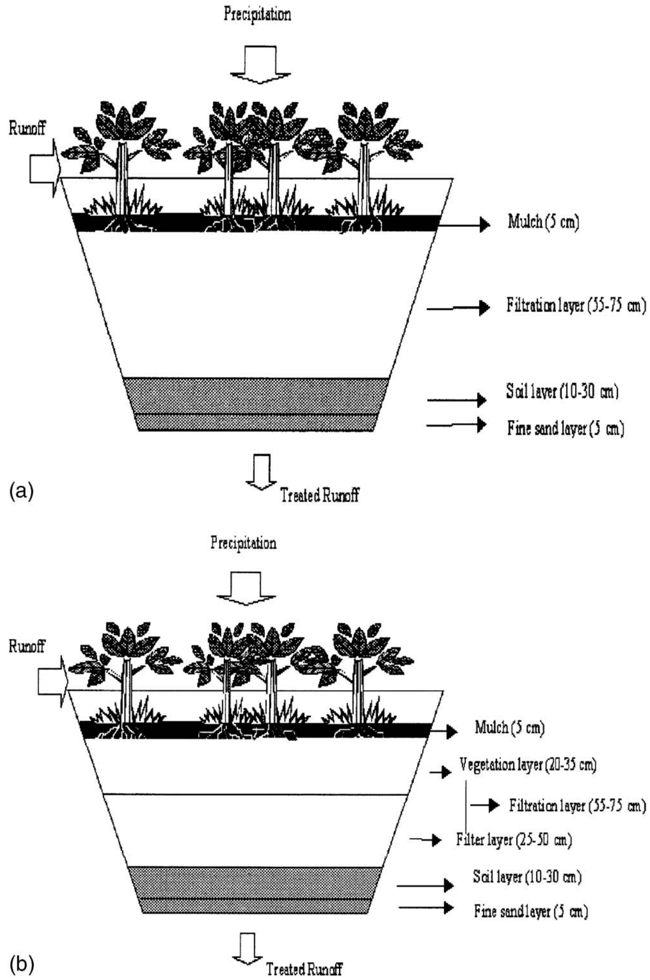

Fig. 4. Proposed profile of bioretention media: (a) single filter media and (b) dual filter media

media. The advantage of this design is that it allows the filter layer to back up the deficiency of the vegetation layer in pollutant removal. Since supporting plant growth is not necessary, the same components are employed, coarse sand (e.g., $d_{10} > 0.30$ mm) with sandy loam soil, but at a greater sand/soil ratio of 50/50 (Experiment 18), which produced the best pollutant removal noted in column studies. The vegetation layer depth recommendation is 25–30 cm with the media tailored to meet the needs of the plants. The filter layer depth is recommended at 25–50 cm. Under this design, >96% of TSS, >96% of O/G, >98% of Pb, ~74% of TP, ~9% of nitrate, and ~20% of ammonium are expected to be removed from the infiltrating runoff.

If nitrate removal is desired, an additional layer is required. Nitrate was poorly removed in all column and most field tests. Improvement was reported by Kim et al. (2003) and Hunt et al. (2002) by promoting denitrification processes through engineered alternatives and results employing a denitrification layer are promising, but so far inconclusive (CP1). Therefore, a sandy loam soil or a coarse sand mixed with an organic material layer is suggested (Hunt et al. 2002) as the lower media component (10–30 cm). This layer may also be kept submerged (Kim et al. 2003). A bottom fine sand layer (5 cm, as used in the column experiments) is packed to prevent soil particles from being mobilized and clogging the drain. The total media depth is 65–115 cm.

Bioretention has potential for significant improvement in storm water runoff quality as well as slowing flows. A high runoff infiltration rate is desired for bioretention design, especially in the upper media to minimize runoff bypass, which compromises both runoff quantity and quality controls goals. Bioretention media, however, cannot efficiently remove all pollutants contained in the runoff. If high infiltration and site conditions lead to ground water contamination concerns, engineering alternatives, such as placing a less permeable soil layer at the bottom can be investigated to address the problem. Long-term evaluation is recommended to confirm these designs and to advance the environmental effectiveness of bioretention.

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