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METALS REMOVAL TECHNOLOGIES FOR STORMWATER

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ABSTRACT

This study, on innovative methods for the capture of metals from stormwater, focused on two major areas of investigation: media filters and swales. The test water for both the filters and the swales was a stormwater which was collected from a parking lot during wet weather events. The characterization of the stormwater showed that the most prevalent metals detected in the runoff were iron, zinc, copper and small amounts of particulate bound lead. Ranges of metals were within national ranges reported by other studies.

In the filter studies twelve media were chosen for initial evaluation. Equilibrium and kinetic studies were completed on these media to assess their performance in capturing metals from urban runoff. The three best performing media: peat-sand mix, compost, and zeolite were then selected for in-depth study. The results of this investigation emphasize the importance of characterizing the stormwater before selecting a treatment media since the type and quantity of metals, pH, and other runoff characteristics can vary a great deal between sites. Additionally determining the range of metal concentrations of the runoff to be treated is crucial to selecting the best media, since the removal efficiencies of the media relative to each other changed with varying metal concentrations. Upflow columns proved more effective than downflow columns in the control of detention time, reduction in clogging of the media by solids and associated head loss in the column. Studies on the effect of anaerobiosis on metal retention by filter systems indicated that heavy metals were not mobilized from filter systems under anaerobic conditions. It was found that metal retention by the filters was not different from what was observed in oxygenated environments. Tests also indicate that the heavy metals of concern remain strongly bound to the particulates during long exposures at the extreme pH conditions likely to occur in receiving water sediments. Several of these filter media were also tested in a pilot-scale device using water from a detention pond that drains a medium-density residential area in Hoover, Alabama. In this series of tests, the runoff water was not spiked and as a result, the metals concentrations in the influent were extremely low (near the detection limit of the analysis). On those occasions where the metals concentration was higher, such as shortly after a rain storm, the filters proved effective at removing influent concentrations down to a level of approximately 10 – 15 μg/L. Removals to concentrations lower than that were not possible on a consistent basis.

In the swale study, the hydraulic characteristics of grass swales appear to be more important than grass species for removing heavy metals from stormwater during single storm events. Many of the concentration reductions were quite large, but some "negative removals", possibly associated with scour of previously deposited materials, were also noted. Because of the potentials for both sediment deposition and scouring, swales can improve or deteriorate water quality during individual storm events. Long term performance considering infiltration has shown significant heavy metal retention in swale systems. Data from the phytoremediation study suggests that there is a relatively similar *behavior among the different grass species. Howeve, in areas where it thrives, centipede is possibly the best choice for its resilience to drought, its nutritional frugality, and its greater ability to accumulate key contaminant metals such as Cu, Zn and Pb.*

KEYWORDS

Heavy metals, runoff, swales, phytoremediation, filters

INTRODUCTION

Stormwater runoff has been identified by the U.S. EPA as a leading cause of water-quality impairment nationwide. Heavy metals in urban stormwater primarily originate from automobile-related activities and the exposure of building materials to rain. Heavy metals may occur as dissolved, colloidal or particulate bound species; however most metals are predominantly associated with particulates. Particle associations and speciation critically affect the toxicity and bioavailability of metals and are greatly dependent upon chemical and physical parameters. Short-term, or acute, toxicity is rare for stormwater, but longer exposures to contaminated stormwater and to contaminated sediment cause longer-term, chronic toxicity, illustrated by major changes in benthic organisms. A successful control strategy for the reduction of heavy metals from stormwater must therefore be effective in capturing and retaining a variety of metals that are in the particle-bound, colloidal, and/or dissolved states.

Strategies for the control of metal-bearing urban runoff can be grouped into three basic categories: source avoidance or reduction; passive systems; and installed treatment technologies. While the concept of pollution avoidance and minimization at critical sources is the most preferred option for the control of metals in urban runoff, it is unlikely that any one method will provide either a realistic or effective solution to the problem. The scope of this project was to address emerging stormwater control technologies for the capture of heavy metals from urban runoff. The processes selected for investigation were media filtration systems and grass swales.

METHODOLOGIES

The stormwater runoff used in the spiked and unspiked lab scale tests was wet weather flow collected from a parking lot. The runoff was characterized (for metals and standard water quality parameters) for an initial series of runoff samples and on each runoff batch collected for subsequent remediation investigations. In low concentration metal (LCM) uptake tests, the effect of metal concentration on the performance of the media was investigated by spiking the runoff with a range of metal concentrations. The range chosen for each metal was representative of the range found nationally (Makepeace, et al. 1995). Spiked de-ionized, distilled water was used in the equilibrium ‘ultimate’ uptake capacity tests and kinetic uptake tests. Other metal uptake tests used unspiked runoff. Table 1 summarizes the water matrix and metal spiking data ranges for the experiments.

Table 1. Summary of Metal Concentration Ranges for all Metal Adsorption Experiments. Pauline- What is the first number in the second range column. Is that a low end?

Test	Metal Concentration Ranges for Individual Tests (mg/L)			
	‘Ultimate’ uptake capacity	Kinetic-rate of uptake	LCM uptake	Variable flow column studies

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Matrix		Distilled, deionized water	Distilled, deionized water	Stormwater runoff	Stormwater runoff
Cu mg/l	total			0.089-0.511	0.168-0.498
	dissolved	0	0.47,0.78-0.87	0.074-0.398	0.127-0.168
Cr mg/l	total			0.043-0.461	0.136-0.339
	dissolved	0	0.49,0.84-0.95	0.029-0.346	0.092-0.129
Pb mg/l	total			0.045-0.461	0.126-0.530
	dissolved	0	0.54,0.60-0.99	0.028-0.350	0.050-0.122
Zn mg/l	total			0.071-0.452	0.329-0.807
	dissolved	0-1000	1.01,1.61-1.76	0.065-0.426	0.254-0.361
Cd mg/l	total			0.070-0.415	0.206-0.412
	dissolved	0	0.57,0.93-1.00	0.074-0.461	0.198-0.265
Fe mg/l	total			0.099-0.526	0.871-9.313
	dissolved	0	0.82,1.33-1.48	0.031-0.368	0.132-0.323
pH		<3.5* - 6	4.43-4.53	6.64-7.01	6.9-7.7
TSS mg/l		0	0	3.7-6.0	29-460
TDS mg/l		0	0	62-74	115-173

Laboratory Media Studies

Twelve media were initially evaluated by means of batch equilibrium and kinetic tests, to compare the rate and extent of metals capture. The three best performing media: peat-sand mix, compost, and zeolite were then selected for an in-depth column study using parallel upflow columns in packed media beds. Metal removal efficiency was examined for different rates of flow and influent conditions. TCLP tests were also performed on spent media to assess disposal options. Finally the effect of microbial growth on metals capture and head loss in the column was investigated. In all cases, samples for metals analysis were filtered (dissolved metals) or digested (total metals), preserved, sealed, and refrigerated pending analysis (see QAPP section below).

Equilibrium and Kinetic Experimental Procedures

Standard batch jar tests were performed to determine the equilibrium capacity of the sorbents for metals. In equilibrium tests, lab-prepared metals solutions were used to determine optimum sorption capacity over a wide range of metals concentrations. The ranges used for these spiked runoff solutions represented the range of runoff metals concentrations found nationally in urban runoff.

The purpose of the kinetic tests was to examine the rate of uptake of metals by the media. These tests were performed using baffled batch adsorbers constructed according to standardized tank design for Continuously Stirred Tank Reactors (CSTRs) (Furasawa and Smith, 1973; 1974). All components of the batch system design (impellers, baffles and vessel), were constructed from perspex and HDPE to minimize metal-ion sorption by the fixtures. Each unit consisted of a 2-L cylindrical tank fitted with eight baffles. Agitation was provided by a flat six-blade impeller driven by a variable speed motor. A known mass of media was added to a stirred tank containing 2 liters of solution. At increasing time intervals over a four-hour period, aliquots of sample were withdrawn by plastic syringe.

Column Studies

Laboratory-scale fixed-bed column studies were set up to evaluate the dynamic characteristics of the metals-capture process. Stormwater runoff was treated using four parallel upflow filter columns to investigate the parameters affecting the performance of the column. All column materials (pump tubing, and stormwater holding containers) were plastic and HDPE. Columns were approximately 26 inches tall with a media bed depth of approximately 12 inches and an inside diameter of 1.5 inches. A sump area was provided below the media to allow space for particulates to settle. The stormwater was pumped from 50L Nalgene holding containers using variable flow peristaltic pumps (Figure 1).

Figure 1. Media Upflow Columns

The Role of Biomass in Metals Uptake

The effect of microbial growth within filters on stormwater metal retention was studied in laboratory column experiments. Parallel column systems similar to those described in the previous section were modified to accommodate sterile and non-sterile operating conditions. The sterile column was packed with media sterilized by autoclave, isolated from light by encasement with aluminum foil to prevent growth of phototrophic microorganisms and fed with pasteurized stormwater (Figure 2). Pasteurization of the runoff was adopted instead of sterilization to prevent major changes in water chemistry. The non-sterile column, containing the non-sterile media, was exposed to normal light and fed with unpasteurized stormwater. Microbial biomass, as protein, was quantified using the BCA protein determination procedure (Urrutia and Roden, submitted). Metal retention, head loss, and pH in the sterile versus non-sterile columns were compared to determine the influence of biomass on the capture of metals. The degree of the microbial presence in the samples of filtered water was determined using the method of reduction of XTT by reduced Fe oxides (procedure after Roslev and King, 1993). This method only provided a measure of relative microbial concentration. Therefore to provide quantitative measure of microbial concentration an XTT standard curve was determined for each column.

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Figure 2. Experimental setup for sterile versus non-sterile columns

Pilot-Scale Field Studies

Testing on the pilot-scale filters was performed in a manner expected to simulate the intermittent use typical in full-scale runoff applications. Eight filtering events were performed, four at Star Lake and four at Georgetown Lake (these "lakes" are stormwater detention ponds that receive runoff from an area that is primarily medium-density residential). Each filtering event lasted approximately 8 hours. Grab samples of approximately 1 L were collected every hour from the effluent of each filter and combined into a cleaned, 8-L Nalgene jug (one per media) to form a composite samples. Similar composite samples were taken of the influent filter water. Periodically during a sampling event, the effluent flow rate and depth of water on top of the filter were noted for each media. Sample collection and handling was in accordance with *Standard Methods* (1999).

Pilot scale tests lasted for approximately 4 weeks, from September 19, 1999 through October 22, 1999. Prior to performing the pilot-scale testing, several potential endpoints for filter runs were delineated: (1) physical clogging, (2) chemical breakthrough for several pollutants, or (3) end of the project. By testing these filters intermittently for several weeks, the effects of intermittent drying (by comparing the results with the laboratory experiments where the filters were run continuously until chemical breakthrough occurred) on filter performance could be determined. The protocols followed for analysis and holding time limits are listed in at least one of following documents:

- *EPA Methods and Guidance for the Analysis of Water* (EPA 821/C-97-001; 1997)
- *Handbook of Sampling and Sample Preservation of Water and Wastewater* (EPA 600/4-82-029, 1982, and including later additions)
- *Methods for Chemical Analysis of Water and Wastes* (EPA 600/4-79-020; revised 1983, and including later additions)
- *Quality Assurance Project Plan: Effects, Sources, and Treatability of Urban Stormwater Toxicants* (Parmer and Pitt 1995)
- *Quality Assurance Project Plan: Natural Media Filtration* (Clark 1999)
- *Standard Methods (1999)*

The collected samples were analyzed according to the following analytical protocols (Table 2). Additional information regarding these procedures can be found in the UAB laboratory Standard Operating Procedures (SOPs) (Pitt and Clark 1998).

Table 2. Analytical Techniques for Pilot-Scale Samples

Analytical Parameter	Analysis Method (EPA Method number shown if available; equivalent Standard Methods method in parentheses, if available)
pH	EPA Method 150 (Standard Methods 4500-H^+.B.)
Conductivity	EPA Method 120.6 (Standard Methods 2510.B.)
Turbidity	EPA Method 180.1 (Standard Methods 2130.B.)
Color	EPA Method 110.3 (Standard Methods 2120.C.)
Hardness	EPA Method 130.2 (Standard Methods 2340.C.)
Toxicity	Microtox Rapid Toxicity Screening (UAB Laboratory SOP)
Pb, Cd, Zn, Cu, Cr, Fe, Ca, Mg	ICP (Standard Methods 200.7)
Solids (Total, Dissolved, Suspended, Volatile)	EPA Method 160.1 and 160.2 (Standard Methods 2540.B.C.D.E.)
Particle Size Distribution	Standard Methods 2560.B. (Coulter Counter, UAB Laboratory SOP)

The filtration columns used during the pilot-scale tests were constructed in large (55 gallon [0.21 m^3]) polyethylene tanks purchased from (Aquatic Eco-Systems, Inc. FL). The inside diameter of the tanks was 0.53 m and the surface area of the tank at any cross-section was 0.217 m^2.

The media selected for study in the pilot-scale filters included those previously used in the laboratory experiments as well as a loamy topsoil and a lightweight sand. The filtration columns were constructed using the same guidelines used in the City of Austin (1988) and specified by CSF Treatment Systems, Inc. (1994) . The inside of each filter valve was covered with a washed fiberglass window screen. A gravel underdrain was placed in the bottom of the filter to a height just above the top of the sampling spigot (approximately 5 cm). A 0.15 m layer of sand was placed above the gravel (sand filter sand). Finally a 0.3-m layer of the medium of choice (usually a mixed media, 50/50 v/v with sand) was placed above the sand.. Nonwoven, synthetic fabrics were placed on the surface of the filters to improve run times and make cleaning of the filters easier. The fabric was used because of its potential potential to catch larger particles and reduce short-circuiting of the filter by the runoff. The filters were then rinsed thoroughly with tap water. The ratio of column diameter to median filter grain particle size for the sand filter (the media used to determine filter height and column diameter) was significantly greater than 100, which, according to other researchers (Clark, *et al.* 1992), should be sufficient to avoid significant wall effects. Two additional filter containers studied were a Jacuzzi filter set (Aquatic Eco-Systems, Inc., FL) and the StormFilter cartridge test tank, filled with compost, supplied by Stormwater Management, Inc., of Portland, Oregon. The filters then were mounted on a trailer for easy transport to the sampling locations.

Test water to the pilot-scale filters was supplied through two submersible pumps. The pumps were attached to a distribution manifold. The purpose of the manifold was twofold: (1) to ensure that the water entering any specific filter plus the sample collected as the influent was a random sample of the water received from the submersible pump, and (2) the flow to any filter could be regulated through the use of gate valves to maintain a flow rate no greater than that dictated as the optimum contact time (approximately 10 to 15 minutes for most pollutants for the media tested). Figure 3 shows the filtration set up for the pilot-scale testing.

Figure 3. The set-up for the pilot-scale tests showing the pumps in the lake, sending water up to the manifold for distribution into the individual filters.

Swale Studies

Indoor Swales

The indoor laboratory swales were developed to accomplish two goals 1) to develop multiple flow profiles for analysis of the grass swales' hydraulic characteristics, specifically Manning's "n", and 2) to examine the ability of common grasses to absorb / retain heavy metals. Indoor swales are comprised of three rectangular channels with dimensions; two feet wide, eight feet long, and six inches deep with nearly frictionless sidewalls(Figure 4). This channel shape yields a relationship between Manning's "n" and depth, unaffected by corner effects (Ree 1958). The frame was built of wood and sealed with non-reactive marine epoxy paint.. Drains were installed along the length of the swale, in two-foot increments, to aid in the recovery of infiltrated water . Water is supplied to the swales via a 1.5 horsepower pump and piping system. Sheet flow is established over the swales by allowing the water to pass through a gravel filter, prior to introduction (Figure 5). Once the water supply system and frame construction was complete, the three swales were filled with a loamy sand soil. This type of soil allows for high infiltration rates while supplying essential nutrients to the experimental grasses. A mixture of seventy percent topsoil and thirty percent sand (by weight) yielded a sand / silt / clay ratio typical of loamy sands. Local topsoil was used in the mixture to provide a reference from which to compare the indoor and outdoor swale sets. Once mixed, the soil was placed in the three indoor swales and planted with the various grass types. The grasses selected for indoor experimentation, based on their common use and physical characteristics, were Centipede, Zoysia, and Kentucky Bluegrass.

Figure 4 Indoor Laboratory Swales

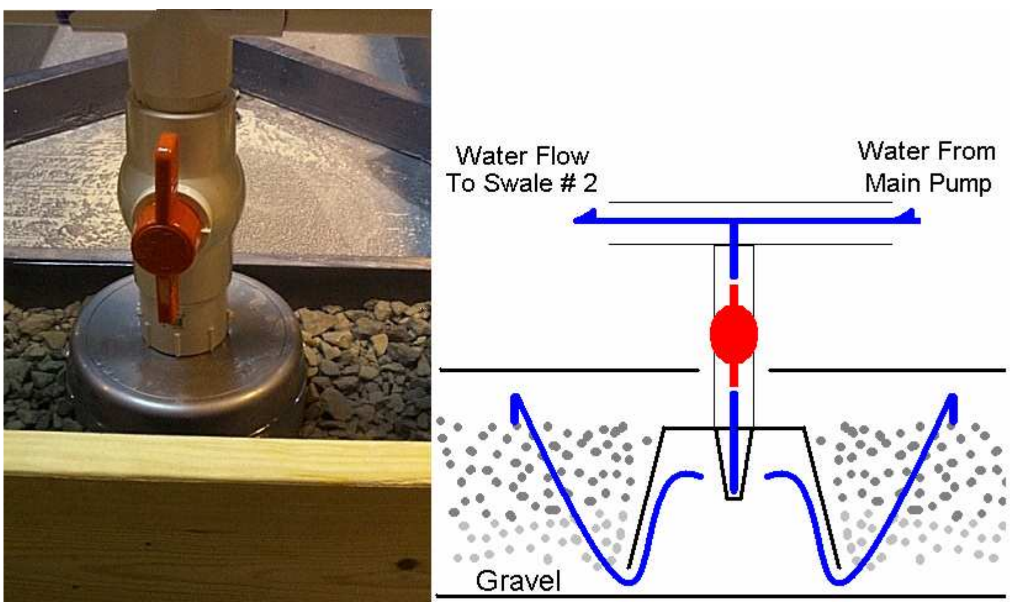


Figure 5: Gravel Chamber Used to Establish Uniform Sheet Flow

Determination of Hydraulic Characteristics: The determination of hydraulic characteristics is accomplished by the manipulation of swale parameters to produce multiple flow profiles. Detailed hydraulic evaluation of the resulting profiles yields an average Manning's "n" value for each configuration. Swale parameters include slope, flow, and grass type / length. Utilizing a removable section of pipe in the water supply system and elevating the head works, the slope can be altered . The experiments utilize seven preset slopes including: 0.1%, 0.2%, 0.5%, 1.0%, 2.0%, 5.0%, and 10.0%. Flow rate (discharge) is controlled by a series of rotary valves. Manipulation of those valves can vary the flow between 50 and 150 L / min with less than 2 mm of water surface oscillation over the testing period of one hour. Grass length is controlled by trimming to the desired height.

Experimental Procedure: Set slope to desired level. Cut grass to desired length. Close all drains, to collect infiltrating water. Turn on pump and adjust to desired flow (inline flow meter is used as a guide). Let water circulate over swale until soil is saturated (approximately 10 min). Sample soil depth and water surface depth according to grid pattern.

All measurements were taken using a specialized pin gauge and recorded to the closest millimeter. These values represent the distance from the reference bar to the surface of interest (soil or water surface). The profile data are transferred into project spreadsheets, in which calculations of the various hydraulic characteristics are performed.

Figure 6 Outdoor Swale #2

Outdoor Swales

Three outdoor swale sets were constructed to examine the swales' abilities to remove metal concentrations from urban runoff. Experiments were conducted to determine the hydraulic characteristics of the grasses, measure metal removal rates (via sedimentation and biological uptake), and to monitor metal accumulations in the underlying soils (infiltration). Swales 1 and 2 comprised of three radial channels with a common concrete flow splitter to ensures an even distribution of stormwater, during rainfall events. Radial swales were two feet wide, ten feet long, six inches in depth and rectangular in shape (Figure 6). This cross sectional geometry was selected to ease construction / maintenance efforts, while assuring results that were comparable to laboratory findings. The first channel was planted with Zoysia, the second channel Centipede and the final channel bare earth to serve as a control. Sharp crested weirs were installed in the entrance of each channel, to provide a means of calculating flow.

Table 3 Swale channel slopes

Test Channel Slopes:	Swale 1	Swale 2
Control (Bare Soil)	2.1%	8.6%
Centipede	11.2%	11.4%
Zoysia	23.6%	4.5%

The Zoysia and Control channels allowed channel slopes to be investigated, while the Centipede channels allowed duplication of results (Table 3).

Determination of Hydraulic Characteristics: The determination of hydraulic characteristics in the outdoor swales was accomplished by an examination of the flow profiles resulting from rainfall events. The swale parameters of slope and grass type / height were established prior to the storm. However, flow in the outdoor swales can be quite unstable. Flow rates are dependent on the intensity / duration of the storm event and the time of concentration of the drainage area. All efforts were made to collect profile data as quickly as possible, to limit the errors which unstable flow may introduce.

Experimental Procedure: Select outdoor swale for measurement. Clean out any surface trash that may have accumulated in the swale. Let stormwater circulate over swale until soil is saturated (approximately 10 min). Sample soil depth and water surface depth according to grid pattern. Once all measurements have been recorded, select new swale for measurement. Continue steps 1-5 until storm event ends or flow is insufficient for measurements. Completed measurements of the flow profiles are transferred into a project spreadsheet for calculation of the various hydraulic characteristics.

Collection of Surface Runoff Samples: Surface (stormwater) runoff samples were taken periodically to monitor the swales' metal removal capabilities. Individual grab samples of 100 mL were collected in twenty-minute intervals to create composites for the entire storm event. Two composites were made for each of the six channels in Outdoor Swale Sets #1 and #2 (six channels = twelve composites). The sampling locations were as follows: 1) as water entered the swale over the weir and 2) as water exits the swale. These composite samples are analyzed in the laboratory for TSS, TDS, total metals, and total filtered metals. The resulting data are then compared (entrance vs. exit) to determine the metal removal ability of each swale.

Amended Swale

The amended outdoor swale (Swale Set #3) was designed to compare the infiltration rate and metal retention capacity between an amended soil and a natural soil. Field observations were used to compare the infiltration rates, while metal accumulation rates were monitored in the lab. The amended swale set (Swale Set #3) receives stormwater runoff from a high traffic road adjacent to the swale entrance, draining an area of 0.289 acres or 12,600 ft^2. The head of the channel test section was located approximately 25 feet from where the roadway runoff entered the swale. The experimental channel exists on a 0.49% slope. The swale set was comprised of two, 24 feet long, parallel channels separated by a 1/8th inch Plexiglas divider. The divider extends ten inches below and rises six inches above the soil surface, ensuring flow (surface and subsurface) between the two channels is separated. The natural soil channel was undisturbed, apart from the installation of two pan lysimeters). The amended channel was constructed by excavating the existing soil eight inches deep, nine inches wide, and twenty-four feet long; yielding a trench volume of twelve cubic feet. The channel was lined with filter fabric, covered in stone, and fit with two pan lysimeters, prior to the addition of amended soil. The amended soil was prepared by mixing fifty percent sand with fifty percent peat moss by volume (weight ratio = 7.7:1 (sand: moss)). The sand and peat moss were placed separately in five gallon buckets and lightly packed to verify that no voids existed in the containers. The ingredients were mixed in a concrete mixer to ensure homogeneity. The final "amended" soil was compacted into the trench and bordering vegetation was encouraged to grow over the surface. Finally, a concrete flow splitter was installed at the swale entrance to evenly distribute the arriving stormwater.

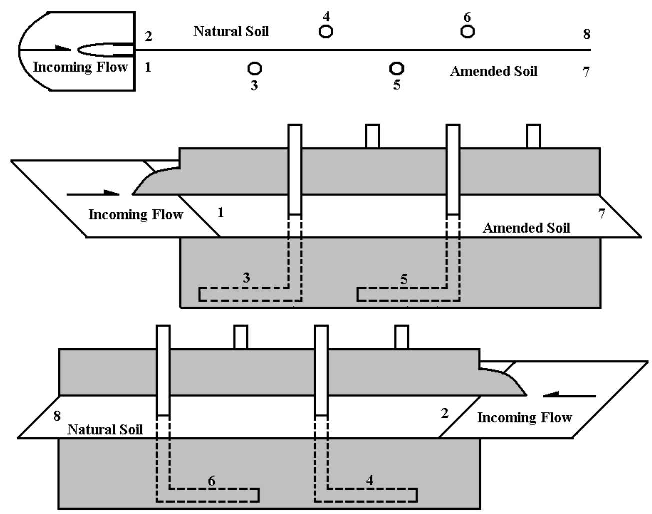


Figure 7: Amended Swale, Sampling Locations

Surface Runoff and Subsurface Leachate Collection. The following procedure details how surface and subsurface water samples are taken for the determination of the metal retention capabilities of the amended swale set.

Sampling Procedure: Clean out any surface trash that may have accumulated in the swale. Collect grab samples (300 mL)at each sampling location (Figure 7). Measure flow depth at each sampling location Measure flow velocity at each sampling location. Measure infiltration rate. Form composite samples for all sampled locations.Individual grab samples of 300 mL (100 mL for metal analysis and 200 mL for dissolved solids / total suspended solids) were collected in 20-minute intervals to create composite samples for the entire storm event. The final composite was separated and preserved as needed (HNO_3 and refrigeration for metals; refrigeration for TSS, TDS). The approximate velocity was determined by floating a marker to observe distance over time (V= D/T). Flow depth is recorded during each sampling. Utilizing the top of the Plexiglas divider as a reference, the distance to ground surface (Ds) and distance to water surface (Dw) was measured. Accurate water depth (WD) was acquired from the comparison of these values (WD = Ds – Dw). Lysimeter saturation time was determined by visual inspection during storm events. Depth measurements (inside lysimeter) vs. time are used to estimate the infiltration rate. Double ring infiltration experiments were conducted before and after selected storm events.

Rainfall Monitoring.

Rainfall was monitored by a Qualimetrics tipping bucket rain gauge and recorded on an Onset HOBO event logger. The rainfall gauge was installed on top of the University of Alabama's Civil and Environmental Engineering Building (MIB). This location was selected because of its close proximity to experimental swales and relative security. Close attention was paid to the manufacturer's setup guide to ensure optimal performance.Rainfall data recorded on the HOBO event logger were downloaded twice per month, utilizing Onset's Boxcar 3.6 software. The data indicated the date and time for each 0.01 inch of rainfall. The collected information was then transferred into Microsoft Excel where graphs are prepared for each month. These graphs display storm events that occurred during the month, and can be analyzed to determine the duration and intensity of each event.

Storm duration was determined by the length of time between the first data pulse (0.01 inch of rainfall) to the final data pulse in any storm event. The final data pulse is defined as the point at which no subsequent data are recorded within thirty minutes. Storm intensity is calculated based on the elapsed time between data pulses.

Rainwater Collection.

The use of actual stormwater was essential for the various experiments throughout the project. During rainfall events, stormwater was collected from a culvert located behind the Civil and Environmental Engineering Building. This catchment is situated so that it receives runoff from both a student parking lot and adjoining rooftops. Utilizing a sump pump, vinyl hoses, and multiple transport (twenty gallon) containers, large volumes of stormwater were quickly obtained. The transport containers were ultimately dumped into two 150 gallon, high-density plastic tanks until needed. Baseline tests were conducted to ensure that the collection process did not influence metal concentrations observed in the stormwater. Additional tests were performed to examine the impact that holding time had on the reserved stormwater. Data for these experiments are available in the data appendix.

Survey

Surveying was conducted utilizing a WILD Heerbrugg scale-reading theodolite (Model T-16). The Stadia (distance; leveling) method was used to determine the drainage area and channel slopes for each of the project swales. Boundaries of the drainage area were determined by observation of flow conditions during actual rainfall events. Distance and elevation measurements were tabulated in Microsoft Excel for analysis. Angles were rounded to the nearest 0.5-degree to permit manual drafting of the drainage basins. The drainage areas were plotted on engineering graph paper at one of two scales (1inch = 20ft or 1 inch = 40ft). Drainage areas were determined by counting squares. The Stadia method is accurate to +- 1ft for distance and +-0.01 ft for elevation. While care was taken to ensure accurate results in area estimates some errors could exist. Worst-case scenarios would indicate an error of one graphic square: +-25 ft^2 for Swale #1 and +-100 ft^2 for Swales 2 and 3.

Soils Characterization

Several experiments / procedures were conducted to determine the characteristics of different soils being utilized in the project. The information acquired from these tests was then used to assess the soil's influence on the hydraulic characteristics data collection. Below is a list of the standard ASTM methods employed, including any alterations of those methods which were made.

ASTM Methods Used:

- ASTM C 136-96a: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.
- ASTM C 702-93: Standard Practice for Reducing Samples of Aggregate to Testing Size.
- ASTM D 653-96: Standard Terminology Relating to Soil, Rock, and Contained Fluids.
- ASTM D 2216-92: Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock.
- ASTM D 2488-93: Standard Practice for Description and Identification of Soils (Visual-Manual Procedure)
- ASTM D 4220-95: Standard Practice for Preserving and Transporting Soil Samples.

Modified ASTM Methods Used:

- ASTM D 3385-94: Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer. This method was modified by utilizing three "Turf Tec International - Field Double Ring Infiltrometers" simultaneously per site, instead of the single (large) double ring infiltrometer, as recommended in the ASTM method. This alternative approach uses the mean of the three observed infiltration rates to represent the overall infiltration rate of the selected area. The smaller field infiltrometers allowed for rapid determination of the infiltration rate and are more time/cost effective.

Quality Assurance for the Analyses

The quality assurance/quality control procedures were documented in the QAPP. To minimize contamination of ambient water samples with the metal(s) of interest and interfering substances, a rigorous quality assurance project plan was developed and implemented. Meticulous equipment preparation and sample collection/preservation protocols were followed as recommended by EPA Method 1669 (EPA 1996). Metals analyses were performed using a dual view model Perkin Elmer Inductively Coupled Plasma – Optical Emission Spectrophotometer (ICP-OES) DV3000 according to Standard Method 200.7 (*Standard Methods* 1999). Data quality in this study was guaranteed through the use of blanks (field blanks, equipment blanks, method blanks, and matrix blanks), NIST standards from two independent sources, spikes (matrix spike) and duplicates (matrix spike duplicates and field duplicates) and lab replicates. Appropriate internal standards and the range and matrix for the calibration solutions were selected from determinations of the range of analyte concentrations in the samples. Multi-element calibration standards were used to matrix match samples. Quality control standards were also included at the beginning and end of the analytical run and repeated every ten samples throughout the run in order to ensure accuracy of the analysis. To ensure quality assurance, quality control standards were selected from a vendor other than the source of the calibration standards. Sufficient matrix blanks (minimum 7 per run) were analyzed to determine the LOD/LOQ for each metal. The LOD and LOQ were determined for each metal and for every instrument run.

Total metals samples were digested (microwave digestion) prior to analyses and dissolved metals samples were filtered through 0.45 μm metricel membrane filters prior to analyses. Changes in pH were noted throughout the all experimental studies.

RESULTS AND DISCUSSION

Runoff Characterization

The type and quantity of metals in runoff can vary widely depending on location and conditions. Makepeace et al. (1995) reviewed a wide sampling of papers that had analyzed stormwater runoff samples. The overall range and the range of the means from these papers for the metals of concern in this study are shown in Table 4. Note that the data in the does not distinguish between dissolved and total metals. This is important because it is typically the dissolved forms of the metals that are most bioavailable and that remain in the water columns for long distances. Particulate-bound metals tend to settle into the sediment. They are also easier to treat with technologies that focus on sedimentation and/or physical straining.

Table 4. Metal concentration ranges (overall and mean) and pH reported by various studies for stormwater samples. From Makepeace et al. (1995).

Metal	Concentration Range (mg/l)	Concentration Range of Means (mg/L)
Cadmium	0.00005-13.73	0.003-0.011
Chromium	0.001-2.30	0.010-0.23
Copper	0.00006-1.41	0.0065-0.15
Iron	0.08-440.0	0.988-12.0
Lead	0.00057-26	0.0209-1.558
Zinc	0.0007-22	0.0166-0.58
pH	4.5-8.7	

The stormwater runoff used in the spiked and unspiked lab scale tests was wet weather flow collected from a parking lot. Runoff characterization was performed on an initial series of runoff samples during wet weather events and for each runoff batch used in media and swale investigations. The results of these samplings are given in Tables 5 and 6. Iron, zinc and copper were the most prevalent metals detected in the collected runoff along with small amounts of particulate bound lead.

In the various experiments in this study both spiked distilled, de-ionized water and spiked runoff were used depending on the experiment. The spiked de-ionized, distilled water was used in the 'ultimate' uptake capacity and kinetic rate of uptake tests. The other metal uptake tests used runoff as the matrix. The runoff used for the low concentration metal (LCM) uptake tests was spiked to different levels to examine uptake by the media at different concentrations. The spiking level for the column tests was then selected such that there would be sufficient metals present to quantify concentration changes accurately in the analysis but such that the metal concentrations would still be reasonable for stormwater runoff. Table 7 summarizes the water matrix and metal spiking data for all of the experiments.

Table 5 Results of Runoff Characterization Tests on 'First Flush' Samples from Parking Lot in Rear of H.M. Comer Building on the University of Alabama Campus.

Date		10/5/2001	11/20/2001	11/24/2001	11/27/2001	6/22/2002	6/27/2002
Cu mg/l	total	0.036	0.051	0.018	0.030	0.181	0.075
	dissolved	0.017	0.030	0.012	0.030	0.038	0.013
Cr mg/l	total	0.015	< 0.010	< 0.010	0.013	0.016	0.011
	dissolved	< 0.003	< 0.010	< 0.010	< 0.010	0.002	< 0.002
Pb mg/l	total	0.024	0.014	0.004	0.009	0.038	0.037
	dissolved	< 0.004	< 0.003	< 0.003	< 0.003	< 0.008	< 0.008
Zn mg/l	total	0.203	0.136	0.034	0.079	0.256	0.197
	dissolved	0.009	0.051	0.001	0.006	0.028	< 0.003
Cd mg/l	total	< 0.001	< 0.001	< 0.001	< 0.001	< 0.0004	< 0.002
	dissolved	< 0.001	< 0.001	< 0.001	< 0.001	0.001	< 0.002
Fe mg/l	total	5.872	4.469	1.373	2.823	5.976	6.924
	dissolved	0.020	0.033	0.016	0.035	0.027	0.013
Na mg/l	total	0.855	2.996	0.755	1.618	2.651	0.337
	dissolved	0.878	2.929	0.828	2.396	0.906	0.241
Mg mg/l	total	8.618	8.673	1.970	3.309	24.934	8.665
	dissolved	2.048	5.422	1.130	1.203	5.680	0.501
Camg/l	total	35.760	46.060	10.189	15.702	139.323	20.949
	dissolved	18.959	38.692	8.956	10.054	41.593	4.454
K mg/l	total	2.784	7.224	1.450	2.653	10.119	2.194
	dissolved	1.567	5.881	1.227	2.004	3.203	0.684
pH		7.42			7.84	7.65	7.85
Color						285.00	55.00
TSS mg/l		271.33	260.00	33.00	82.00	104.00	348.67
TDS mg/l		106.70	309.33	59.80	75.40	396.55	34.10

Table 6. Results of Runoff Characterization Tests on Composite Samples from Parking Lot in Rear of H.M. Comer Building on the University of Alabama Campus.

Date		10/5/2001	11/20/2001	11/24/2001	11/27/2001	6/22/2002	6/27/2002
Cu mg/l	total	0.059	0.034	0.027	0.046	0.072	0.064
	dissolved	0.041	0.022	0.021	0.011	0.031	0.015
Cr mg/l	total	0.005	< 0.010	< 0.010	< 0.010	0.007	0.005
	dissolved	< 0.003	< 0.010	< 0.010	< 0.010	0.001	< 0.002
Pb mg/l	total	0.009	0.007	< 0.003	0.004	0.014	0.027
	dissolved	< 0.004	< 0.003	< 0.003	< 0.003	< 0.008	< 0.008
Zn mg/l	total	0.089	0.080	0.026	0.045	0.116	0.137
	dissolved	0.019	0.039	0.009	0.001	0.022	0.003
Cd mg/l	total	< 0.001	< 0.001	< 0.001	< 0.001	< 0.0004	< 0.002
	dissolved	< 0.001	< 0.001	< 0.001	< 0.001	< 0.0004	< 0.002
Fe mg/l	total	1.898	1.967	0.641	1.274	2.755	4.006
	dissolved	0.025	0.023	0.019	0.058	0.024	0.012
Na	total	0.545	1.817	0.605	2.447	1.230	0.367

mg/l	dissolved	0.532	1.806	0.620	1.517	0.862	0.286
Mg mg/l	total	4.049	5.662	1.395	2.181	10.946	4.992
	dissolved	1.617	4.359	1.001	1.182	5.333	0.831
Ca mg/l	total	20.089	34.712	8.705	12.447	61.485	16.197
	dissolved	13.781	31.146	7.690	10.557	39.950	7.302
K mg/l	total	2.461	4.623	1.508	2.264	4.166	1.837
	dissolved	2.032	4.187	1.370	1.820	2.677	1.025
pH		7.33			7.46	7.71	7.92
Color						260.00	45.00
TSS mg/l		70.00	91.00	11.00	38.00	103.33	204.00
TDS mg/l		74.80	216.20	46.80	65.00	348.70	41.80

Note: Italicized numbers were above ICP-OES LOD (limits of detection) but below LOQ (limits of quantification). Concentrations below LOD are reported as less than the LOD value for the ICP run in which that sample was tested.

Table 7. Summary of Metal Concentration Ranges for all Metal Adsorption Experiments.

Test		Metal Concentration Ranges for Individual Tests (mg/L)			
		'Ultimate' uptake capacity	Kinetic-rate of uptake	LCM uptake	Variable flow column studies
Matrix		Distilled, deionized water	Distilled, deionized water	Stormwater runoff	Stormwater runoff
Cu mg/l	total			0.089-0.511	0.168-0.498
	dissolved	0	0.47,0.78-0.87	0.074-0.398	0.127-0.168
Cr mg/l	total			0.043-0.461	0.136-0.339
	dissolved	0	0.49,0.84-0.95	0.029-0.346	0.092-0.129
Pb mg/l	total			0.045-0.461	0.126-0.530
	dissolved	0	0.54,0.60-0.99	0.028-0.350	0.050-0.122
Zn mg/l	total			0.071-0.452	0.329-0.807
	dissolved	0-1000	1.01,1.61-1.76	0.065-0.426	0.254-0.361
Cd mg/l	total			0.070-0.415	0.206-0.412
	dissolved	0	0.57,0.93-1.00	0.074-0.461	0.198-0.265
Fe mg/l	total			0.099-0.526	0.871-9.313
	dissolved	0	0.82,1.33-1.48	0.031-0.368	0.132-0.323
pH		<3.5* - 6	4.43-4.53	6.64-7.01	6.9-7.7
TSS mg/l		0	0	3.7-6.0	29-460
TDS mg/l		0	0	62-74	115-173

*The lower pH limit for the zinc test was hard to quantify. As the Zn concentration increased, the pH dropped up to the point where the Zn concentrations reached between 200 and 300ppm. Once the zinc concentration was this high, the pH began to increase. The reason for this is uncertain; analysis interference and/or complexation with other metals are potential explanations.

Filter Studies

Results of filter studies emphasized the importance of characterizing the stormwater before selecting a treatment media since the type and quantity of metals, pH, and other runoff characteristics can vary a great deal between sites. For example, determining the range of metal concentrations to be treated is crucial to selecting the best media, since the removal efficiencies of the media relative to each other changed with varying metal concentration. Media that were effective at high metals concentrations were outperformed by some media at the low metals concentrations typically found in stormwater. In addition, some media that offer potential as sorbents of metals may create water quality problems of their own. In equilibrium tests for all media, correlations were evident between the metals sorbed and the Ca, Mg, K, and Na ions desorbed. The ions desorbing and their quantity varied depending on the media and exchange metals present. The three best performing media (peat-sand mix, compost, and zeolite) were then selected for in-depth study.

Based on the unsteady state tests representing unsaturated media, the order of preference for removal on a mass basis was Pb>Cr, Cu>Cd>Zn, Fe for the peat-sand, Pb,Cr>Cu,Fe>Zn,Cd for the St. Cloud zeolite, and Cd>Zn>Pb>Cu>Fe>Cr for the compost. The order of preference for removal based equilibrium conditions on the low concentration metal uptake tests, was Cd, Pb>Zn,Cu>Cr>Fe for peat-sand, Zn,Cd>Pb>Cu>Cr>Fe for St. Cloud zeolite, and Cd>Zn>Pb>Cu>Cr>Fe for compost. In extensive comparisons of the three media, the peat-sand mix performed best at removing dissolved metals (Figure 8).

Figure 8 Percent Dissolved Copper Removal in Upflow Media Columns

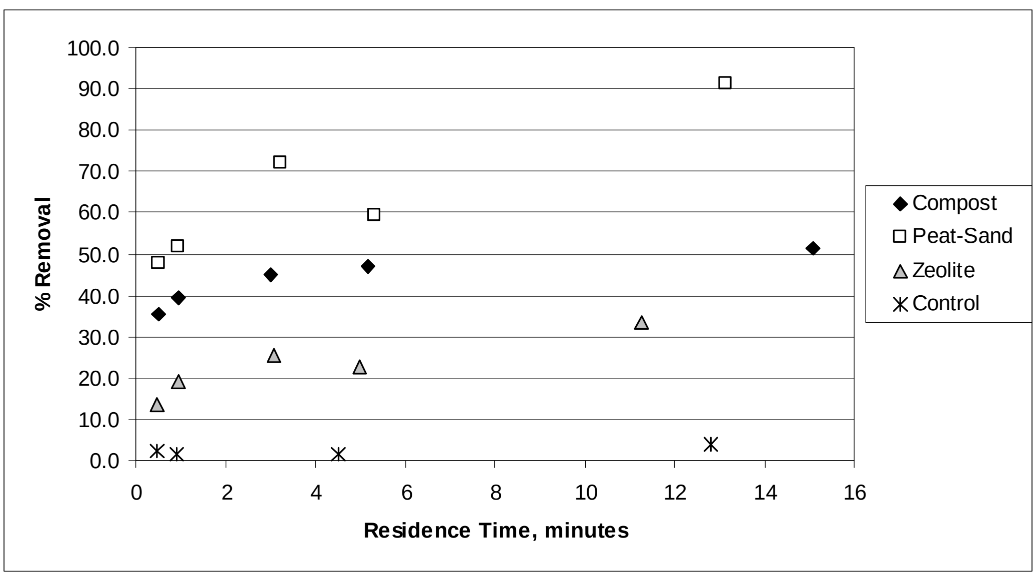
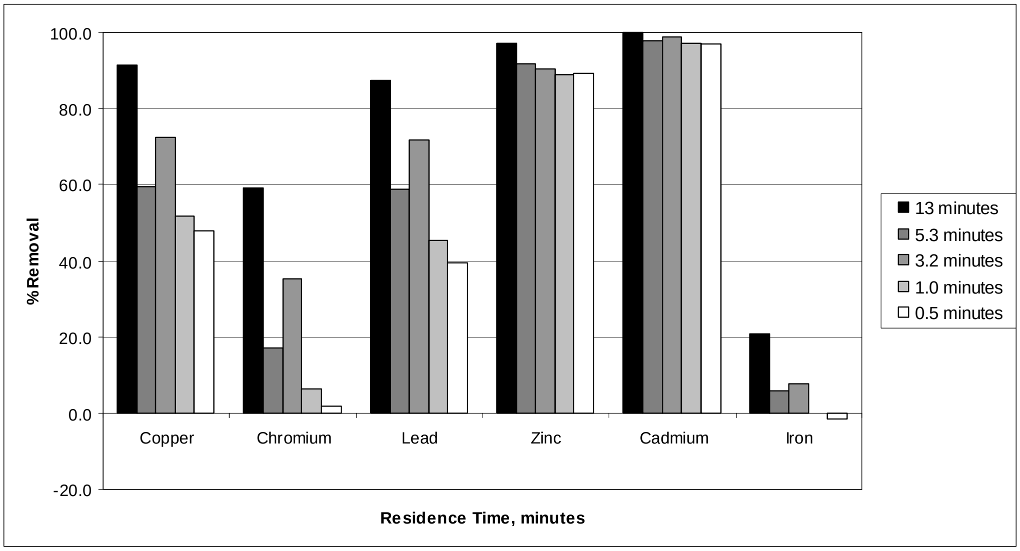


Figure 9 compares the percent removal of all six metals by the peat-sand column for the second of the three series of runs. Cadmium and zinc had the highest removals while chromium and iron had much lower removals. This is typical of the results for all three media for all runs. Overall, the figure shows that, as residence time increased metal removal increased. Comparing results between runs showed that removal efficiency was decreasing, due to the capacity of the media being used up.

Figure 9 Percent Dissolved Metals Removal by the Peat-Sand Column.



All three media removed total suspended solids well over all runs, but only peat-sand showed any removal of total dissolved solids. Compost increased the total dissolved solids concentrations. As expected, the behavior of the total suspended solids and particulate-bound metals paralleled each other. Copper and chromium typically had lower removal efficiencies than the other metals; one possible explanation is that these metals had a larger fraction of their particulate-bound metal concentrations associated with smaller particulates which passed more easily through the columns. Peat had the best removal efficiencies for particulate-bound metals. Removal efficiencies of compost and zeolite were approximately the same.

Peat-sand had the greatest headloss and the greatest change in headloss over the course of each run. Zeolite and compost beds offered considerably less headloss. The degree of change in headloss increased as the total suspended solids concentration of the influent increased for all media. The advantages and disadvantages of the three media summarized in the table below.

Table 8 Advantages and Disadvantages of Media

Media	Main Advantages	Main drawbacks
Peat-Sand mix	Best metal capture capability	Most detrimental impact on pH, the greatest headloss, and showed the most potential for clogging
Compost	Second best metal capture capability	Added color to the effluent. less impact on the pH of the effluent, less headloss, and exhibited less potential for clogging
Zeolite	Lowest metal capture capability	Less impact on the pH of the effluent, less headloss, and exhibited less potential for clogging

Upflow columns proved more effective than downflow columns in the control of detention time and a reduction in clogging of the media by solids and associated head loss in the columns. At residence times of three to ten minutes, most of the suspended solids settled out in the sump area of the columns. Compost and zeolite columns showed little sign of increased headloss during these runs, even when influent suspended solids concentrations were around 400 mg/L.

In order to evaluate whether the spent media can be disposed of at a Subtitle D landfill, samples of spent media from column studies underwent TCLP analysis for those metals regulated by

RCRA. Under the Land Disposal Restrictions program, a restricted waste may be land disposed only if a TCLP extract of the waste, or a TCLP extract of the treatment residue of the waste, does not exceed the regulatory levels for hazardous constituents listed for that waste. The regulatory levels are 1 mg/L for cadmium and 5 mg/L for chromium and lead. Chromium and lead did not present a problem, however, the cadmium concentration in the leachate was above the acceptable limit for peat-sand, and was close to the limit for zeolite and compost. Compost performed best in retaining all three RCRA metals.

Results of the Pilot-Scale Testing

Figure 10 depicts the ability of the filters to remove copper. Copper, lead, and zinc removals were not found to be statistically significant for any of the filter media, even though the media loading was small. It has been assumed in the modeling equations that adsorption is irreversible, assuming that the influent water characteristics, especially pH and conductivity, do not change significantly. However, at a certain low concentration, it would be expected that an equilibrium would be established where removal below that equilibrium concentration would not occur. Concentrations below the equilibrium concentration, whether due to high removal efficiencies or to low influent concentrations, would encourage the reversal of the driving force for the sorption reaction, causing desorption. The locations of this equilibrium for many of the media are indicated in Figure 10. For copper and lead, the minimum water concentration attainable was approximately 5 to 10 μg/L, and approximately 10 to 20 μg/L for zinc, for all of the media.

The influent iron concentrations are significantly greater than the influent copper, lead and zinc concentrations. Therefore, adsorption is the primary removal mechanism occurring. It is overwhelming the desorption and makes it appear that the adsorption is irreversible. Statistically significant removals were seen for the sand, cotton-sand, agrofiber-sand and carbon-sand filters. The peat-sand and compost-sand filters had a probability of 0.054 that the effluent was less than the influent concentrations.

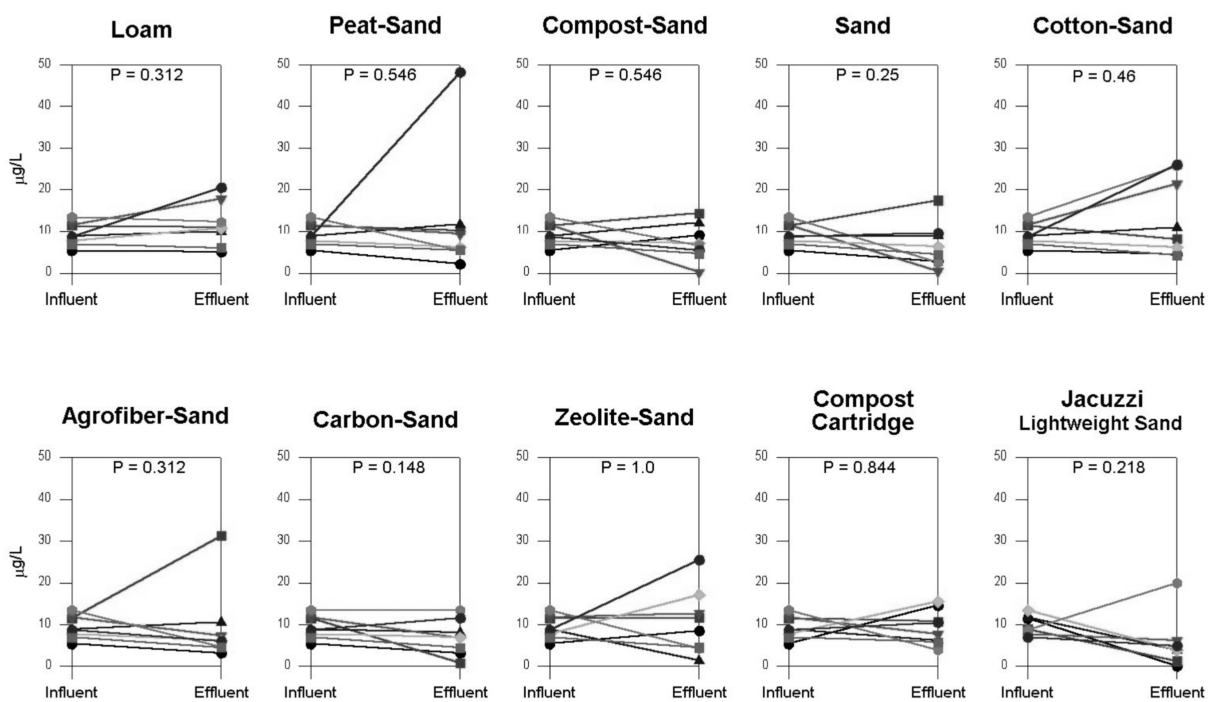


Figure 10. Copper removal during pilot-scale filtration experiments.

Calcium capture by the media to is shown in Figure 11. The loam, peat-sand, and cotton-sand filters were able to consistently remove calcium from the influent water. The behavior of the peat-sand filter was not unexpected based upon the literature review and the behavior of the laboratory filter column. The potential of the cotton to remove a small amount of calcium was also seen in the laboratory columns. As can be seen from Figure 11, only the peat had the ability to almost completely remove the calcium from the influent water (with one exception). The compost-sand filter consistently added calcium to the runoff water. This also is in agreement with the laboratory column results and with the ability of compost-sand filters to neutralize its influent when the influent pH is significantly different from 7.0 to 7.5.

No filter had the ability to remove magnesium consistently. Hardness removal was only statistically significant with the peat-sand and loam filters, with only the peat-sand filter able to remove large percentages of hardness. This is not unexpected given the ability of the peat filter to remove calcium. Mimicking its behavior with calcium, the compost-sand filter contributed hardness to the runoff water.

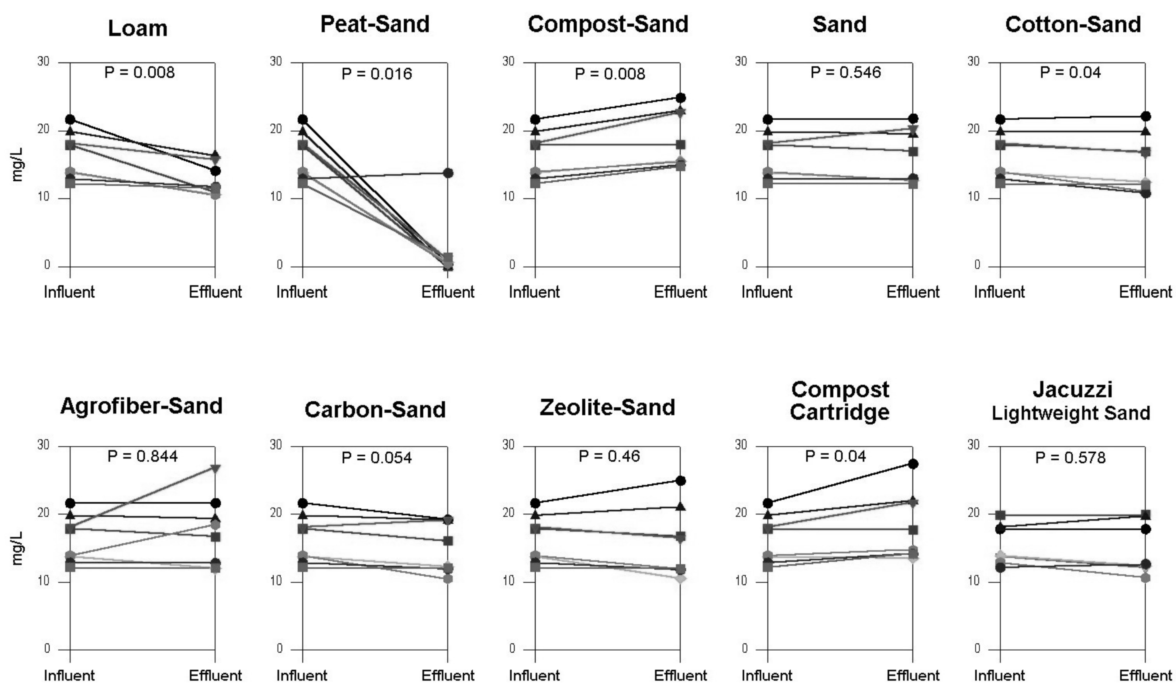


Figure 11. Calcium removal during pilot-scale filtration experiments.

The peat-sand filter is the only filter that had a measurable effect on pH. Hydrogen as the hydronium ion, H_3O^+, is one of peat's easily exchangeable ions, and in general, as peat adsorbs other cations, it releases the hydronium ion. pH has been proposed as a method of monitoring remaining life in a peat-filter. The other filter media, when treating an influent at a neutral or near-neutral pH, tend not to affect the pH measurably. Although, previous research (Clark 1996, 2000) has shown that when the influent water to a compost-sand column is not near a neutral pH, compost-sand will attempt to neutralize it.

In real-world applications for stormwater treatment, filters that contain adsorption media typically clog before the media can experience chemical break-though. It is not yet clear if depth filtering media will be a cost-effective stormwater control, considering the pre-treatment needed to prevent this clogging. The necessary pretreatment alone may provide adequate control, without the additional filtration cost. Large-scale filtration installations (especially sand) have been shown to perform well for extended periods of time with minimal problems. The use of supplemental materials (such as organic compounds) should increase their performance for soluble compounds. The use of upflow filtration is also expected to increase the life of filters before clogging, for some media types (not for peat/sand combinations).

The confirmation of the modeling equations for a few pollutants for some media indicate that this modeling approach has the potential to provide an estimate of the life of the filter, i.e., the time until media replacement is needed, for applications where the influent concentration is not quite as low as it was in the two detention ponds used in this pilot-scale study. The best application for these filters may then be to further treat the effluent from a detention pond in critical source areas, such as scrap metal recyclers, rather than as a polisher for effluent from a detention pond in a residential area. During these field pilot-scale tests and related full-scale tests, the minimum attainable concentration for these metals using media filtration appears to be approximately 5 to 10 μg/L for copper and lead, and approximately 10 to 20 μg/L for zinc, irrespective of media. These tests do confirm the utility of different filtration arrangements, especially concerning the problems associated with clogging and reduced filtration performance.

Swale Hydrologic and Phytoremediation Studies

Grass swales reduce heavy metal discharges through a combination of sedimentation, infiltration through the soil, and biological uptake. Grass swales can incorporate many positive features to reduce heavy metal discharges to surface and groundwaters. Sedimentation occurs due to increased channel lining roughness, infiltration is common, and amended soils can easily be incorporated in swale liners. Critical source area controls can be used incorporating special sorption/filtration media. Finally, sedimentation in wet detention ponds can be improved to better remove and contain finer particulates, and post-treatment with wetlands can be used for increased biological control processes.

The outdoor phytoremediation study on the role of common grass varieties in the capture of metals from runoff indicated that both Centipede and Zoysia grass varieties, common in many lawns in the Southeastern United States, exhibit a capability to uptake metals from soil that receives stormwater. Experiments in indoor swales with spiked stormwater, however, suggested that Centipede had a greater maximum ability to accumulate Cu and Zn than Zoysia and Kentucky Bluegrass, commonly used in northern areas of the country. Centipede seemed to also be able to accumulate more Pb. All three grasses accumulated Cd and Cr at similar rates of uptake, but the extent of uptake was small (~30 mg/Kg and 10 mg/Kg, respectively). Zoysia accumulated the least Pb, Cu and Zn of all three varieties in these studies. However, the overall results suggest that there is relatively similar behavior among the different grass species. In other words, any grass added to the surface of a swale system would represent a positive influence on metal uptake from runoff. However, if a recommendation should be made for systems designed to have a long life as filters for metal accumulation from stormwater, Centipede could possibly be the best choice for its resilience to drought, its nutritional frugality, and its greater ability to accumulate key contaminant metals, such as Cu, Zn and Pb (Figure 12).

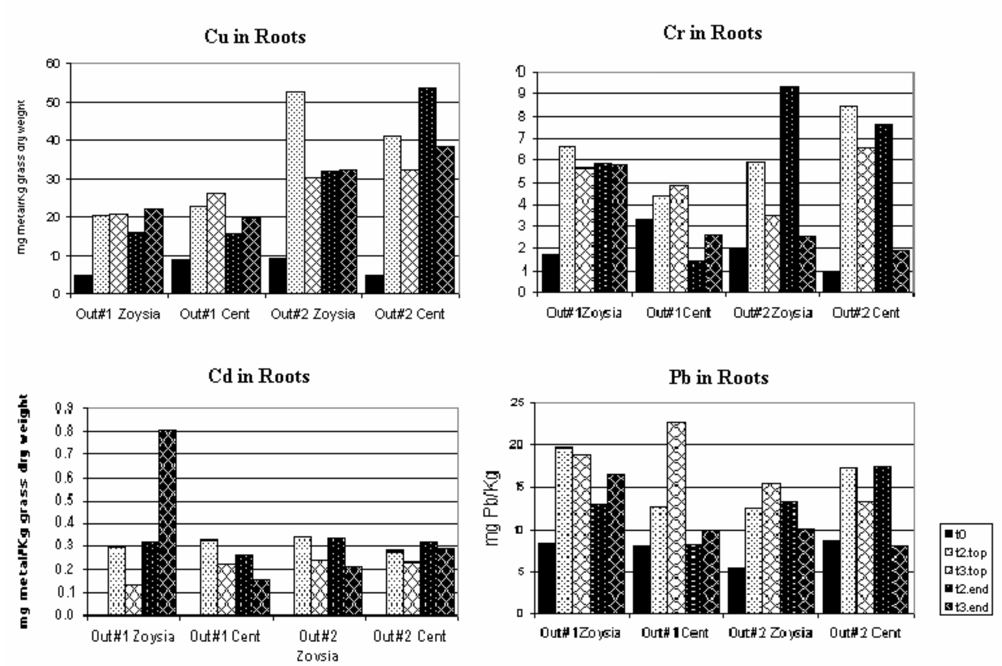


Figure 12. Outdoor Swales (#1 and #2) metal accumulation in root structures

Indoor laboratory swale experiments produced retardance curves for Centipede, Kentucky Bluegrass, and Zoysia species for flow depths that will optimize heavy metal removal (Figure 13). The hydraulic characteristics of grass swales may be more important than the grass species for removing heavy metals from stormwater during single storm events. Because of the potentials for both sediment deposition and scouring, swales can improve or deteriorate water quality during storm events. The outdoor swale tests showed highly variable results. Many of the concentration reductions were quite large, but some "negative removals" possibly associated with scour of previously deposited materials, were also noted. However, mass metal removals would generally occur due to infiltration in the swale.

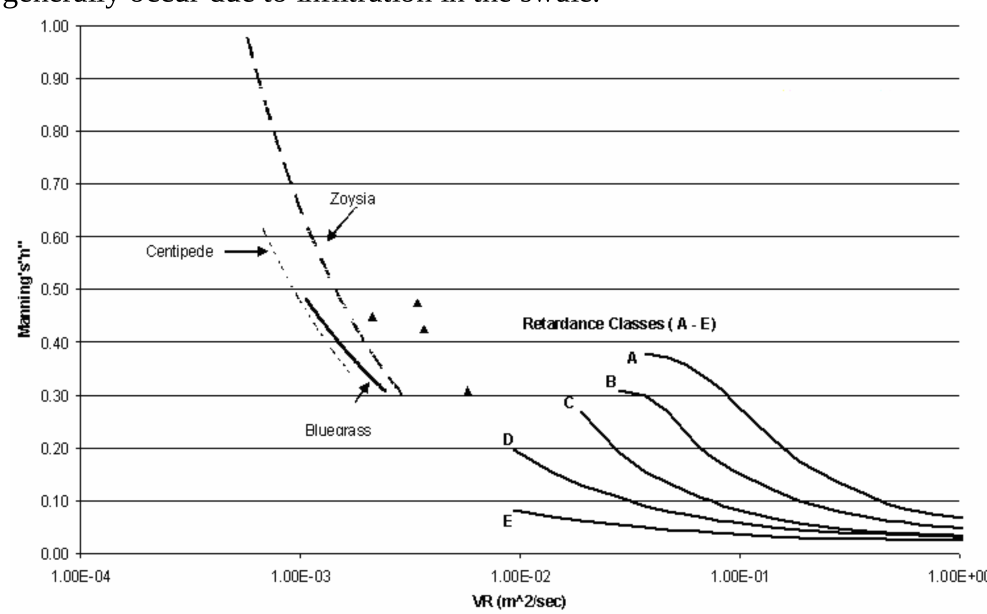


Figure 13. Indoor Grass "n" vs. VR Curves / Historical Retardance Curves

Treatability Testing

Treatability tests were performed to assess the effectiveness of different treatment trains and processes by quantifying improvements in stormwater toxicity and metals capture. The treatability tests included intensive analyses of samples from twelve sampling locations in the Birmingham, AL, area that all had elevated toxicant concentrations, compared to the other urban source areas initially examined. The treatability tests conducted were settling column, floatation, screening and filtering, photo-degradation, aeration, and a combined photo-degradation and aeration. These results were compared to the analysis of an undisturbed control sample. More than 900 toxicity tests were performed using the Microtox™ procedure. Turbidity tests were also conducted on all samples. Results indicated a reduction in toxicity as the level of treatment increased. All samples, with one exception, showed dramatic reductions in toxicity with increasing settling times. Even though the data were separated into three source groups, as expected, there were greater apparent differences between the treatment methods than between the sample groupings.

Metals Associations

Metal-particulate association tests using Chelex-100 resin revealed that more than 90% of the filterable forms of calcium, magnesium, potassium, iron, and zinc were in ionic forms, with very little colloidal, or other bound forms. Also, more than 80% of the filterable chromium and lead were also ionic, while only about 50% of the filterable copper and 30% of the filterable cadmium were ionic. This data can be used to estimate the level of control that may be associated with different designs of particle trapping devices. Some pollutants can be significantly reduced by a reduction in particulates, such as suspended solids, total phosphorus and most heavy metals. Other pollutants, such as nitrates, are reduced much less, even after filtration down to 0.45 µm.

Experiments were also conducted to examine the likelihood of the metals disassociating from the particulates under pH conditions ranging from about 4 to 11 with both weak and strong acids. These tests indicated that the heavy metals of concern remain strongly bound to the particulates during long exposures at the extreme pH conditions likely to occur in receiving water sediments. They will also likely remain strongly bound to the particulates in stormwater control device sumps or detention pond sediments where particulate-bound metals are captured.

Related tests were conducted as part of the filter media evaluation task of this research to measure the disassociation potential of heavy metals and nutrients under aerobic and anaerobic conditions having extreme Eh values. Studies on the effect of anaerobiosis on metal retention by filter systems indicated that heavy metals were not mobilized from filter systems under anaerobic conditions. It was found that metal retention within the filters was not different from what was observed in oxygenated environments. However, it is plausible that under certain specific environmental conditions, co-precipitation of metals by iron- and sulfate- reducing bacteria may take place in stormwater treatment systems.

Design Guidelines

Much information has been collected during this WERF-sponsored research project that can be directly used for the design of stormwater controls for the reduction of heavy metals. The treatability of stormwater heavy metals chapter contained in the final report for this project includes overviews of the associations of metals with different stormwater fractions. These associations are also useful in predicting the performance of sedimentation controls in removing heavy metals. This information can be used to predict the heavy metal control associated with a wet detention pond that is designed to remove particles of a specific minimum size. Additionally, material on the selection of filtration media, the clogging rates under different conditions, and the metal retention capacity of the different media are summarized from previous chapters. A simple approach in the selection of filtration media and the sizing of stormwater filters is outlined. Investigations of several important issues associated with the upflow filters are discussed in that chapter. These filters hold promise in being much more cost-effective than the more-commonly-used traditional slow filters. Additional tests were also conducted that investigated the clogging behavior of the different media under upflow conditions. Both the hydraulic and the water quality objectives of a swale design were examined. The chapter includes information on the selection of the grass species and other channel parameters.

CONCLUSIONS

The results of this investigation emphasize the importance of characterizing the stormwater before selecting a treatment media since the type and quantity of metals, pH, and other runoff characteristics can vary a great deal between sites. For example, determining the range of metal concentrations to be treated is crucial to selecting the best media, since the removal efficiencies of the media relative to each other changed with varying metal concentration. Media that were effective at high metals concentrations were outperformed by some media at the low metals concentrations typically found in stormwater. Upflow columns proved more effective than downflow columns in the control of detention time and a reduction in clogging of the media by solids and associated head loss in the column. Studies on the effect of anaerobiosis on metal retention by filter systems indicated that heavy metals were not mobilized from filter systems under anaerobic conditions. It was found that metal retention within the filters was not different from what was observed in oxygenated environments. However, it is plausible that under certain specific environmental conditions, co-precipitation of metals by iron- and sulfate- reducing bacteria may take place in stormwater treatment systems. Tests also indicate that the heavy metals of concern remain strongly bound to the particulates during long exposures at the extreme pH conditions likely to occur in receiving water sediments. They will also likely remain strongly bound to the particulates in stormwater control device sumps or detention pond sediments where particulate-bound metals are captured.

In the swale study, the hydraulic characteristics of grass swales appear to be more important than grass species for removing heavy metals from stormwater during single storm events. The outdoor swale tests showed highly variable results. Many of the concentration reductions were quite large, but some “negative removals”, possibly associated with scour of previously deposited materials, were also noted. Because of the potentials for both sediment deposition and scouring, swales can improve or deteriorate water quality during storm events. Long term performance considering infiltration has shown significant heavy metal retention in swale systems. Data from the phytoremediation study suggests that there is a relatively similar behavior among the different grass species. In other words, any grass added to the surface of a swale system would represent a positive influence on metal uptake. However centipede is possibly be the best choice for its resilience to drought, its nutritional frugality, and its greater ability to accumulate key contaminant metals such as Cu, Zn and Pb.

ACKNOWLEDGEMENTS

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