Engineered Bioretention Media for Industrial Stormwater Treatment

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ABSTRACT

This presentation describes the detailed laboratory tests of biofiltration media that is being considered for use in engineered stormwater treatment systems recently proposed for a large field laboratory testing site in the southwestern United States. These stormwater treatment systems were designed to treat 90% of the long-term runoff volume from drainage areas ranging from 5 to 60 acres at the site. The pollutants of interest for the project include cadmium, copper, lead, and dioxins, and the effluent concentrations had to meet design criteria that are based on numeric effluent limits that are applied to stormwater discharges through the site's NPDES permit. An additional feature of the project is that existing runoff concentrations for the pollutants of interest are generally below levels typically seen in urban and industrial stormwater runoff, therefore the tests needed to simulate site-specific conditions by adjusting raw influent samples to representative, where possible.

The media tested vary widely in terms of cost, performance, and maintenance requirements. However, because of the large volume of media specified for the proposed designs, unit volume cost savings (during construction) are potentially significant if media volume and types can be optimized. Furthermore, the potential for long-term cost savings is also significant, and therefore this study also considers life-cycle costs (e.g., media replacement frequency) and maintenance problems (e.g., clogging frequency). This optimization activity should result in improved predictions of life-cycle costs, of pollutant removals over the media's lifespan, and of maintenance issues and intervals, and should result in improved design and performance when installed in the field.

INTRODUCTION

The drainage areas consist primarily of steep catchments with significant open space consisting primarily of chaparral habitat and exposed bedrock (generally sandstone), with significant sediment loads expected during intense storms. An addition feature of the project is that existing runoff concentrations for the pollutants of interest are generally below levels typically seen in urban and industrial stormwater runoff. Therefore, testing was needed to simulate site-specific conditions by evaluating the potential media with spiked stormwater runoff where the concentrations had been adjusted to concentrations representative of the site's runoff.

Prior research has shown that a targeted suite of controlled laboratory tests can evaluate effectively filtration/biofiltration media for stormwater runoff treatment. They included standard column tests to determine flow rates, breakthrough capacity, clogging problems, and general contaminant removal; contact time and media depth tests to optimize depth as a design parameter; traditional isotherm and kinetics tests to determine the contaminant retention in the media as a function of contact time; and aerobic and anaerobic retention tests to determine whether pollutant retention is permanent under changing pore water chemistry conditions. These tests were conducted using stormwater collected from the Pennsylvania State – Harrisburg campus with spiking to bring some of the contaminant concentrations into the desired testing range.

The media examined included six different materials: rhyolite sand, granular activated carbon (GAC), surface-modified zeolite, a zeolite currently used on the site, a filter sand used on the site (all supplied by the client or client's representative), and a sphagnum peat moss The column tests examined each of these six materials separately, along with four mixtures of these components. A table of the properties of each filter medium is shown below.

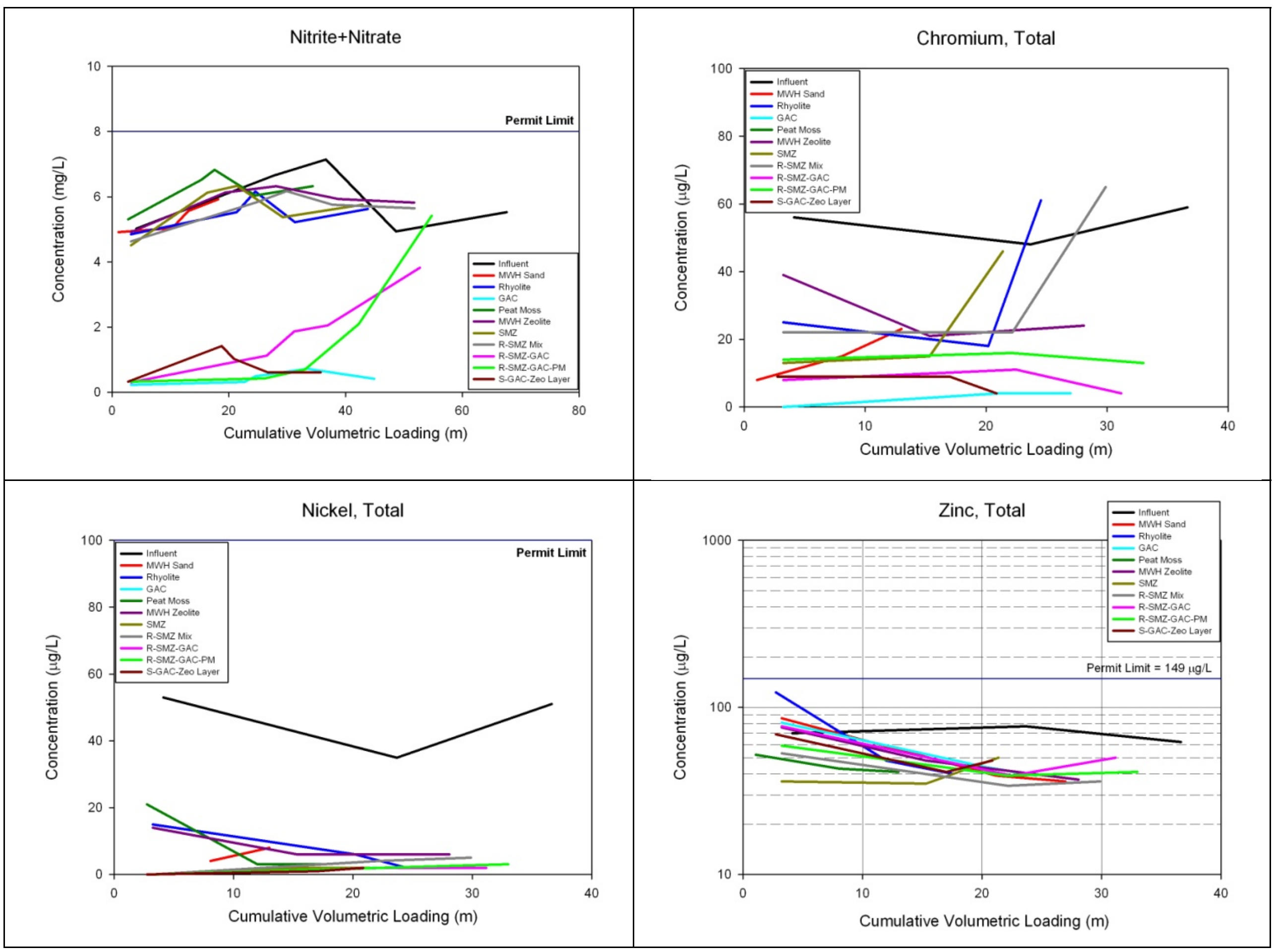
Media	**Description**
Granular Activated Carbon (GAC)	VCC 8X30 Virgin Coconut Shell Activated Carbon (Baker Corp.); 29 lbs/ft^3 (1.8 to 2.1 g/cm^3); $0.98/lb
Rhyolite Sand	D1 biofilter media sand (Rhyolite Topdressing Sand) from Golf Sand, Inc., North Las Vegas, NV;75 in/hr infiltration rate; particle density 2.38 g/cm^3; bulk density 1.28 g/cm^3; 98.6% sand, 1.1% silt, 0.3% clay; 45.4% greater than 0.25 mm; 44.6% between 0.18 and 0.25 mm.
Site Zeolite	Z-200 Modified Zeolite (Baker Corp.); $1.36/lb
Surface Modified Zeolite	14-40 Saint Cloud Zeolite with 325 µm Modified Zeolite at 3% Vol:Vol
Sphagnum Peat Moss	Purchased from nursery in Elizabethtown, PA
Site Sand	Fine textured silica sand

LABORATORY MEDIA EVALUATION TESTS

1) Clogging, breakthrough, and removal tests. In these traditional column tests, the media were subjected to intermittent stormwater flows over several months. The primary information from these tests included: treatment flow rates, pollutant removal, and clogging/maintenance requirements. The test water was a modified stormwater. Based on our experience, stormwater should be used to test media, even in a laboratory situation. The inherent chemistry of stormwater is substantially different from most artificial mixes reported in the literature. The collected runoff water was modified daily to increase the concentration of several pollutants to a target concentration of about the 90th percentile concentration levels seen in the runoff water from the site. Most of these concentrations are substantially lower than industrial wastewater concentrations used in some of the past testing of treatment media. These test results are being used to confirm the ability of these media to treat runoff at relatively low influent concentrations over time, as well as the sizing of the treatment systems, and the benefits of the sedimentation pre-treatment process. The challenge stormwater also has a mixture of different constituents that may affect the treatment performance of the media, again in contrast to traditional media tests that only examine individual contaminants at one time.

The following plots are examples of the test results. An extensive set of data has been collected as part of these tests, and the report showing these results is nearing completion. The first set of four plots show effluent vs. influent quality as a function of time. Time is shown as the cumulative volumetric loading of stormwater, in meters. Using the cumulative loading as a measure of time allows the results to be transferred to other sites. For the water quality, as an example, the nitrite+nitrate and the total chromium plots indicate some breakthrough after about 20 to 40 m of stormwater has been applied to the columns. Not all columns experienced this breakthrough, and the time to breakthrough varied among the media. One surprising result was the removal of nitrates by the columns that contained GAC. Past experience has shown that nitrate treatment is problematic in stormwater runoff unless the system contains vegetation (nutrient uptake) or an anoxic zone (denitrification). The total nickel removals are substantial and consistent for all of the columns, while the total zinc removals interestingly are most evident only after about 10 to 20 m of stormwater has been treated.

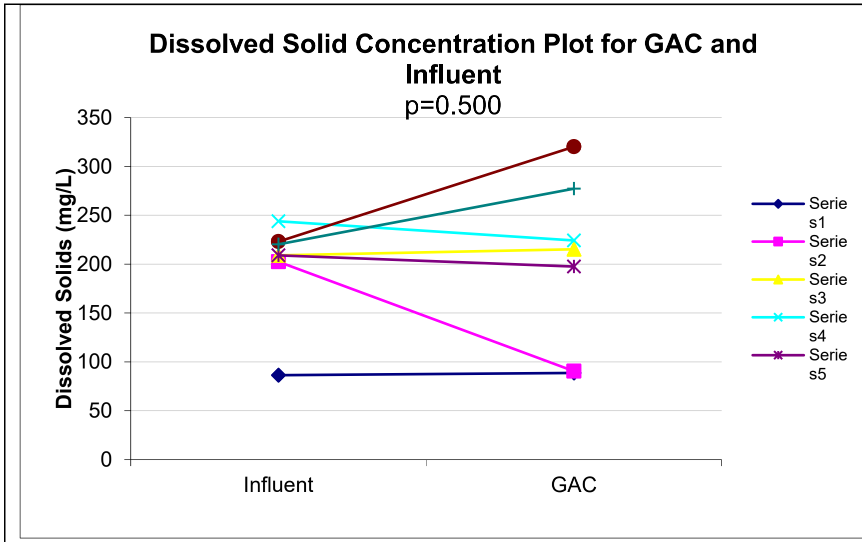
The advantage to analyzing for a suite of pollutants, rather than just the targeted ones, is that other issues that affect design may become apparent. For example, several of these media release ("leach") pollutants such as phosphorus or participate in ion-exchange reactions with sodium and potassium being released, potentially in high concentrations. Further data analyses will summarize the flow capacities and clogging potentials for the different materials, along with the likely removal mechanisms (and removal capacities) for the different types of constituents.



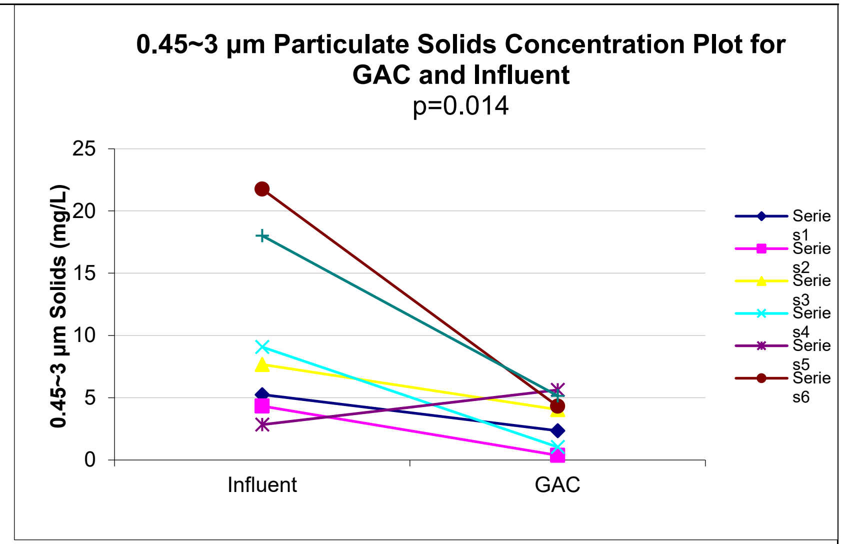
The following plots show how the particulate trapping information is being summarized for the column tests. These plots are only for the granular activated carbon (GAC) and sand mixture column. These plots are line graphs comparing the influent and effluent concentrations for each particle size range. Also show on each plots are the probabilities that the effluent and influent concentrations are the same, based on the paired-sample Wilcoxon rank sum test. Generally, if the p value is <0.05, it is assumed that the observed concentration sets are significantly different. If the p value is larger, this indicates that not enough data observations are available to indicate that they are different. In all cases, except for the TDS (<0.45 µm particle size) values, there are significant differences between the influent and effluent concentrations. These plots also indicate that the reductions are generally quite large, with effluent concentrations limited to a narrow range of values, compared to the wide range of influent concentrations.

Other plots contain paired probability plots showing the influent and effluent concentrations, along with the 95% confidence intervals of the values. Regression analyses (with ANOVA and residual evaluations) were used to evaluate the scatterplots of influent vs. effluent concentrations. In most cases, the effluent concentrations are a constant. The equations shown on the plots are therefore usually in the form of effluent = average (coefficient of variation), when the ANOVA analyses did not indicate any significant slope coefficient for a first order polynomial. In some cases, where the initial paired tests did not indicate any difference between the influent and effluent concentrations, the equations are in the simple form of effluent = influent (only seen for some of the TDS data).

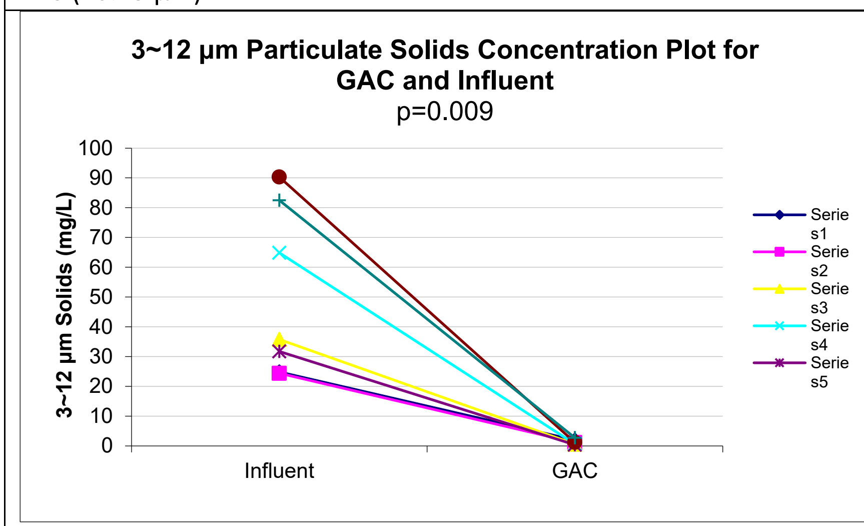
Column Test Results for Granular Activated Carbon Media



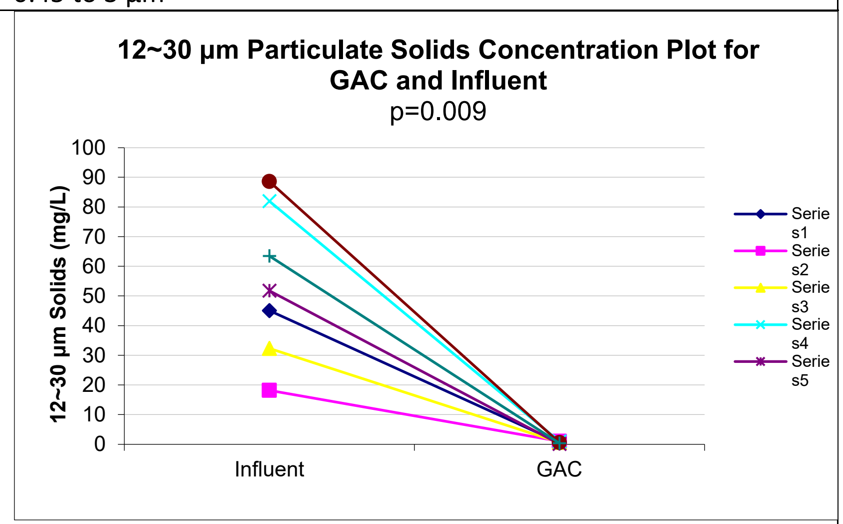
TDS (<0.45 µm)



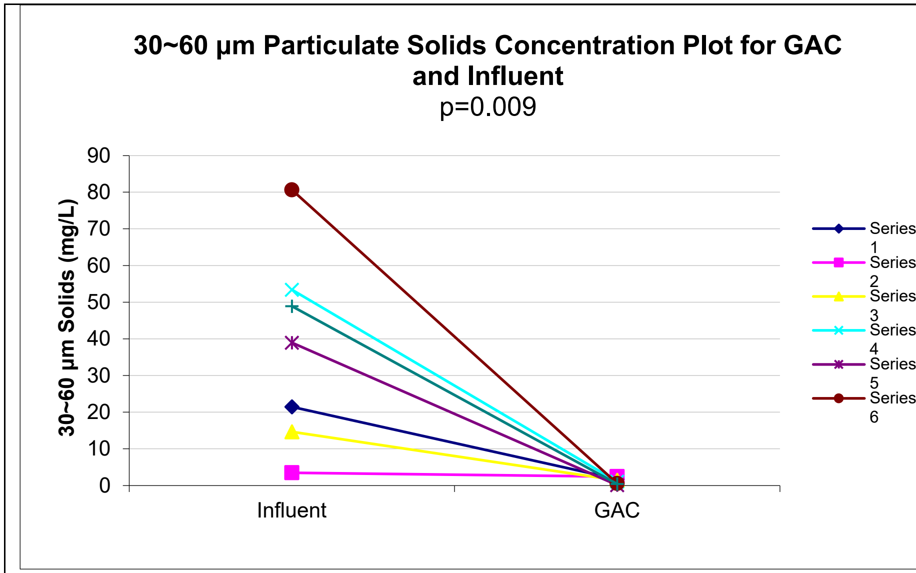
0.45 to 3 µm



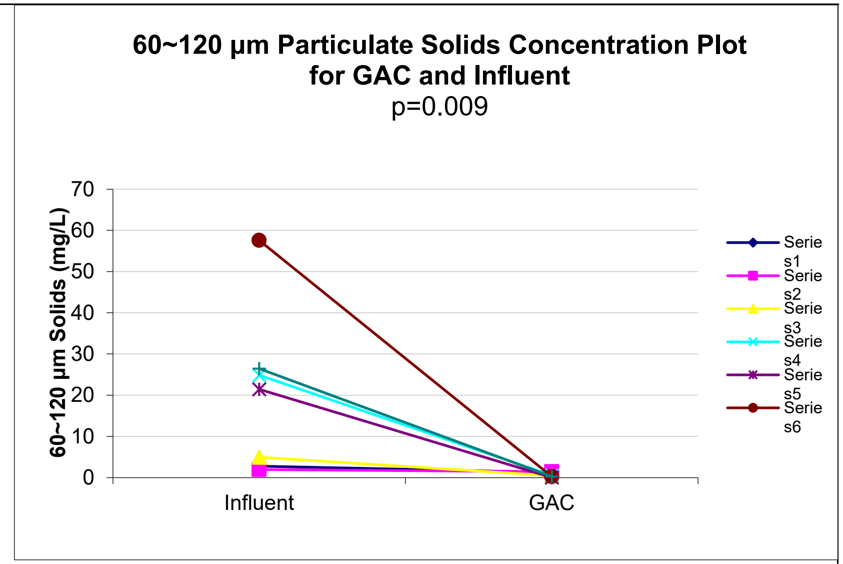
3 to 12 µm



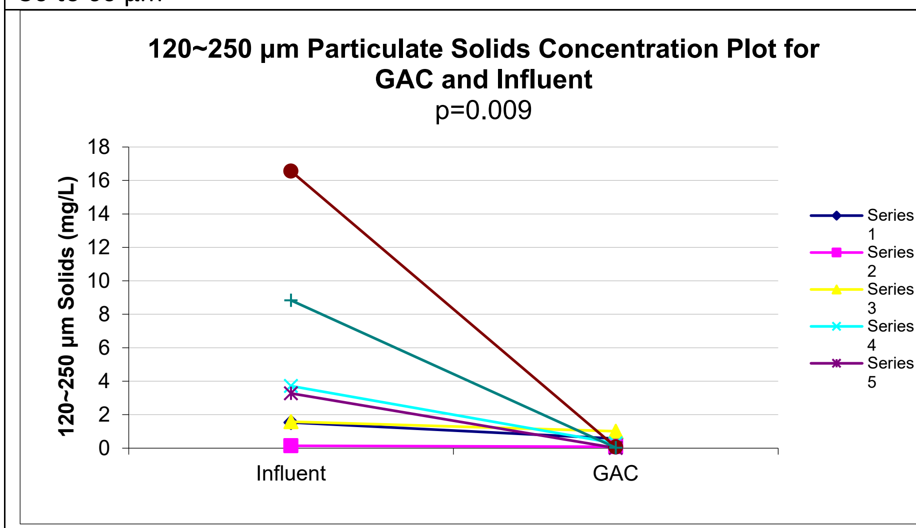
12 to 30 µm



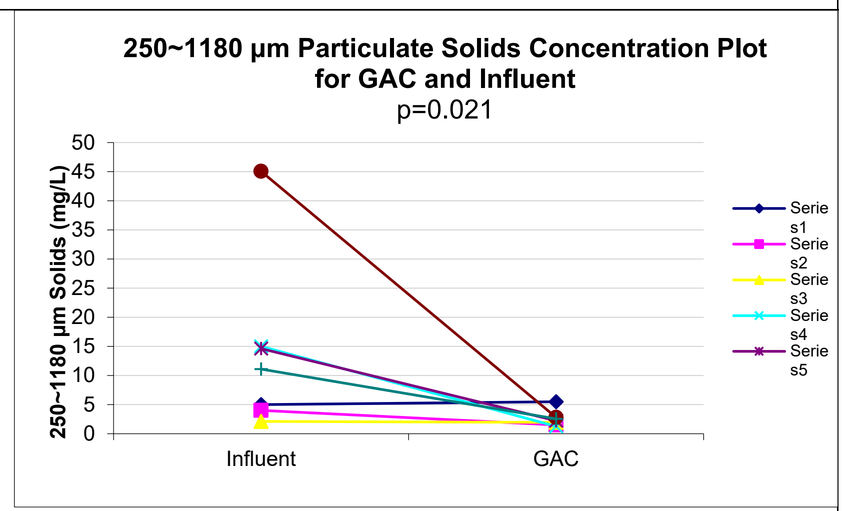
30 to 60 µm



60 to 120 µm



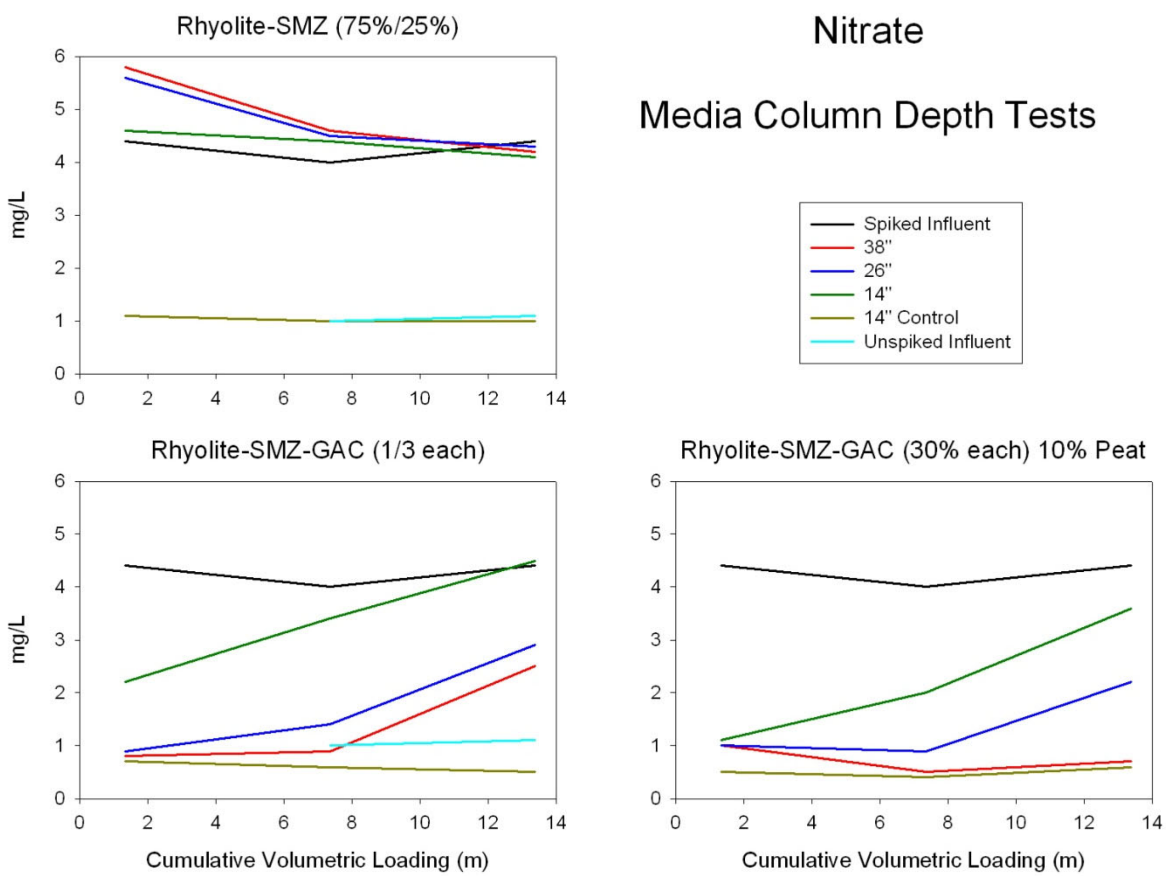
120 to 250 µm

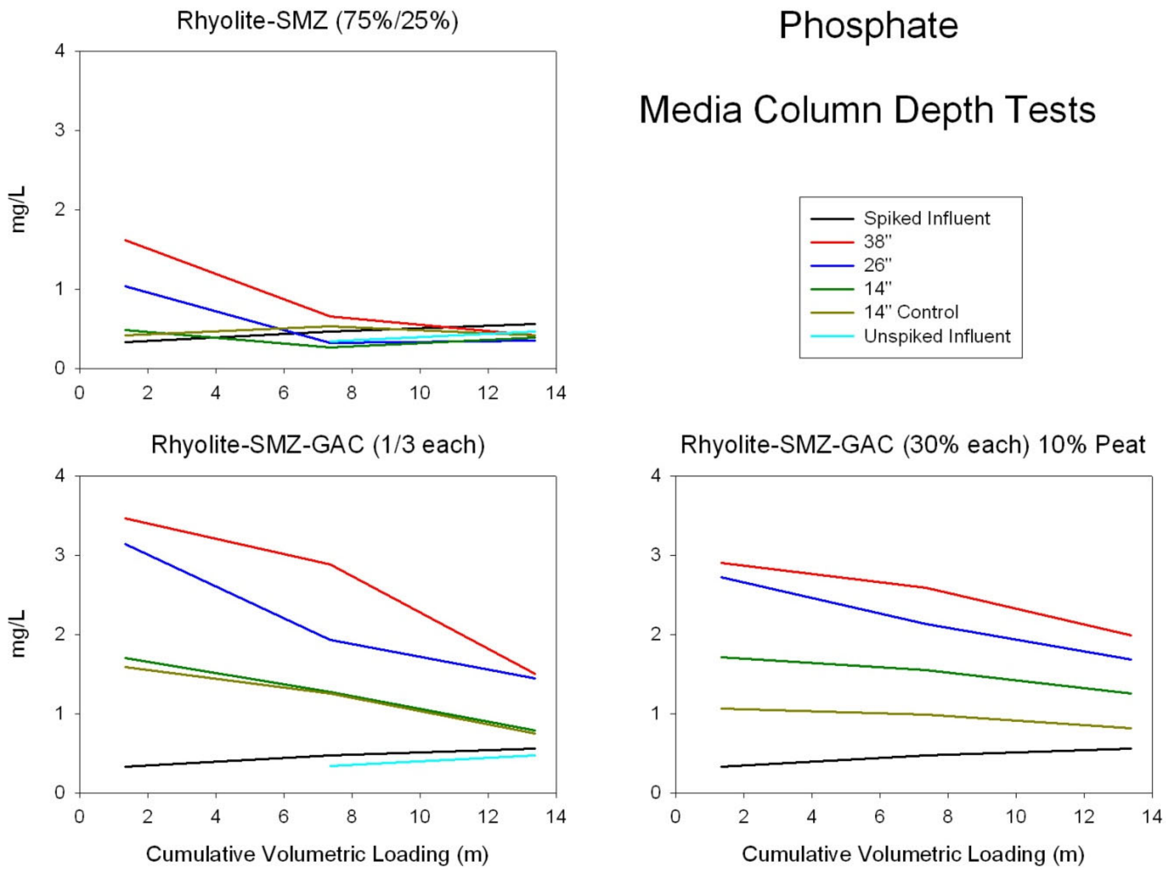


250 to 1180 µm

2) Contact time and media depth tests. These tests determined the effect of contact time (controlled by the media depth for a given loading rate) on pollutant removal. For many of the filterable pollutants, longer contact times should enhance pollutant removals. Increased contact time corresponds in the design to either larger surface areas (to distribute the flow and reduce the loading rate) or increased media depths. These data enable more detailed calculations of expected performance to be made for the treatment systems for the candidate media.

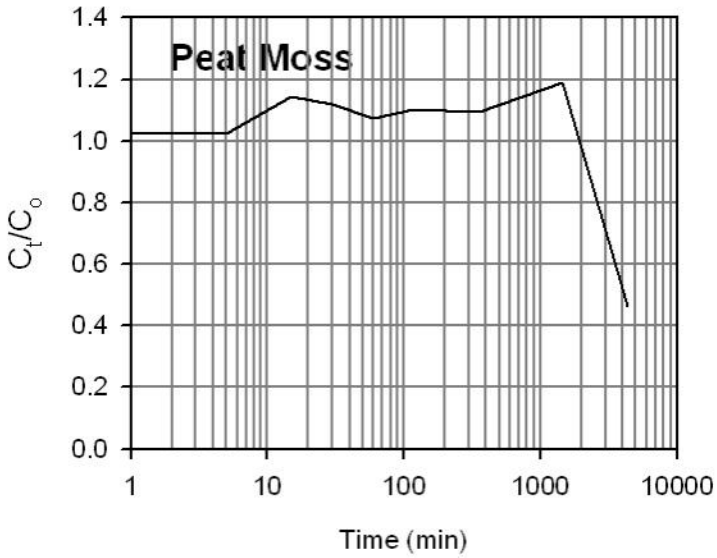
The following plots for nitrate and phosphate indicate slight differences with the different column depths. For nitrates, longer GAC columns resulted in slightly better nitrate removals, while the longer columns for phosphate resulted in greater leaching of the phosphate from the media. Again, substantial data has been collected for these tests and these are only examples, and further data analyses are being conducted.





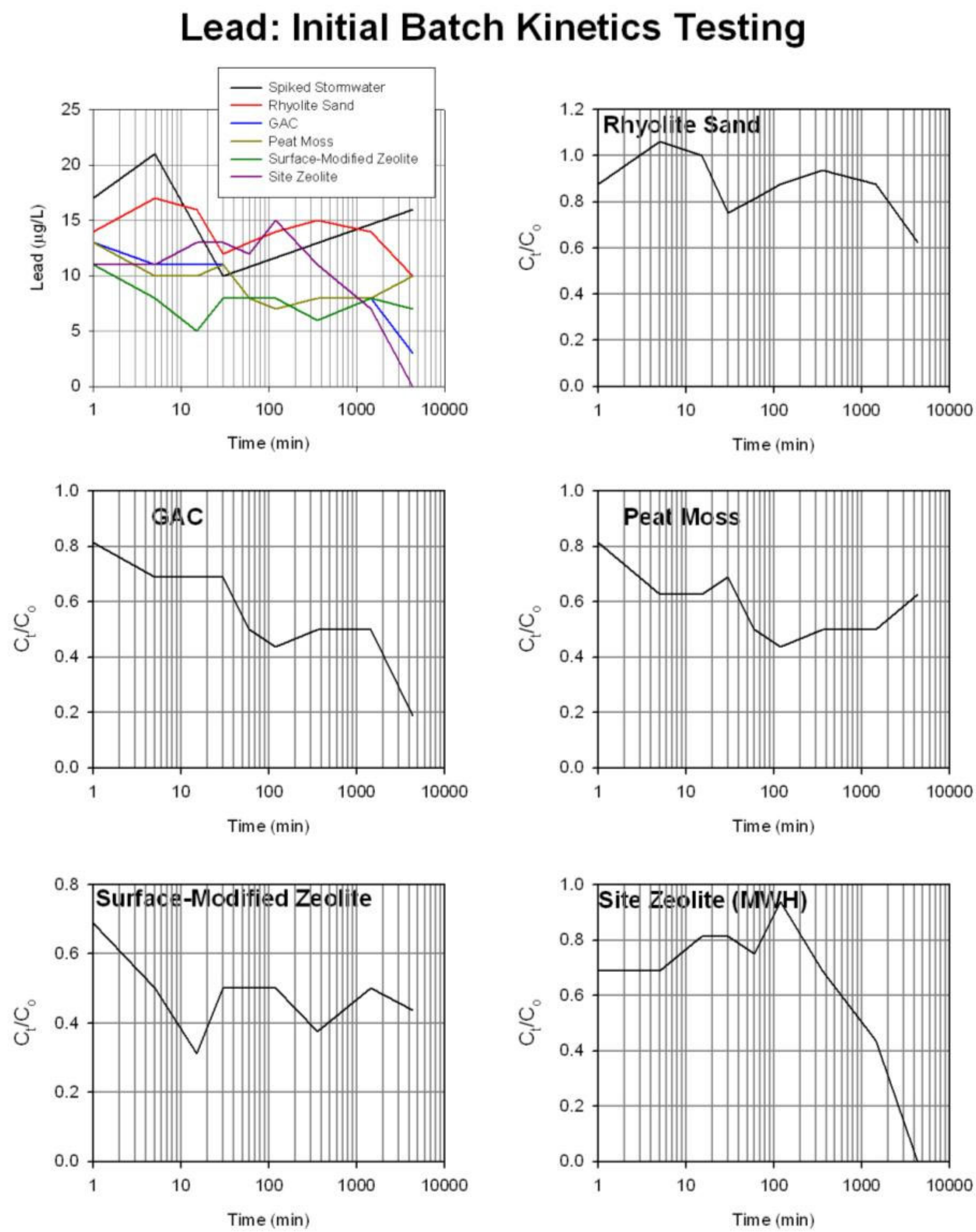
3) Media capacity tests. These batch tests have been adapted to meet the range of conditions seen in stormwater filtration. The purpose of these tests is to determine the amount of contaminant that can be retained by the media, given a specific contact time. These tests, unlike some of the tests reported in the literature, are multi-component tests with stormwater as the base test water. Stormwater was used because of its wide range of numerous constituents which may affect removal performance (competitive ions, bacterial interference, etc.) These tests were conducted at similar concentrations to the column breakthrough tests. Prior testing has shown that kinetics and isotherm testing at high concentrations, typical of industrial wastewater batch tests, does not translate to most low-concentration stormwater treatment observations. Isotherms that indicated favorable adsorption, for example, may become unfavorable at low concentrations. These data then are used to extrapolate the column test results to better indicate the ultimate end point for chemical capacity for the different media.

Several constituents demonstrated exponential decay curves when the ratio of the concentration remaining in solution to the initial concentration was plotted as a function of time. In several media-pollutant combinations, there was a lag before any removal was observed. This initial lag period was followed with a period of rapid uptake. As the final concentration decreased substantially, the rate slowed. The following is one example, for ammonia and the peat moss media, where very little ammonia was removed until after about one day of contact. These rate curves plot a normalized concentration (the concentration at time t, C_t, divided by the initial concentration, C_o, versus the exposure time.



Normally, an exponential decay equation is fitted to the entire data set for a pollutant-media combination. However, it is apparent from a visual observation of the data that removal does not occur until approximately 1 day after exposure in the above example. The kinetics for the low concentration solutions and mixed constituents in the water clearly indicates serious problems when standard kinetic models are used with typical stormwater.

In the following plots of lead vs. time, a more traditional, relatively constant removal is seen for the GAC material, while the peat moss data indicates a leveling off of removals after a period of time. The site zeolite test indicates the delay, then the rapid removal, as noted above.



4) Aerobic and anaerobic effects on contaminant retention in media. These tests examine long-term retention of captured pollutants by the media under varying pore water chemical conditions. Prior research by this group and others has shown that conversion of an aerobic pore water environment, such as during active filtration, to an anaerobic environment, such as might occur if water were sitting stagnant in the filter for an extended period of time between storm events, may result in the release of previously trapped pollutants. These results not only describe long-term retention during changing chemical conditions, but also can be used to predict the potential for a "first-flush" of very elevated concentrations at the beginning of subsequent events. These tests are ongoing.

SELECTION OF CONSTITUENTS TO MONITOR

The constituents that were monitored during these controlled laboratory experiments fall into the following four categories:

1) critical constituents that likely exceed the permit limits more than 1% of the time over a long period of site monitoring, if untreated. For this site, these include: oil and grease, nitrate+nitrite, zinc, cadmium, copper, mercury, lead, and dioxin.

2) constituents that can have detrimental effects on filtering performance. These include:

- water salinity. Salts can strip accumulated heavy metals from sorption sites, for example.

- dissolved oxygen (DO) ORP and DO. If a treatment system goes anaerobic between events, many pollutants, especially nutrients and some heavy metals, can be released from the media.

- pH. ORP in conjunction with pH determines the electro-chemical state of the media and the specific speciation of heavy metals, which in turn affects their removal and retention.

- cation exchange capacity. Major cations, such as K, Ca, Mg, and Na, and predominant metals, such as Al and Fe, in abundance consume the cation exchange capacity of the media that was assumed to be available for targeted pollutant removal.

- SAR, sodium adsorption ratio. Adverse SAR conditions, caused by an abundance of Na in comparison to Mg and Ca, causes an unbalance in the surface charges of clays in the soil-media mixture, causing premature clogging of the system.

3) constituents that assist in understanding the performance of the different types and combinations of media. These include:

- exchangeable cations and anions. Major cations and anions need to be monitored to evaluate which are being exchanged as targeted pollutants are being removed. If these differ, the driving forces of both cation and anion exchange may change, reflecting in loss of treatment capacity, or loss of previously captured/bound pollutants from the media.

- organic compounds and toxicants. The presence of organic compounds adds to the CEC of the mixture and also provides a basis for organmetallic compounds to form, which are very stable. However, organic toxicants may also be present and their behavior in the media needs to be considered. Since these compounds are difficult and expensive to directly monitor, this project will examine UV absorption at 254 nanometers and COD as indicators of total organic content. In addition, Microtox screening tests will be used to examine the presence and removal of organic and metallic toxicants in the stormwater. Finally, pesticides will be periodically analyzed as an indicator and direct measure of these likely stormwater organic toxicants.

• metallic compounds. Although only total forms of heavy metals are listed in the site permit, filtered forms of the metals are usually of most interest when considering harmful effects on humans and wildlife. They also are removed through sorption/ion-exchange in the media, whereas total metals' concentrations may be reduced by these chemical reactions to a limited extent or, more likely, through physical straining of the particles to which these metals are associated. Movement of the filtered metals indicates the predominance of each of these mechanisms in the media. Alkalinity and hardness are also used to determine the relationship of the effluent metal concentrations to water quality objectives. Filtered forms of Al, Cd, Cr, Cu, Fe, Ni, Pb, and Zn are being monitored for their behavior in the media profiles.

• bacteria. Stormwater indicator bacteria are normally critical contaminants in most areas, but the presence and retention of bacteria should also be evaluated in media used for capturing stormwater pollutants as increased indicator bacteria in the media are a good indicator of beneficial bacteria that are needed to assist in the degradation of captured organic material. However, large concentrations of bacteria in the columns may indicate a potential for washout during subsequent storm events. *E. coli* will be used to indicate the bacteria loading onto the media and their retention.

• nutrients. Nitrogen and phosphorus compounds are also often critical stormwater constituents and their retention in media filters can also indicate replenishment of plant nutrients needed to support plant growth. The biofiltration devices will be planted and phytoremediation will be encouraged to enhance pollutant capture. Monitoring phosphate, ammonia, and nitrates will be used to determine the addition of nutrients by the different media that can be used by the plants.

4) other constituents listed in the site discharge permit, but have a lower likelihood of exceeding the limits were also periodically included in the analytical effort.

CONCLUSIONS

These extensive media evaluation tests are unique in that they are using a coordinated set of tests with actual multi-component stormwater samples. In addition, many of the constituents on the extensive list have never been tested in stormwater filter/biofilter media evaluations before. Combinations of media in addition to individual medium are also being evaluated. In most cases, there has been very extensive removal of particulates larger than just a few micrometers in size. The removal of dissolved constituents varies, with some materials being more effective than others for different constituents. Therefore, combinations of media are expected to provide the most effective control of stormwater.