# Evaluation of Biofiltration Media for Engineered Natural Treatment Systems

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# 1.0 Executive Summary

This report describes the results of detailed laboratory performance tests of candidate biofiltration media types and mixtures conducted to support media selection and treatment system design. The media tested are either currently used in existing stormwater filtration systems or have been proposed for new Engineered Natural Stormwater Treatment Systems (ENTS) at 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 main pollutants of interest for the project are cadmium, copper, lead, and dioxins, with other constituents being of secondary interest, based on historic stormwater quality monitoring results at the site. One primary project objective is for treated effluent concentrations to meet the low numeric effluent limits that have been applied to stormwater discharges through the site's NPDES permit. These numeric effluent limits are based on water quality standards. A challenge to the project design is that current site 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 (runoff water collected at Penn State-Harrisburg) to representative levels, where possible.

A review of the literature on filtration media and onsite monitoring data (including existing treatment system performance results and previous media pilot testing studies) indicated that several promising media exist for consistently treating the pollutants of interest to the required effluent concentrations. However, many of these materials are very expensive; with potential construction costs being significant given the large volumes required for the systems based on early designs (estimated media volumes for the project have ranged from 5,000 – 12,000 cubic yards). There are newly available materials that are promising, but little, if any, data are available to quantify their performance. These tests therefore evaluated these candidate materials under procedures that have proven successful during past media investigations for stormwater treatment effectiveness.

These media vary widely in terms of cost, performance, and maintenance requirements. However, because of the large volume of media currently used at the site and/or proposed for new systems, unit volume cost savings (during replacement or construction) are potentially significant if media volume and types can be optimized. Furthermore, the potential for long-term cost savings is also significant if media lifetimes can be maximized, 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.

## *1.1 Flow Rates and Clogging Observations*

Clogging often is the cause of premature failure of stormwater (bio)filtration devices. While pre-treatment may reduce substantially the load of larger particulates, a portion of the suspended and colloidal particulates pass through pre-treatment devices. These smaller particulates contribute both to surface clogging and depth clogging of these devices. During these studies, the media mixtures that had the longest run times before clogging in combination with desirable moderate flow rates were:

- Rhyolite sand, surface modified zeolite, granular activated carbon, and peat moss
- Rhyolite sand, surface modified zeolite, and granular activated carbon

The sand and zeolite currently in use at the site, with granular activated carbon (GAC) (layered mixture) demonstrated a good flow rate, but would require more frequent maintenance compared to the other mixtures. This faster clogging is likely associated with the additional interfaces from the layering compared to the other mixtures that relied more on full-depth capture.

These hydraulic results are summarized in Figure 1-1, showing the relative flow rates and loading capacities for the different media combinations tested. The values shown on this figure are typical flow rates associated with long-term operation of full-depth columns. The cumulative load to initial maintenance (kg/m$^2$) values describe the period from initial construction and operation to the time when the flow rate first dropped to a pre-determined maintenance trigger point. Maintenance (scraping the surface) was performed in an attempt to restore the flows. Surface scraping had little long-term benefits. Removal of the top several inches of material resulted in flow recoveries longer than scraping activities did, but neither helped substantially for a long period, except for the site sand that responded well to removal of the surface material (visual observation indicated primarily surface accumulation of solids on this filtering medium). In most cases, clogging resulting in flow rates that could not be restored after two or three maintenance intervals. The total load to clogging was about 1.5 to 2 times the load before the first maintenance (again, except for the site sand where the improvement was about 6.5 times). The general ineffectiveness of the surface maintenance was likely due to the particulate trapping over a range of depths in the filters, and not just concentrated at the surface. This allowed substantially longer operation times of the filters, but did hinder the maintenance. Shorter columns had greater treatment flow rates, but trade-offs occurred with the removal of other pollutants.

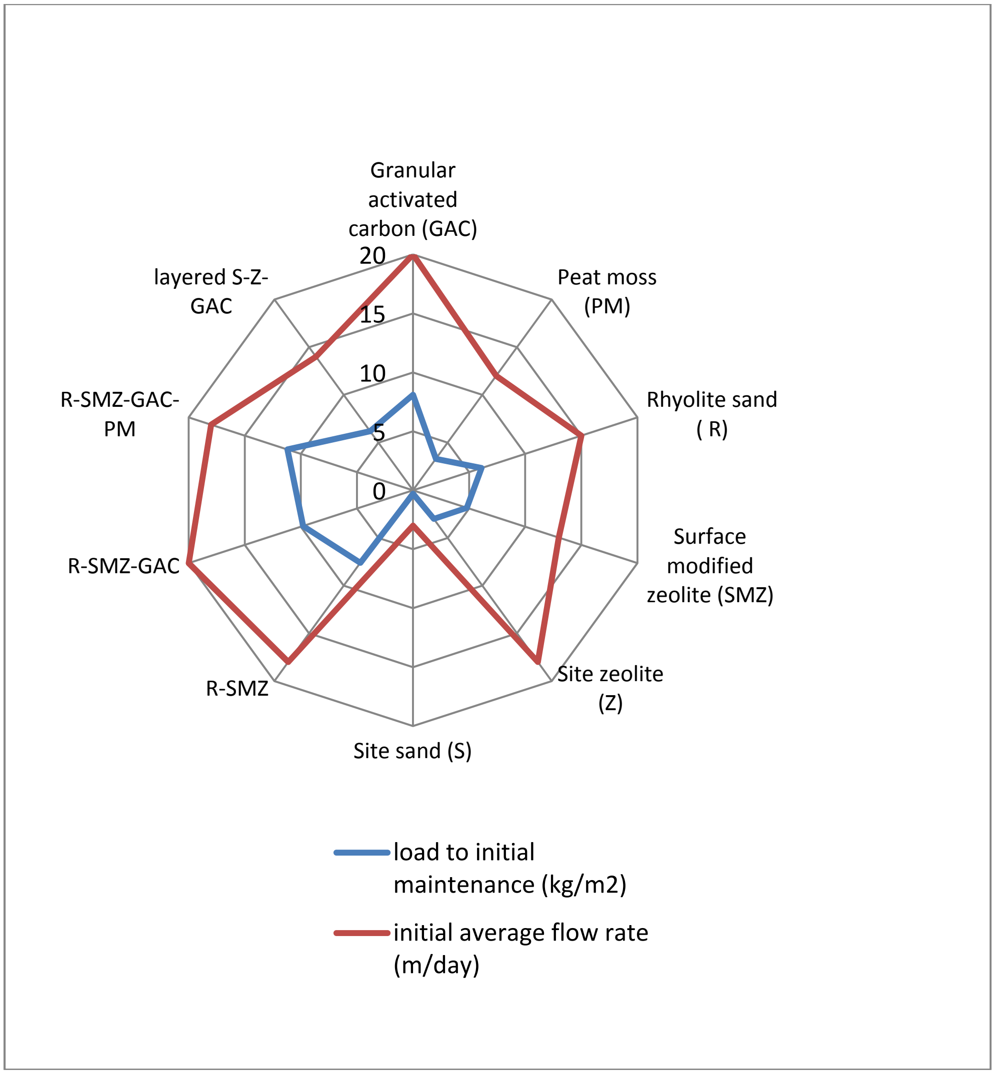


**Figure 1-1. Observed Infiltration and Clogging Characteristics for Tested Media**

Tables 1-1 and 1-2 summarize the flow rate and clogging test results. The flow rates are similar for all of the single components and mixtures tested, except for the site sand that had a much lower flow rate (3 m/day) compared to the others (12 to 20 m/day). These other flows are similar as the columns were constructed to provide a moderate flow rate by using the site sand (in a 50/50 v/v mixture), or the Rhyolite sand (in a 33/66 to 50/50 v/v mixture), to optimize the contact time between the stormwater and the media. During prior treatment media tests (Clark and Pitt 1999 and Clark 2000), it was found that coarse media had very fast filtration rates, but did not provide good treatment. In contrast, very fine grained and organic materials easily compressed or otherwise caused very slow filtration rates. Adding moderately fine grained sand to these materials resulted in a much more uniform and desired treatment flow rate. The mixed media columns did not have any additional sand added to moderate the flows besides that shown in the mixture. As noted, this approach also provides good contact times to improve constituent pollutant removal performance.

The sediment load before maintenance was needed and the flow rates are indicated on these tables. Because the test columns were 3.5 inches in diameter, it is necessary to apply a scaling factor to make the data representative of larger systems. Factors from 3 to 5 have been used in the past to approximate full-scale conditions, based on lab and pilot-scale tests. The original work plan for these tests included parallel full-scale tests (using roll-off demolition debris boxes filled with media). These tests have not been conducted yet, so a factor of 5 was applied to the observed values, based on our past studies, as an indicator of approximate full-scale results that can be used until the larger tests are conducted.

**Table 1-1. Clogging Conditions Observed during Long-Term Full-Depth Column Tests**

| Media, ranked by clogging potential | Cumulative load to initial maintenance, at 5 m/d (kg/m$^2$)* | Cumulative load to clogging, if no maintenance at 1 m/d (kg/m$^2$)* |
|---|---:|---:|
| Granular Activated Carbon (GAC) | 7 (35) | 7.5 (38) |
| Peat moss | 3.3 (17) | 4 (20) |
| Rhyolite sand | 6.5 33) | 7 (35) |
| Site sand | 0.3 (1.5) | 2 (10) |
| Site zeolite | 3.1 (15) | 3.5 (17) |
| Surface modified zeolite (SMZ) | 4.8(24) | 5.5 (28) |
| Rhyolite sand and surface modified zeolite | 7.5 (38) | 7.5 (38) |
| Rhyolite sand, surface modified zeolite, and granular activated carbon | 9.7 (49) | 10.5 (53) |
| Rhyolite sand, surface modified zeolite, granular activated carbon, and peat moss | 10.5 (53) | 11 (55) |
| MWH sand, MWH Zeolite, and Granular Activated Carbon (layered mixture) | 6.2 (31) | 6.5 (33) |

*Column study results and estimated full-scale results, with 5X factor in parentheses

Table 1-3 shows the range of cumulative loads expected to cause final clogging of the media filters. The engineered natural treatment system (ENTS) designed for Outfall 008 (designated as TT7) is also compared to these loading values to indicate the expected life of the ENTS under these conditions. This ENTS has the largest expected sediment loading per unit filter area and the expected replacement period is therefore the shortest for any of the designed ENTS on the project site. These performance periods range from 3 to 84 years. The planted vegetation on the ENTS biofilters will also increase the expected performance period, as vegetation has been shown to help keep biofilter soils in the root zones from compacting and to help migrate surface clogging particulates further down into the treatment media. Since these ENTS are only expected to be in place for about 10 years, any of the mixed media choices, which have calculated service lives ranging from 10 to 84 years, should have a suitable performance period before media replacement would be needed to rectify any clogging problems.

**Table 1-2. Flow Rates Observed during Long-Term Full-Depth Column Tests**

| Media, ranked by clogging potential | Initial flow rate before degradation |  | Average flow rate before initial clogging |  |
|---|---|---|---|---|
|  | m/day | gal/min/ft$^2$ | m/day | gal/min/ft$^2$ |
| Granular Activated Carbon (GAC) | 25 | 0.058 | 20 | 0.046 |
| Peat moss | 20 | 0.046 | 12 | 0.028 |
| Rhyolite sand | 20 | 0.046 | 15 | 0.035 |
| Site sand | 7 | 0.016 | 3 | 0.007 |
| Site zeolite | 25 | 0.058 | 18 | 0.041 |
| Surface modified zeolite (SMZ) | 17 | 0.039 | 13 | 0.030 |
| Rhyolite sand and surface modified zeolite | 20 | 0.046 | 18 | 0.041 |
| Rhyolite sand, surface modified zeolite, and granular activated carbon | 23 | 0.053 | 20 | 0.046 |
| Rhyolite sand, surface modified zeolite, granular activated carbon, and peat moss | 20 | 0.046 | 18 | 0.041 |
| Site sand, Site Zeolite, and Granular Activated Carbon (layered mixture) | 26 | 0.060 | 14 | 0.032 |

**Table 1-3. Cumulative Particulate Loading to Clogging Failure and Years of Operation for Outfall 008, TT7 Engineered Natural Treatment System (ENTS)**

|  | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ |
|---|---|---|---|---|---|---|
| load to clogging (kg/m$^2$)* | 7.5 - 38 | 4 - 20 | 7 - 35 | 2 - 10 | 3.5 - 17 | 5.5 - 28 |
| Years to Replacement (008 TT7)* | 12 - 58 | 6 - 30 | 11 - 53 | 3 - 15 | 5 - 26 | 9 - 43 |

|  | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|
| load to clogging (kg/m$^2$)* | 7.5 - 38 | 11 - 53 | 11 - 55 | 6.5 - 33 |
| Years to Replacement (008 TT7)* | 12 - 58 | 16 - 81 | 17 - 84 | 10 - 50 |

* the range is shown based on the laboratory column tests plus the expected scaling factor to represent large-scale applications.

## *1.2 Chemical Treatment by Media*

The Rhyolite sand, SMZ, and GAC mixture met all current site discharge permit limits, except for copper and mercury during periods with unusually high influent concentrations (such as when the influent total copper concentration is greater than 100 µg/L and when the influent mercury concentration is greater than 1 µg/L, which are not expected to occur at the site). These media also had significant removals for all constituents measured, except for phosphorus and the very-low-concentration gross beta radioactivity. The layered sand, zeolite, and GAC mixture resulted in all effluent samples meeting the current site permit limits, except for slightly elevated pH conditions when the filter was first placed in service. This higher-pH flush disappeared quickly, with the filter effluent within the desired pH range. The addition of peat to the mixtures improved removal of certain constituents with relatively low influent concentrations and tended to retain good removals when conditions allowed for only short residence times, such as during periods of high flows.

Media filtration performance plots for copper, lead, and TCDD are shown on Figures 1-2 through 1-6. These are box and whisker plots showing the influent concentrations used during the tests, along with the observed effluent concentrations for each of the long-term full-depth columns. The boxes in the figures represent the probability distributions of the observed concentrations: the central box represents the 25th (lower edge), 50th (central line), and 75th (upper edge) percentiles of the probability distributions, while the end of the bottom “whisker” represents the 5th percentile and the end of the top whisker represents the 95th percentile. Any circles or stars outside of the whiskers represent concentrations larger or smaller than these percentiles. On these figures, the concentrations are shown with a log scale to better represent the spread of the data and to better represent the typical log-normal probability distributions of most water quality observations. These figures also show the site benchmark values as a dashed red horizontal line: obviously, it is desired that all effluent concentrations would be below this line. However, because the long-term full-depth tests were conducted to determine the “life” of the media, some media-constituent concentrations approached breakthrough near the end of the tests. Independence of observations, an assumption inherent in drawing conclusions from both the statistical tests and the box-and-whisker plots, cannot be assumed. Analyzing the figures and statistical data, therefore, results in a conservative estimation of the removal ability of the media mixtures. In addition, the goal was to conduct the tests with influent concentrations above the benchmark limits, but close to the site conditions. The test stormwater generally met these objectives, but was also adjusted where possible. In some cases, the test stormwater was already well above the site stormwater quality (copper, for example) and it was not possible to reduce them for these tests. The radioactive constituents and very low concentration constituents were also not adjusted due to safety considerations and other limitations.

Figure 1-2 shows the copper performance plots with influent concentrations that were quite high compared to site concentrations. This plot indicates very large reductions for most media types tested, likely due both to the removal ability of the media themselves, plus the relative ease of reducing higher pollutant concentrations, compared to reducing low pollutant concentrations. Figure 1-3 is a similar presentation of the data in a probability plot format. These figure show that the best reductions were found for the granular activated carbon (GAC), the peat moss, and the mixtures that contained large fractions of these materials. The rhyolite sand-surface modified zeolite-granular activated carbon mixture performed well with most of the effluents below the site benchmark value. Similar excellent performance is shown for the layered site sand-granular activated carbon-site zeolite mixture. The other mixtures and individual components provided significant removals, but were not as consistently below the benchmark value for copper as these two mixtures and the GAC alone.

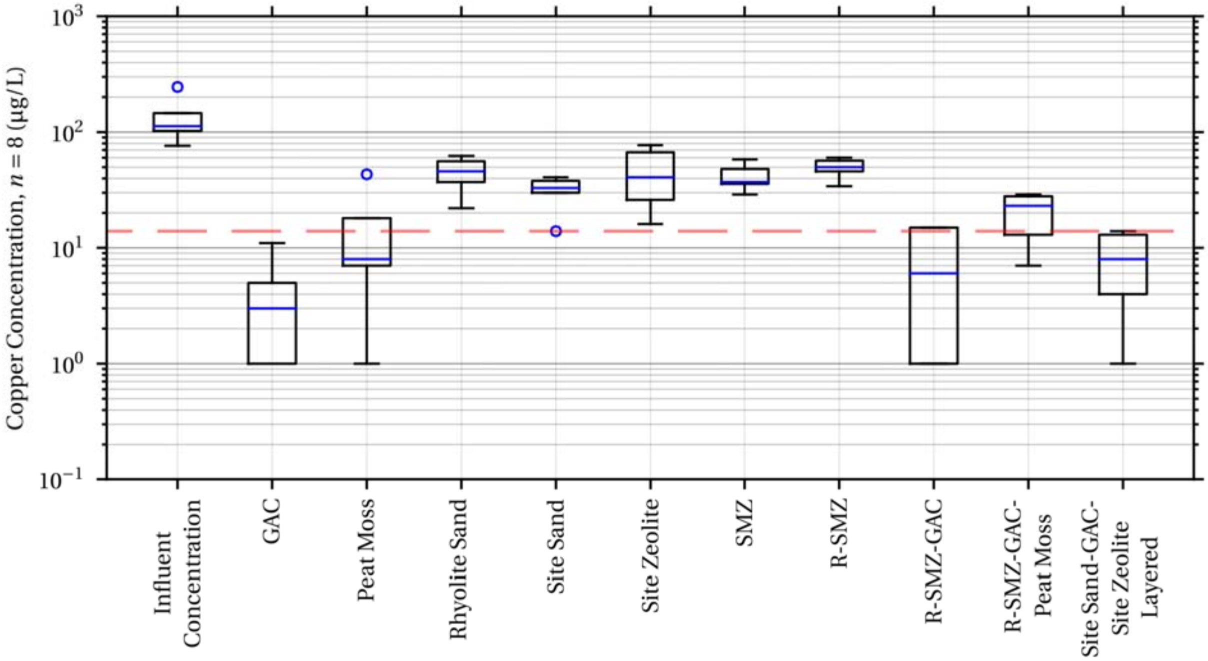


Figure 1-2. Media Performance Plots for Copper from Long-Term, Full-Depth Column Tests

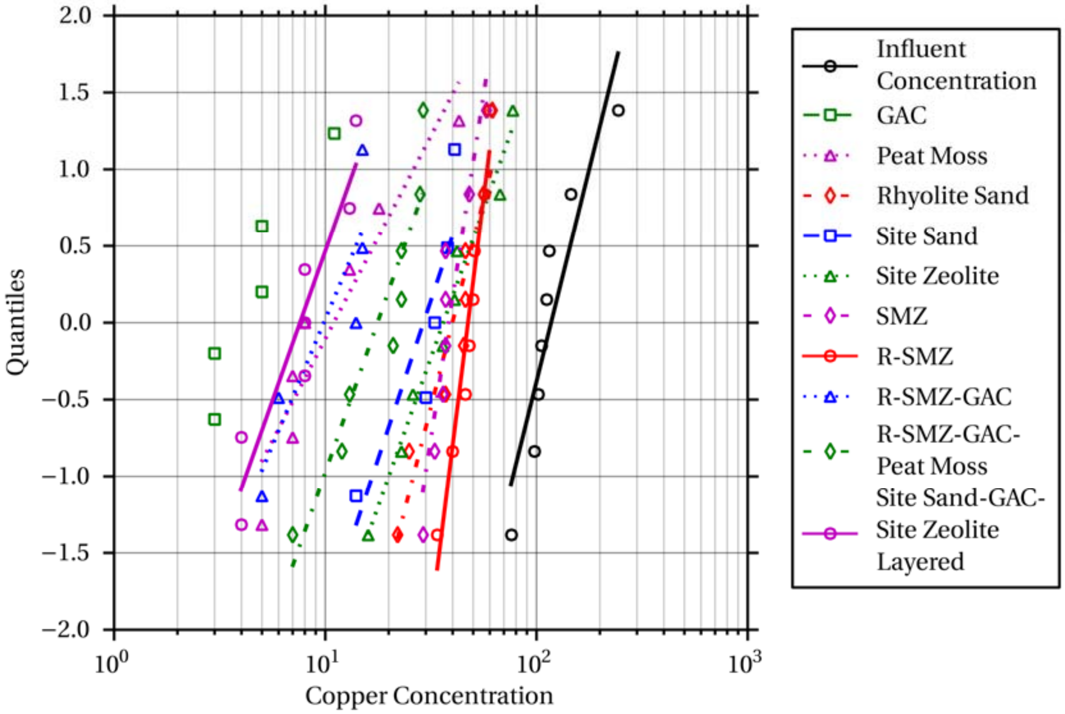
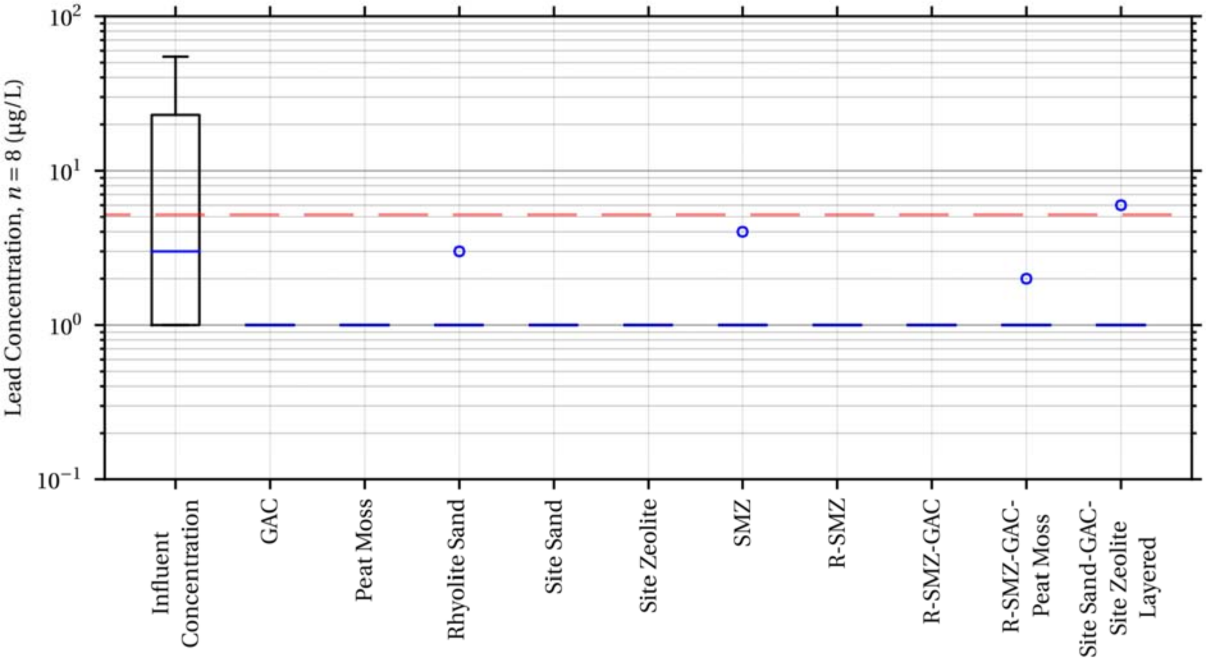


Figure 1-3. Probability Plots of Influent and Effluent Copper Concentrations

Figure 1-4a (lead) highlights the challenges and removals for constituents whose influent values were not always above the benchmark values for these long-term, full-depth column tests. However, except for one test for the layered combination media, all of the effluents were below the benchmark value, and in fact, most of the effluent concentrations were below the very low detection limits for lead (1 µg/L). Therefore, all of the media types and combinations provided excellent removals for lead, as expected due to the large fraction of lead that exists as the more easily removable particulate fraction (contrast to measurable copper in dissolved fraction in Figure 1-4b). The varying depth column results for lead are shown in Figure 1-5 and verify the excellent removals by the >14-inch rhyolite-SMZ-GAC and rhyolite-SMZ-GAC-peat mixture columns, even when using much higher influent lead concentrations.

The dioxin test results (presented as TEQ, the toxicity equivalency quantity, relative to 2,3,7,8-TCDD) shown in Figure 1-6 also indicate good control for some of the combination media columns tested. However, few data are available due to the complexities and costs of the dioxin analyses. Two of the three effluent observations for each of the columns were below the detection limit (the detection limits were less than the benchmark limits of 2.8 x $10^{-8}$ µg/L). The R-SMZ-GAC and layered media column had a single detected effluent dioxin concentrations at about 1/3 of the benchmark value, while the R-SMZ and R-MSZ-GAC-peat column had a single detected effluent dioxin effluent concentrations each at about 1.25 times the benchmark value. The detected effluent concentrations were at least an order of magnitude less than the observed influent concentrations, indicating consistently good removals to close to, or below, the extremely low site benchmark value for dioxin.



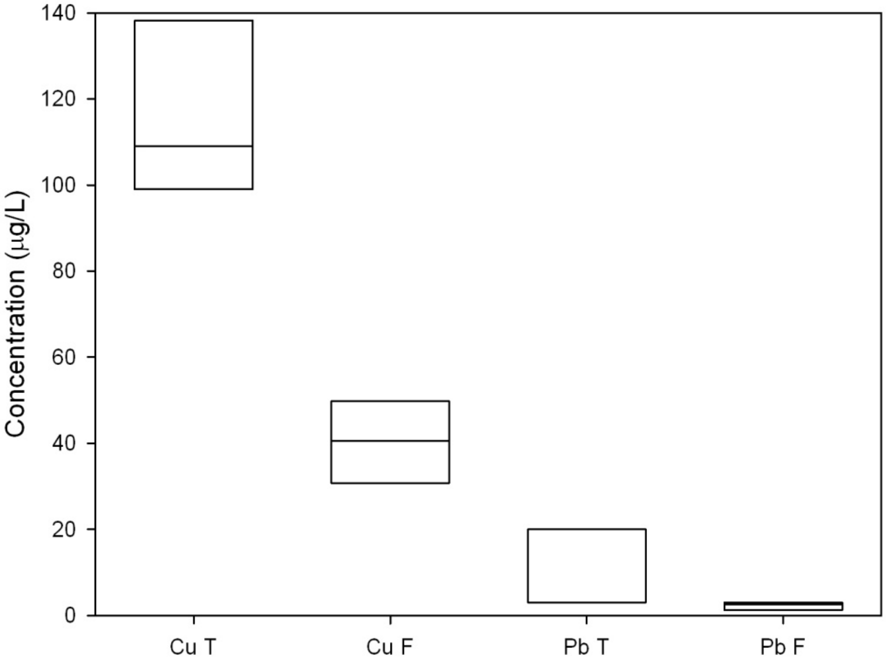
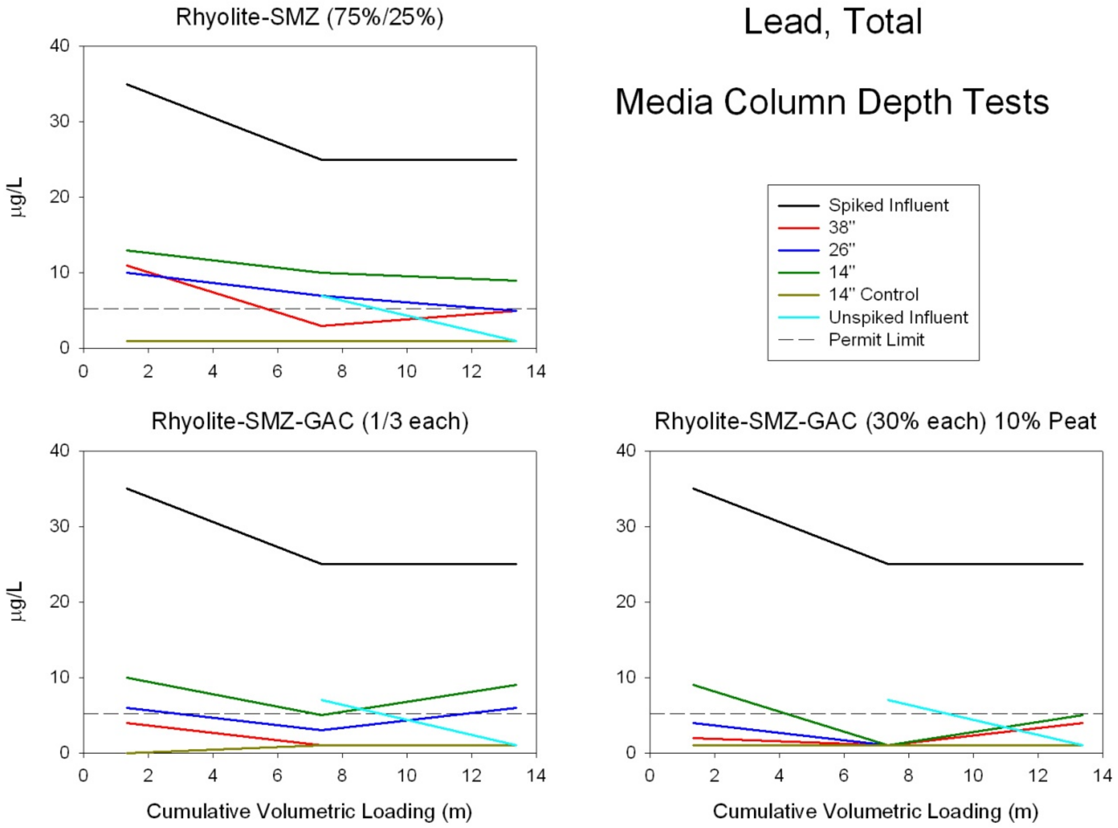


**Figure 1-4. (a, top) Media Performance Plots for Lead from Long-Term, Full-Depth Column Tests. (b, bottom) Fraction of Total (T) Copper and Lead Influent Concentrations that Are Filterable (F)**



Lead, Total

Media Column Depth Tests

Rhyolite-SMZ (75%/25%)

Rhyolite-SMZ-GAC (1/3 each)

Rhyolite-SMZ-GAC (30% each) 10% Peat

**Figure 1-5. Media Performance Plots for Lead from Varying-Depth Column Tests.**

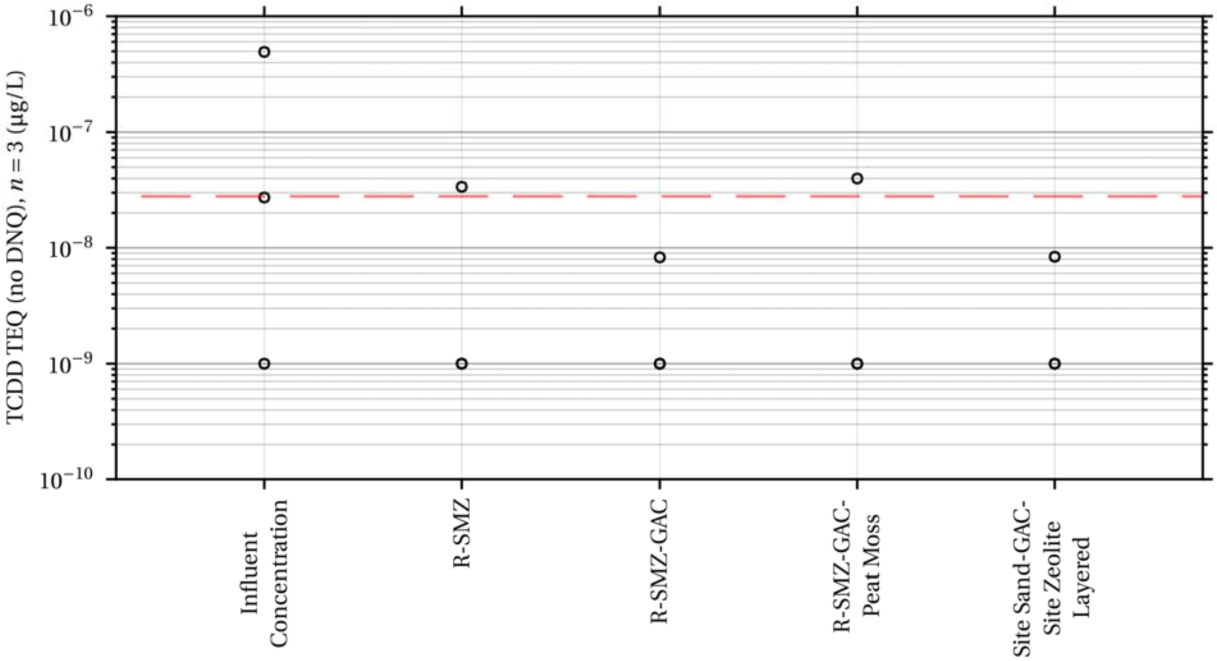


**Figure 1-6. Media Performance Plots for TCDD from Long-Term, Full-Depth Column Tests**

## 1.3 Chemical Capacity and Useful Life of the Filtering Media

Table 1-4 summarizes the chemical capacity of the different treatment media and combinations, based on mg constituent (or pCi) per m$^2$ of filter area. These capacity units are not traditional (traditional: mg constituent/g media); however, these biofilter capacity units are better related to the design parameter of surface area since the media depth is similar to the depth of the full-depth columns used in the tests. These surface loading capacities would not be applicable if the filter depth changed substantially. The constituents shown on this summary table are for the most critical constituents that have exceeded the site benchmark limits at least once during site monitoring. These maximum chemical loading rates are based on the observations of breakthrough during the long-term full-depth column studies (based on loadings of 60 to more than 80 m of spiked runoff). As indicated on this table, most of the breakthrough values are indicated as a lower limit, as breakthrough was not observed during the long period and high loadings of the tests. Therefore, the capacities are shown as larger than the total load applied to each column. The exceptions are for oil and grease for two columns (the column where GAC was not included with other media, and the layered column), where oil and grease breakthrough occurred. Breakthrough was more common for the other constituents examined, as shown later in this report.

**Table 1-4. Capacity of Full-Depth Columns for Retention of Contaminants that Have Exceeded Site Benchmark Limits during Outfall Monitoring (mg/m$^2$ of filter surface, unless otherwise noted)**

| Constituent | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium, Total | > 4,380 | > 4,250 | > 4,890 | > 1,660 | > 5,590 | > 5,110 | > 5,120 | > 5,160 | > 5,420 | > 3,900 |
| Copper, Total | > 8,280 | > 7,440 | > 6,390 | > 2,450 | > 7,400 | > 6,880 | > 6,180 | > 9,490 | > 9,140 | > 7,210 |
| Lead, Total | > 730 | > 710 | > 800 | > 275 | > 940 | > 820 | > 860 | >860 | > 910 | > 630 |
| Mercury | not tested | not tested | not tested | not tested | not tested | not tested | > 4,120 | > 4,960 | > 5,330 | > 3,760 |
| Oil and Grease | not tested | not tested | not tested | not tested | not tested | not tested | 16,700 | > 32,400 | > 34,700 | 0 |
| TCDD | not tested | not tested | not tested | not tested | not tested | not tested | > 1.27E-5 | > 1.35E-5 | > 1.35E-5 | > 1.02E-5 |
| Gross Alpha (pCi/m$^2$) | not tested | not tested | not tested | not tested | not tested | not tested | > 316,000 | > 337,000 | > 358,000 | > 249,000 |

As noted earlier, the different media had different expected maximum particulate loadings before clogging may occur. This useful life can be compared with the useful life based on chemical breakthrough to predict whether chemical or physical “breakthrough” should be the primary concern of the ENTS. In general for biofilter operation, it would be preferable to have excess chemical capacity when clogging occurs, since measuring physical clogging through infiltration rate evaluations and comparison to historical measurements is substantially easier and more cost-effective than determining whether chemical capacity is exhausted.

The maximum runoff volume that can be treated per unit area of filter before clogging was calculated using an assumed annual flow-weighted particulate solids concentration of about 50 mg/L for the water entering the stormwater biofilter (after partial treatment in the sedimentation basin). The corresponding constituent unit area loading was also calculated using the annual flow-weighted constituent concentrations (based on site measurements, or estimated for some of the constituents that have not been monitored on site).

Table 1-5 shows the ratios of these calculated media chemical capacities to the clogging capacities for each media-constituent combination for those constituents that have exceeded the current site benchmark limits for Outfalls 008 and 009. Ratios greater than 1.0 (green high-lighted) indicate the constituent-medium combinations have excess chemical removal capacity (clogging by particulates is likely to occur before the removal capacity is met). Some cells show combinations where the upper limits of the removal capacities were uncertain and may have excess removal capacity before clogging (yellow high-lighted). The cells with ratios <1.0 (red high-lighted) are for combinations where the constituent removal capacity may be exceeded before the filter is clogged. For these critical constituents, only the oil and grease in two combination media columns (R-SMZ and the layered media) may not have sufficient capacity before clogging occurs. The other two mixed media tests (with GAC mixed throughout the media column) for oil and grease are uncertain, as the complete capacity was not reached during the tests. The gross alpha results also indicate uncertain results due to un-measured maximum capacities for the four mixed columns. Three of the total lead tests (SMZ, R-SMZ-GAC-PM and the layered media) also had uncertain results for the same reason, but the ratios are quite high (>0.9) for the mixed media candidates and are likely to have excess capacity when the filter clogs. None of these measurements indicated initial flushing or washout of the lead.

As shown on Table 1-5, there is significant excess capacity for all of the media for most of the critical constituents (cadmium, copper, mercury, and dioxin). Lead capacity about equals the clogging period, gross alpha is mostly uncertain, and oil and grease capacity is insufficient for two of the mixtures and uncertain for the other two mixtures. There is less variety between the media types than between the different critical constituents, but the R-SMZ-GAC and the same with the peat may be very slightly advantageous. The improved performance of the columns mixed with GAC is likely due to the mixing of the GAC, versus the layering of the GAC. A layer of GAC likely had flow rates sufficiently high to reduce contact time in that layer below the contact time required for removal.

This hypothesis cannot be confirmed from this data set because the flow rate through the layered column was measured for the total column and was controlled by the slowest flowing medium, the site sand. However, past research (Clark and Pitt 1999) and the batch testing performed here for other pollutants has shown that contact time varies among pollutants for optimal removal and may not be negligible. Most importantly, though, from a design standpoint, chemical capacity is not a critical factor in selecting the most appropriate media, as clogging potential is a much more significant factor in limiting the useful life of the media for almost all critical constituents.

**Table 1-5. Ratios of Media Capacity to Clogging (ratios of years to failure) for Constituents that Have Exceeded the Current Benchmark Limits at Outfalls 008 and 009**

| Ratios of Media Capacity to Clogging Period | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium, Total | >140 | >270 | >180 | >210 | >420 | >120 | >230 | >170 | >130 | >150 |
| Copper, Total | >2.2 | >3.7 | >18 | >2.5 | >4.2 | >1.2 | >2.2 | >3.4 | >1.7 | >2.2 |
| Gross Alpha radioactivity | not tested | not tested | not tested | not tested | not tested | not tested | >0.3 | >0.3 | >0.2 | >0.2 |
| Lead, Total | >1.0 | >1.7 | >1.1 | >1.4 | >2.8 | >0.4 | >2.1 | >1.6 | >0.9 | >0.9 |
| Mercury | not tested | not tested | not tested | not tested | not tested | not tested | >250 | >230 | >130 | >140 |
| Oil and Grease | not tested | not tested | not tested | not tested | not tested | not tested | 0.1 | >0.1 | >0.1 | <0.1 |
| TCDD | not tested | not tested | not tested | not tested | not tested | not tested | >3.1 | >2.5 | >1.3 | >1.5 |

## *1.4 Recommendations*

The media performance studies have advanced significantly the ability to optimize the design and effectiveness of advanced filtration-based stormwater controls, such as those that have been proposed for these watersheds.

### 1.4.1 Recommended Media Mixtures

Media mixtures perform more consistently under a broader range of conditions than individual components used separately. The mixtures capitalize on the pollutant removal strengths of their components, while providing other components that may address the weaknesses (such as the release of cations in large concentrations during ion exchange). Table 1-6 summarizes some of the major performance attributes for the mixed media column tests.

The media mixtures that are most robust (longest run times before clogging, with moderate flow rates and suitable contact times for pollutant removal) are:

- Rhyolite sand, SMZ, and GAC mixture (blended mixture) and the Rhyolite sand, SMZ, GAC-PM mixture (blended mixture). They had very similar performance attributes. The added peat provided some additional benefits for metal reductions at high flow rates. The GAC in these mixtures (when mixed with the other components) also provided better control for a number of other constituents, including nitrates.
- Site filter sand-GAC-site Zeolite (layered) clogged earlier, but possibly would have fewer exceedences overall. The drawback to the layering of the filter components is the change in flow rate and contact time.

In terms of statistically significant removals, both R-SMZ-GAC and S-Z-GAC (layered) media combinations performed similarly, although the current site layered media combination did not demonstrate statistically significant removals for lead. As shown in the detailed test results later in this report, the media combinations had effluent concentrations through 60 to 80 m of volumetric loading that met all current site permit limits, except for copper and mercury during peak conditions, and had significant removals for all constituents measured, except for phosphorus and the very low gross beta radioactivity levels. The layered media combination treated the runoff to the level where all effluent samples met the current site permit limits at relatively low treatment flow rates, except for a slightly elevated pH, when maximum site runoff pH may occur. In addition, most of the media combinations were effective for copper and lead reductions (the site does not need to reduce the filtered metal fractions to meet permit limits). Also, any media combination that included GAC was effective for TCDD removal. All of the media tested had very high levels (approaching 90%) of removals of particulates, even down to very small particle sizes (as small as 3 μm), with concurrent good removals of pollutants strongly associated with the particulates (such as for total aluminum, iron, and lead).

### 1.4.2 Replacement Frequencies and Sizing of Biofilter Components of ENTS

Maintenance by scraping the surface layers of most of the media was only partially effective at restoring the loading rate, with improved flow rates lasting for only short durations. In all cases, after about 2 or 3 maintenance intervals, scraping ceased being effective and media removal of approximately 1 to 2 inches was required. Media removal was only somewhat more effective than simply scraping the media surface, again with improvements not lasting long. The lack of substantial flow rate recovery indicates that penetration of small solids is occurring below the media surface to depths where surface maintenance practices do not extend. It is expected that vegetation in a biofilter, with underlying media mixtures, will provide longer run times before clogging than biofilters without vegetation. Table 1-7 shows the time to clogging of the most critical biofilter ENTS on the project site, the outfall control at outfall 008. The range of expected particulate loadings before failure is from 10 to more than 80 years, sufficient for the expected 10 year service life.

## Table 1-6. Performance Summary of Mixed Media Column Tests

| | **R-SMZ** | **R-SMZ-GAC** | **R-SMZ-GAC-PM** | **Site Sand-GAC-Site Zeolite Layered** |
|---|---|---|---|---|
| Typical treatment flow rates (m/day) | 15 | 15 | 15 | 15 |
| Cumulative sediment loading before clogging (kg/m$^2$) | 38 | 53 | 55 | 33 |
| Pollutant removal (constituents that may exceed benchmark limits under peak influent conditions after treatment, and peak effluent concentration shown)* | pH (8.8 at 009), copper (15 µg/L at 008; 39 µg/L at 009), and mercury (0.17 µg/L at 008; 0.21 µg/L at 009) | pH (8.8 at 009), copper (15 µg/L at 008; 16 µg/L at 009), and mercury (0.17 µg/L at 008; 0.21 µg/L at 009) | pH (8.8 at 009), copper (15 µg/L at 008; 21 µg/L at 009), and mercury (0.17 µg/L at 008; 0.21 µg/L at 009) | pH (8.8 at 009) |
| Significant reductions for key constituents (at least 25% reductions for constituents that have exceeded site permit limits during past monitoring) | Total cadmium,<br>Total copper,<br>Total lead,<br>Mercury, Oil and Grease, and,<br>Gross alpha radioactivity | Total cadmium,<br>Total copper,<br>Total lead,<br>Mercury,<br>TCDD, Oil and Grease, and,<br>Gross alpha radioactivity | Total cadmium,<br>Total copper,<br>Total lead,<br>Mercury, Oil and Grease,<br>TCDD, and,<br>Gross alpha radioactivity | Total cadmium,<br>Total copper,<br>Total lead,<br>Mercury,<br>TCDD, Oil and Grease, and,<br>Gross alpha radioactivity |
| Key constituents with uncertain removals | TCDD | | | Total lead |
| Potential for pollutant export (generally greater than 25% increases, mostly due to ion exchange processes)** | Cr, Mg, K, Na, hardness | Mg, K, Cl | Mg, K, Cl, $PO_4$ | K, Na, $NH_3$, conductivity, hardness |
| Recommended rank (1 to 3 close, based on many factors) | 4 | 2 | 1 | 3 |

* pH site benchmark permit limits: between 6.5 and 8.5
Copper site benchmark permit limit: 14 µg/L
Mercury site benchmark permit limit: 0.13 µg/L
** copper may be leached during extended interevent periods when GAC, peat, or the site filter sand is used in the media at large fractions

Seven of the biofilters in the ENTS in 008 and 009 watersheds were evaluated for potential maintenance problems. These evaluations were based on calculated loading factors for each media-constituent combination (percentage of drainage area per year of operation before failure). The biofilters were from about 1 to 10% of the drainage area, and the water loading rates were about 0.3 to 10 m/year.

The media capacities for heavy metals for the tested columns are quite large, with most capacities being in the 1,000 to 10,000 mg/m$^2$ range. The filters would likely clog before the removal capacity is exceeded for most media-critical pollutant combinations. For oil and grease, the two mixture columns that exceeded criteria were the R-SMZ and the layered media columns, with the other two mixture columns (R-SMZ-GAC and R-SMZ-GAC-PM) being uncertain since the chemical capacity was not reached during the tests. For the ENTS designs in the 008 and 009 watersheds, the biofilters are not expected to clog during an expected 10 year useful life, and the chemical treatment capacity is also expected to be sufficient, with a possible few exceptions.

**Table 1-7. Cumulative Particulate Loading to Clogging Failure and Years of Operation for Outfall 008, TT7 Engineered Natural Treatment Systems (ENTS)**

| | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|
| load to clogging (kg/m$^2$)* | 7.5 - 38 | 11 - 53 | 11 - 55 | 6.5 - 33 |
| Years to Replacement (008 TT7)* | 12 - 58 | 16 - 81 | 17 - 84 | 10 - 50 |

* the range is shown based on the laboratory column tests, and an expected scaling factor to represent large-scale applications.

All media combinations would likely have an operational life of at least 10 years for the constituents of greatest concern (those that have exceeded the current benchmark values), with the exception of oil and grease, as discussed above. Other constituents of concern include gross beta radioactivity and nitrate (service lives less than 10 years for some media in the watershed 008 ENTS) and sulfate, radium 226+228, and zinc (service lives less than 10 years for some media for the watershed 009 ENTS. There are other calculated service lives shorter than 10 years for other constituents, but they are very unlikely to exceed the benchmark limits.

The most robust media, e.g., service life based on the full-depth column tests, were the mixed media, especially those having the largest variety of materials (R-SMZ-GAC; R-SMZ-GAC-PM; and layered site sand-GAC-site zeolite). The R-SMZ-GAC-PM mixture was slightly more consistent in the service life expectations. The site sand-GAC-site zeolite combination was tested as a layered combination and may perform better if mixed because of the improved contact time with the treatment media (zeolite and GAC). It is important that mixtures be used for treatment to provide removal-ability redundancy that can better address varying influent conditions. These media also have a history of performing well when influent concentrations are closer to the permit limits (compared to the benchmark limits).

### 1.4.3 Contact Time and Media Depth Design Information

The prior discussion focused on the useful life and design information for columns of a certain depth. However, depth also can be considered a design parameter with the resultant question of whether the increased contact time provided in deeper columns improved performance. Longer retention times (deeper media beds or slower flow rates with concomitant larger surface areas) improved effluent quality for some constituents, but not all. These tests already had relatively slow to moderate flow rates (5 to 60 meters/day) and moderate contact times of the water with the media (10 to 40 minutes). Batch testing, as described in Section 3, was performed first to provide estimates of required contact time to achieve a specific water concentration. As an example, for contact times less than 10 minutes, the metal removals were much less than for the longer contact times for all media. Also, for the GAC, greater contact times resulted in slightly better nitrate removals, but greater losses of the phosphate from the media.

The following observations for the component media were noted during the batch contact time tests:

- GAC: most consistent removal and reasonably fast (10 min) removal for organic and metallic compounds; however, rapid (6 min) leaching of nutrients and slow leaching (>6 hrs) for major ions.
- SMZ: relatively slow (at least an hour) and is less consistent for most constituents. Leaching occurred after about 20 min for nutrients and after about 2 hours for metals.
- Rhyolite sand: relatively fast (about 15 min) for nutrients and slow for major ions and metals (>1.5 to 2.5 hrs); no leaching observed.
- Peat: very fast (< 5 min) for metals; very slow and inconsistent for other constituents. Leaching of carbon-containing constituents (organic surrogates) occurred after about 10 minutes, and after about 30 minutes for some major ions and nutrients.
- Site zeolite: very last (1 min) for some organics and nutrients; slow (>1 to 2 hrs) for major ions and metals. Rapid leaching (after 1 min) occurred for some major ions and metals.

Compared to the batch contact time testing, the treatment flow rates for the 14” columns resulted in residence times of about 4 to 30 minutes, which is in the range of optimal contact times for most constituents of interest. The media mixtures without the site sand had much faster flow rates and reduced contact times compared to the mixtures that contained large fractions of the site filter sand. The 38” columns had contact times of about 10 to 90 minutes, again in the range of optimal removals for most constituents, although the longer contact times were likelier to produce leaching. The media mixture having the best overall control (R-SMZ-GAC-PM) had short contact times (4 minutes for 14”, 10 minutes for 26”, and 16 minutes for 38”), within the range of optimal removal for most constituents of greatest concern. To be conservative, the overall slower treatment flow rates observed during the long-term column tests are recommended for final control practice designs, with treatment flow rates of about 15 m/day, and corresponding contact times of about 10 minutes, or more. These also are more likely to be achieved in the field where gravity and porosity will control the treatment flow rate and contact time. Ten minutes should be considered as a minimum contact time, with optimal contact times possibly being as great as ten times this value for some constituents. Increasing contact time, though, has the drawback of increasing the leaching of undesirable constituents from the column.

The approximately three-foot (38” in these tests) media depth should be a reasonable media depth for most constituents and conditions. There are other options to control flow through the media filters, but slow draining underdrains with these low drainage rates would be very difficult to control without causing clogging.

## 2.0 Project Conclusions

For most stormwater treatment devices, treatment effectiveness varies for the different pollutants of interest, as the influent characteristics of the targeted pollutants (fraction filterable, ionic forms, associations with different particle sizes, etc.) also vary. In many cases, a combination of treatment processes is needed. A treatment train incorporating different unit processes that target different pollutant characteristics can be designed as separate units dispersed throughout a drainage area, or they can be adjacent. In addition, redundancy is often necessary to provide the most robust control to achieve the strict numeric discharge limits being applied. In many cases, and similar to wastewater treatment facilities, an effective treatment train is composed of sedimentation unit processes followed by filtration unit processes (media filtration, infiltration through amended soils, bioretention/biofiltration devices, etc.) with the logic being to remove first the particles that will interfere with and/or shorten the life of the filtration devices. Well-designed sedimentation practices typically are effective in removing particulates and associated particulate-bound pollutants down to approximately 5 to 10 µm at low surface overflow rates (SOR). The treatment efficiency of sedimentation practices decreases with increasing SOR (resulting from the device being under-sized or when otherwise operating under excessive flow conditions). Even thought sedimentation may remove particles smaller than 10 µm, the reliable removal of pollutants and their associated particulates with diameters smaller than about 10 to 25 µm is typically accomplished using filtration techniques (such as biofiltration or bioretention devices), a process redundant but more reliable than sedimentation for these small particulates. The removal of “dissolved” pollutant loads (usually defined as being contained in the water that passes through a 0.45-µm filter), depends on the pollutant form (ionic, complexed, etc.) and on the chemical composition of the sorption/ion-exchange media.

The removal of nitrates and chlorides (single electron-donating, negatively-charged contaminants) is very difficult and limited in most media. Nitrate removal occurs mostly from uptake in the root zones of plants or the creation of anaerobic zones to encourage denitrification. Phosphate removal is much easier since it reacts with metals, metal oxides, and organic matter, plus it also can be taken up by vegetation. It will, however, be released from some treatment media materials, especially those having a high natural phosphorus content, with leaching exacerbated during the anaerobic/micro-anaerobic conditions that often develop in the media during interevent periods. For “dissolved” metals that do not form complexes (aggregates) with organics, hydroxides, chlorides, other metals, etc., removal by an ion exchange media (such as a zeolite) can be effective. It must be remembered that all ion exchange processes (sorption is a special case of ion exchange) involve the release of another compound when the pollutant is trapped. The designer should know whether the exchangeable compound is a pollutant of concern. Cation Exchange Capacity (CEC) measures this exchange capacity, but the value for CEC is dependent on the analytical method. For complexed “filterable” metals, removal appears to be related both to organic content and CEC, with exchanges occurring between complexes and compounds that are not measured using traditional CEC values. Therefore, CEC is a suitable method to rank removal potential for media, but it cannot be used as an exact measure of remaining pollutant removal capability.

These tests assessed stormwater quality characteristics similar to those historically observed at the project site, and they included constituents (e.g., dioxins) that have not been evaluated in typical urban runoff treatment studies in the past. Most of the media and mixtures examined also have not been evaluated during prior work, necessitating these results to assist in the final design process. In addition, soil chemistry comparisons of clean media versus used media were performed to investigate whether rapid, commercially-available soil chemistry tests can be used to provide an estimate of remaining removal capacity.

Stormwater treatment systems investigated for the watersheds draining to the site locations of interest generally consist of advanced Engineered Natural Treatment Systems (ENTS), e.g., treatment trains containing a combination of detention basins followed by bioretention filter basins (i.e., large, vegetated, vertical-flow, outlet-controlled media filters). Phytoremediation processes are encouraged through the use of plants in the biofiltration units (added root zone benefits of soil aeration, active microbial rhizosphere, and porosity maintenance). The ENTS were designed to treat 90% of the long-term runoff volume from drainage areas ranging from 5 to 60 acres. The pollutants of most interest for the project include cadmium, copper, lead, and dioxins, with effluent concentration design criteria that are based on stringent water quality criteria expressed as NPDES-permit numeric effluent limits. An additional feature of this project and media evaluation is that site runoff concentrations for the pollutants of interest are generally below levels typically seen in urban and industrial stormwater runoff.

These extensive media evaluation tests were unique in that they used a coordinated set of tests with actual multi-component stormwater samples set at concentrations of importance to this project (many lower than seen in urban runoff). In addition, many of the constituents on the extensive analytical list have never been tested in stormwater filter/biofilter media evaluations before this project. Combinations of media in addition to individual materials were also evaluated. In most cases, there were very extensive removals of particulates larger than just a few micrometers in size. The removal of filterable 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.

The following are the most important conclusions found during these studies:

- **Removal of specific constituents:**
    - Particulate removals (90% or greater) were high for all media, even down to very small particle sizes (even as small as 3 µm). Good removals were seen then for pollutants that strongly associate with the particulates (such as for aluminum, iron, and lead for most of the media).

  - Radionuclide, mercury and TCDD also had significant and large removals (75 to 90+% reductions) by most of the media mixtures tested when detectable influent concentrations were seen.

  - Nitrate removal occurred only in media columns containing GAC. Removals typically were approximately 90% for fresh media, with decreasing efficiency as nitrate capacity was exhausted. Breakthrough occurred more rapidly as the amount of GAC in the media mixture decreased. Removal of nitrate by GAC, though, resulted in the release of phosphate (effluent concentration approximately 80% than influent concentration).

  - Phosphorus and phosphate had statistically significant and low to moderate concentration reductions (about 30 to 70%) removals in the Rhyolite sand, the site sand, the site zeolite and the surface modified zeolite.

  - The filtered forms of cadmium, thallium, and nickel had statistically significant and moderate to high removals (50 to 90%) by most media, while filtered lead and filtered zinc were poorly removed (0 to 15%) by all of the tested media and mixtures. Filtered copper removals were statistically significant, but highly variable (5 to 80% concentration reductions). Except for filtered lead, these removal efficiencies could be related to the likely form of the pollutant in the influent (complexed vs. dissolved), with the complexed form being more difficult to remove. Filtered lead removal likely was poor because the influent concentration was very low and near the detection level of the analytical method.

- **Contact time:**
  - Some constituents and some media required a certain contact time before retention, while others were more capable of pollutant retention more rapidly and at lower influent concentrations. For example, when the contact time was less than 10 minutes, the metal removals were much less than for the longer contact times. Also, greater contact with GAC resulted in slightly better nitrate removals, while the greater contact time for phosphate resulted in greater losses of the phosphate from the media. This type of trade-off between improved removal and increased leaching was seen for several media-constituent combinations.

  - Longer retention times can be achieved through deeper media beds or slower flow rates and larger surface areas. The column tests confirmed generally the results of the laboratory studies that showed that good removals could be achieved with relatively slow to moderate flow rates (5 to 60 meters/day) and moderate contact times of the water with the media (10 to 40 minutes).

- **Physical clogging and maintenance:**
  - Clogging by sediments generally occurred before chemical retention capacity was exceeded for most media mixtures. Highly effective (sedimentation)

pretreatment is therefore critical to reduce the sediment load. This will result in longer useful lives of the devices and more use of the chemical capacity of the media.

  - Maintenance by scraping the surface layers of most media was only partially effective at restoring the loading rate and for only short durations. Removal of the surface clogged layers from the sand, in contrast, did restore much more of the flow capacity. In all cases, there benefits were only temporary and after about 2 or 3 maintenance intervals, they ceased in being effective. It is expected that plants in a biofilter, with underlying media mixtures, will provide the longest run times before clogging.

- **Trade-offs from ion-exchange reactions in the media:**
  - Both anion and cation exchanges occur in media filters, based on clean media composition. For the media tested here, phosphorus, chlorides, potassium, and sodium were found to be commonly released constituents. Shifts in pH were also found for some media, indicating changes in the $H^+$ and $OH^-$ ion concentrations with treatment. Use of mixtures where one medium releases potential pollutants and another component captures the released ions provides the best overall pollutant removal performance.

- **Development of anaerobic/micro-anaerobic zones during quiescent times:**
  - Anaerobic conditions may develop in filters that do not experience much water exchange, with a concurrent potential for release of some constituents (generally more of a problem for organics and nutrients than for metals). Anaerobic conditions lead to losses of previously captured contaminants and can increase the degradation rate of some of the media. During these tests, the stripping of nutrients was more severe during anaerobic conditions for the media having higher organic content or where removal was poor (the sands). In contrast, for lead and most metals, retention was very good under all conditions for both anaerobic and aerobic storage conditions. Copper losses were more common. It is important that the design of the treatment systems minimize the potential for the formation of anaerobic and poorly draining media, especially in areas of the filter where the organic matter is located.

- **Summary performance:**
  - During these studies, the media mixture that had the longest run times before clogging and moderate flow rates was the Rhyolite sand, SMZ, and GAC mixture (blended mixture, which demonstrated much better flow rates and clogging run times compared to the layered mixture).

  - The Rhyolite sand, SMZ, plus GAC mixture met all current site permit limits, except for copper and mercury during periods having unusually high influent concentrations (such as when the influent total copper concentration is greater than 100 µg/L and when the influent mercury concentration is greater than 1 µg/L, which are not expected to occur). This mixture also had significant removals for all constituents measured, except for phosphorus and the very low gross beta radioactivity influent concentrations found at the site. This Rhyolite sand-SMZ-GAC mixture had very similar performance attributes to the same mixture with the peat moss added. The peat added some additional benefits associated with metal reductions at high flow rates.

  - Treatment with the layered site sand, zeolite, and GAC mixture resulted in all effluents meeting the current site permit limits, except for a slightly elevated pH for the first sample, which then was reduced with further filtering.

- **Design Summary:**
  - Fine grained media (e.g., sands) clogged quickly and had poor flow rates, while large-grained media had high flow rates with very short residence times, generally resulting in poorer effluent quality. Therefore, the final treatment media composition should contain particles in the range of fine sands and silts to slow down the flow and increase the water's contact time with the larger-sized treatment media such as the GAC and zeolites. An alternative would be to use an effluent flow control on the biofilters.

  - The addition of GAC to a media mixture generally improved removal performance, especially for nitrates. However, the drawback to this GAC was the release of phosphorus and potassium. This can be minimized by the use of another component, such as peat, that has some affinity for these pollutants. Peat, when added in quantities around 10% by volume, provided additional removal, especially for metals at shorter contact times, such as would be expected during periods of high flows.

  - The GAC was the most important component in these mixtures, while the addition of either of the zeolites was also needed. The specific choice of which would be dependent on costs and specific ion exchange issues. The sand is critical to moderate the flow rates and to increase the contact times with the coarser media, unless other flow controls were used in the filter designs. The Rhyolite sand added some removal benefits compared to the site sand. As noted, a small amount of peat added to the mixture increases metal removals during high flow rates. Therefore, the best mixture for removal of pollutants to levels that met the effluent discharge limits was the combination of Rhyolite sand (30%), surface modified zeolite (30%), GAC (30%), and approximately 10% peat. To minimize the leaching of constituents from the GAC, its concentration could be reduced, but then nitrate removals would be limited.

## 3.0 Materials and Methods

Prior research has shown that a targeted suite of controlled laboratory tests can effectively evaluate filtration/biofiltration media for stormwater runoff treatment. The tests, and the specific objectives and benefits of each, are described in the following sections of this report. 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 capacity of the media for the different constituents; 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 test methods and descriptions of the media selected for examination are described in the following subsections.

### *3.1 Media Selected for Testing*

The media examined included six different materials: rhyolite sand (R), granular activated carbon (GAC), surface-modified zeolite (SMZ), a zeolite currently used on the site (Z) as part of other stormwater treatment systems, a filter sand also being currently used on the site (S) (all supplied by the client or client's representative), and a sphagnum peat moss (PM). The column tests examined each of these six materials separately, along with four mixtures of these components. Photographs and tables of the properties of each filter medium are shown in Figures 3-1 through 3-7and Tables 3-1 through 3-3.

**Figure 3-1. Media (from left to right): GAC, Rhyolite Sand, Site Zeolite, Surface Modified Zeolite, Sphagnum Peat Moss**

## Table 3-1. Description of Media Tested

| Media | Manufacture's description | Bulk density | Approx. cost | median particle size ($D_{50}$) (mm)* | uniformity coefficient ($D_{60}/D_{10}$)** |
|---|---|---|---|---|---|
| Granular Activated Carbon (GAC) | VCC 8X30 Virgin Coconut Shell Activated Carbon (Baker Corp.) | 29 lbs/ft$^3$ (1.8 to 2.1 g/cm$^3$) | $0.98/lb | 1.45 | 2.13 |
| Rhyolite Sand | D1 biofilter media sand (Rhyolite Topdressing Sand) from Golf Sand, Inc., North Las Vegas, NV | 1.28 g/cm$^3$ | $0.10/lb delivered | 0.39 | 1.79 |
| Site Zeolite | Z-200 Modified Zeolite (Baker Corp.) | | $1.36/lb | 2.9 | 1.55 |
| Surface Modified Zeolite | 14-40 Saint Cloud Zeolite with 325 µm Modified Zeolite at 3% Vol:Vol | | $0.15/lb delivered | 0.73 | 2.35 |
| Sphagnum Peat Moss | Purchased from nursery in Elizabethtown, PA | | | 0.60 | 7.31 |
| Site Filter Sand | Fine textured silica sand from source local to project site | | | 0.95 | 2.3 |

* measured in lab

** measured in lab; uniformity coefficient <5 indicates a very uniform medium; 5 is moderate uniformity; >5 indicates a well-graded and non-uniform medium

## Table 3-2. Additional Media Information

| Medium | Additional Information |
|---|---|
| Rhyolite Sand | 75 in/hr infiltration rate; 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 | material currently used on site for stormwater treatment |
| Site Filter Sand | material currently used on site for stormwater treatment |

## Table 3-3. Porosity for Test Mixtures Measured in Lab

| Full-Depth Column Tests | Porosity | Bulk Density (gm/cc) |
|---|---|---|
| SMZ (with 50% Filter Sand) | 0.40 | 1.35 |
| R (w/ 50% Filter Sand) | 0.36 | 1.48 |
| PM (w/ 50% Filter Sand) | 0.50 | 0.93 |
| GAC (sub) (w/ 50% Filter Sand) | 0.32 | 1.21 |
| Z (w/ 50% Filter Sand) | 0.35 | 1.24 |
| Sand | 0.32 | 1.66 |
| R-SMZ-GAC | 0.41 | 0.94 |
| R-SMZ-GAC-PM | 0.43 | 0.87 |
| R-SMZ | 0.43 | 1.23 |
| Layered | N/A | 1.00 |
| | | |
| Additional Mixture used in Varying Column Depth Tests | | |
| GAC (2/3 Sand, 1/3 GAC) | 0.36 | 1.25 |

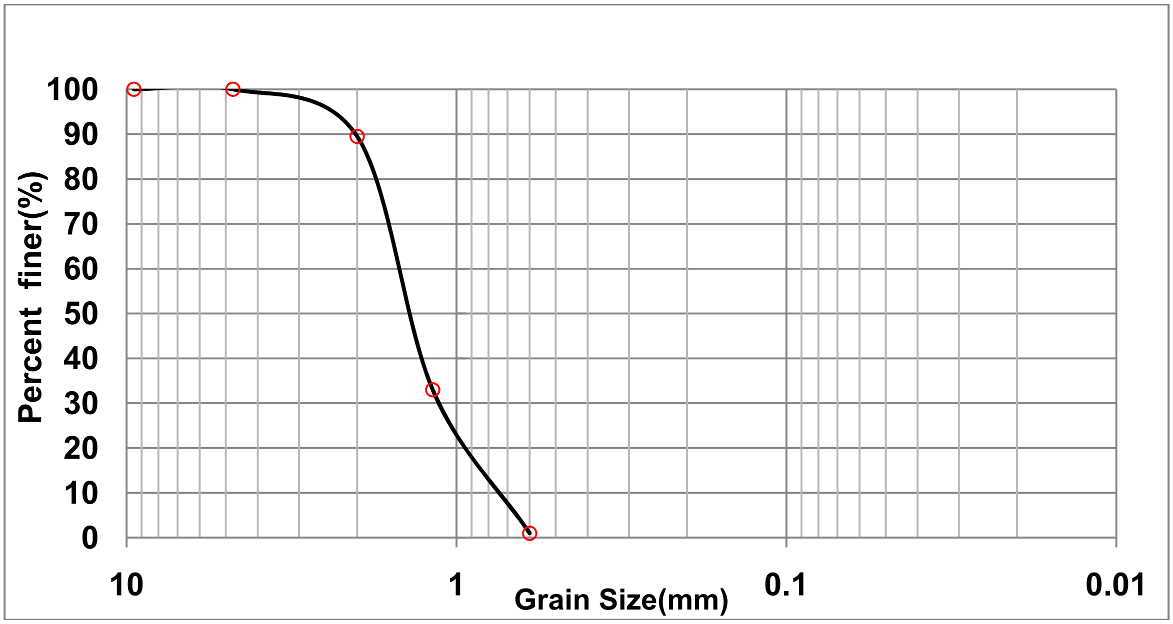


Figure 3-2. Particle Size Distribution of Granular Activated Carbon Medium

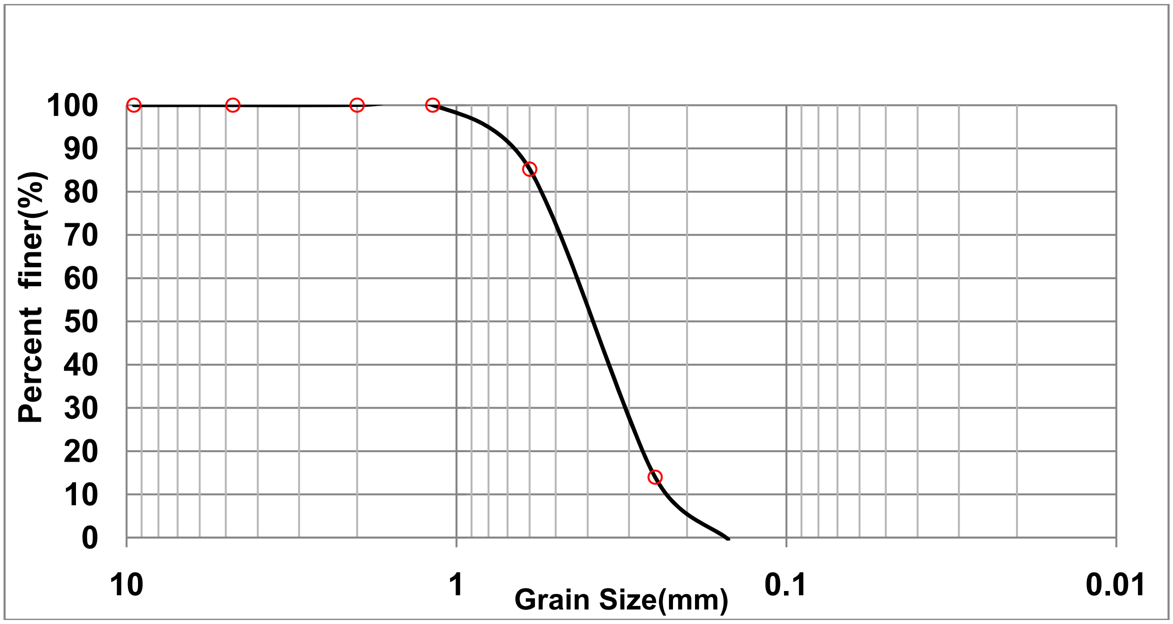


Figure 3-3. Particle Size Distribution of Rhyolite Sand Medium

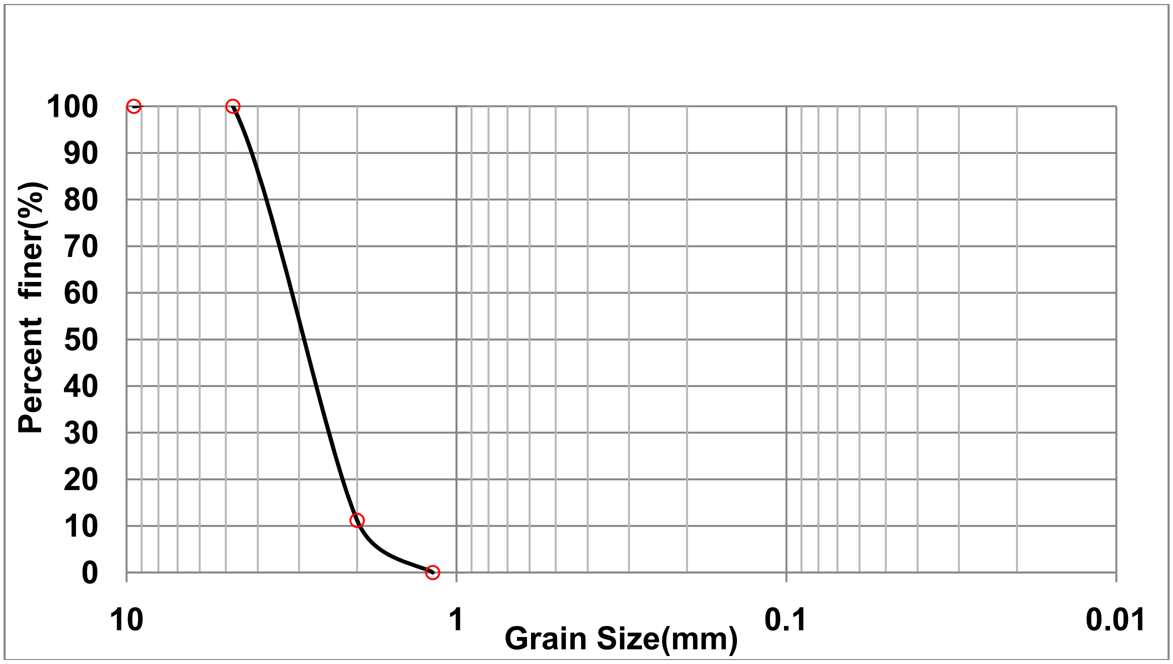


Figure 3-4. Particle Size Distribution of Site Zeolite Medium

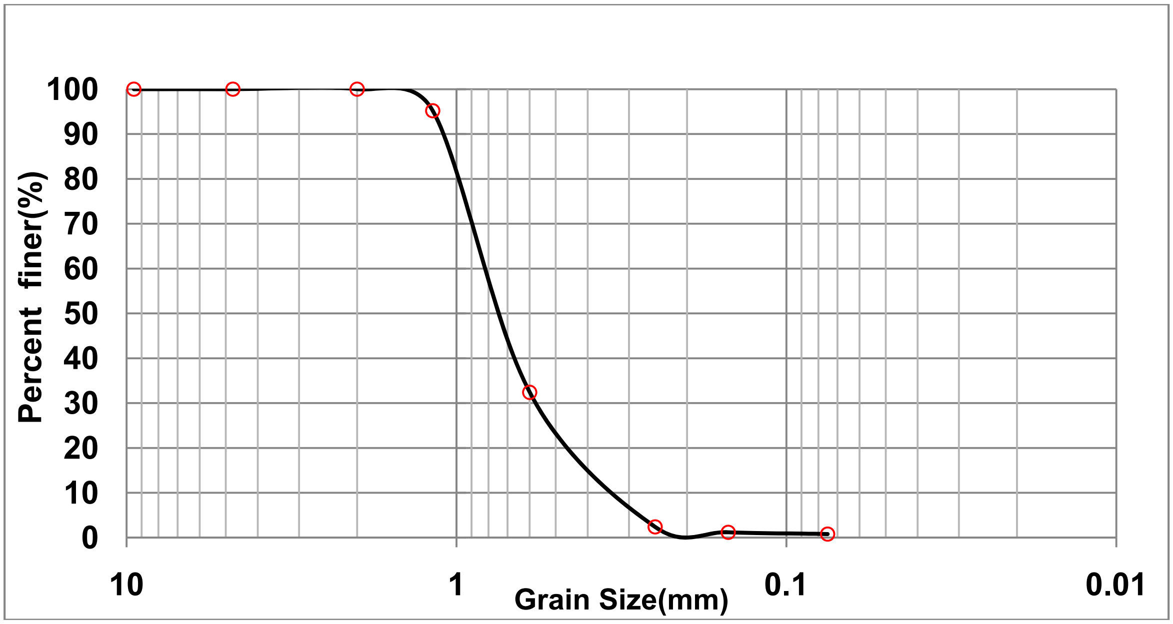


Figure 3-5. Particle Size Distribution of Surface Modified Zeolite Medium

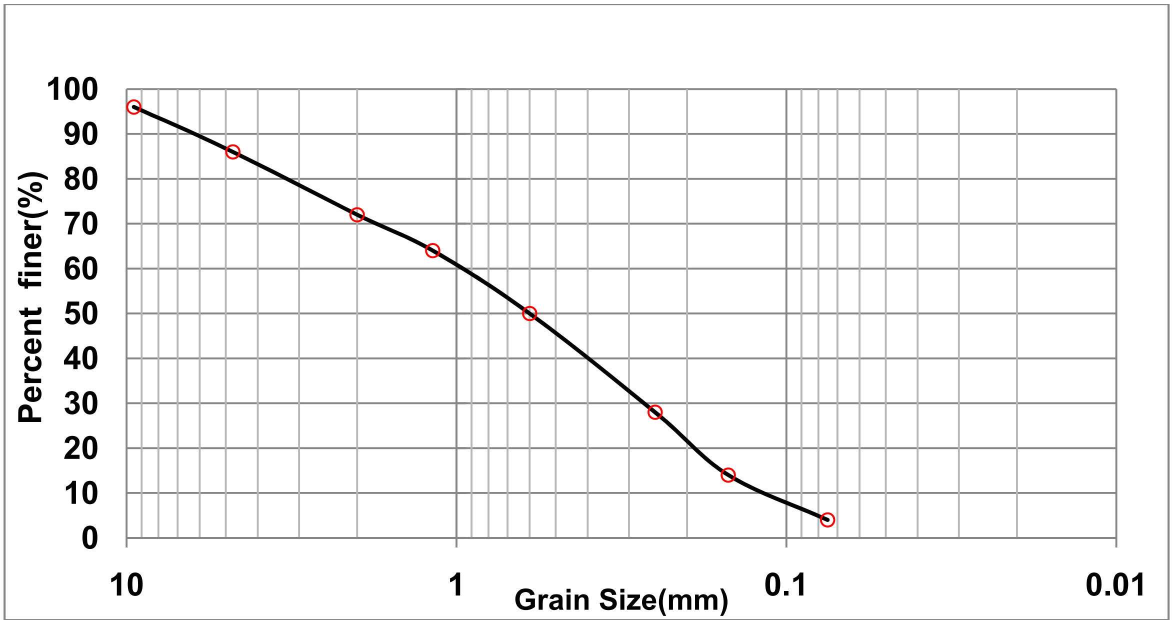


Figure 3-6. Particle Size Distribution of Peat Moss Medium

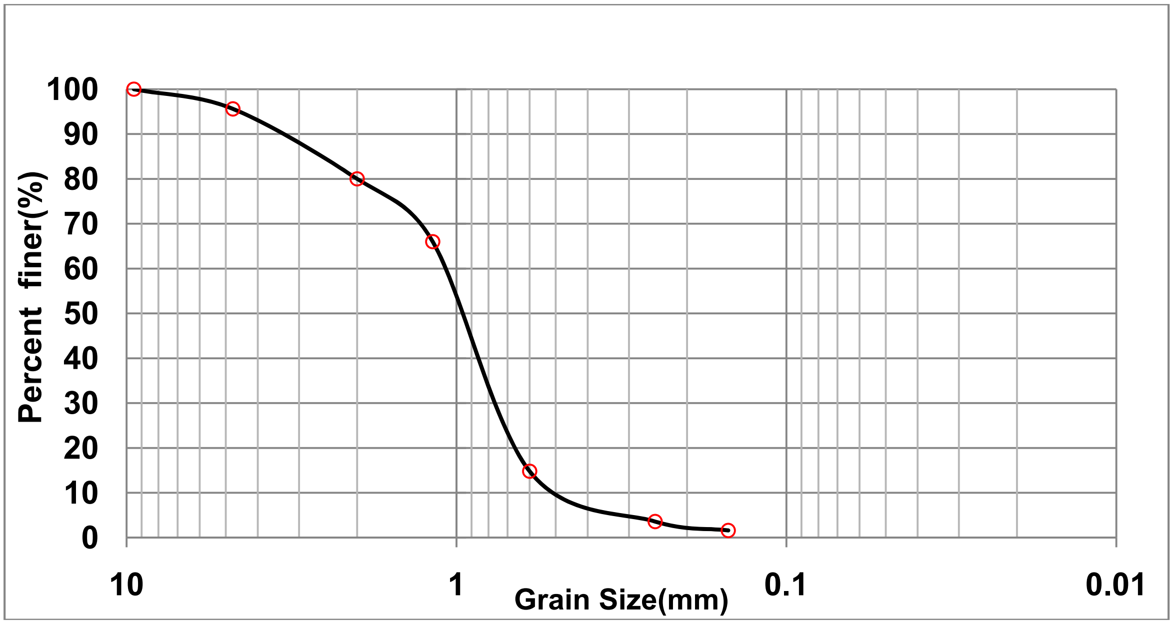


Figure 3-7. Particle Size Distribution of Site Filter Medium

## *3.2 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 have exceeded site benchmark limits, or may exceed the permit limits in the future, if untreated. For the Outfall 008 and 009 locations, these

include the following: cadmium, copper, lead, mercury, dioxin, oil and grease, pH, and gross alpha radioactivity for constituents that have exceeded the current site benchmarks; plus antimony, iron, manganese, zinc, nitrite plus nitrate, sulfate, gross beta radioactivity, and radium 226 plus 228 that may exceed the benchmark values during future extended monitoring.

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, may 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 may be 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 included the following:

    - Exchangeable cations and anions. Major cations and anions were 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 a loss of treatment capacity or loss of previously captured/bound pollutants from the media.

    - Organic compounds. The presence of organic compounds adds to the CEC of the mixture and also provides a basis for organometallic compounds to form, which are very stable (but which restricts ion exchange of the metals). 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 examined UV absorption at 254 nm and COD as indicators of total organic content.

- 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 the removal of the filtered fraction or, more likely, through physical sedimentation or straining of the particles to which these metals are associated. Comparison of the fraction of total versus filtered metals removed indicates the predominance of each of these mechanisms in the media. Alkalinity and hardness also are 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 were monitored for their behavior in the media profiles and for the other test phases.

- Nutrients. Nitrogen and phosphorus compounds are often critical stormwater constituents and their retention in media filters may 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 was used to determine the addition of nutrients by the different media that can be used by the plants, and the potential that excessive leaching of these materials could cause water quality problems.

4. Other constituents listed in the site discharge permit, but have a very low likelihood of ever exceeding the limits were also periodically included in the analytical effort.

### 3.2.1 Critical Constituents for Evaluation of Treatment Media

As noted in the above discussion on the selection of constituents to monitor, there are several parameters of greatest interest in relationship to treatment, as they have already exceeded the benchmark values during monitoring, or they have a high potential of exceeding the benchmarks during extended monitoring. These have received the greatest attention in the various tests to evaluate treatment media.

The most recently available monitoring season data from the 2008 /2009 wet season included 4 samples collected at outfall 009, and one sample at outfall 008. Outfalls 001 and 002 are also of potential interest, as they are also outfalls having large open space drainage areas and also do not have any complete treatment systems. These two additional outfalls had one sample each during the 2008/2009 season. The reported exceedences at these outfalls were:

Outfall 001: TCDD, iron, lead, and manganese
Outfall 002: TCDD, iron, lead, and manganese
Outfall 008: no exceedences reported
Outfall 009: TCDD and lead

In prior periods, the following current benchmarks have been exceeded:

Copper (outfalls 008 and 009)
Cadmium (outfall 009)
Gross alpha radioactivity (outfall 009)
Lead (outfalls 008 and 009)
Mercury (outfalls 008 and 009)
Oil and grease (outfall 009)
pH (too high at outfall 009)
TCDD (outfalls 008 and 009)

In addition to these constituents, there are several others that may exceed the benchmark concentrations in about 1% of the samples, or more, with continued sampling (based on probability distribution analyses of existing observations):

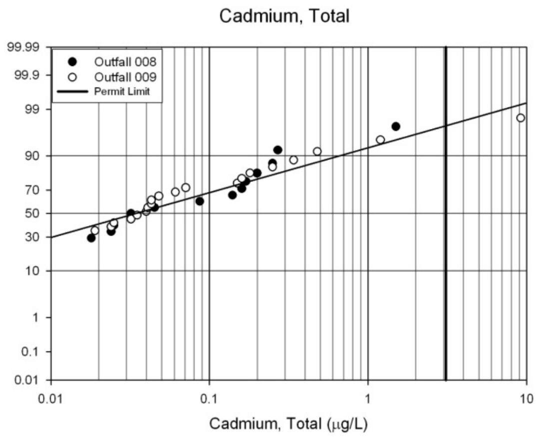
Antimony (outfall 009)
Cadmium (outfall 008)
Gross beta radioactivity (outfall 008)
Nitrite plus nitrate (outfall 008)
Oil and grease (outfall 008)
pH (too low at outfalls 008 and 009)
Radium 226 plus 228 (outfalls 008 and 009)
Sulfate (outfall 009)

Therefore, the constituents can be divided into two groups for each of the two outfalls, as shown on Table 3-4.

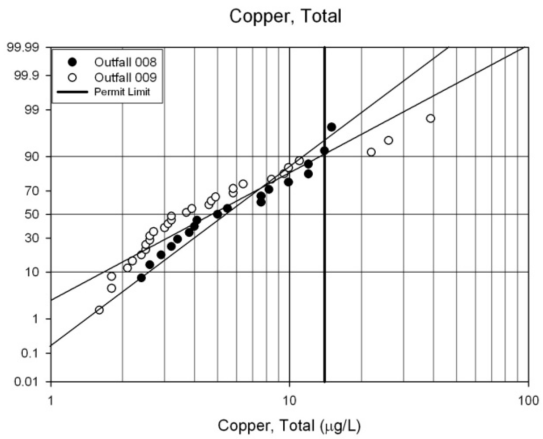
Probability plots for the constituent observations are shown in Figures 3-8 and 3-9 for samples collected prior to the 2008/2009 monitoring year. These plots indicate the calculated percentiles for the observed concentrations, and also show the permit limits. As an example, the probability plots for total cadmium are not significantly different for Outfall 008 and 009 observations, so they have been combined. The data reasonably fits a straight line, indicating a likely log-normal distribution (this is verified by statistical analyses). One sample from 009 has exceeded the cadmium permit limit (4 µg/L), while no samples from 008 have exceeded the permit limit. About 5% of the samples from either site would be expected to exceed the permit limit over an extended monitoring period. The median concentration (50th percentile) of total cadmium at both sites is approximately 0.035 µg/L. A substantial number of the samples had results of no-detected concentration (<LOD, or less than the limit of detection), which is slightly less than 0.02 µg/L, for total cadmium at both sampling locations. The observed concentrations are therefore shifted indicating the occurrence of these non-detected observations (about 30% at both sampling locations). In contrast, the total copper concentration distributions are different for Outfall 008 and 009 and are therefore indicated by separate lines. In addition, the likely exceedence frequencies for long-term monitoring also are different (possibly more frequent at 009 than at 008).

## Table 3-4. Constituent Groupings

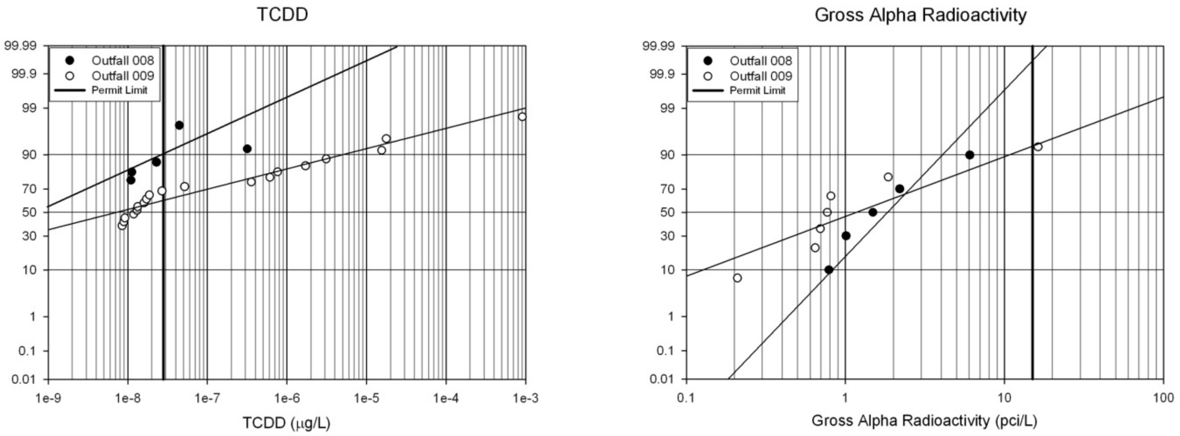
| | Constituents that have exceeded the benchmark values, benchmark value (# exceeding benchmark value/total number of samples prior to 2008/2009 sampling season) | Constituents that have a likelihood of exceeding the benchmark values during future monitoring, benchmark value (# exceeding benchmark value/total number of samples prior to 2008/2009 sampling season) |
|---|---|---|
| Outfall 008 | Copper,14 µg/L (2 of 19)<br>TCDD, 2.8 X $10^{-8}$ µg/L (2 of 19)<br>Lead, 5.2 µg/L (8 of 19)<br>Mercury, 0.13 µg/L (4 of 19) | Cadmium (0 of 19)<br>Iron (no data, based on recent observations at other site locations)<br>Gross beta, 50 pCi/L (0 of 5)<br>Manganese (no data, based on recent observations at other site locations)<br>Nitrite plus nitrate, 8 mg/L (0 of 19)<br>Radium 226 plus 228, 5 pCi/L (0 of 3) |
| Outfall 009 | Cadmium, 4 µg/L (1 of 31)<br>Copper, 14 µg/L (3 of 31)<br>TCDD, 2.8 X $10^{-8}$ µg/L (9 of 31)<br>Gross alpha radioactivity, 15 pCi/L (1 of 7)<br>Lead, 5.2 µg/L (7 of 31)<br>Mercury, 0.13 µg/L (5 of 31)<br>Oil and grease, 15 mg/L (1 of 31)<br>pH, between 6.5 and 8.8 (1 high of 26) | Antimony, 6 µg/L (0 of 31)<br>Iron (no data, based on recent observations at other site locations)<br>Manganese (no data, based on recent observations at other site locations)<br>Radium 226 plus 228, 5 pCi/L (0 of 4)<br>Sulfate, 250 mg/L (0 of 31)<br>Zinc (only if the 008 benchmark value of 159 µg/L was applicable at 009) |



Cadmium

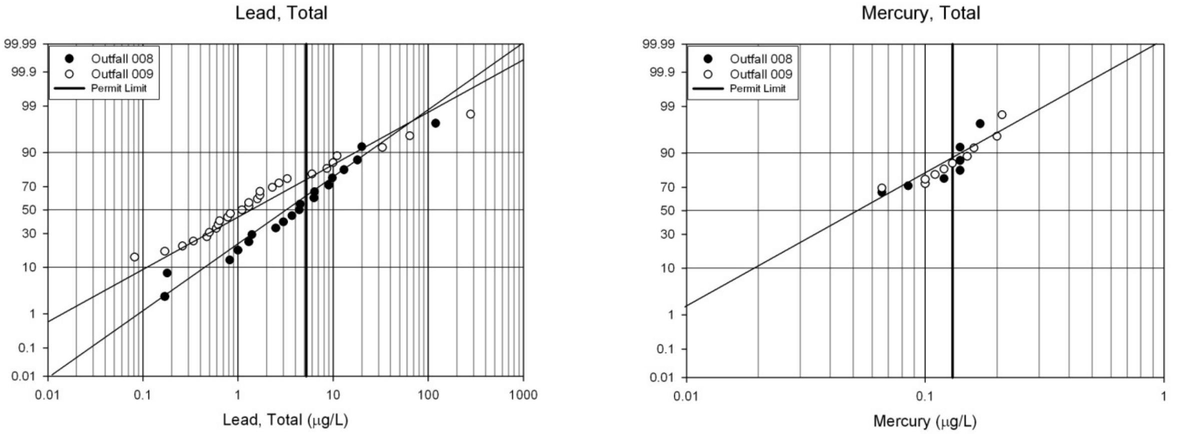


Copper



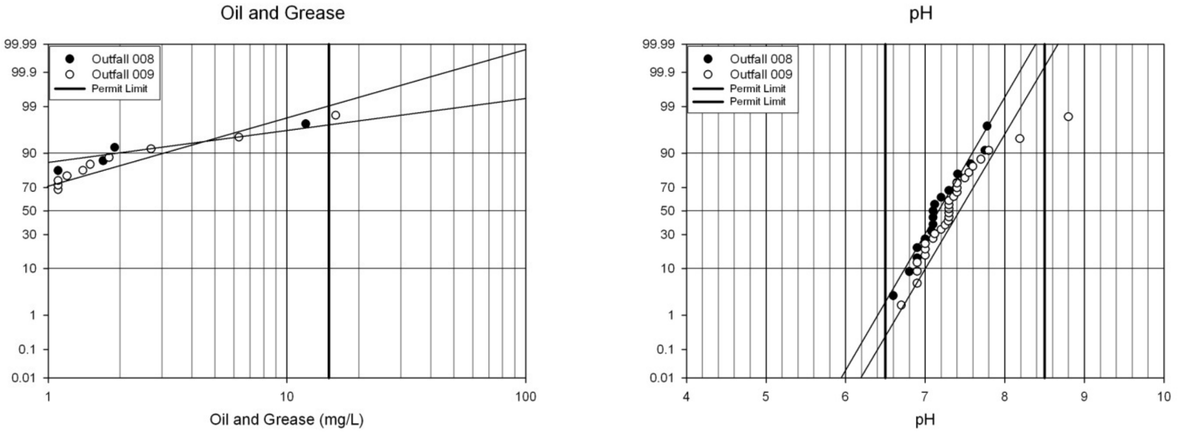
TCDD

Gross alpha radioactivity



Lead

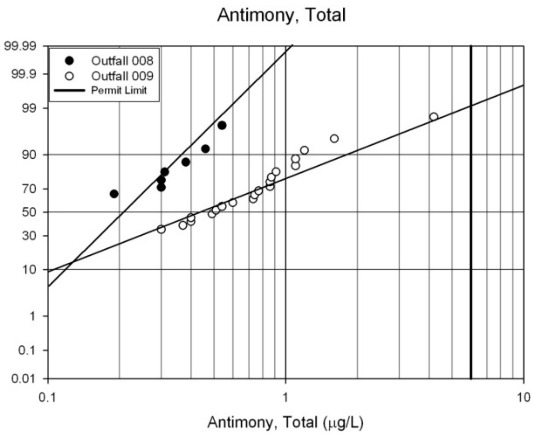
Mercury



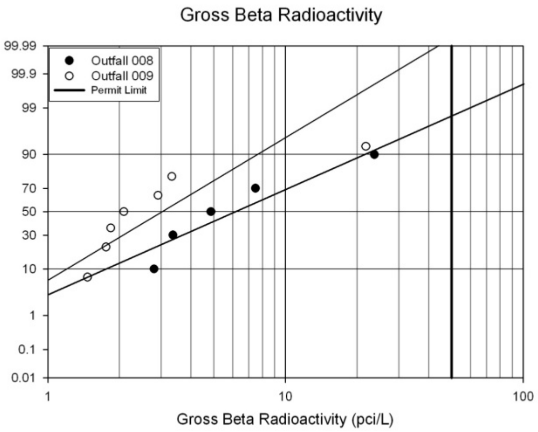
Oil and Grease

pH

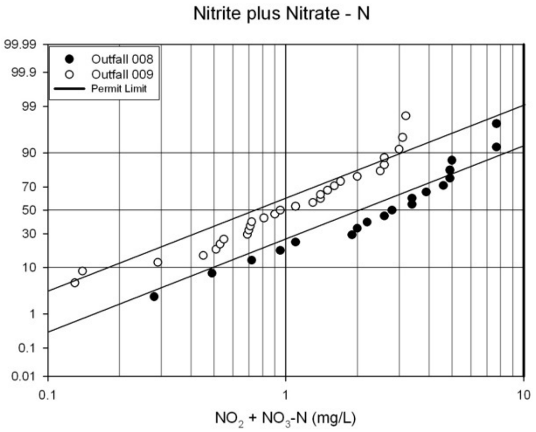
**Figure 3-8. Constituents that Have Exceeded Benchmark Limits during Monitoring (prior to 2008/2009 monitoring year).**



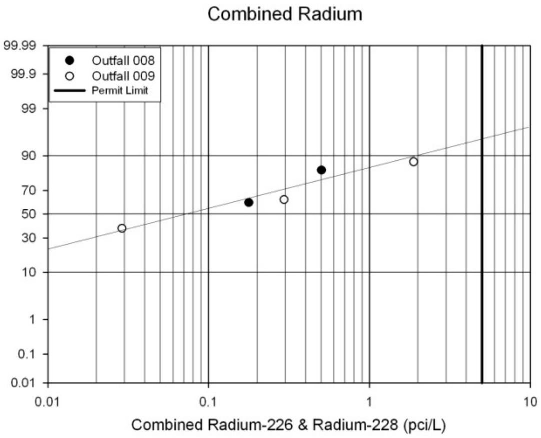
Antimony



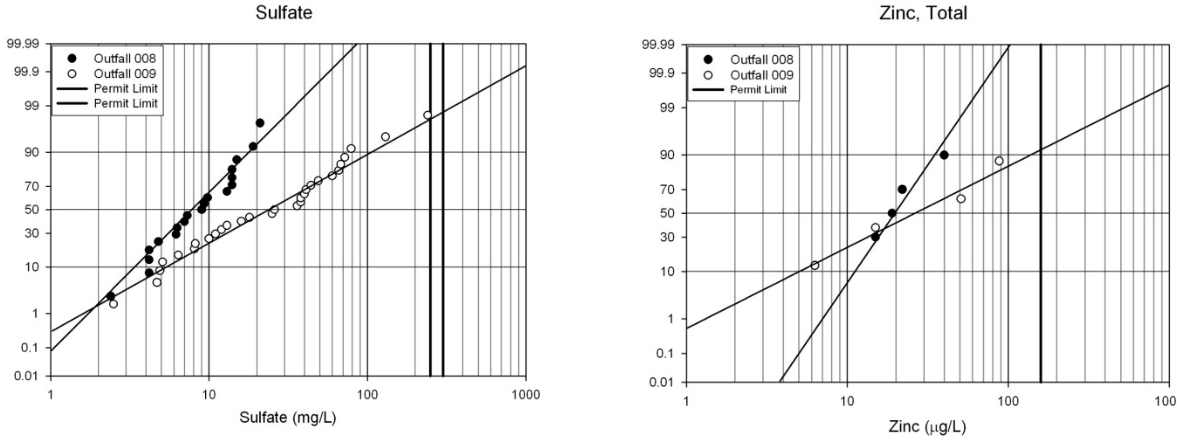
Gross beta radioactivity



Nitrite plus Nitrate



Radium 226 plus 228



Sulfate

Zinc (no permit limit for 009; 159 µg/L for 008 only). Therefore, 009 only highly likely to exceed the benchmark value for 008, which is not directly applicable.

**Figure 3-9. Constituents that Have Not Exceeded Permit Limits during Monitoring (prior to the 2008/2009 monitoring period), but Likely to Exceed during Future Extended Monitoring**

## *3.3 Descriptions of Tests Conducted*

The goals of the media investigations were the following:

- To provide information for design (e.g., optimal media components, depths, and contact times), and
- To maximize the likelihood that filtration-based treatment controls will achieve performance objectives in the most cost effective manner.

### 3.3.1 Major Testing Activities

The tests conducted were divided into four main activities:

1. **Clogging, breakthrough, and removal tests**. In these traditional downflow 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.

2. **Contact time and media depth tests.** These tests determined the effect of contact time (as determined by the media depth and porosity and the treatment flow 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

over a larger area 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.

3. **Media capacity tests and kinetics tests.** These traditional isotherm and kinetics batch tests have been adapted to meet the range of conditions seen in stormwater filtration treatment. 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 that was modified to better represent expected site conditions.

4. **Aerobic and anaerobic effects on contaminant retention in media.** These tests examined long-term retention of captured pollutants by the media under varying porewater chemical conditions.

This series of laboratory-scale batch and column breakthrough tests were performed to evaluate several potential filtration media and media combinations for their ability to remove a wide suite of pollutants from stormwater runoff. The testing and analytical methods used during these tests are described in the following sections.

### 3.3.2 Stormwater for Testing

Stormwater was collected from several storms in the late fall and early winter 2008-2009 at an inlet not far from the Science & Technology building on the Penn State Harrisburg campus. Prior research on soil columns using this stormwater runoff had found that the runoff was slightly contaminated with copper and nutrients, and contained a wide range of particle sizes and major ions generally representative of stormwaters. The inlet where this runoff was collected drains several roofs, sidewalks and grassy areas on the campus.

For each test or day of testing for two series of column tests, the tank where the stormwater was stored was stirred vigorously for at least 20 minutes and then some of the water was transferred to a 50-gallon day tank. For the batch testing, 10+ liters were transferred to a 10-L Nalgene® jug and transported to the stormwater lab. For the column tests, the stormwater was adjusted to increase the concentrations of certain pollutants as needed by dissolving a variety of salts in the day tank and vigorously stirring. Salts were selected, as opposed to using liquid chemical standards, because most of the liquid standards used a strong acid as the diluents. The type of salt selected was based on whether the salt was an interference to testing and on its solubility. In general, the most soluble salt was selected for use. The salts were analytical grade salts and purchased from VWR International. Typically, metals were adjusted to a total metal concentration of 100 µg/L, which for several permit constituents was greater than the permit limits. These higher concentrations were chosen both to evaluate whether the media could remove the pollutants to the permit limit during high concentration periods and to ensure that measurable concentrations were in the influent water since metals solubility and suspension in the test water was not guaranteed. The results will show for some of the metals, poor recoveries from the known dose to the measured influent concentration. Major cations and anions were adjusted to reasonable values of urban runoff, based on a review of the National Stormwater Quality Database, unless those values were substantially greater than the permit limits at the site. Then the concentrations were adjusted to concentrations slightly above the permit limits. These levels were selected to determine whether the media and mixtures were capable at removing pollutants at low concentrations. Suspended solids concentrations were adjusted with soil sent by Geosyntec from a park site near the Santa Susanna Laboratory. The soil was sieved through a 150-μm sieve and only the smaller particles were used to spike the stormwater.

For the kinetics and aerobic-anaerobic testing, 10 L of stormwater were transferred to a Nalgene jug. The concentrations then were adjusted as necessary. For these two series of tests, concentrations were spiked in a similar manner but to concentrations that were greater than those used for the column tests. These tests were designed to measure the capacity and reaction time of the media. Therefore, to ensure relatively complete loading of the media, larger concentrations were used. Once the spike concentrations were added, the jug was vigorously shaken for at least a minute and then allowed to stand for at least 15 minutes. Before separating the spiked stormwater into the testing subsamples, the jug was shaken again to encourage dissolution of the spiked pollutants and, if dissolution had not occurred completely, to ensure that the spike was well-suspended in the water before pouring into individual bottles.

Only the second phase of the aerobic-anaerobic testing, as described below, used unadjusted stormwater. This stormwater was collected from the storage tank after transfer to the day tank. Then it was transported to the stormwater lab and used in the exposure part of the testing.

### 3.3.3 Analytical Methods

The analytical methods for the samples generated in the four series of tests did not vary among the test series. Therefore, these are described in this section and referenced later in the descriptions of the various testing protocols. The constituents that were monitored during these controlled laboratory experiments were previously described.

Table 3-5 lists the analytes, sorted into primary, secondary, and frequent check parameters. The laboratory which conducted these analyses, along with the method used also is shown. The constituents are coded with footnotes indicating with which category they are associated (primary, secondary, frequent check). The frequent check parameters were used to indicate rapid and potentially ephemeral changes that may occur during some of the tests. The primary constituents were those that will be evaluated to quantify these changes at important stages in the tests, while the secondary constituents were evaluated when important changes are noted in the behavior of the media during the tests. Table 3-6 lists the methods that were used by the Penn State Agricultural Analytical Services Lab to characterize both clean media and the column media after testing, as described in the appropriate section.

## Table 3-5. Analyses Supporting Media Tests

| Test Constituent | Long-Term Column Break-through | Contact Time Column Break-through | Batch Kinetics and Aerobic-Anaerobic | Laboratory | Method Number (*Standard Methods* unless otherwise noted) | Limit of Detection (LOD) |
|---|---|---|---|---|---|---|
| **PHYSICO-CHEMICAL DESCRIPTORS OF MEDIA BEHAVIOR AND POLLUTANT REMOVAL** | | | | | | |
| Flow Rate[2] | X | X | | PSH | direct | N/A |
| pH[2, 4] | X | X | X | PSH | 4500-H+. B | 0.02 pH units |
| Total Dissolved Solids[2, 4] | X | X | | PSH | 2540.C | 5 mg/L |
| Suspended Solids[2] | X | X | | PSH | EPA Method 160.2/ISO 11923 | 5 mg/L |
| Suspended Sediment Concentration[2] | X | X | | PSH and UA | ASTM D3977-97B | 5 mg/L |
| Particle Size Distribution[2] | X | | | UA | gravimetric with sieves and Coulter Counter III | N/A |
| Turbidity[2] | X | X | | PSH | 2130B | 2 |
| Conductivity[2] | X | X | X | PSH | 2510.B | 3 µS |
| Dissolved Oxygen[2] | | | X | PSH | 4500-O | |
| Oxidation-Reduction Potential[2] | X | X | X | PSH | 2580 | 1 mV |
| COD[3] | X | X | X | PSH | 5220.D | 10 mg/L |
| UV-254[3] | X | X | X | PSH | Absorbance measure with Spectrometer using 254-nm wavelength | 0.005 absorb-ence units |
| **MAJOR CATIONS** | | | | | | |
| Ammonia[3, 4] | X | X | X | PSH | EPA Method 350.2 | 0.015 mg/L |
| Sodium[2,3] | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Na.C | 41 µg/L |

| **Test Constituent** | **Long-Term Column Break-through** | **Contact Time Column Break-through** | **Batch Kinetics and Aerobic-Anaerobic** | **Laboratory** | **Method Number (*Standard Methods* unless otherwise noted)** | **Limit of Detection (LOD)** |
|---|---|---|---|---|---|---|
| Calcium[2,3] | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Ca.C | 140 µg/L |
| Magnesium[2,3] | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Mg.C | 80 µg/L |
| Potassium[2,3] | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-K.C | 91 µg/L |
| Hardness[3] | X | X | X | PSH | 2340.C | 3 mg/L |
| **MAJOR ANIONS** | | | | | | |
| Sulfate[3,4] | X | X | X | PSH | 4500-$SO_4$ | 1 mg/L |
| Chloride[2,3,4] | X | X | X | PSH | 4500-Cl | 1 mg/L |
| Nitrite[4] | X | X | X | PSH | 4500-$NO_2$.B | 0.002 mg/L |
| Nitrate[3] | X | X | X | PSH | 4500-$NO_3$.E | 0.2 mg/L |
| Fluoride[4] | X | X | X | PSH | 4500-F.D | 0.03 mg/L |
| Phosphate[3] | X | | | PSH | 4500-P.E | 0.06 mg/L |
| Alkalinity ($HCO_3$ and $CO_3$)[3] | X | X | X | PSH | Based on 4500-CO2.D. | N/A |
| **HEAVY METALS** | | | | | | |
| Aluminum | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Al.C | 2 µg/L |
| Arsenic | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-As.D | 1 µg/L |

| **Test Constituent** | **Long-Term Column Break-through** | **Contact Time Column Break-through** | **Batch Kinetics and Aerobic-Anaerobic** | **Laboratory** | **Method Number (*Standard Methods* unless otherwise noted)** | **Limit of Detection (LOD)** |
|---|---|---|---|---|---|---|
| Antimony[4] | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Sb.C | 5 µg/L |
| Boron | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 4500-B.D | 90 µg/L |
| Cadmium[1] | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Cd.C | 3 µg/L |
| Chromium | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Cr.C | 2 µg/L |
| Copper[1] | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Cu.C | 3 µg/L |
| Iron | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Fe.C | 2 µg/L |
| Lead[1] | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Pb.C | 4 µg/L |
| Manganese | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Mn.C | 0.5 µg/L |
| Nickel[4] | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Ni.C | 2 µg/L |
| Thallium[4] | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Tl.C | 5 µg/L |

| **Test Constituent** | **Long-Term Column Break-through** | **Contact Time Column Break-through** | **Batch Kinetics and Aerobic-Anaerobic** | **Laboratory** | **Method Number (*Standard Methods* unless otherwise noted)** | **Limit of Detection (LOD)** |
|---|---|---|---|---|---|---|
| Zinc[1] | X (total and filtered fractions) | X (total and filtered fractions) | X (filtered fraction only) | UA | 3500-Zn.C | 3 µg/L |
| **MISCELLANEOUS PARAMETERS** | | | | | | |
| *E. coli*[3] | X | | | PSH | Based on appropriate sections of section 9000. | N/A |
| Oil & grease[1, 2] | X | X | | outside lab | | 2.1 mg/L |
| Mercury[1] | X | X | | outside lab | 3500-Hg.B cold vapor fluorescence | 0.2 µg/L |
| TCDD[1] | X | | | outside lab[5] | | |
| perchlorate[4] | X | X | | outside lab[5] | | 4 µg/L |
| gross alpha radioactivity[1] | X | | | outside lab[5] | | 1.2 pCi/L |
| gross beta radioactivity[1] | X | | | outside lab[5] | | 2.0 pCi/L |
| Tritium[4] | | X | | outside lab[5] | | 180 pCi/L |
| Uranium[4] | | X | | outside lab[5] | | 0.29 µg/L |
| Strontium-90[4] | | X | | outside lab[5] | | 1.2 pCi/L |
| combined radium 226+228[1] | | X | | outside lab[5] | | 0.6 pCi/L |

Footnotes:

1: critical site constituent, untreated stormwater expected to exceed permit limit >1% of the time over long period

2: constituents that likely affect performance of media in removing contaminants

3: constituents that help in understanding removal mechanisms of media

4: other constituents listed on permit, but are expected to exceed limits 1% of the time, or less, over a long period

5: these specialized constituents would be analyzed by an outside laboratory.

## Table 3-6. Soil Analytical Methods

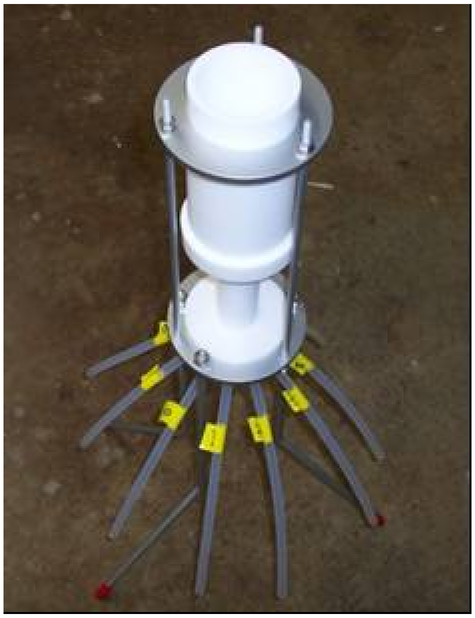
| Analyte | Method | Reference |
|---|---|---|
| pH | Water | Eckert, D. and J. Thomas Sims. 1995. Recommended Soil pH and Lime Requirement Tests. p. 11-16. In J. Thomas Sims and A. Wolf (eds.) Recommended Soil Testing Procedures for the Northeastern United States. Northeast Regional Bulletin #493. Agricultural Experiment Station, University of Delaware, Newark, DE. |
| Lime requirement | Mehlich buffer | Mehlich, A. 1976. New buffer pH method for rapid estimation of exchangeable acidity and lime requirement of soils. Commun. Soil Sci. Plant Analysis. 7, 637-652. |
| Available P, K, Ca, and Mg | Mehlich 3 (ICP) | Wolf, A.M. and D.B. Beegle. 1995 Recommended soil tests for macronutrients: phosphorus, potassium, calcium, and magnesium. p. 25-34. In J. Thomas Sims and A. Wolf (eds.) Recommended Soil Testing Procedures for the Northeastern United States. Northeast Regional Bulletin #493. Agricultural Experiment Station, University of Delaware, Newark, DE. |
| Cation Exchange Capacity (CEC) | Summation | Ross, D. 1995. Recommended soil tests for determining soil cation exchange capacity. p. 62-69. In J. Thomas Sims and A. Wolf (eds.) Recommended Soil Testing Procedures for the Northeastern United States. Northeast Regional Bulletin #493. Agricultural Experiment Station, University of Delaware, Newark, DE. |
| Organic matter | Loss on Ignition | Schulte, E.E. 1995. Recommended Soil Organic Matter Tests. p. 47-56. In J. Thomas Sims and A. Wolf (eds.) Recommended Soil Testing Procedures for the Northeastern United States. Northeast Regional Bulletin #493. Agricultural Experiment Station, University of Delaware, Newark, DE. |
| Total C | Combustion | Nelson, D.W. and L.E. Sommers. 1996. Total Carbon, Organic Carbon, and Organic Matter. p 961-1010. In D.L. Sparks (ed). Methods of Soil Analysis, Part 3. Chemical Methods. Soil Science Soceity of America Book Series Number 5. American Society of Agronomy, Madison, WI.<br>Pella, E. 1990. Elemental organic analysis. Part 1. Am. Lab 22: 116-125 |
| Total N | Combustion | Bremner, J.M.. 1996. Nitrogen-Total. p. 1085-1121. In D.L. Sparks (ed). Methods of Soil Analysis, Part 3. Chemical Methods. Soil Science Soceity of America Book Series Number 5. American Society of Agronomy, Madison, WI.<br>Pella, E. 1990. Elemental organic analysis. Part 1. Am. Lab 22: 116-125 |

| Analyte | Method | Reference |
|---|---|---|
| Soluble Salts | Electrical Conductivity (1:2) | Gartley, Karen. 1995. Recommended Soluble Salts Tests. p. 70-75. In J. Thomas Sims and A. Wolf (eds.) Recommended Soil Testing Procedures for the Northeastern United States. Northeast Regional Bulletin #493. Agricultural Experiment Station, University of Delaware, Newark, DE. |
| Total Sorbed Cu, Zn, Pb, Ni, Cd, Cr, Mo | EPA Method 3050B/3051 + 6010 | USEPA. 1986. Test Methods for Evaluating Solid Waste. Volume IA: 3rd Edition. EPA/SW-846. National Technical Information Service. Springfield, Va. |
| Particle Size Analysis | Hydrometer Method | Gee, G.W. and J.W. Bauder. 1986. Particle size analysis. p. 383-411. In A. Klute (ed.) Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. Agronomy Monograph #9 (2nd Edition). Amer. Soc. Agron. Madison, WI. |

### Laboratory Procedure for Particle Size Distribution and SSC Analyses

1. Ten 250 mL capacity graduate cylinders (short graduates) are placed under each tube of the splitter in order to measure the volume of each subsample (needed for SSC calculations).
2. Nylon screening material with 1180 µm openings is used at the top of the USGS/Dekaport cone splitter to capture large particles such as leaves, twigs and insects (these materials are also dried and weighed and chemically analyzed). This screening material is washed and dried completely before use. Aluminum dish and the screening are weighted. A 1-L (or larger) bottle sample water is carefully poured into the splitter.
3. The unfiltered water subsamples are used for total SSC analyses, so the total sample particulate content less than 1180 µm can be determined.
4. Two of the split subsamples are separately poured through a 3-inch stainless steel Tyler #60 sieve, leaving subsamples having particulates smaller than 250 µm in the subsample. One of these is used for duplicate total solids analyses, while one will be used for the Coulter Counter particle-size-distribution analyses.
5. One subsamples is separately poured through a 3-inch stainless steel Tyler #140 sieve, leaving subsamples having particulates smaller than 106 µm in the subsample. The sample analyzed for solids less than 107 µm in diameter.
6. The remaining 250-µm-sieved subsample is used for the Coulter Counter particle size distribution (PSD) analyses. The composite particle size distribution is created using the software provided by Coulter that overlaps the different aperture tube results. Each aperture tube can quantify particles in the range of approximately 2% to 60% of the aperture size (e.g., 30 µm tube – 0.6 µm to 18 µm; 140 µm tube – 2.8 µm to 84 µm; 400 µm tube – 8 µm to 240 µm). As can be seen, each of the tubes substantially overlaps the other tube, providing sufficient duplication of particle diameters for the software overlap. Three-inch stainless steel Tyler sieves are used to pre-sieve the subsamples before analyses by each aperture to minimize clogging; the sieve size selected is the smallest commercially-available sieve that exceeds the maximum analytical range of each tube, while still being smaller than the tube aperture itself (e.g., 30-µm tube – 20-

µm sieve [Tyler #625], 140-µm tube – 106-µm sieve [Tyler #150], 400-µm tube – 250-µm sieve [Tyler #60]).



USGS/Dekaport Teflon $^{TM}$ Cone Splitter

### Sampling Process

In order to conduct the analysis in several constituents, 1 L bottles are separated into10 subsamples by the USGS/Dekaport Cone Splitter. Subsampling process is also required to measure the volume of water required for the calculation of the soil analysis.

1. 250 mL capacity short graduate cylinders are placed at each leg of the splitter.
2. Nylon screening material with 1180 µm openings is used at the top of the cone splitter to capture large particles such as leaves, twigs and insects (these materials are dried and weighed and chemically analyzed also). This screening material is washed and dried completely before use. Aluminum dish and the screening are weighted. A 1-L bottle sample is carefully poured into the splitter.
3. Initial volume of each subsamples are measured and these values are used for the calculation of soil concentrations.
4. Subsamples are transferred into the clean bottles for the further analysis.

### Analysis for Suspended Sediment Concentration (SSC), Dissolved Solids (TDS), and Total Suspended Solids (TSS)

Once the sample is prepped for analysis by separating it into the required number of subsamples using the cone splitter (repeatability verified in several masters and Ph.D. papers), the samples are analyzed for SSC, TSS, and TDS using the methods listed in Table 3-5.

### 3.3.4 Long-Term Column Breakthrough Testing

The purpose of these tests was to simultaneously determine several important stormwater filter media behavioral characteristics, including pollutant removal and effluent quality, treatment flow rates, and losses in both pollutant removal and flow rate performance associated with clogging and breakthrough as the media becomes exhausted. These tests involved intermittent loading of the filter columns (on a Monday, Wednesday, Friday schedule) for 10 weeks (to approximately 60 to 80 m of volumetric loading, depending on the flow rate through the media). The intermittent loading schedule was designed to accelerate the loading but still to allow for a measure of the potential porewater chemistry changes associated with quiescent times in the filter columns. Prior testing has shown that stormwater, with its intermittent flows and relatively low concentrations, is not as easily treated as industrial wastewater having continuous flows and high concentrations. The low concentrations reduce the concentration gradient for sorption/ion-exchange and the intermittent flows often result in variable pore water chemistries that affect both the quality of the first flush from the filter in a new storm event and the potential availability of removal sites in the media.

Ten media columns were constructed on the wooden test frame in the PSH pilot-scale laboratory. Prior to column construction, the Kimax™ glass columns and glass drainage funnels were washed with hydrochloric acid and rinsed with deionized water. Squares of pre-washed fiberglass window screen were placed across the bottom of the glass column as a support for the column media. The columns were inserted into the wooden supports on top of the funnel. Gravel purchased at a local home improvement store was washed, air dried and placed to a depth of approximately 2 inches in the bottom of the column. Then the media was added to a depth of approximately 38 inches in three batches. After each batch was added (approximately 1 foot in depth), the media was rinsed with deionized water. Figure 3-10 shows the column set-up.

The media used in the columns were supplied by GeoSyntec and Boeing. The six component media were designated as Site Sand, Rhyolite Sand, Site Zeolite, a Surface-Modified Zeolite, Granular Activated Carbon, and Peat Moss, as previously described.

One column contained only Site Sand to evaluate the effectiveness of unmodified sand. Unmodified sand was expected to provide only removal of the particulates and particulate-associated pollutants. The other media listed were placed into five individual columns after being mixed 50-50 (v/v) with the Site Sand. The last four columns were used to evaluate several mixes of the media. They are described and their designations are given in Table 3-7.

**Figure 3-10. Long-Term Column Breakthrough Testing Setup. Left: Glass column under construction. Right: Complete column testing setup.**

**Table 3-7. Description of Mixed Media**

| Media Mixture | Description |
|---|---|
| R-SMZ | Rhyolite Sand – Surface Modified Zeolite mixed 75%/25% (v/v), respectively |
| R-SMZ-GAC | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon mixed 1/3 each (v/v) |
| R-SMZ-GAC-PM | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon – Peat Moss mixed 30% each for R, SMZ, and GAC, plus 10% PM (v/v) |
| Site Sand-Site Zeolite-GAC (Layered) | Site Sand – Size Zeolite – GAC Layered at approximately 1 foot each. |

At the start of each testing day, 55 gallons of stored stormwater were transferred to the day tank after the storage tank was mixed for at least 20 minutes. Spike chemicals were added to the day tank to create the concentrations described above. The day tank then was stirred in order to dissolve as much of the spike chemicals as possible. While the spike salts were selected based on solubility, based on the analytical results, several spikes did not dissolve or emulsify to a large extent in the water. Examples include oil and grease and lead spikes, where the concentrations were recovered in the unfiltered water analysis, but very little was recovered in the filtered fraction. For oil and grease, little was recovered in the initial analyses, although a sheen was seen on the top of the tank water and the water pumped to the columns appeared to have oil drops mixed in the water. Other spikes dissolved almost completely and were seen primarily in the filtered fraction. Examples included calcium, potassium and magnesium, as expected.

A Teflon$^{TM}$ cone splitter (USGS/Dekaport) was used to distribute water evenly among the 10 columns. Because of the nature of the test water, a bilge pump was used to transfer test water from the day tank to the cone splitter (see Figure 3-10 Right). Water was pumped to the column until the water level on top of the column reached a level of 6 inches above the media. This corresponded to the maximum ponding depth expected in the field. After the media was saturated each day and a steady flow was achieved, the flow rate was measured by collecting a volume of water in a small clean bucket and measuring the time it took to collect the volume with a stopwatch. Columns were refilled once the water level dropped to the level of the top of the media. The time that the pump was on was recorded using a stopwatch. When the flow rate dropped below 5 m/day, the top of the media was disturbed. When disturbing the media became ineffective, the top 1 to 2 inches of media were removed from the column.

The water collected as part of flow rate measurements was used to measure in real-time four parameters: turbidity, conductivity, color, and oxidation-reduction potential (ORP). Water was pumped into the columns until the pump could not reach the tank water surface (approximately 5 gallons remaining). Separate water samples were collected for analytical analysis of the parameters described in Table 3-5. Samples were collected on the first day, and then periodically throughout the testing. Eight samples were collected for metals and major cations; seven samples for the PSH analyses, and three samples for the outside lab. For all samples for the outside laboratories, samples were collected only from the influent water and from the mixed media columns. Influent water was collected from one of the tubes distributing water to the columns. At the end of the test period, the columns were air-dried in place to the maximum extent practical. Then the media was removed from the column intact and then spread out on several plastic sheets and allowed to air dry (Figure 3-11). The column media were sectioned into four pieces and two samples were collected from the middle of each section. One soil sample was sent to the University of Alabama for metals digestion and analysis by ICP. The second sample was sent to the Penn State Agricultural Analytical Services Laboratory in State College, PA, for analysis of soil parameters other than metals (as listed in Table 1).

**Figure 3-11. Soil Media after Removal from Columns Prior to Soil Sample Collection. Upper layers of the columns are to the left side of the picture.**

### 3.3.5 Short-Term Contact Time Depth Breakthrough Tests

The purpose of this series of tests was to investigate the impact of media contact time on pollutant removal. Contact time was controlled by adjusting the media depth in the columns. These tests involved intermittent loading of the filter columns (several hours per day Monday through Friday) for five sampling days (to approximately 20 m of volumetric loading, depending on the flow rate through the media).

These tests were performed in two separate filtering setups. For each test setup, twelve columns were constructed as described in the prior section. Two columns of each media or mix were 38” in depth, one was 26” and one was 14”. The first test setup investigated the effects of media depth on pollutant removal for the mixes R-SMZ, R-SMZ-GAC, and R-SMZ-GAC-PM. The second test setup investigated the same effects but for three media components: GAC, PM, and SMZ. These media components were selected based on the testing results from the long-term tests. Figure 3-12 shows the column set-up for these varying depth column tests.

**Figure 3-12. Media Depth Test Column Setup (14-inch to 38-inch columns per media from left to right)**

At the start of each testing day, 55 gallons of stored stormwater were transferred to each of two day tanks after the storage tank was mixed for at least 20 minutes. Spike chemicals were added to one of the two day tanks to create the concentrations described previously. The day tank then was stirred in order to dissolve as much of the spike chemicals as possible. Similar solubility problems were noted in this phase of testing. The second day tank was not spiked and was used to create a control to determine whether the media leached pollutants when exposed to relatively clean water.

A Teflon$^{TM}$ cone splitter (USGS/Dekaport) was used to distribute water evenly to the nine columns, one from each media mix for each depth. The bilge pump was used to transfer test water from the day tank to the cone splitter. Water was pumped to the column until the water level on top of the column reached a level of six inches above the media. This corresponded to the maximum ponding depth in the field. After the media was saturated each day and a steady flow was achieved, the flow rate was measured by collecting a volume of water in a small clean bucket and measuring the time it took to collect the volume with a stopwatch. Columns were refilled once the water level dropped to the level of the top of the media. The time that the pump was on was recorded using a stopwatch. When the flow rate dropped below 5 m/day, the top of media was disturbed. When disturbing the media became ineffective, the top 1 – 2 inches of media were removed from the column. For the control columns, water was manually added to the columns to the depth of six inches above the media. Flow rates were measured for these columns as described above and samples were collected as described above.

The water collected as part of flow rate measurements was used to measure in real-time four parameters: turbidity, conductivity, color, and oxidation-reduction potential (ORP). Water was pumped into the columns until the pump could not reach the water surface (approximately 5 gallons remaining). Separate water samples were collected for analytical analysis of the constituents listed previously. Samples were collected on the first day, and then periodically throughout the testing. Three samples were collected for metals and major cations; five samples (one daily) for the PSH analyses, and one sample for the outside lab for analysis of oil and grease, perchlorate, and mercury. Influent water was collected from one of the tubes distributing water to the columns.

### 3.3.6 Batch Kinetics Testing to Determine Reaction Time

This series of tests were traditional batch kinetic tests where an aliquot of water and media are exposed together while being shaken gently for a specific period of time. While traditional batch testing often is only a moderate predictor of performance in stormwater filter columns, knowledge of the parameters allows comparisons of these media to traditional filter media. These tests were performed first in order to provide an estimate of media behavior.

The volume of water used for each individual combination of media and time was 500 mL. These tests were performed on the individual media separately (six media plus the blank). The mass of the media used for each test was approximately 2 g for peat moss, 5 g for GAC, 3 g for SMZ, and 10 g for rhyolite sand, site sand, and site zeolite. Stormwater was collected as described above and the stormwater was spiked to concentrations similar to those used in the two series of column tests. Once the spiked stormwater was added to a bottle containing media (or the blank bottles), the lid was loosely screwed shut (to capture splash if needed but not sufficient to prevent oxygen transfer with the outside air) and the sample bottle placed on a shaker rotating at 120 rpm. At the end of the test time (1 min, 15 min, 30 min, 60 min, 2 hours, 6 hours, 12 hours, 1 day, and 3 days), the sample bottle was removed from the shaker and the water and media poured into an acid-washed filter flask. The purpose of passing the water through a 0.45-μm membrane filter was to quench the reaction by removing the media's exposure to the water. The filtrate was analyzed for the constituents listed previously. Because of the results of the pH analyses for several media, some tests were rerun and additional times were added.

The shaking and reaction quenching steps of these tests is highlighted in Figure 3-13.

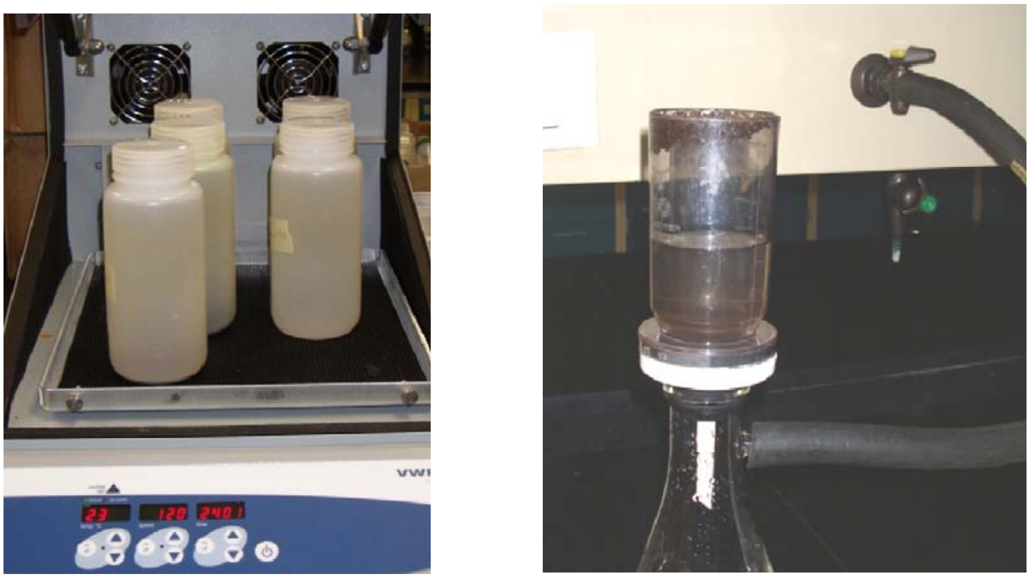


**Figure 3-13. Batch Testing Setup. Left: Shaking Media and Spiked Stormwater on Oscillating Shaker. Right: Filtering Media and Stormwater through 0.45-μm membrane filter to quench reaction.**

### 3.3.7 Batch Testing for Pollutant Retention under Aerobic and Anaerobic Conditions

This series of tests were conducted similar to the traditional batch capacity tests where an aliquot of water and media are exposed together while being shaken gently for a specific period of time. The goal of these tests was to load a specified mass of media to close to capacity and then expose the two portions of the media to unspiked stormwater for a period of several weeks.

Initially, specified masses of media were exposed to stormwater spiked with very high concentrations of pollutants. The masses of media recovered from the initial loading portion of the testing were 10 g for peat, 37 g for site zeolite, 30 g for fine sand, 30 g for rhyolite, 9 g for surface modified zeolite, and 25 g for granular activated carbon. The initial exposure concentrations were substantially higher than would be seen in site runoff. The purpose was to load the media to near capacity conditions. Once the stormwater was added to an acid-washed bottle containing media, it was shaken in a tumbler for a minimum of four hours. At the end of tumbling, the water and media were poured into an acid-washed filter flask containing a 0.45-μm membrane filter. The filtrate was collected and saved for later analysis. The media then was rinsed with 500 mL of deionized water and that filtrate was collected. The purpose of the rinse and collection of the filtrate was to determine the concentration of pollutants that were loosely held by the media and easily disturbed upon further release. Because the initial spike concentrations were very high, these tests also provided an estimate of capacity of the media in a mixed pollutant solution. These results were compared to the long-term column breakthrough tests' capacity calculations.

The media then was separated into two portions – half in each portion. For the aerobic-anaerobic exposure tests, each media portion was split in two again, with half going into one of two bottles for each combination of media-exposure type (Figure 3-14). The purpose of using two bottles was to ensure that sufficient volume was available for later analysis. Unspiked stormwater then was added to each bottle. For the aerobic bottles, the tops were covered in parafilm or through a hole in the bottle lid and they were attached to the building air system through a series of hoses. For the anaerobic exposure bottles, traditional BOD bottles were used and the bottle filled to the top and water sealed. Stormwater was used to fill the area around the stopper before the plastic caps were put on the bottles.

At the end of the exposure, the two bottles representing a media-exposure combination were filtered through a 0.45-µm filter after having their pH, ORP, and dissolved oxygen concentrations measured in the bottle. The filtrate was collected for further analyses. Then the media was rinsed with 500 mL of deioinized water and the rinse filtrate was collected. The media then was allowed to air dry and was saved for further analysis for metals. The analyses were listed previously.

**Figure 3-14. Anaerobic Bottles (left) and Aerobic Bottles (right) during Exposure**

### 3.3.8 Batch Testing for Pollutant Retention as a Function of Media Mass (Traditional Capacity)

This series of tests were conducted similar to the traditional batch capacity tests where an aliquot of water and media are exposed together while being shaken gently for a specific period of time. However, traditional tests typically hold the mass of media constant and vary the water concentration. These tests were designed to do the opposite. The water concentration (and therefore the concentration gradient) was held constant and the mass of media in each bottle was varied. Initial estimates of capacity were made from the long-term column breakthrough tests and this data was used to calculate a range of media masses estimated to bracket the capacity assuming that all of the constituent would be removed by the media.

The spiked stormwater concentrations were on the high end of urban runoff and more typical of traditional industrial stormwater concentrations, especially for the metals. For the other site constituents, concentrations were in the range of the permitted values. The metals concentrations were increased to this level to ensure that there were sufficient metals in the water for removal to occur. Once the stormwater was added to an acid-washed bottle containing media, it was shaken in a tumbler for a minimum of four hours. At the end of tumbling, the water and media were poured into an acid-washed filter flask containing a 0.45-µm membrane filter. The filtrate was collected and saved for later analysis. The samples were analyzed for the constituents in Table 3-5.

### 3.3.9 Testing for Bacterial (*E. coli*) Retention in Treatment Media

The initial test plan proposed spiking *E. coli* bacteria into the day tank and testing both the influent and effluent from the full-depth columns periodically during a day's run. These initial results showed that the bacteria, however, was not measurable in the day tank (column influent) at the end of the day's run. Further testing was performed to determine the approximate time in the day tank in which the bacteria would be measurable at concentrations meaningful for this project. Figure 3-15 shows the die-off curve for spiked *E. coli* in the spiked stormwater. These results show that the testing window was approximately 2 hours (1-log die-off) and not the 8-hour day used in the long-term full-depth column tests.

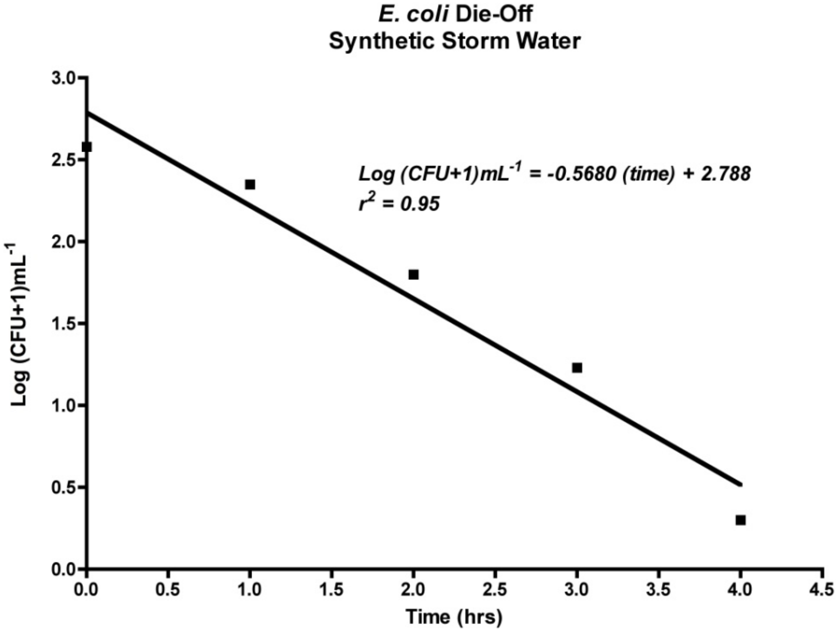


**Figure 3-15.** ***E. coli*** **Bacteria Die-off Investigation**

Therefore, *E. coli* retention (and potential regrowth) in the media was investigated separately. The two selected media for these tests were peat moss and a leaf-litter compost for two reasons. First Clark (2000) and other research has shown that filters with organic matter can provide excellent removals of *E. coli*. Second, the use of an organic substrate for bacterial retention has raised concerns regarding the potential for creating a reservoir of *E. coli* that could be flushed from the media during subsequent storm events. Similar to the full-depth column tests, spiked stormwater was used as the challenge water, but with *E. coli* also added. These tests replicated first flush or short filtering time conditions. The peat moss was mixed 30/70 (v/v) with the site sand and the compost was mixed with the site sand at an equivalent organic matter content as the 30% peat. Triplicates were run of every column condition. One set of columns of each media never received bacteria (control columns) and a second set received the bacterial spike. The purpose of the control columns was to measure the residual washout of *E. coli* from the media itself. Columns were treated with spiked stormwater every other day for three weeks. One day per week the stormwater was spiked with *E. coli* for the two sets of columns receiving bacteria-spiked stormwater. The samples were analyzed using the method listed in Table 3-5.

## 4.0 Findings of the Media Studies

The following sections of this report summarize the findings of these test phases. The appendices contain the basic data and complete sets of graphs and tables, while the discussions in this report section summarize these findings and show selected illustrations from the appendices. Further analyses and comparisons also are presented here.

### *4.1 Flow Rates and Maintenance Requirements due to Clogging*

Figure 4-1 shows the typical flow rates observed for the set of long-term column tests for each of the ten media combinations tested, along with the accumulative sediment load to initial maintenance. Detailed information on the flow and clogging tests is provided in Appendix A1. Figure 4-2 is an example of one of the types of data plots provided in Appendix B for the varying column depth tests. This figure shows the effluent suspended sediment concentrations (SSC) for three sets of columns (14, 26, and 38 inches) plus a duplicate shorter column, compared to influent conditions. The duplicate shorter column did not have sediment added to the water. Flow rate measurements were also obtained as part of these varying depth column tests.

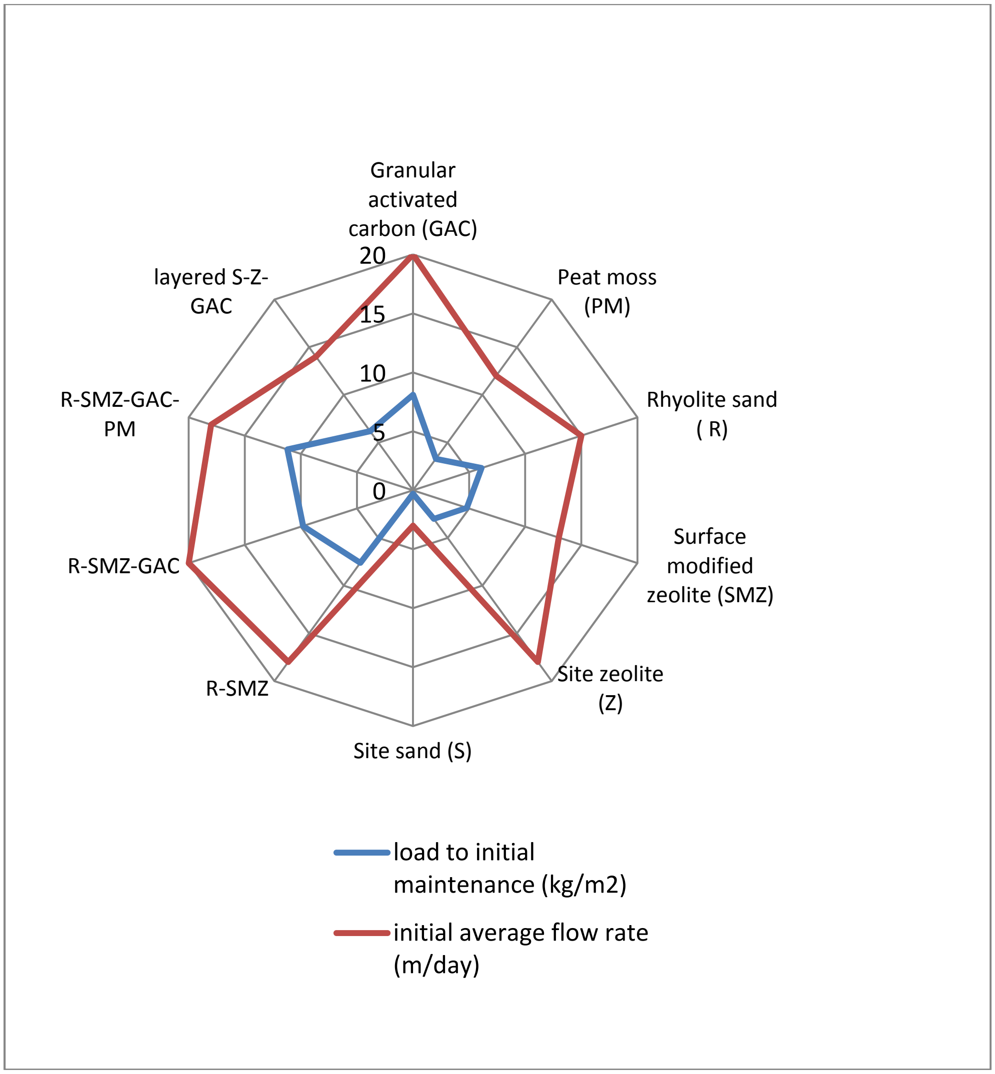


**Figure 4-1. Flow Rate and Maximum Loadings before Clogging for Different Long-Term Column Tests**

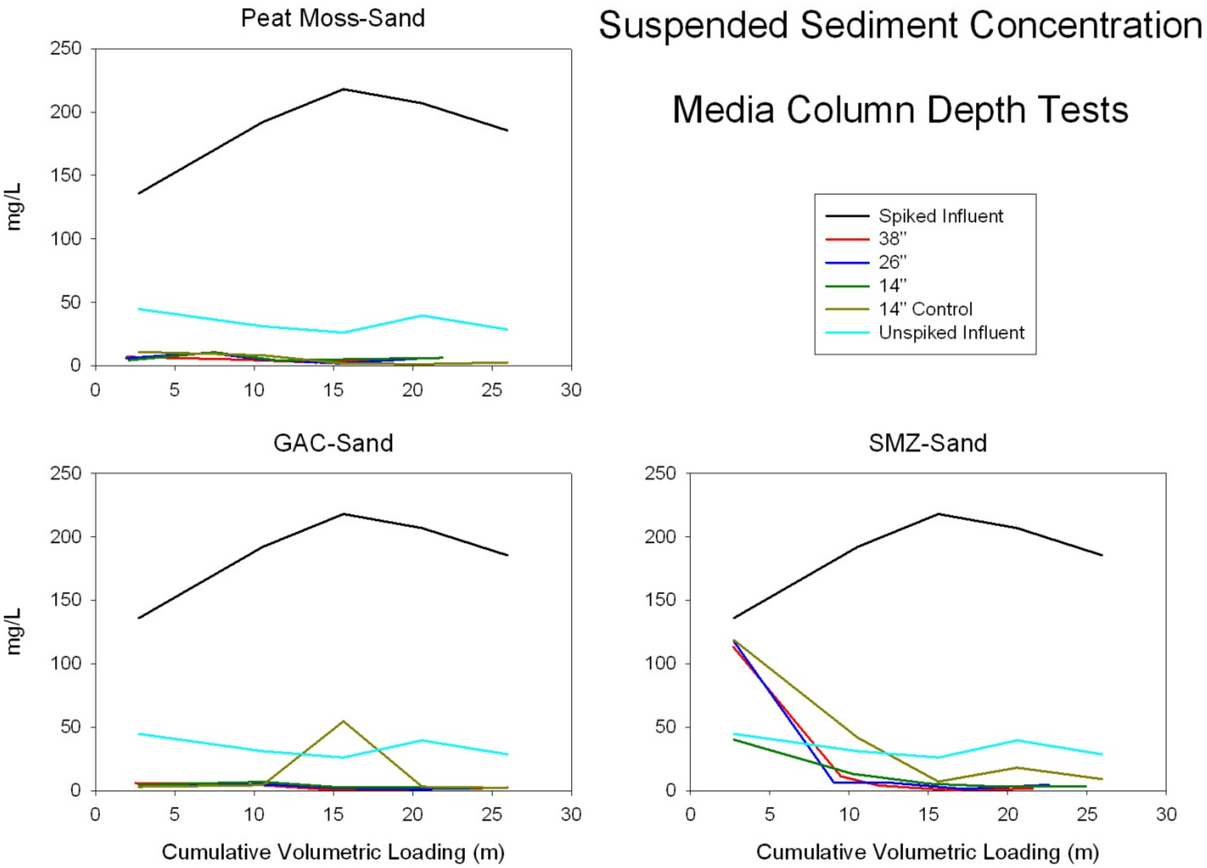


**Figure 4-2. Example SSC Removal Data (as provided in Appendix B)**

The flow rates through the treatment media should be moderate, between about 5 to 35 m/day (to provide suitable contact time for treatment), with a long run time before maintenance is required (and certainly before clogging occurs). Figure 4-1 shows that the site sand's flow rate and clogging loading are too low. The media mixes provide a better balance of the flow rate and maintenance loading requirements. As shown later when discussing the residence times in the varying depth columns, the shorter columns provided more rapid treatment flow rates compared to the columns having deeper media, and, as noted in Figure 4-2, they may not necessarily provide worse treatment for solids. This lack of performance difference between the column heights for solids is not transferable to other pollutants where surface straining is not the primary pollutant removal mechanism.

Treatment flow rates typically decreased over a device's life due to solids capture on the surface of and in the media, as shown on Figure 4-3 for the peat moss column tests.

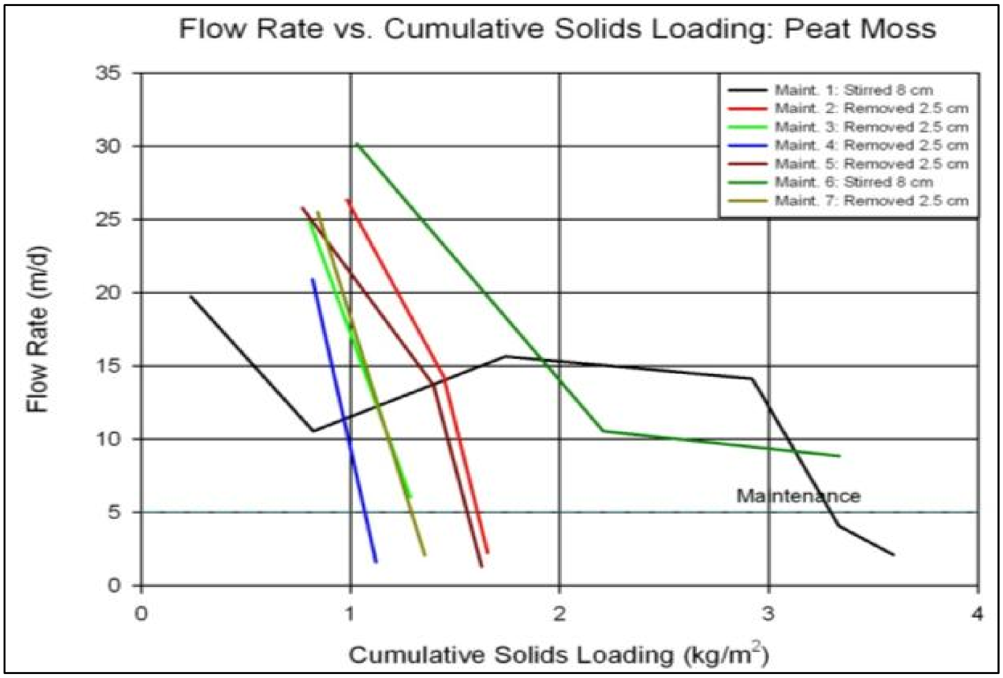


**Figure 4-3. Sequential Maintenance Effects on Flow Rate in Peat Moss Column (Little Benefit while Treatment Flow Rates Continued to Decrease)**

Potential maintenance options once the flow rate decreased to 5 m/d were examined. These options included disturbing the surface of the media versus removing the top several inches of the media. Surface media removal generally was more effective than only disturbing the media surface, but removal of at least 4 – 6 inches was needed because clogging solids are captured deep in the media (deeper than visible solids buildup). However, these maintenance options had relatively minor benefits. As shown on Figure 4-3, the run times after maintenance were only about one-half to one-fourth as long as the run time before the initial maintenance.

Tables 4-1 and 4-2 summarize the flow rate and clogging test results, showing both the sediment load before maintenance and the flows. Because the test columns were 3.5 inches in diameter, it was necessary to apply a scaling factor to translate the data from the small columns to field scale installations. Factors from 3 to 5 have been used in the past to approximate full-scale conditions (Clark and Pitt 1999 and Clark 2000). The original work plan for these tests included parallel full-scale tests (using large roll-off demolition debris storage units filled with media). These tests were not conducted, so the factor of 5 was applied to the table results as an indicator of approximate full-scale results that can be used until the larger tests are conducted.

### Table 4-1. Clogging Conditions Observed during Long-Term Full-Depth Column Tests

| Media, ranked by clogging potential | Cumulative load to initial maintenance, at 5 m/d (kg/m²)* | Cumulative load to clogging, if no maintenance at 1 m/d (kg/m²)* |
|---|---|---|
| Granular Activated Carbon (GAC) | 7 (35) | 7.5 (38) |
| Peat moss | 3.3 (17) | 4 (20) |
| Rhyolite sand | 6.5 33) | 7 (35) |
| Site sand | 0.3 (1.5) | 2 (10) |
| Site zeolite | 3.1 (15) | 3.5 (17) |
| Surface modified zeolite (SMZ) | 4.8(24) | 5.5 (28) |
| Rhyolite sand and surface modified zeolite | 7.5 (38) | 7.5 (38) |
| Rhyolite sand, surface modified zeolite, and granular activated carbon | 9.7 (49) | 10.5 (53) |
| Rhyolite sand, surface modified zeolite, granular activated carbon, and peat moss | 10.5 (53) | 11 (55) |
| MWH sand, MWH Zeolite, and Granular Activated Carbon (layered mixture) | 6.2 (31) | 6.5 (33) |

*Column study results and estimated full-scale results, with 5X factor in parentheses

### Table 4-2. Flow Rates Observed during Long-Term Full-Depth Column Tests

| Media, ranked by clogging potential | Initial flow rate before degradation | | Average flow rate before initial clogging | |
|---|---|---|---|---|
| | m/day | gal/min/ft² | m/day | gal/min/ft² |
| Granular Activated Carbon (GAC) | 25 | 0.058 | 20 | 0.046 |
| Peat moss | 20 | 0.046 | 12 | 0.028 |
| Rhyolite sand | 20 | 0.046 | 15 | 0.035 |
| Site sand | 7 | 0.016 | 3 | 0.007 |
| Site zeolite | 25 | 0.058 | 18 | 0.041 |
| Surface modified zeolite (SMZ) | 17 | 0.039 | 13 | 0.030 |
| Rhyolite sand and surface modified zeolite | 20 | 0.046 | 18 | 0.041 |
| Rhyolite sand, surface modified zeolite, and granular activated carbon | 23 | 0.053 | 20 | 0.046 |
| Rhyolite sand, surface modified zeolite, granular activated carbon, and peat moss | 20 | 0.046 | 18 | 0.041 |
| Site sand, Site Zeolite, and Granular Activated Carbon (layered mixture) | 26 | 0.060 | 14 | 0.032 |

## 4.2 Particulate Removals in the Long-Term Test Columns

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, as previously described. 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. For several of the metals of interest, though, the 90th percentile was still very low and the concentrations were increased to approximately 50 µg/L to ensure that removals could be detected. Generally, these concentrations are substantially lower than industrial wastewater concentrations that have been used in some past testing of treatment media. These test results document the ability of these media to treat runoff at relatively low influent concentrations over time, as well as provide design information for the sizing of the treatment systems, and for estimating the benefits of the sedimentation pre-treatment process. Another challenge in treating stormwater is that influent water chemistry is different from the traditional spiked distilled, deionized or tap water used in the past to test media performance. The influent constituents and their forms (particulate-associated, colloid-associated, organic-bound, dissolved) affect the removal ability of the media. Also the concentrations of the variety will affect performance.

The plots in this section are summarized from the full set of data presented in Appendices A2 through A9. Figure 4-4 shows effluent vs. influent quality as a function of volumetric loading of stormwater, in meters. Using the cumulative loading as a measure of time allows the results to be transferred to other sites. As an example, the nitrite+nitrate and the total chromium plots on Figure 4-4 indicate some breakthrough after about 20 to 40 m of stormwater has been filtered. Not all columns experienced this breakthrough for all constituents, and the time to breakthrough varied among the media and by pollutant. In general, breakthrough occurred last for the metals. For example, the total nickel removals are substantial and consistent for all media, while the total zinc removals interestingly are evident only after about 10 to 20 m of stormwater has been treated. One surprising result was the removal of nitrates by the columns that contained GAC. Past experience has shown that nitrate treatment is very difficult for stormwater runoff unless the system contains vegetation (nutrient uptake) or an anoxic zone (denitrification).

The advantage of analyzing a suite of pollutants, rather than just fewer targeted ones, is that other issues that affect design may become apparent. For example, some past studies of filtration media have assumed that the pollutant removal is not an ion-exchange reaction. As can be seen in this data set, ion exchange is occurring and the uptake on the media of one constituent is concomitant with the release of an equivalent amount of one or more constituents. Past studies did not examine this trade-off. For example, several media release pollutants such as phosphorus, sodium and potassium, potentially in high concentrations. The data analyses presented later in this report 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.

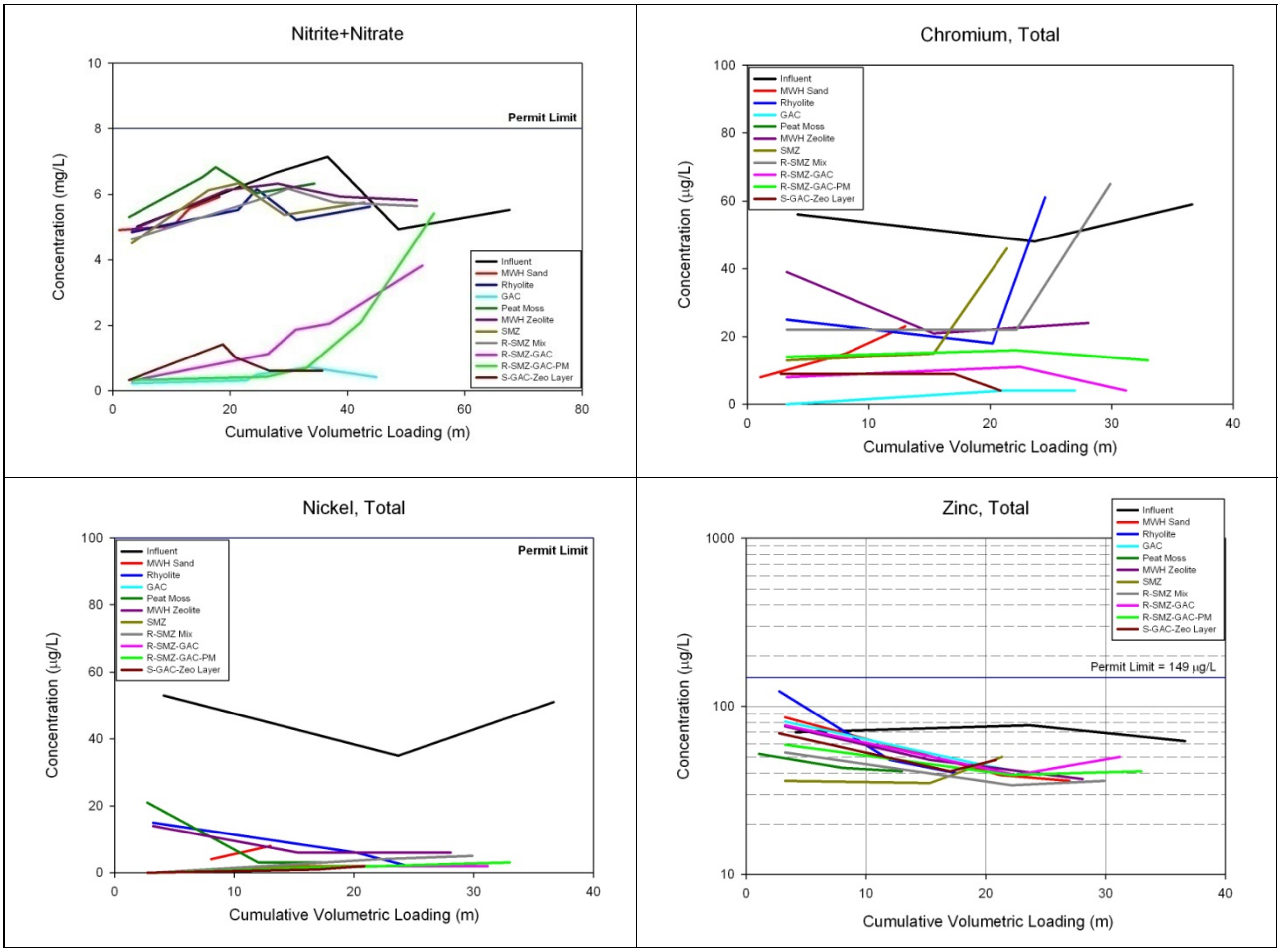


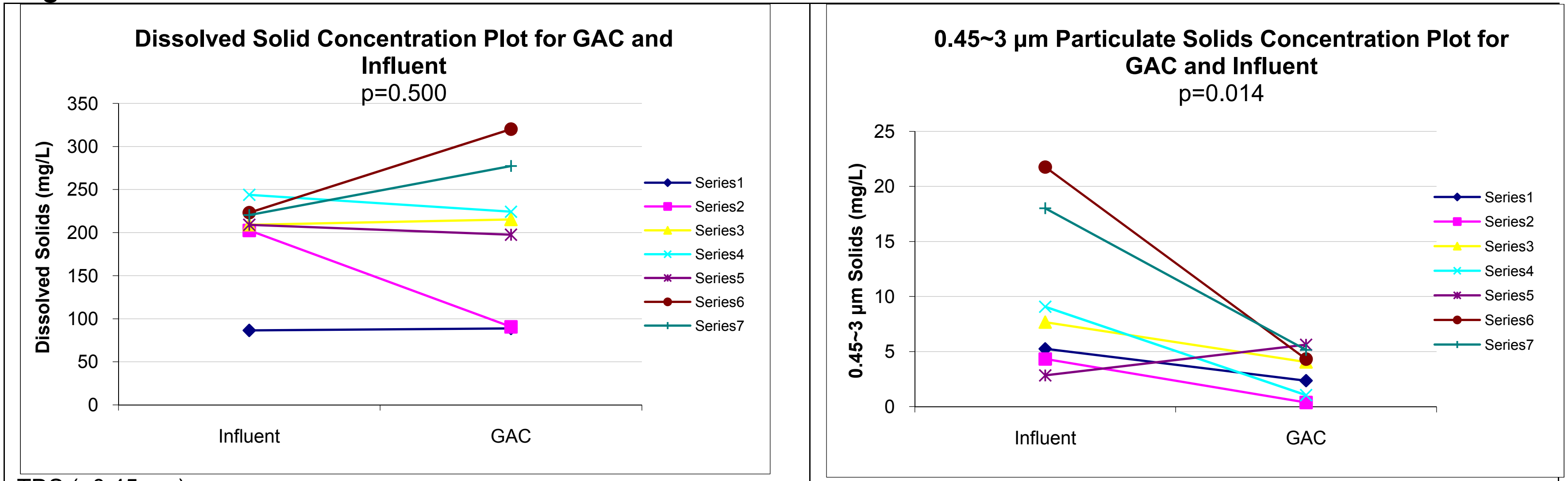
**Figure 4-4. Influent and Effluent Concentrations as a Function of Time for Different Media (from Appendix A3)**

The set of plots shown in Figures 4-5 and 4-6 illustrate how the particulate trapping information was summarized for the column tests and presented in Appendix A6. These plots are only for the granular activated carbon (GAC) and sand mixture column tests. The first set of plots contains line graphs comparing the influent and effluent concentrations for each particle size range. Also shown on each plot is the probability 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 particulate solids reductions are generally quite large, with effluent concentrations limited to a narrow range of values, compared to the wide range of influent concentrations.

The second set of data graphs in Figure 4-6 are paired probability plots showing the influent and effluent concentrations, along with the 95% confidence intervals of the values. Straight lines (and Anderson Darling, AD, test statistic values of $p > 0.05$) indicate that the distribution of the values is normally distributed. Most are normally distributed, but the variance of the influents and effluents are usually quite different (the lines are not parallel and the standard deviations are different).

Regression analyses (with ANOVA and residual evaluations) then were used to evaluate the scatterplots of influent vs. effluent concentrations, as shown Figure 4-7. In most cases, the effluent concentrations are relatively constant and the equations are shown are in the form of effluent = average (coefficient of variation). These are based on the ANOVA analyses that did not indicate any significant slope coefficient for a first order polynomial. In a few cases, where the initial paired tests did not indicate any difference between the influent and effluent concentrations for the number of sample pairs available, the equations are in the simple form of effluent = influent (only seen for some of the TDS data).

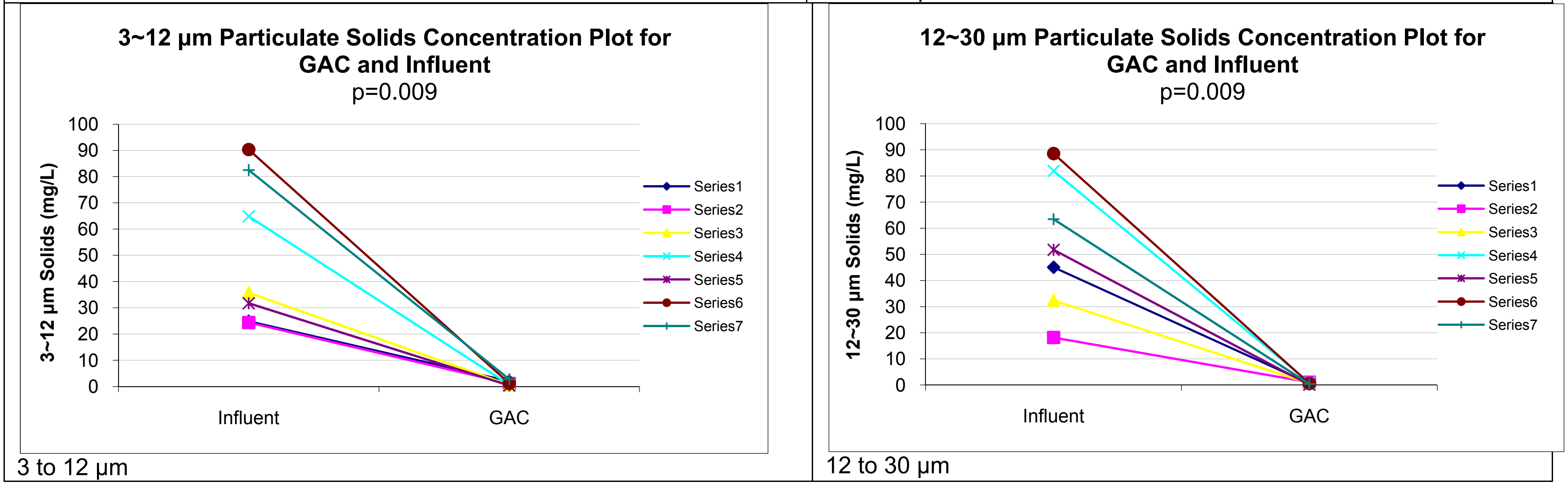
**Figure 4-5. Column Test Results for Granular Activated Carbon Media**


Dissolved Solid Concentration Plot for GAC and Influent
p=0.500

0.45~3 µm Particulate Solids Concentration Plot for GAC and Influent
p=0.014

TDS (<0.45 µm)

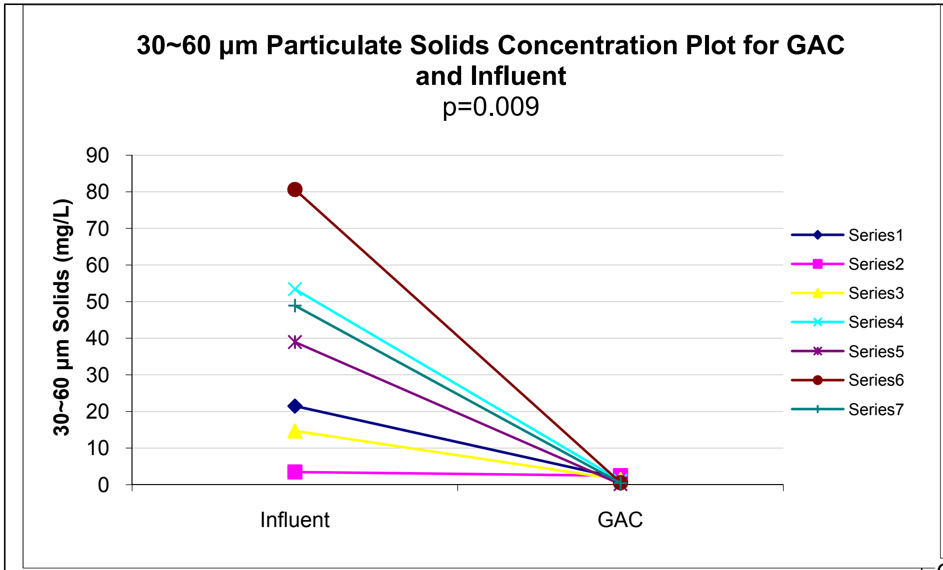
0.45 to 3 µm


3~12 µm Particulate Solids Concentration Plot for GAC and Influent
p=0.009

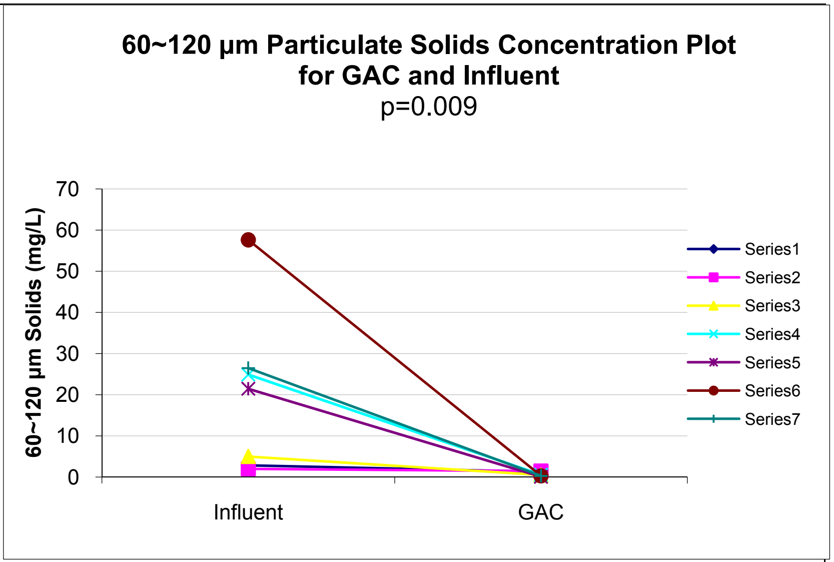
12~30 µm Particulate Solids Concentration Plot for GAC and Influent
p=0.009

3 to 12 µm

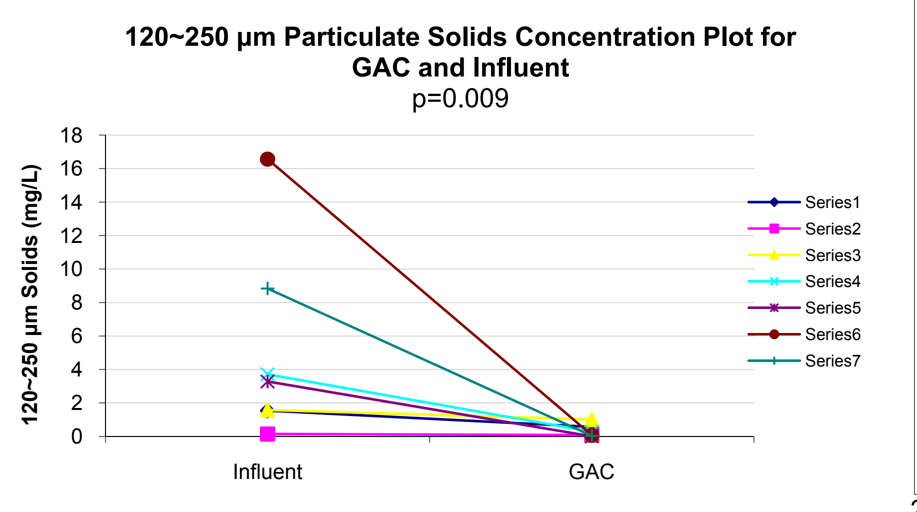
12 to 30 µm



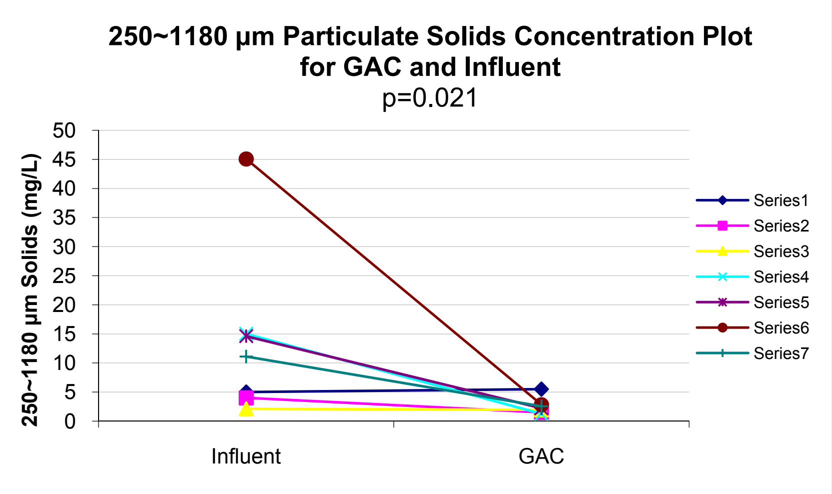
30 to 60 µm



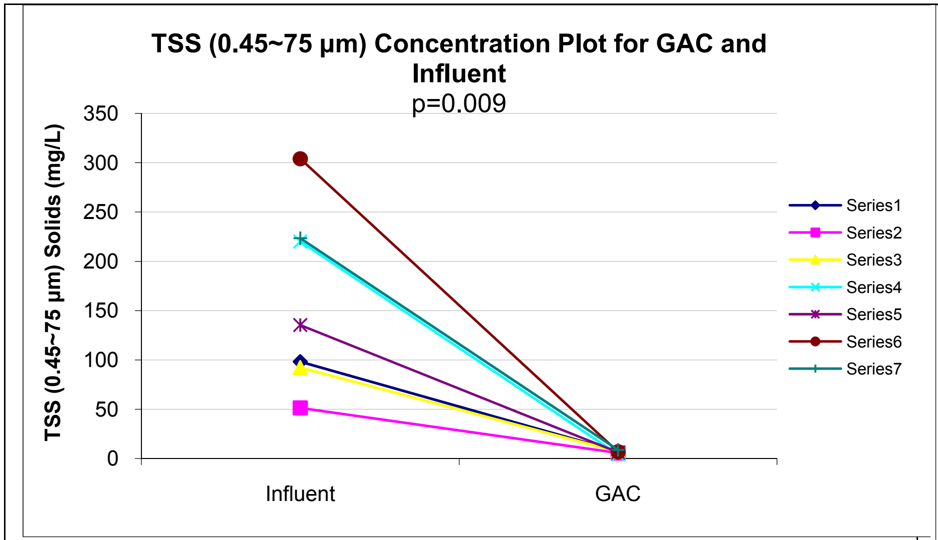
60 to 120 µm



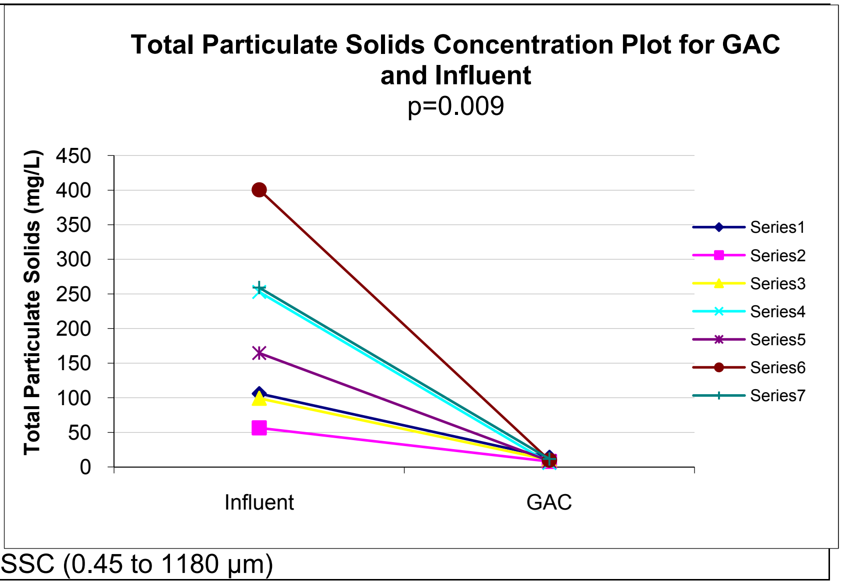
120 to 250 µm



250 to 1180 µm

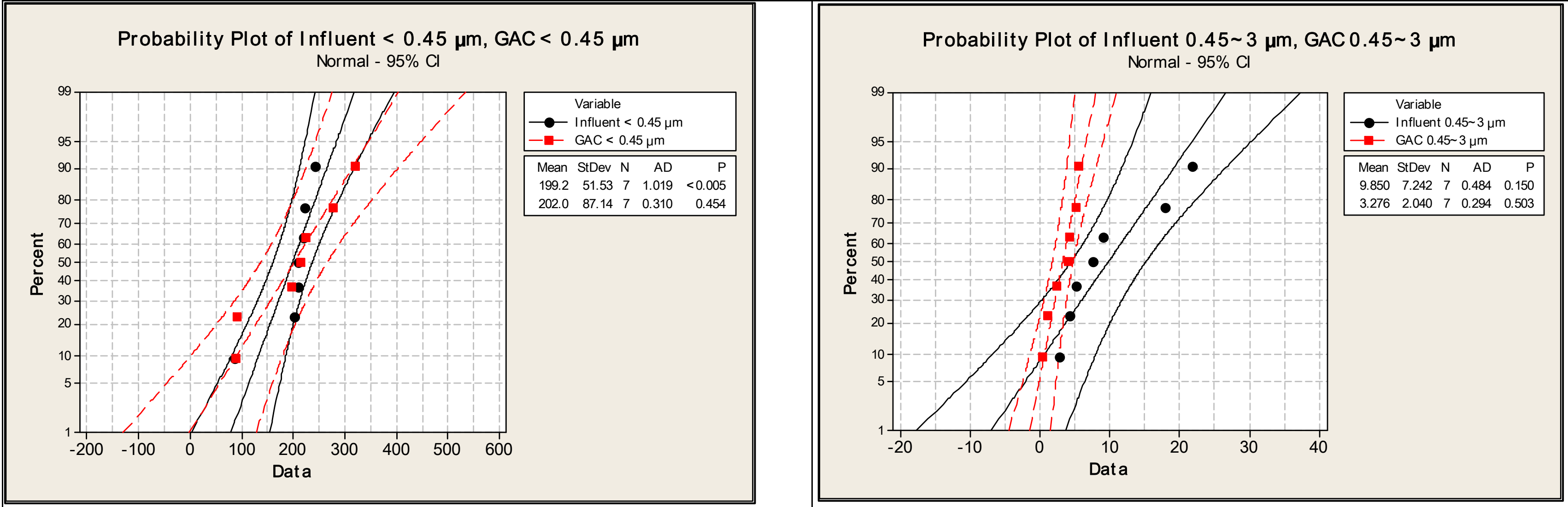


TSS (0.45 to 75 µm)



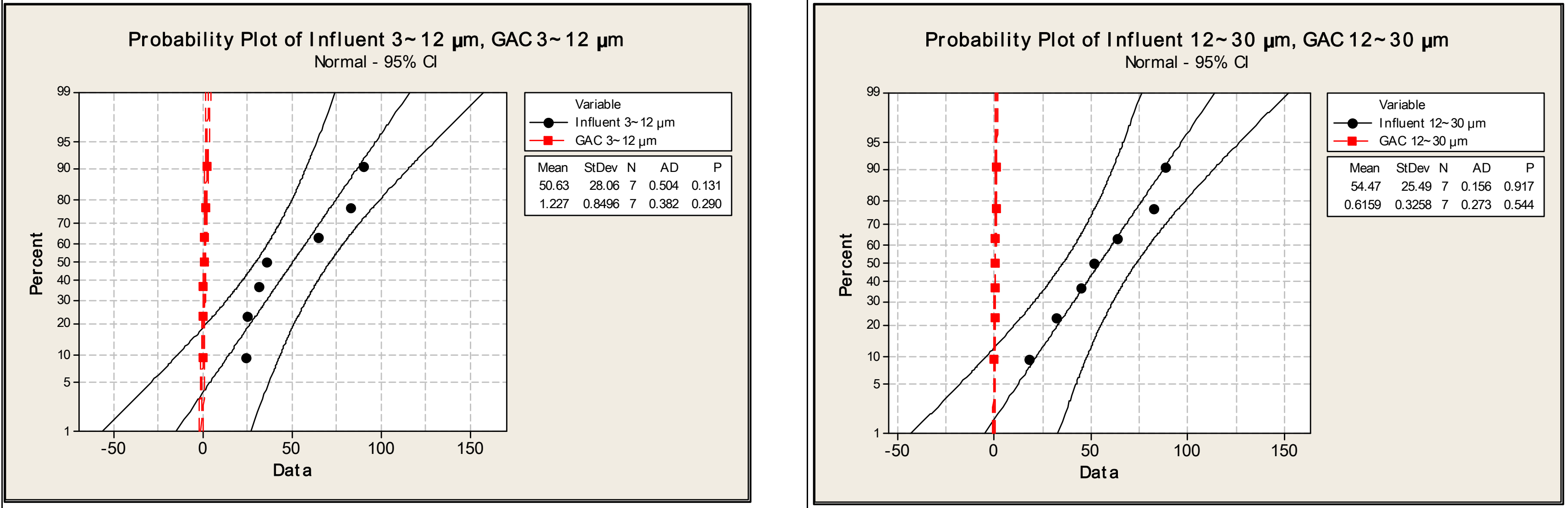
SSC (0.45 to 1180 µm)

## Figure 4-6. Probability Plots of Particulate Removal by Particle Size for GAC



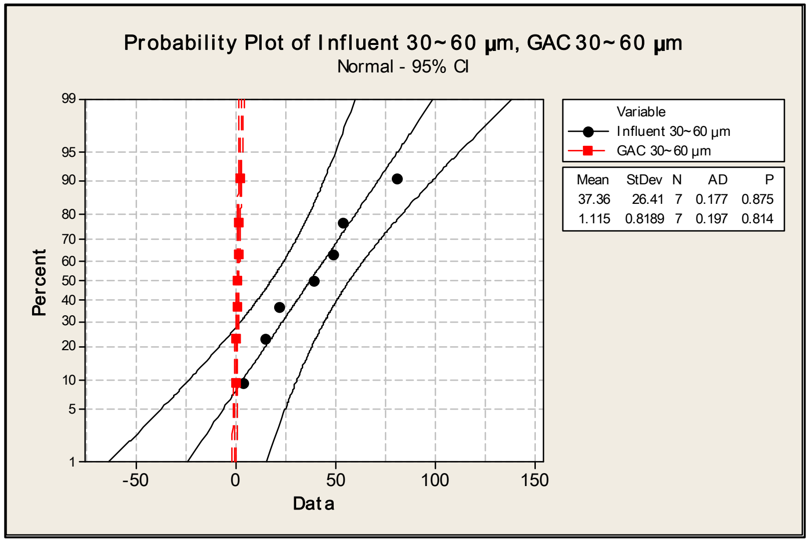
TDS (<0.45 µm)

0.45 to 3 µm

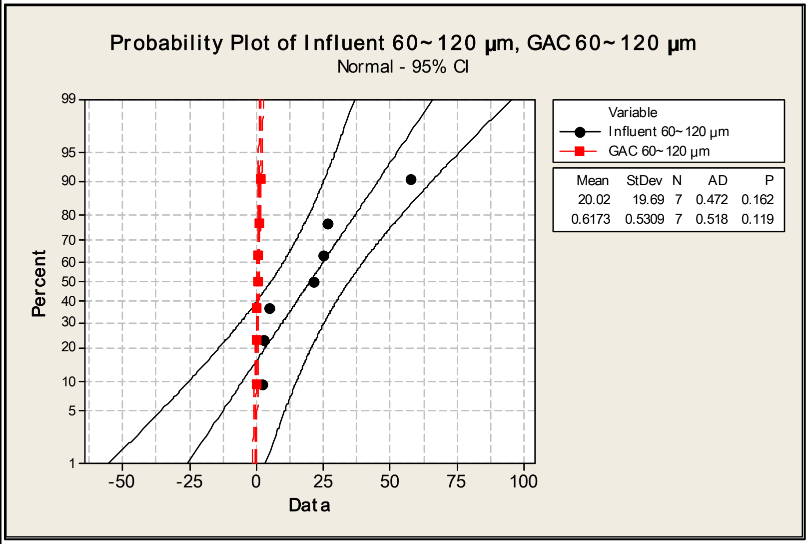


3 to 12 µm

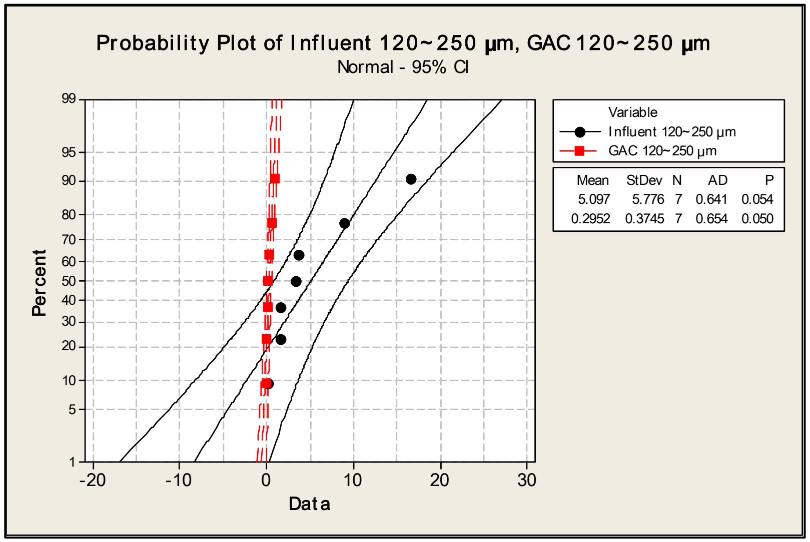
12 to 30 µm



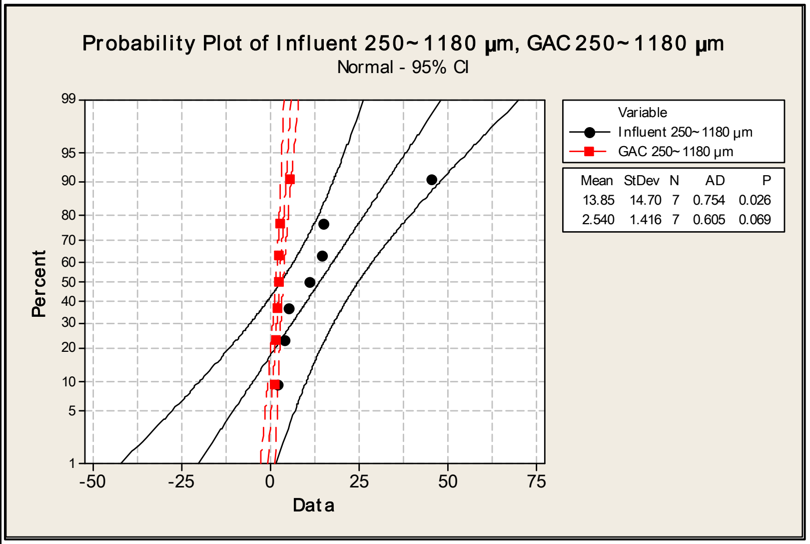
30 to 60 µm



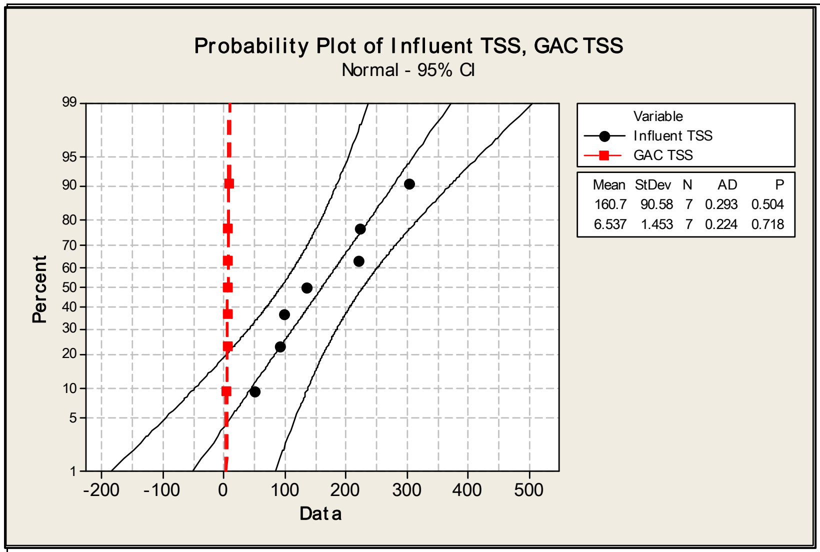
60 to 120 µm



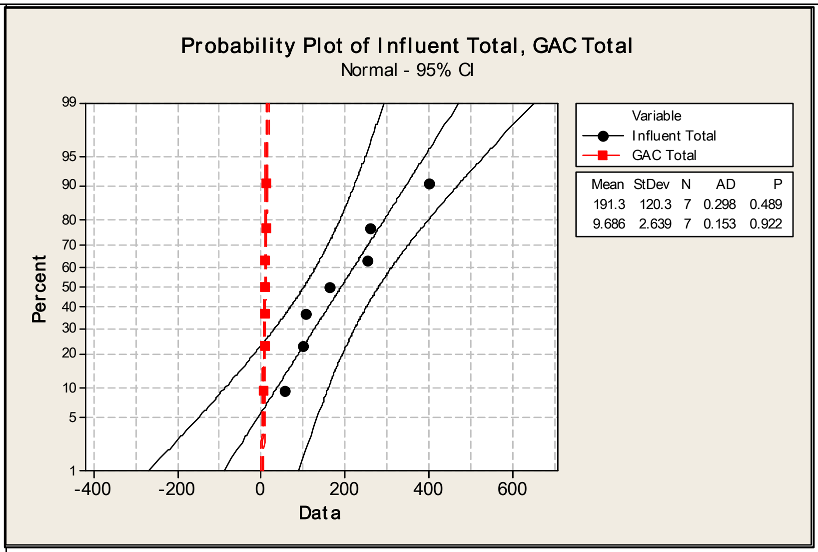
120 to 250 µm



250 to 1180 µm

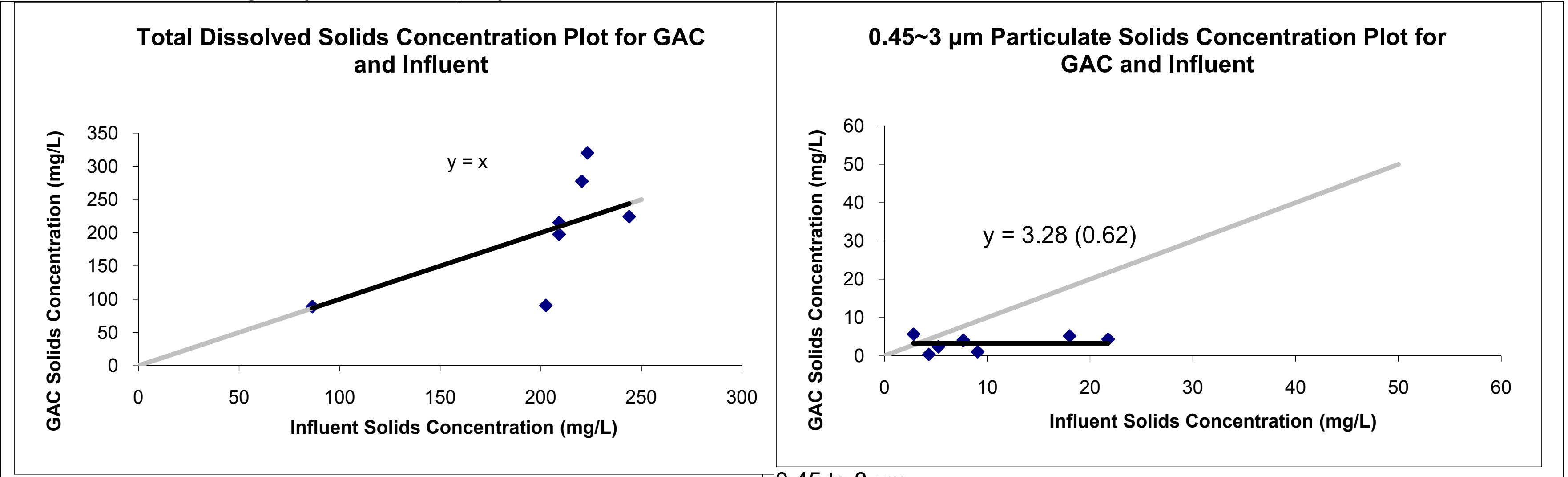


TSS (0.45 to 75 µm)



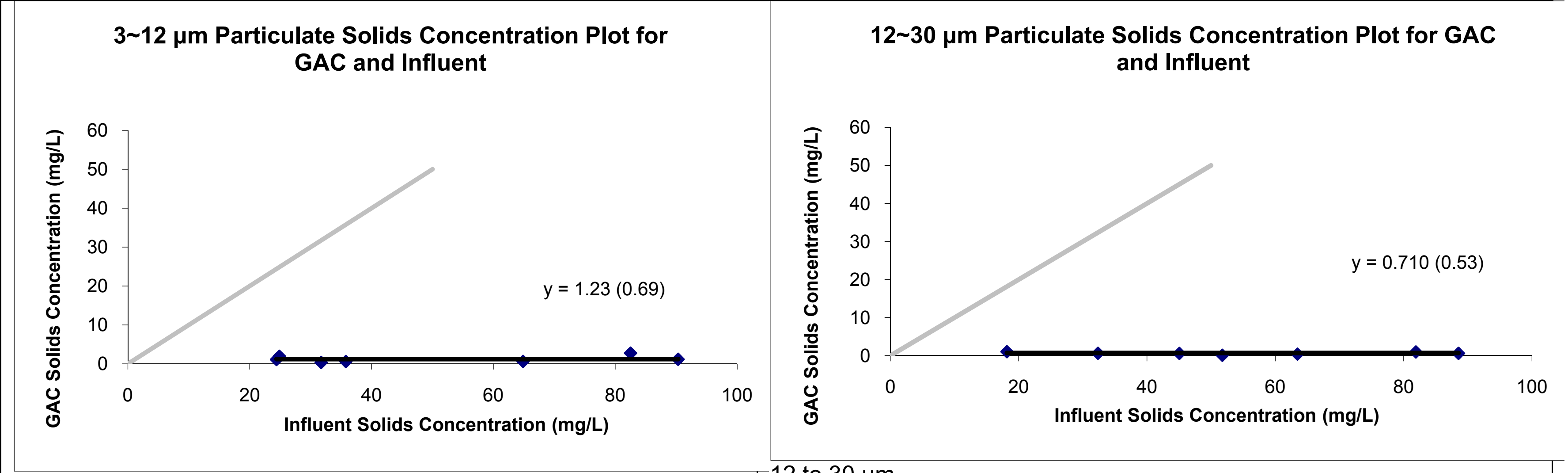
SSC (0.45 to 1180 µm

**Figure 4-7. Scatterplots and Regression Equations Relating Effluent to Influent Solids Concentration for Different Particle Size Ranges (GAC Example)**



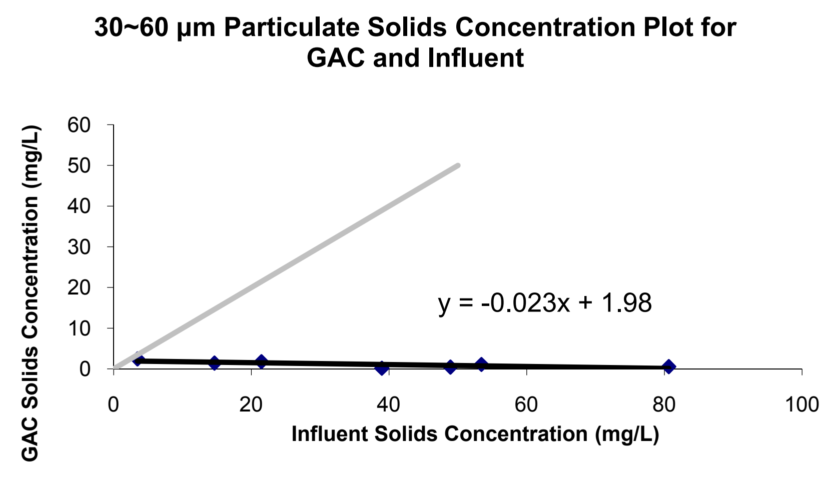
TDS (<0.45 µm)

0.45 to 3 µm

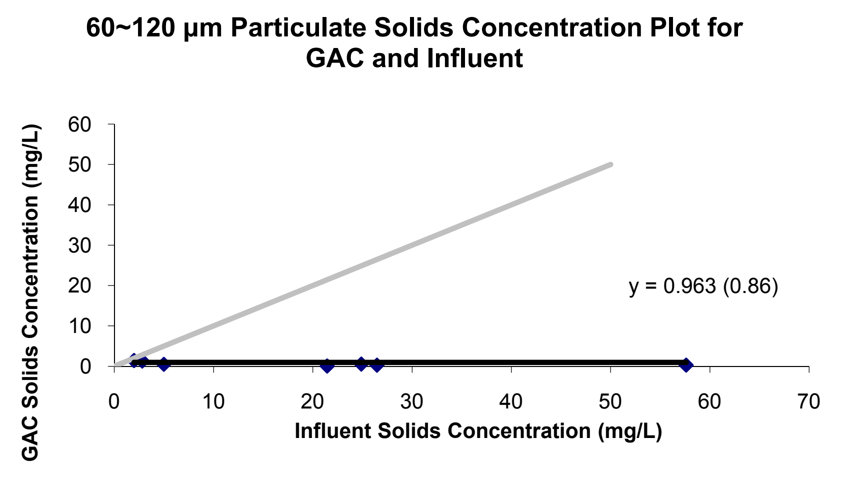


3 to 12 µm

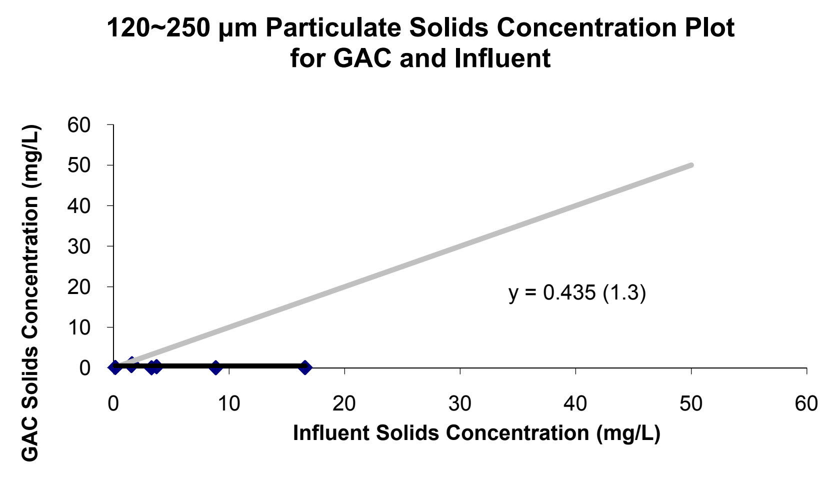
12 to 30 µm



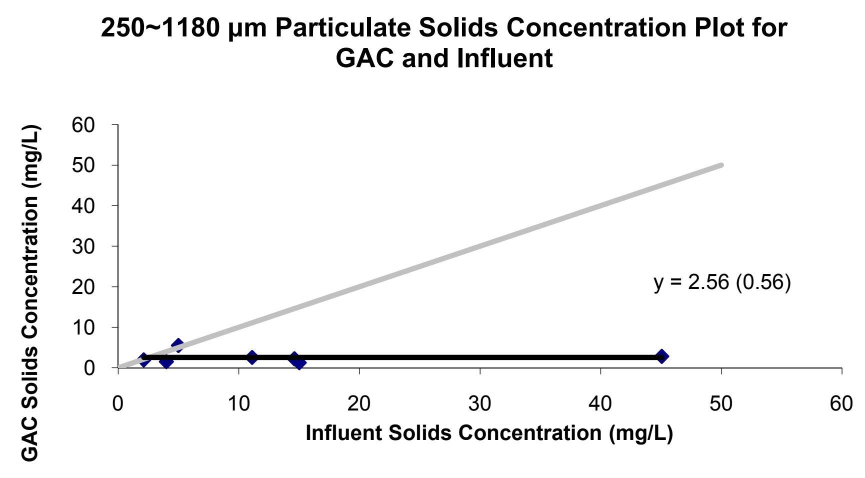
30 to 60 µm



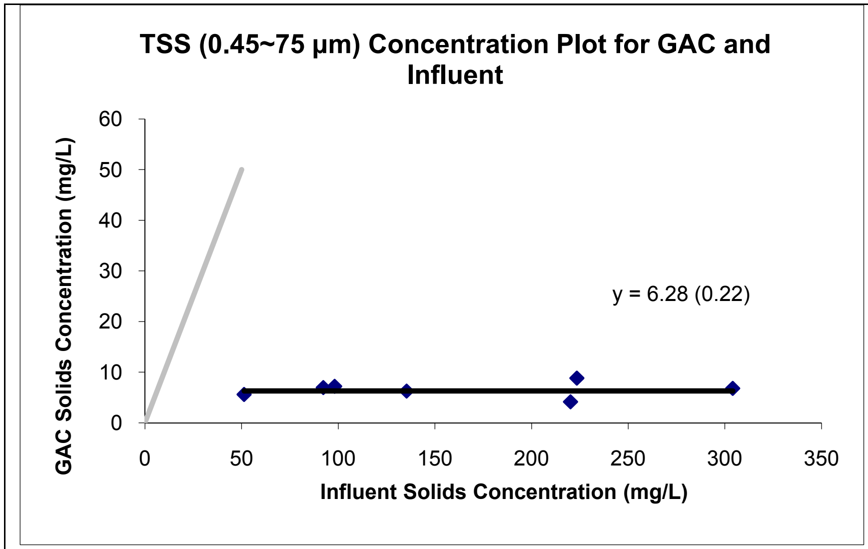
60 to 120 µm



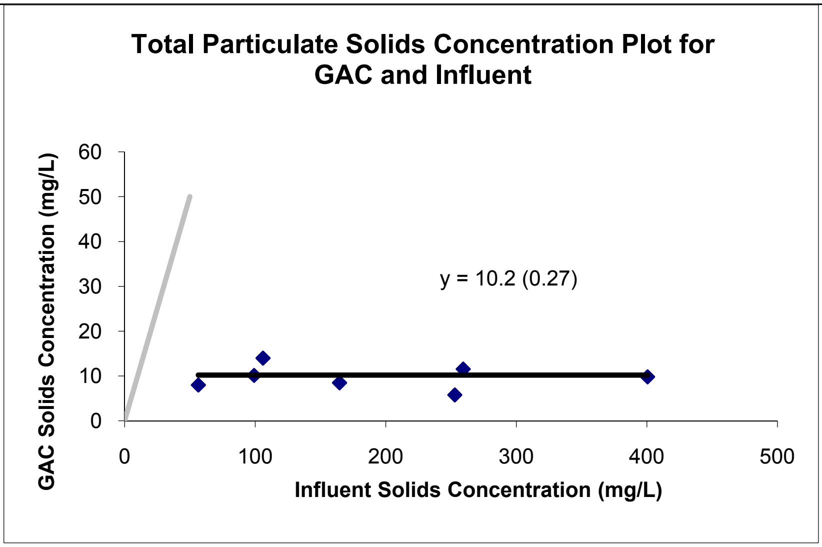
120 to 250 µm



250 to 1180 µm



TSS (0.45 to 75 µm)



SSC (0.45 to 1180 µm)

All of the media tested were very effective at removing a wide range of particle sizes. Figure 4-8 shows the removals for very small (0.45 to 3 µm) particles and for larger (12 to 30 µm) particles by the GAC media, as a representative material. Detailed information for all media types tested is presented in Appendix A6.

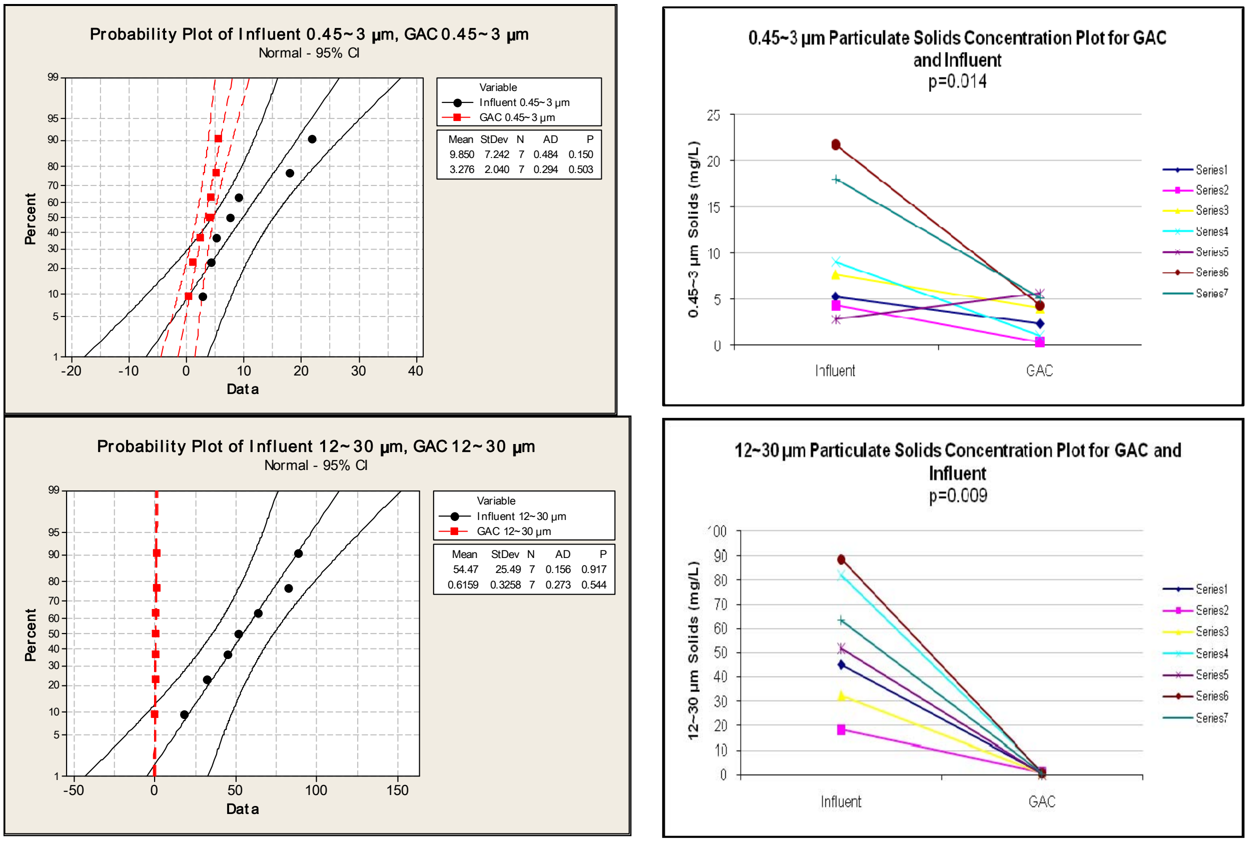


**Figure 4-8. Effluent Particle Size Concentration Comparison (GAC Example, from Appendix A6)**

Tables 4-3 through 4-12 show the influent and effluent concentrations for the different particle size ranges for the different media tested. As expected, the levels of control for the particles larger than 3 µm is almost complete (>90% reductions) for a wide range of influent conditions. The TSS effluent concentrations were in the 5 to 20 mg/L concentration range, with influent TSS concentrations ranging from 50 to 310 mg/L.

## Table 4-3. Granular Activated Carbon (GAC) Removal by Particle Size Range

| Particle Size (µm) | Mean Influent Concentration (mg/L) (approximate range) | Mean Effluent Concentration (mg/L) | Reduction (%) |
|---|---|---|---|
| < 0.45 | 199 (80 to 250) | 202 | 0* |
| 0.45 to 3 | 9.9 (3 to 22) | 3.3 | 67 |
| 3 to 12 | 50.6 (22 to 90) | 1.2 | 98 |
| 12 to 30 | 54.5 (18 to 90) | 0.62 | 99 |
| 30 to 60 | 37.4 (3 to 80) | 1.1 | 97 |
| 60 to 120 | 20.0 (2 to 58) | 0.62 | 97 |
| 120 to 250 | 5.1 (0 to 17) | 0.30 | 94 |
| 250 to 1180 | 13.9 (3 to 45) | 2.5 | 82 |
| > 1180 | n/a (no particles in this size range observed | n/a (no particles in this size range observed | n/a |
| SSC | 191 (50 to 400) | 9.7 | 95 |
| TSS (0.45 to 75 µm) | 161 (50 to 310) | 6.5 | 96 |

## Table 4-4. Surface Modified Zeolite (SMZ) Removal by Particle Size Range

| Particle Size (µm) | Mean Influent Concentration (mg/L) (approximate range) | Mean Effluent Concentration (mg/L) | Reduction (%) |
|---|---|---|---|
| < 0.45 | 199 (80 to 250) | 232 | 0* |
| 0.45 to 3 | 9.9 (3 to 22) | 3.8 | 62 |
| 3 to 12 | 50.6 (22 to 90) | 1.6 | 97 |
| 12 to 30 | 54.5 (18 to 90) | 0.74 | 99 |
| 30 to 60 | 37.4 (3 to 80) | 1.3 | 97 |
| 60 to 120 | 20.0 (2 to 58) | 0.97 | 95 |
| 120 to 250 | 5.1 (0 to 17) | 0.19 | 96 |
| 250 to 1180 | 13.9 (3 to 45) | 3.1 | 78 |
| > 1180 | n/a (no particles in this size range observed | n/a (no particles in this size range observed | n/a |
| SSC | 191 (50 to 400) | 11.7 | 94 |
| TSS (0.45 to 75 µm) | 161 (50 to 310) | 8.0 | 95 |

*The influent and effluent were not significantly different

## Table 4-5. Rhyolite Sand (R) Removal by Particle Size Range

| Particle Size (µm) | Mean Influent Concentration (mg/L) (approximate range) | Mean Effluent Concentration (mg/L) | Reduction (%) |
|---|---|---|---|
| < 0.45 | 199 (80 to 250) | 228 | 0* |
| 0.45 to 3 | 10.6 (3 to 22) | 6.1 | 0* |
| 3 to 12 | 54.9 (22 to 90) | 1.7 | 97 |
| 12 to 30 | 54.5 (18 to 90) | 1.2 | 98 |
| 30 to 60 | 37.4 (3 to 80) | 2.4 | 94 |
| 60 to 120 | 20.0 (2 to 58) | 1.07 | 95 |
| 120 to 250 | 5.1 (0 to 17) | 0.31 | 94 |
| 250 to 1180 | 13.9 (3 to 45) | 3.8 | 73 |
| > 1180 | n/a (no particles in this size range observed | n/a (no particles in this size range observed | n/a |
| SSC | 206 (50 to 400) | 13.4 | 93 |
| TSS (0.45 to 75 µm) | 171 (50 to 310) | 10.2 | 94 |

## Table 4-6. Rhyolite Sand - Surface Modified Zeolite - Granular Activated Carbon (R-SMZ-GAC) Removals by Particle Size Range

| Particle Size (µm) | Mean Influent Concentration (mg/L) (approximate range) | Mean Effluent Concentration (mg/L) | Reduction (%) |
|---|---|---|---|
| < 0.45 | 199 (80 to 250) | 225 | 0* |
| 0.45 to 3 | 9.9 (3 to 22) | 7.2 | 0* |
| 3 to 12 | 54.9 (22 to 90) | 2.9 | 95 |
| 12 to 30 | 54.5 (18 to 90) | 0.67 | 99 |
| 30 to 60 | 37.4 (3 to 80) | 1.0 | 97 |
| 60 to 120 | 20.0 (2 to 58) | 0.76 | 96 |
| 120 to 250 | 5.1 (0 to 17) | 0.08 | 98 |
| 250 to 1180 | 13.9 (3 to 45) | 4.1 | 71 |
| > 1180 | n/a (no particles in this size range observed | n/a (no particles in this size range observed | n/a |
| SSC | 206 (50 to 400) | 13.6 | 93 |
| TSS (0.45 to 75 µm) | 171 (50 to 310) | 10.2 | 94 |

## Table 4-7. Layered Site Sand - Site Zeolite - Granular Activated Carbon (S-Z-GAC) Removals by Particle Size Range

| Particle Size (µm) | Mean Influent Concentration (mg/L) (approximate range) | Mean Effluent Concentration (mg/L) | Reduction (%) |
|---|---|---|---|
| < 0.45 | 199 (80 to 250) | 249 | 0* |
| 0.45 to 3 | 9.9 (3 to 22) | 2.3 | 77 |
| 3 to 12 | 50.6 (22 to 90) | 1.4 | 97 |
| 12 to 30 | 54.5 (18 to 90) | 0.64 | 99 |
| 30 to 60 | 37.4 (3 to 80) | 1.1 | 97 |
| 60 to 120 | 20.0 (2 to 58) | 0.44 | 98 |
| 120 to 250 | 5.1 (0 to 17) | 0.14 | 97 |
| 250 to 1180 | 13.9 (3 to 45) | 2.2 | 84 |
| > 1180 | n/a (no particles in this size range observed | n/a (no particles in this size range observed | n/a |
| SSC | 191 (50 to 400) | 8.2 | 96 |
| TSS (0.45 to 75 µm) | 161 (50 to 310) | 5.6 | 97 |

## Table 4-8. Site Zeolite (Z) Removals by Particle Size Range

| Particle Size (µm) | Mean Influent Concentration (mg/L) (approximate range) | Mean Effluent Concentration (mg/L) | Reduction (%) |
|---|---|---|---|
| < 0.45 | 198 (80 to 250) | 183 | 0* |
| 0.45 to 3 | 9.9 (3 to 22) | 2.5 | 75 |
| 3 to 12 | 50.6 (22 to 90) | 1.6 | 97 |
| 12 to 30 | 54.5 (18 to 90) | 0.78 | 99 |
| 30 to 60 | 37.4 (3 to 80) | 1.0 | 97 |
| 60 to 120 | 20.0 (2 to 58) | 0.73 | 96 |
| 120 to 250 | 5.1 (0 to 17) | 0.20 | 96 |
| 250 to 1180 | 13.9 (3 to 45) | 2.9 | 79 |
| > 1180 | n/a (no particles in this size range observed | n/a (no particles in this size range observed | n/a |
| SSC | 191 (50 to 400) | 9.7 | 95 |
| TSS (0.45 to 75 µm) | 161 (50 to 310) | 6.3 | 96 |

## Table 4-9. Peat Moss (PM) Removals by Particle Size Range

| Particle Size (µm) | Mean Influent Concentration (mg/L) (approximate range) | Mean Effluent Concentration (mg/L) | Reduction (%) |
|---|---|---|---|
| < 0.45 | 199 (80 to 250) | 216 | 0* |
| 0.45 to 3 | 10.6 (3 to 22) | 4.7 | 0* |
| 3 to 12 | 54.9 (22 to 90) | 0.5 | 99 |
| 12 to 30 | 54.5 (18 to 90) | 1.3 | 98 |
| 30 to 60 | 37.4 (3 to 80) | 1.6 | 96 |
| 60 to 120 | 20.0 (2 to 58) | 1.0 | 95 |
| 120 to 250 | 5.1 (0 to 17) | 0.27 | 95 |
| 250 to 1180 | 13.9 (3 to 45) | 3.5 | 75 |
| > 1180 | n/a (no particles in this size range observed | n/a (no particles in this size range observed | n/a |
| SSC | 206 (50 to 400) | 9.9 | 94 |
| TSS (0.45 to 75 µm) | 171 (50 to 310) | 7.1 | 96 |

## Table 4-10. Rhyolite - Surface Modified Zeolite - Granular Activated Carbon - Peat Moss (R-SMZ-GAC-PM) Removals by Particle Size Range

| Particle Size (µm) | Mean Influent Concentration (mg/L) (approximate range) | Mean Effluent Concentration (mg/L) | Reduction (%) |
|---|---|---|---|
| < 0.45 | 199 (80 to 250) | 205 | 0* |
| 0.45 to 3 | 9.9 (3 to 22) | 4.8 | 52 |
| 3 to 12 | 50.6 (22 to 90) | 2.6 | 95 |
| 12 to 30 | 54.5 (18 to 90) | 0.48 | 99 |
| 30 to 60 | 37.4 (3 to 80) | 0.97 | 97 |
| 60 to 120 | 20.0 (2 to 58) | 0.78 | 96 |
| 120 to 250 | 5.1 (0 to 17) | 0.15 | 97 |
| 250 to 1180 | 13.9 (3 to 45) | 2.8 | 80 |
| > 1180 | n/a (no particles in this size range observed | n/a (no particles in this size range observed | n/a |
| SSC | 191 (50 to 400) | 12.6 | 93 |
| TSS (0.45 to 75 µm) | 161 (50 to 310) | 14.5 | 91 |

**Table 4-11. Rhyolite - Surface Modified Zeolite (R-SMZ) Removals by Particle Size Range**

| Particle Size (µm) | Mean Influent Concentration (mg/L) (approximate range) | Mean Effluent Concentration (mg/L) | Reduction (%) |
|---|---|---|---|
| < 0.45 | 198 (80 to 250) | 196 | 0* |
| 0.45 to 3 | 9.9 (3 to 22) | 12.2 | 0* |
| 3 to 12 | 50.6 (22 to 90) | 5.0 | 90 |
| 12 to 30 | 54.5 (18 to 90) | 0.76 | 99 |
| 30 to 60 | 37.4 (3 to 80) | 1.5 | 96 |
| 60 to 120 | 20.0 (2 to 58) | 1.3 | 94 |
| 120 to 250 | 5.1 (0 to 17) | 0.19 | 96 |
| 250 to 1180 | 13.9 (3 to 45) | 4.9 | 65 |
| > 1180 | n/a (no particles in this size range observed | n/a (no particles in this size range observed | n/a |
| SSC | 191 (50 to 400) | 25.8 | 96 |
| TSS (0.45 to 75 µm) | 161 (50 to 310) | 20.1 | 88 |

**Table 4-12. Site Sand (S) Removals by Particle Size Range**

| Particle Size (µm) | Mean Influent Concentration (mg/L) (approximate range) | Mean Effluent Concentration (mg/L) | Reduction (%) |
|---|---|---|---|
| < 0.45 | 199 (80 to 250) | 202 | 0* |
| 0.45 to 3 | 9.9 (3 to 22) | 3.2 | 68 |
| 3 to 12 | 50.6 (22 to 90) | 2.4 | 95 |
| 12 to 30 | 54.5 (18 to 90) | 1.6 | 97 |
| 30 to 60 | 37.4 (3 to 80) | 1.8 | 95 |
| 60 to 120 | 20.0 (2 to 58) | 1.3 | 94 |
| 120 to 250 | 5.1 (0 to 17) | 0.30 | 94 |
| 250 to 1180 | 14.4 (3 to 45) | 2.6 | 82 |
| > 1180 | n/a (no particles in this size range observed | n/a (no particles in this size range observed | n/a |
| SSC | 191 (50 to 400) | 13.3 | 93 |
| TSS (0.45 to 75 µm) | 161 (50 to 310) | 9.5 | 94 |

## *4.3 Removals of Chemical Constituents during the Media Tests*

Table 4-13 shows the media combinations that had the most significant removals of selected constituents. The significance levels were determined using the paired sign test comparing the influent vs. the effluent water quality. Because of the small number of replicate observations during these tests, the confidence level used for this table is generally at p=0.1, and lower. The yellow highlighted columns are the constituents of greatest concern at the site monitoring locations.

The limitation of using this selected statistical test is that it assumes the observations are independent, i.e., the assumption that prior removals and retention on the media does not affect the ability of the media to remove pollutants from future runoff flows. For treatment using bioretention, where the chemical removal mechanisms are used, this independence assumption is only truly valid during the media's early life. When the filter run is sufficiently long enough to approach chemical breakthrough, this assumption is not correct. In this instance, however, using a statistical test such as this one to predict statistically significant removals should provide a conservative estimate of performance. If breakthrough was achieved during the run, then several observations would show no removal and potentially would show leaching/release of previously-trapped pollutants. This lack of removal would cause a statistical result that indicated that no significant removal occurred in the media. The second limitation of this test is that these results are valid only through the run length of the column testing (60 to 80 m of volumetric loading, depending on the media mix).

**Table 4-13. Significant Contaminant Removals during Full-depth, Long-Term Column Studies**

| **Media Type** | **SSC** | **As, B** | **Cr, Cu, Sb, Al** | **Pb** | **Zn** | **Mn** | **Cd, Ni, Tl, Fe** | **Hg** | **$NO_3$** | **TN** | **TP** | **TCDD** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R-SMZ | T | | **T** | **T** | **T** | T | **T**, F | T | | | T | |
| R-SMZ-GAC | T | T, F | **T,** F | **T** | **T** | T, F | **T**, F | T | T | T | | **T** |
| R-SMZ-GAC-PM | T | T, F | **T,** F | **T** | **T** | T | **T**, F | T | | T | | **T** |
| S-Z-GAC (layered) | T | T, F | **T,** F | | **T** | T, F | **T**, F | T | T | | | **T** |

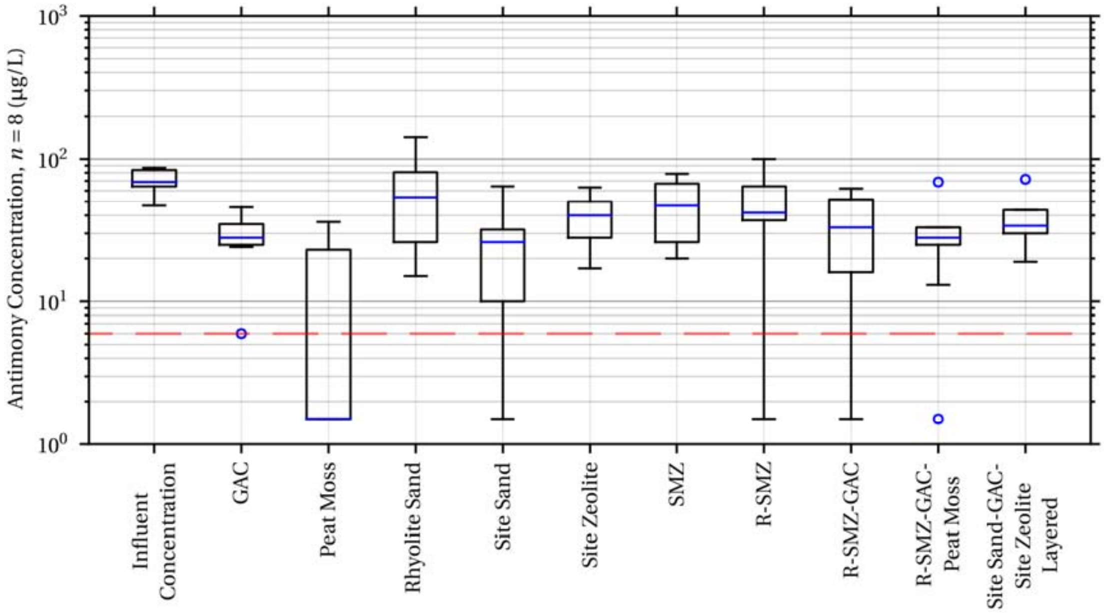
R = rhyolite; SMZ = surface modified zeolite; GAC = granular activated carbon;
PM = peat moss; S = site sand; Z = site zeolite

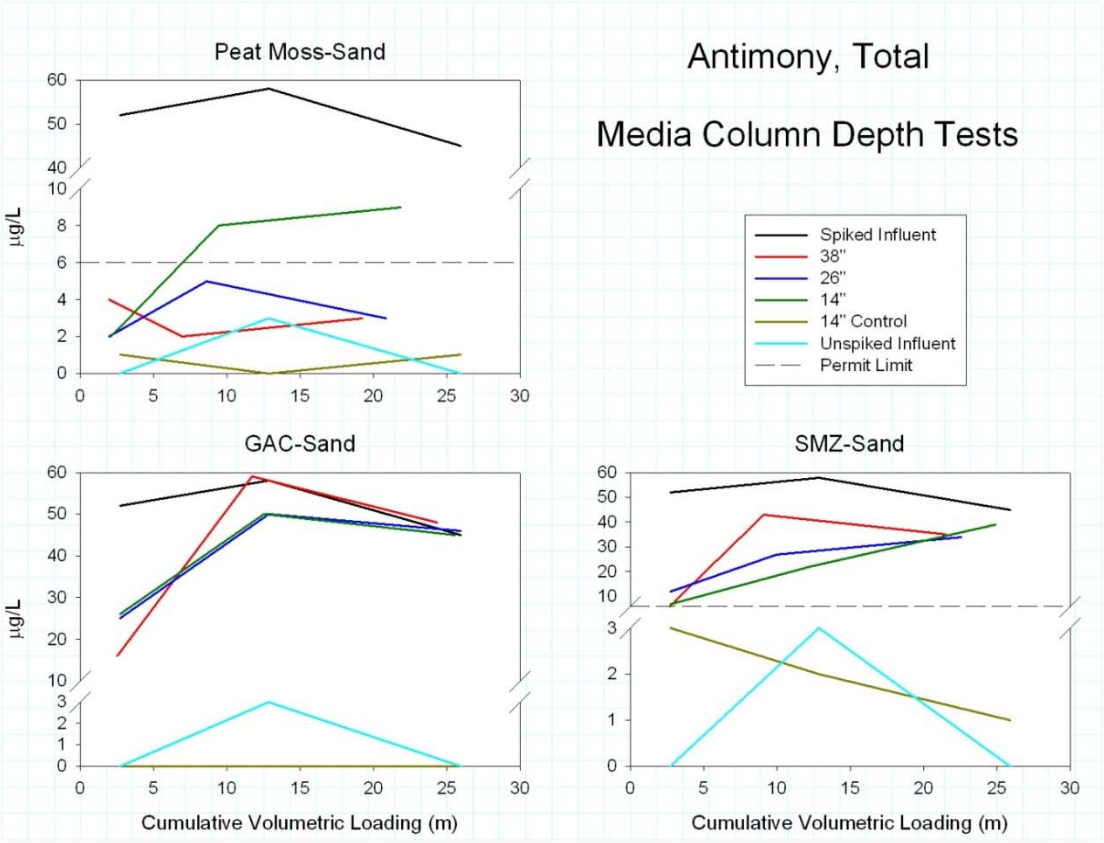
T = removal for total form (unfiltered);
F = removal for filtered form (passed through 0.45 μm membrane filter)

In terms of statistically significant removals, both R-SMZ-GAC and S-Z-GAC (layered) media combinations performed similarly, although the current site layered media combination didn't demonstrate statistically significant removals for lead. As shown in the detailed test results later in this report, the bioretention media combinations met all current site permit limits, except for copper and mercury during peak conditions, and had significant removals for all constituents measured, except for phosphorus and for the very low gross beta radioactivity levels. The current site layered media combination resulted in all effluent samples meeting the current site permit limits, except for a slightly elevated pH, when maximum site runoff conditions were considered. In addition, most of the media combinations removed copper and lead to permit limits (filtered removals were not considered since they are not on the permit). Also, any media combination that included GAC was effective for TCDD removal.

### 4.3.1 Removal of Chemical Constituents during Column Tests

Figures 4-9 through 4-17 are box and whisker plots that summarize the removal performance for the most critical constituents that have exceeded current site benchmark limits during past monitoring. Box and whisker plots have the same limitations that are described above for the statistical tests; similar to the statistical tests, box-and-whisker differences may be a conservative estimate of performance. For many parameters where breakthrough was approached, the removal performance, after initial flushing of the media after construction, was excellent to start and, as removal sites were filled, the removal performance decreased and the effluent concentration increased. Figures 4-18 through 4-24 show the removal performance data for constituents that may exceed current site benchmark limits during extended monitoring. Also shown are the line plots indicating removals during the separate varying depth column tests that indicate similar removal abilities. The variable column graphs for the media components found to most influence removal performance and for the mixes of interest also indicate for each pollutant the influence of contact time (as indicated by column depth) on treatment ability. Appendix A11 contains the probability plots of influent and effluent concentrations for most of the constituents of greatest concern. Probability plots are shown for constituents where there is sufficient data to create a valid analysis. Several parameters are not shown because many of the effluent concentrations were at or below the analytical detection limit.


Antimony Concentration, $n = 8$ (µg/L)
$10^3$
$10^2$
$10^1$
$10^0$
Influent Concentration
GAC
Peat Moss
Rhyolite Sand
Site Sand
Site Zeolite
SMZ
R-SMZ
R-SMZ-GAC
R-SMZ-GAC-Peat Moss
Site Sand-GAC-Site Zeolite Layered


Antimony, Total
Media Column Depth Tests
Peat Moss-Sand
GAC-Sand
SMZ-Sand
µg/L
60
50
40
30
20
10
8
6
4
2
3
1
0
0
5
10
15
20
25
30
Cumulative Volumetric Loading (m)
Spiked Influent
38"
26"
14"
14" Control
Unspiked Influent
Permit Limit

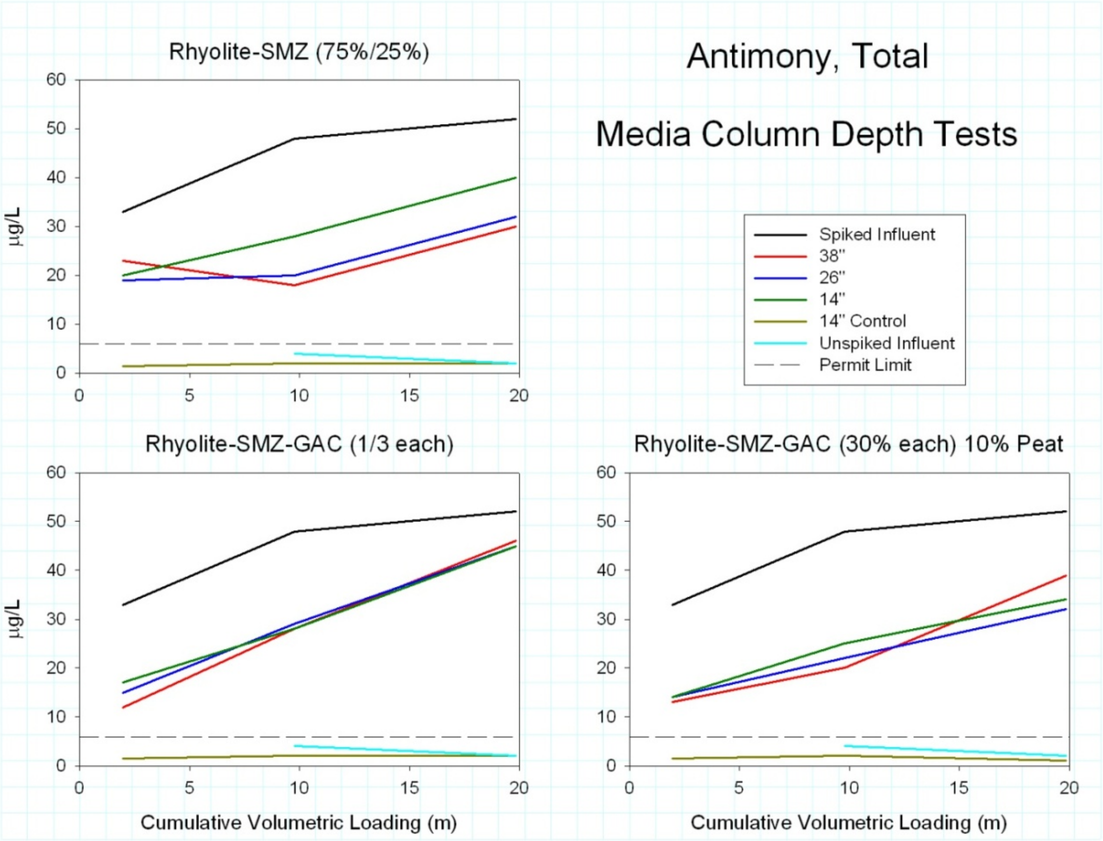
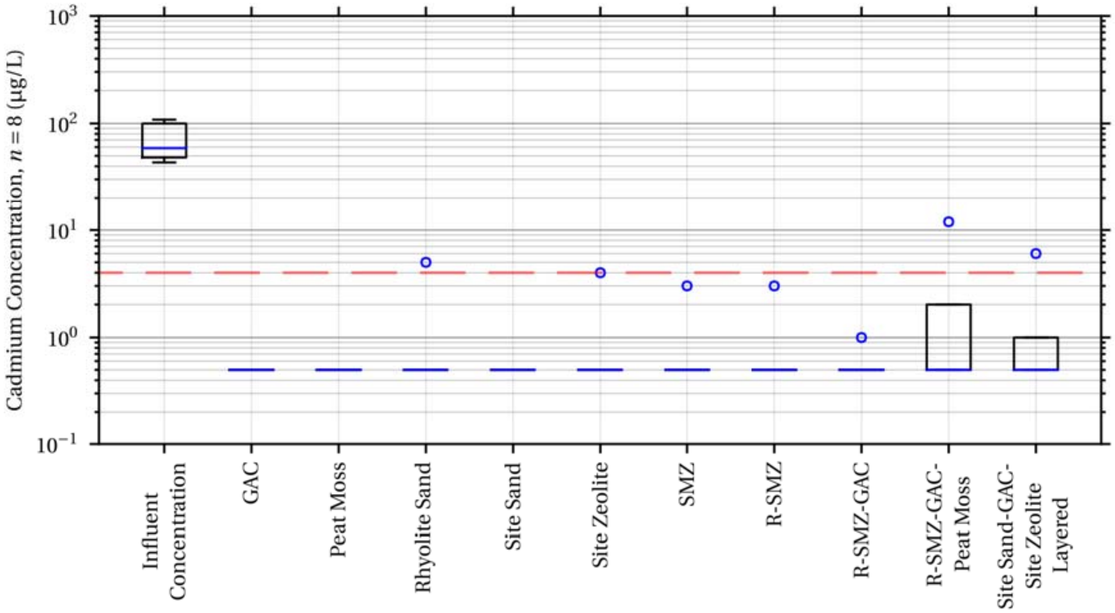
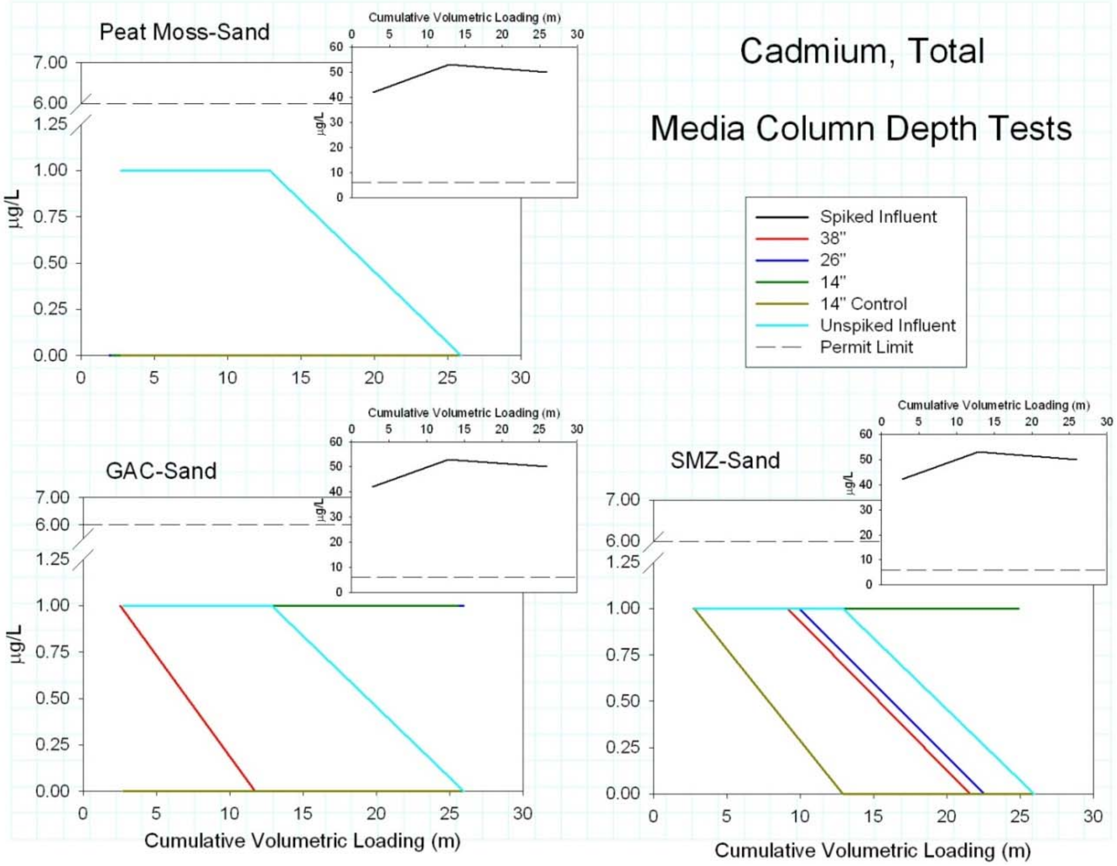


Figure 4-9. Antimony Removal from Column Tests


Cadmium Concentration, n = 8 (µg/L)
10³
10²
10¹
10⁰
10⁻¹
Influent Concentration
GAC
Peat Moss
Rhyolite Sand
Site Sand
Site Zeolite
SMZ
R-SMZ
R-SMZ-GAC
R-SMZ-GAC-Peat Moss
Site Sand-GAC-Site Zeolite Layered


Cadmium, Total
Media Column Depth Tests
Peat Moss-Sand
GAC-Sand
SMZ-Sand
µg/L
7.00
6.00
1.25
1.00
0.75
0.50
0.25
0.00
0
5
10
15
20
25
30
Cumulative Volumetric Loading (m)
µg/L
60
50
40
30
20
10
0
Spiked Influent
38"
26"
14"
14" Control
Unspiked Influent
Permit Limit

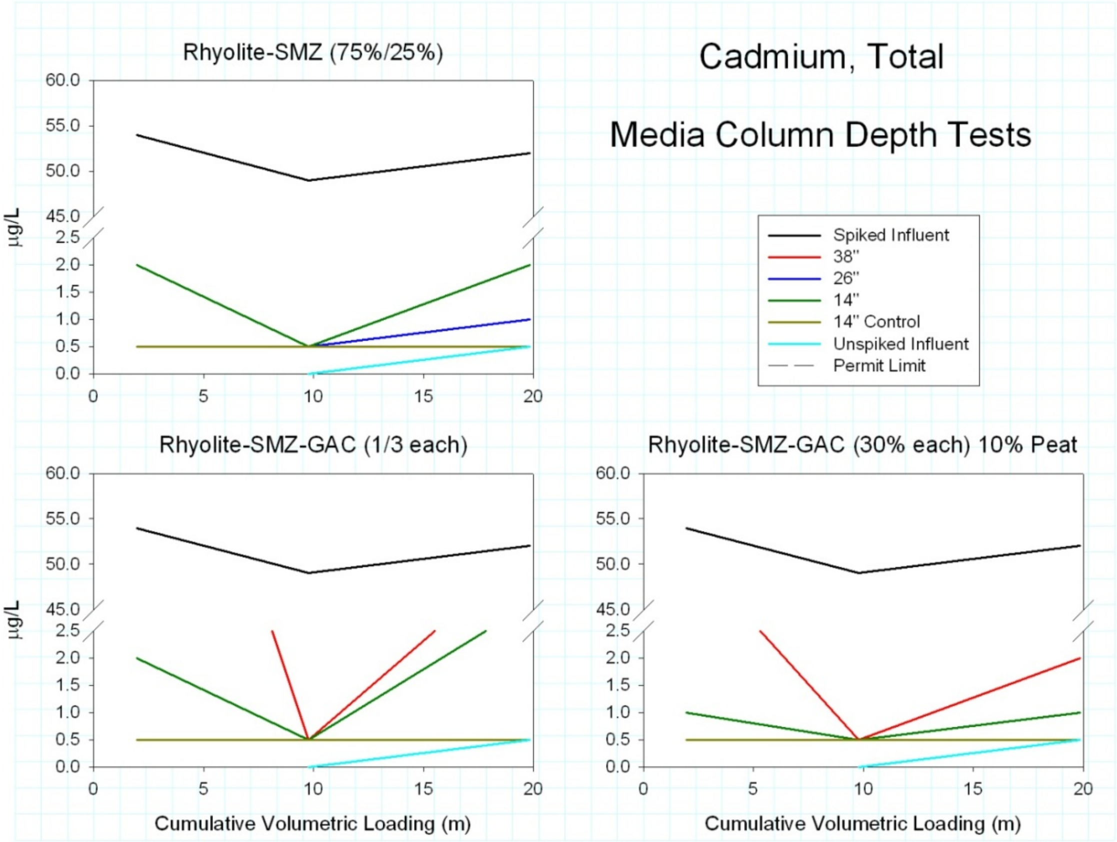
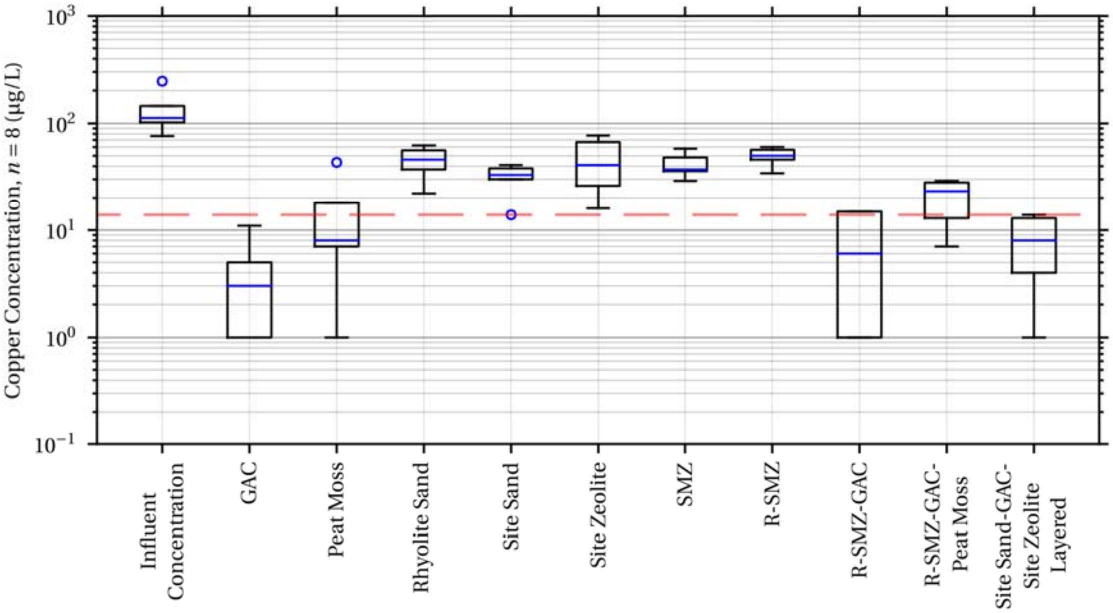
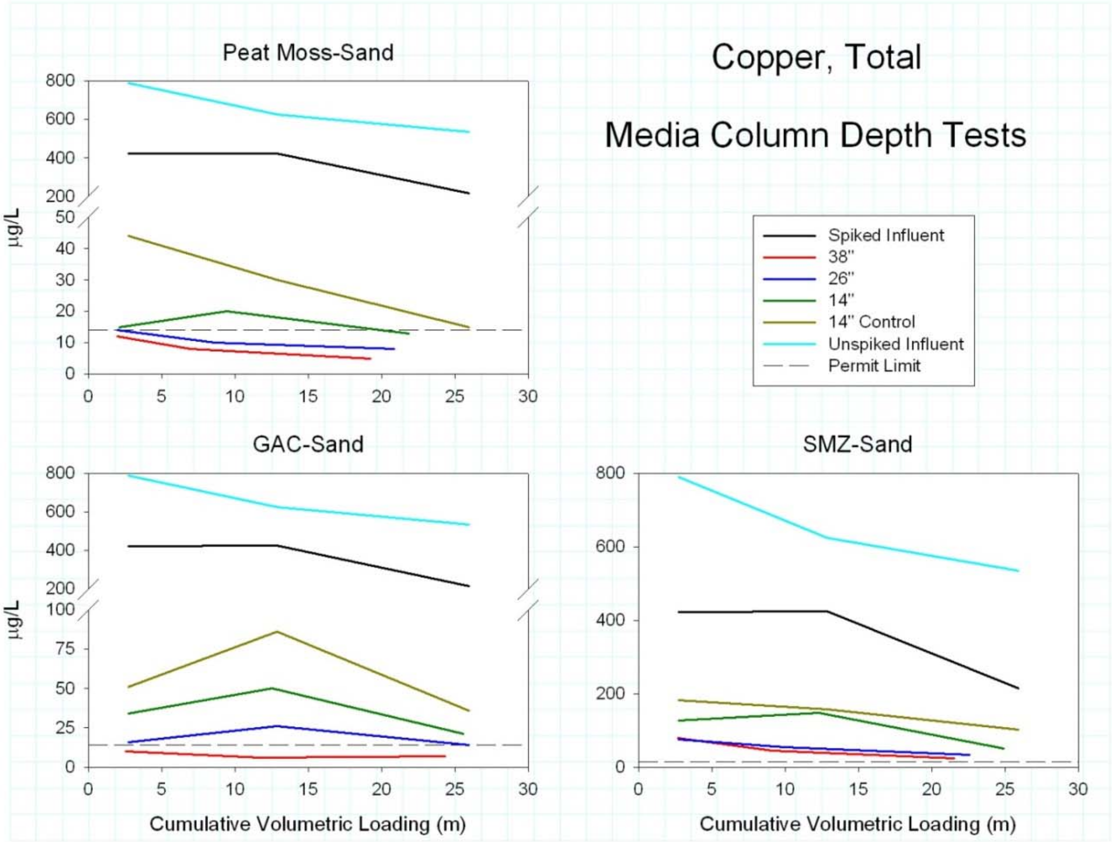


Figure 4-10. Cadmium Removal from Column Tests


Copper Concentration, n = 8 (µg/L)
10³
10²
10¹
10⁰
10⁻¹
Influent Concentration
GAC
Peat Moss
Rhyolite Sand
Site Sand
Site Zeolite
SMZ
R-SMZ
R-SMZ-GAC
R-SMZ-GAC-Peat Moss
Site Sand-GAC-Site Zeolite Layered


Copper, Total
Media Column Depth Tests
Peat Moss-Sand
GAC-Sand
SMZ-Sand
µg/L
800
600
400
200
100
75
50
25
0
40
30
20
10
5
15
25
30
Cumulative Volumetric Loading (m)
Spiked Influent
38"
26"
14"
14" Control
Unspiked Influent
Permit Limit

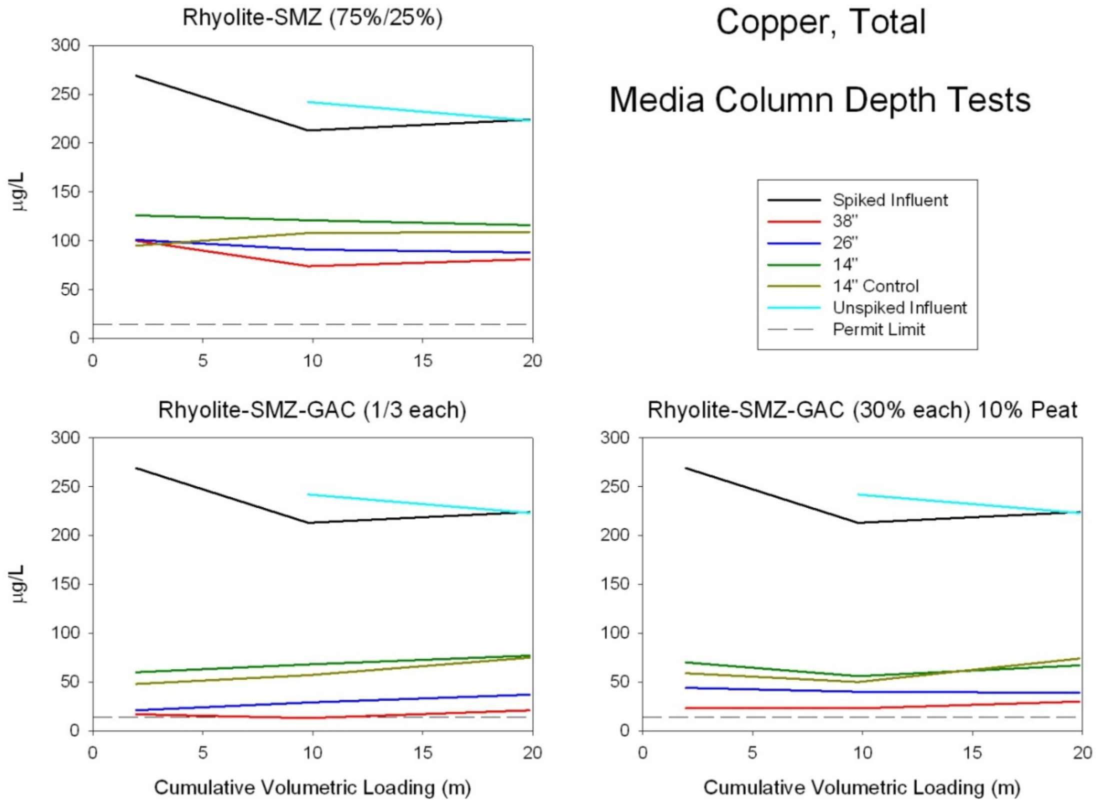


**Figure 4-11. Copper Removal from Column Tests**

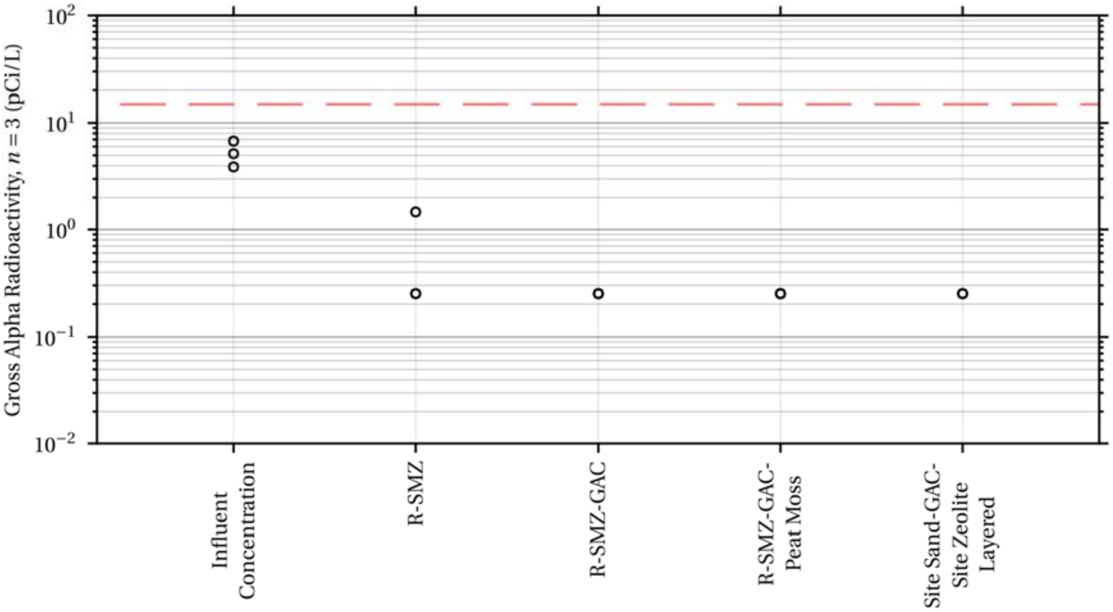
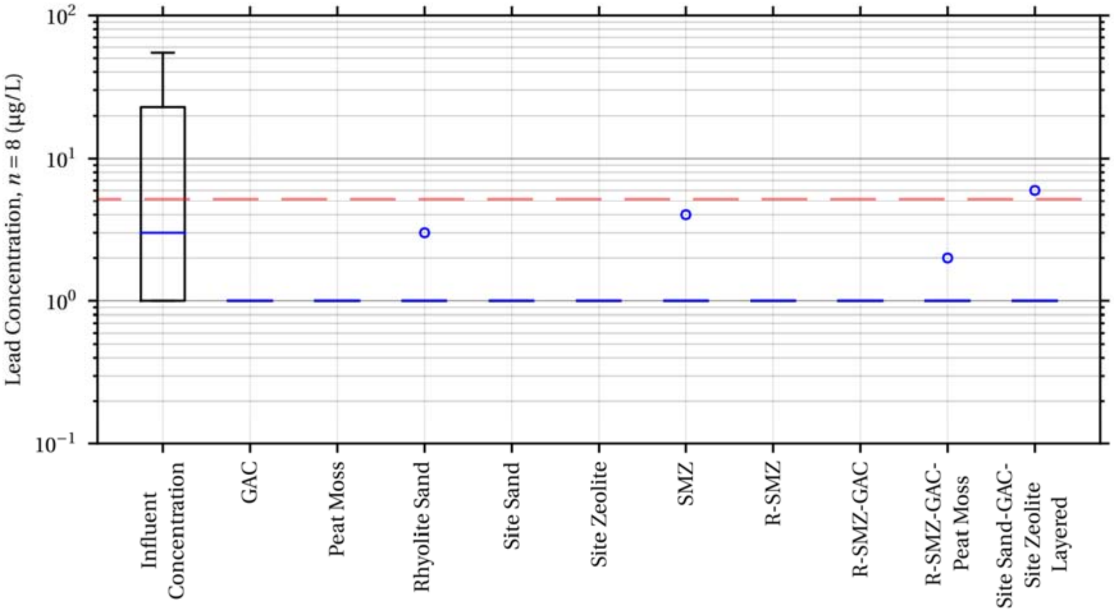
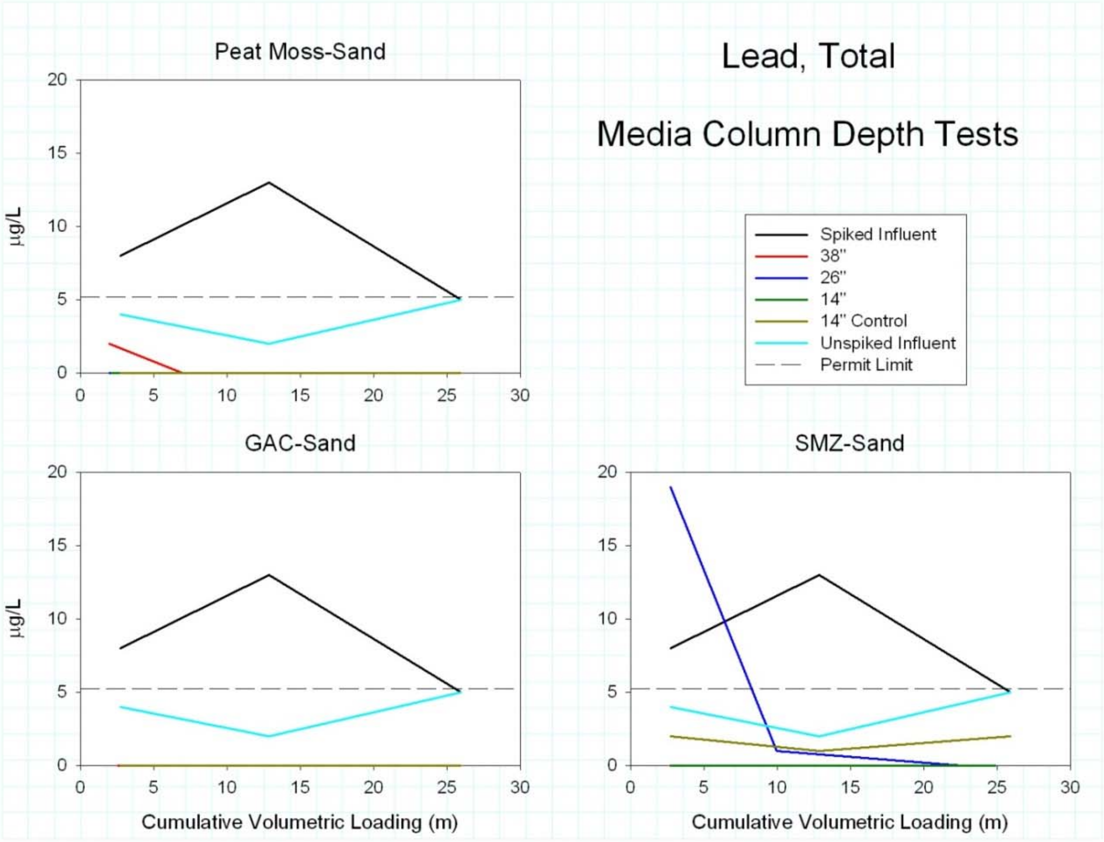


Figure 4-12. Gross Alpha Radioactivity Removal from Column Tests



Lead Concentration, n = 8 (µg/L)
$10^2$
$10^1$
$10^0$
$10^{-1}$
Influent Concentration
GAC
Peat Moss
Rhyolite Sand
Site Sand
Site Zeolite
SMZ
R-SMZ
R-SMZ-GAC
R-SMZ-GAC-Peat Moss
Site Sand-GAC-Site Zeolite Layered



Lead, Total
Media Column Depth Tests
Peat Moss-Sand
GAC-Sand
SMZ-Sand
µg/L
0
5
10
15
20
25
30
Cumulative Volumetric Loading (m)
Spiked Influent
38"
26"
14"
14" Control
Unspiked Influent
Permit Limit

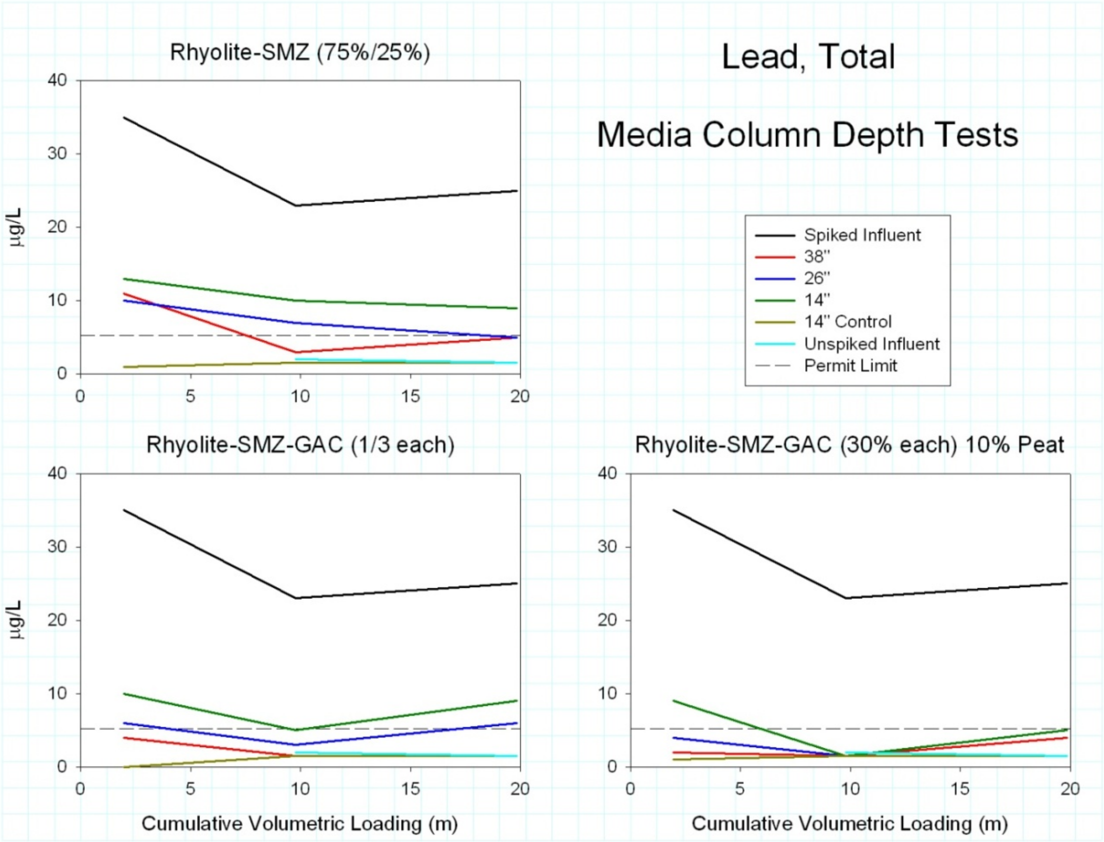


Figure 4-13. Lead Removal from Column Tests

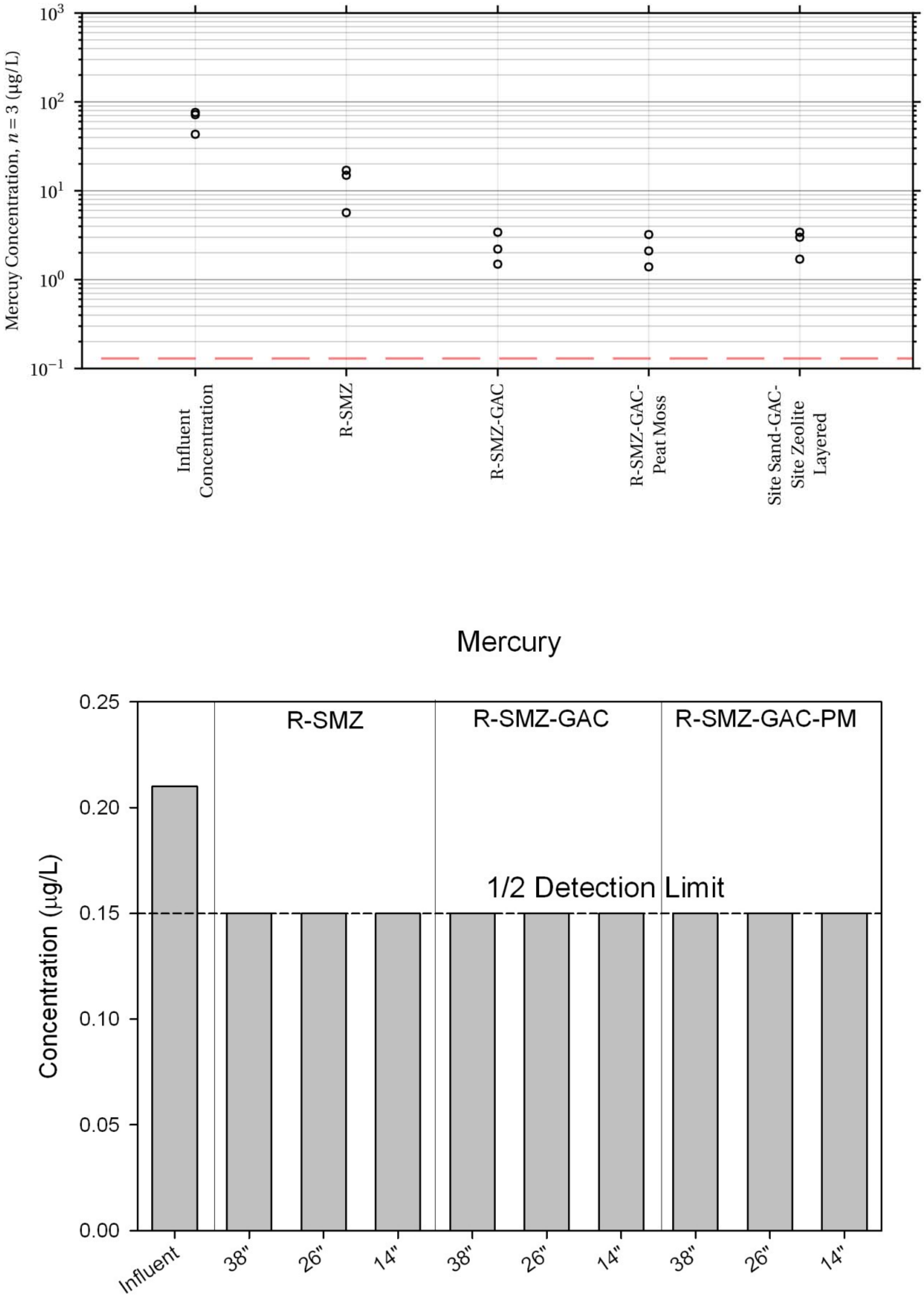


**Figure 4-14. Mercury Removal from Column Tests**

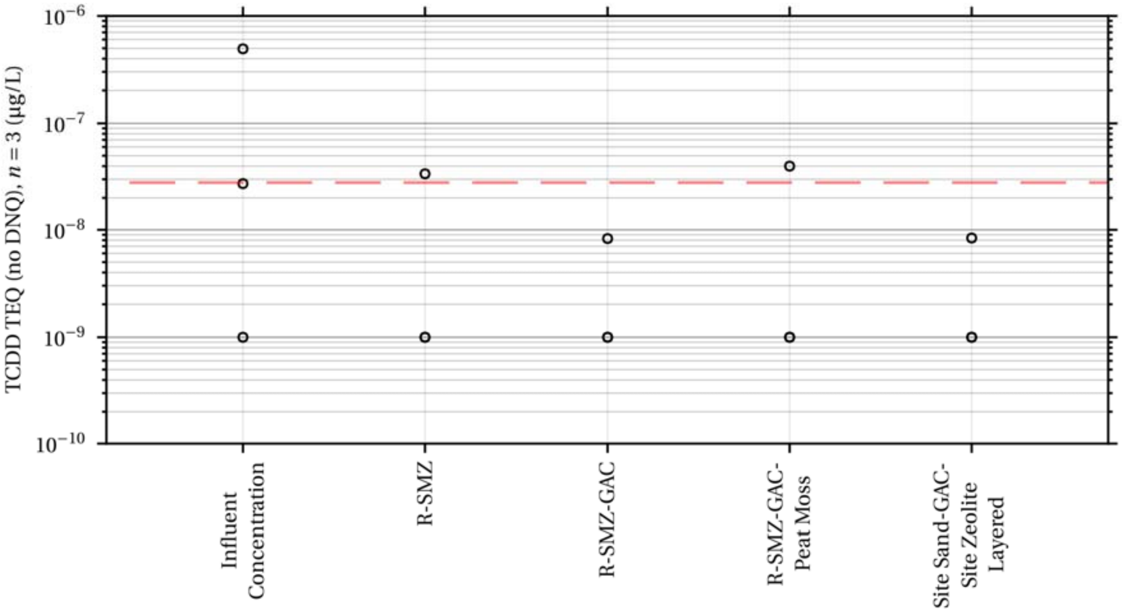


Figure 4-15. TCDD TEQ Removal from Column Tests

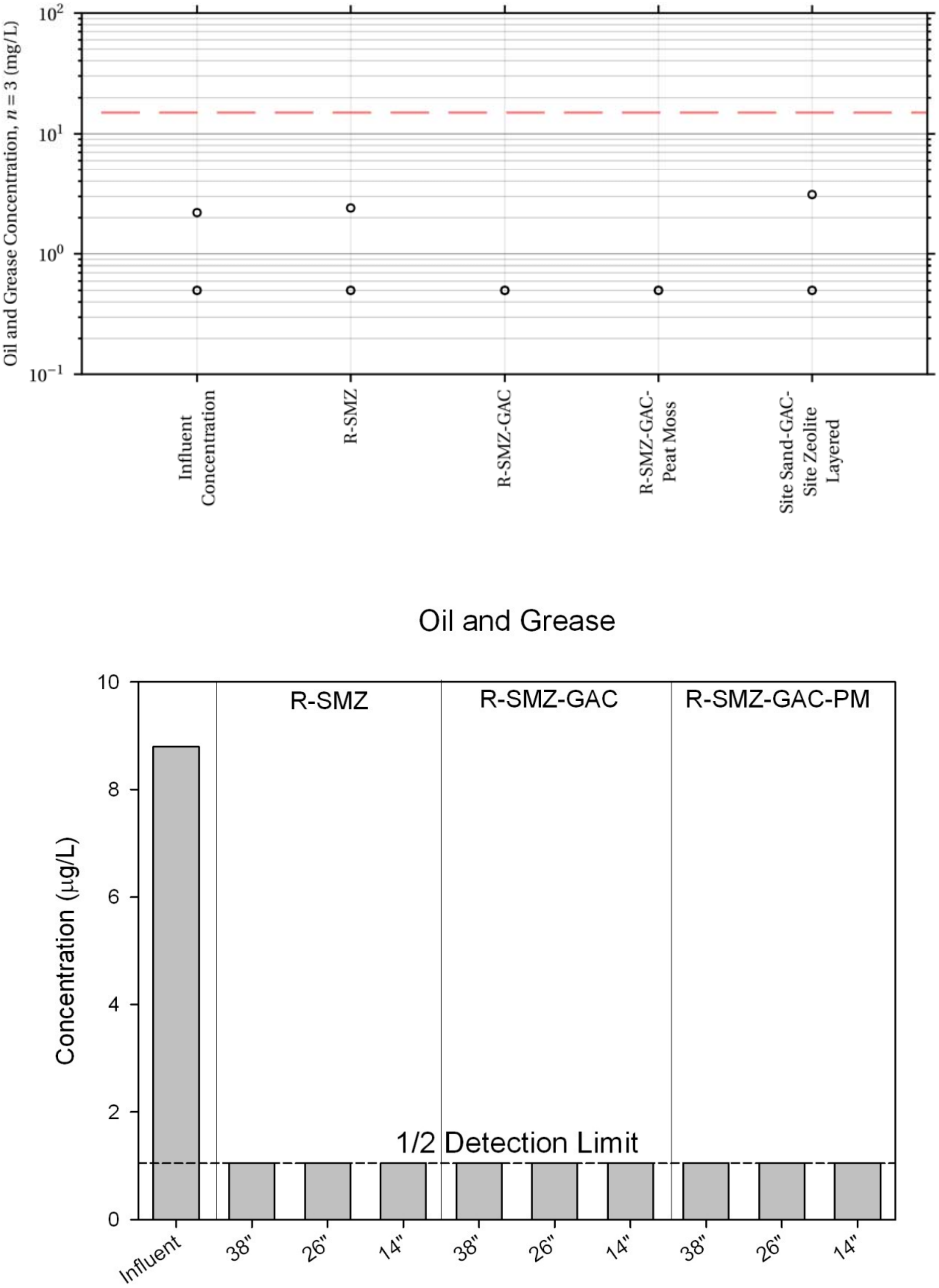
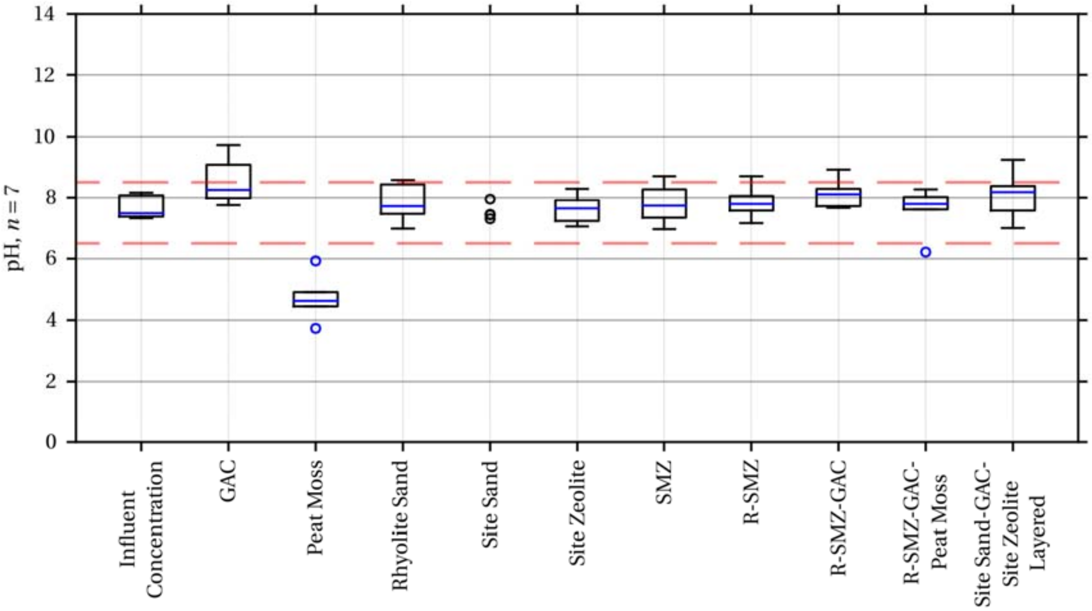
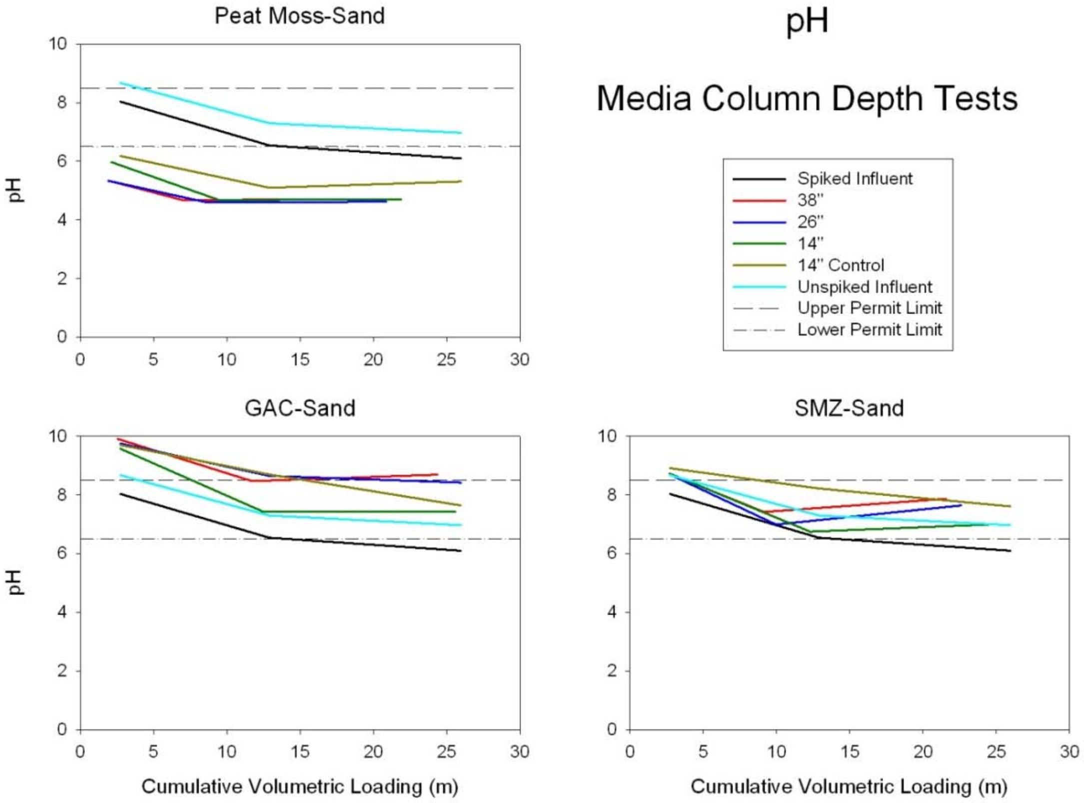


Figure 4-16. Oil and Grease Removal from Column Tests


pH, $n = 7$
0
2
4
6
8
10
12
14
Influent Concentration
GAC
Peat Moss
Rhyolite Sand
Site Sand
Site Zeolite
SMZ
R-SMZ
R-SMZ-GAC
R-SMZ-GAC-Peat Moss
Site Sand-GAC-Site Zeolite Layered


pH
Media Column Depth Tests
Peat Moss-Sand
GAC-Sand
SMZ-Sand
pH
Cumulative Volumetric Loading (m)
0
2
4
6
8
10
0
5
10
15
20
25
30
Spiked Influent
38"
26"
14"
14" Control
Unspiked Influent
Upper Permit Limit
Lower Permit Limit

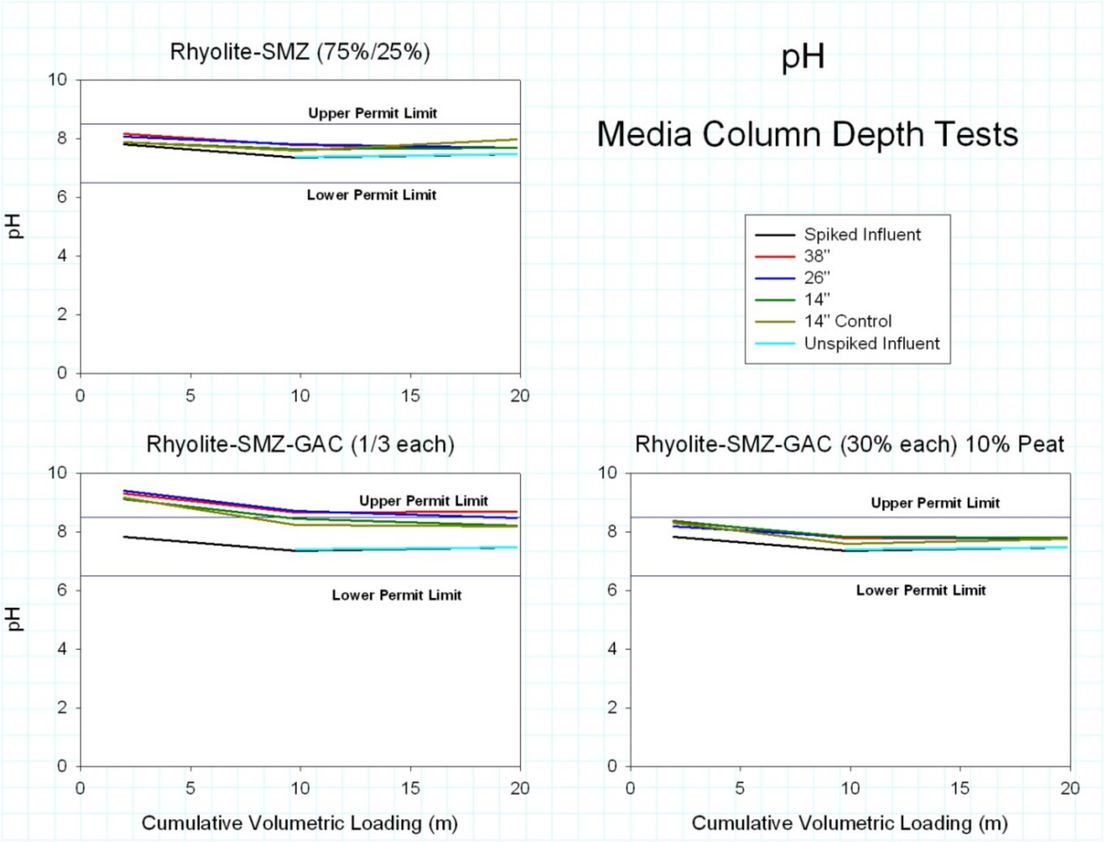
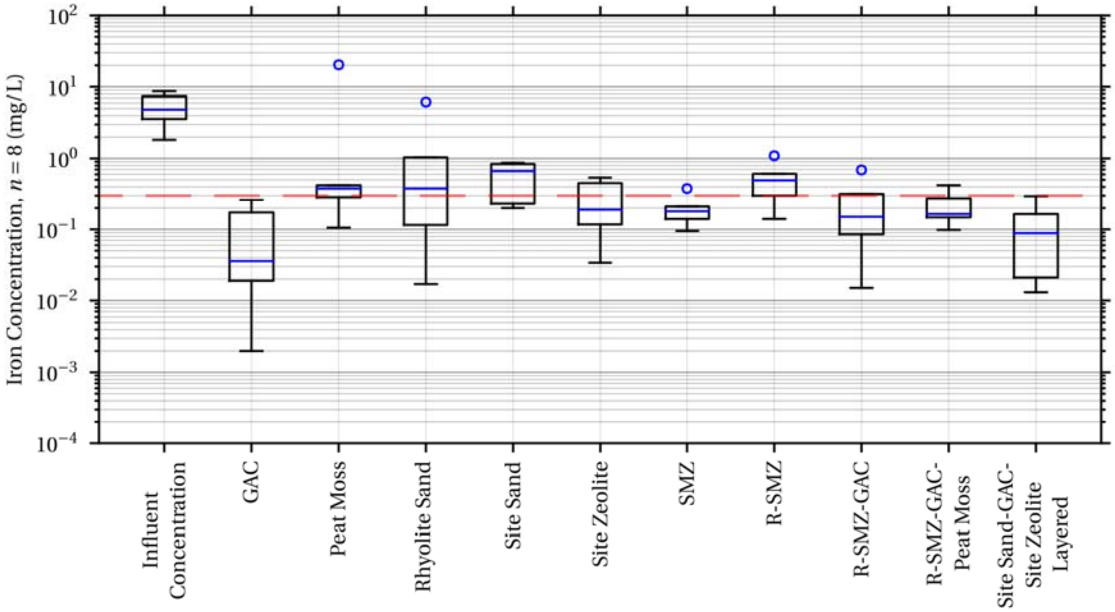
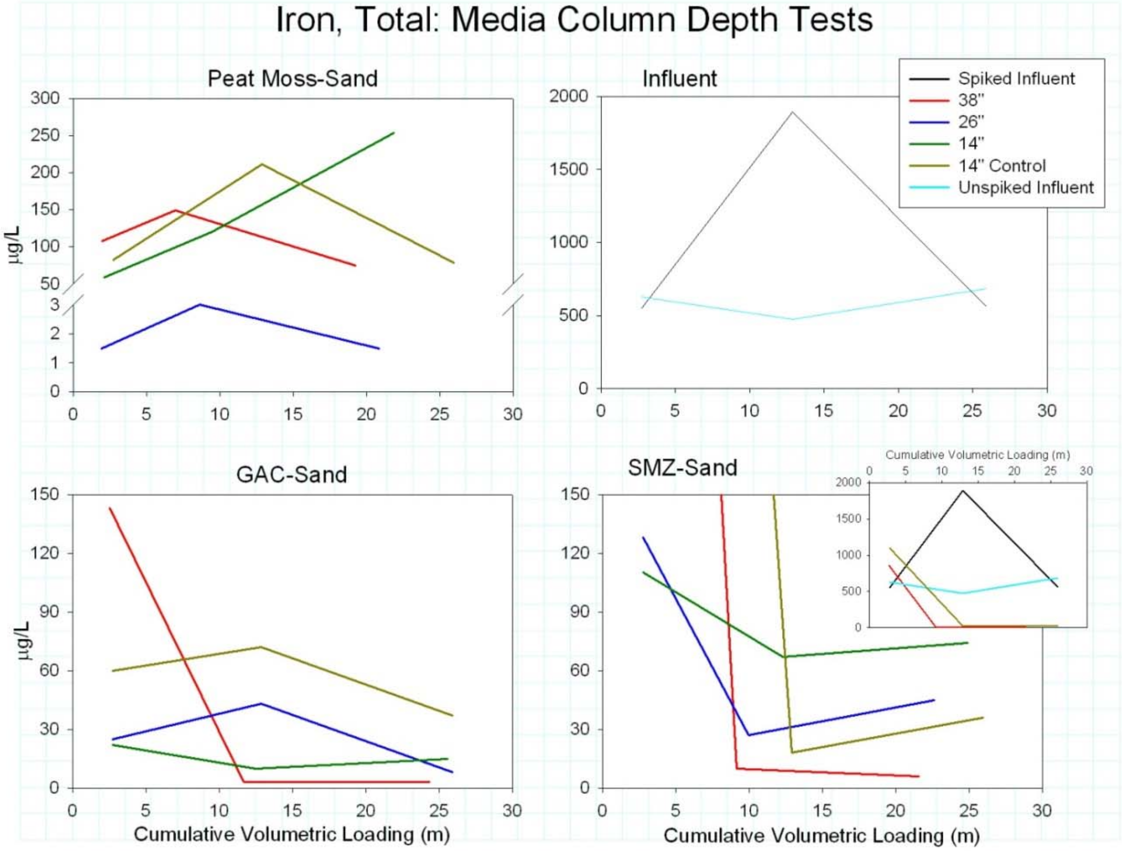


Figure 4-17. pH Changes during Column Tests


Iron Concentration, n = 8 (mg/L)
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
Influent Concentration
GAC
Peat Moss
Rhyolite Sand
Site Sand
Site Zeolite
SMZ
R-SMZ
R-SMZ-GAC
R-SMZ-GAC-Peat Moss
Site Sand-GAC-Site Zeolite Layered


Iron, Total: Media Column Depth Tests
Peat Moss-Sand
Influent
GAC-Sand
SMZ-Sand
Spiked Influent
38"
26"
14"
14" Control
Unspiked Influent
µg/L
Cumulative Volumetric Loading (m)
0
5
10
15
20
25
30
50
100
150
200
250
300
1
2
3
500
1000
1500
2000
30
60
90
120
150

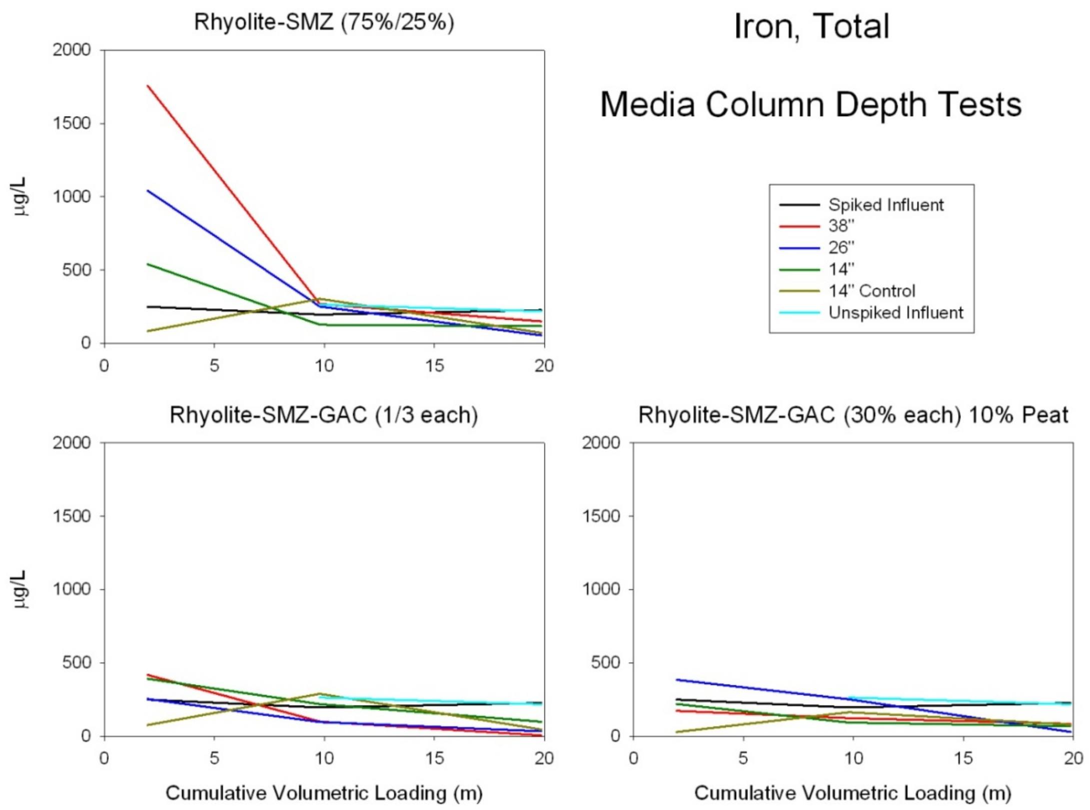
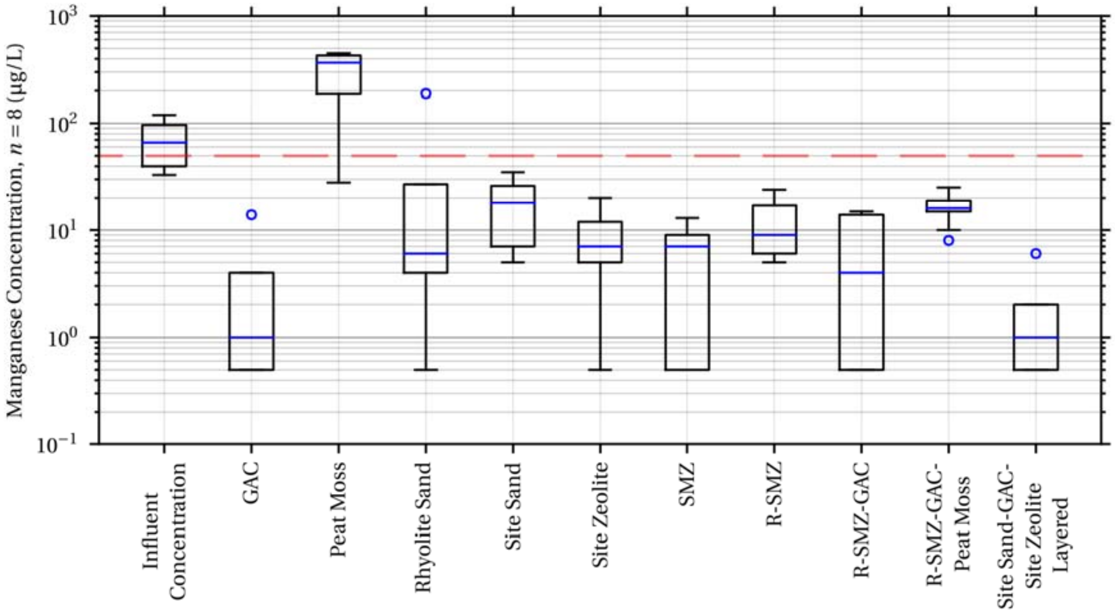
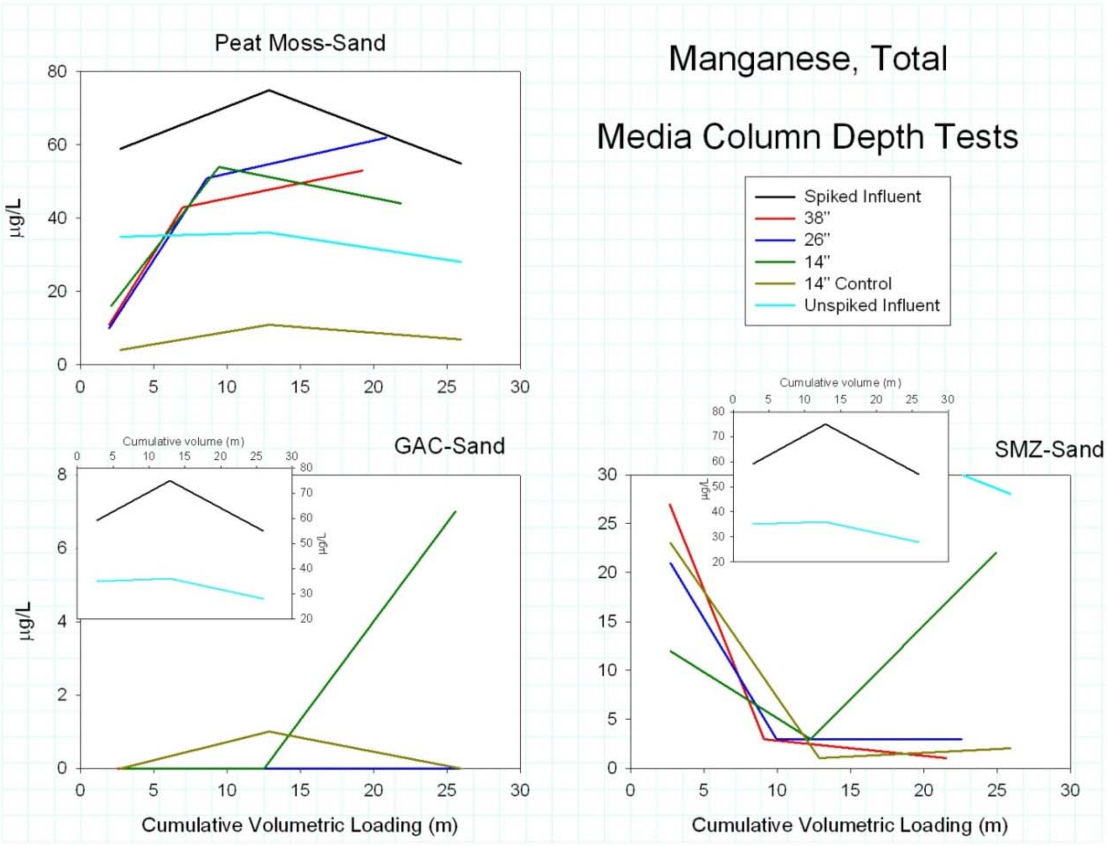


**Figure 4-18. Iron Removal from Column Tests**


Manganese Concentration, n = 8 (μg/L)
10^3
10^2
10^1
10^0
10^−1
Influent Concentration
GAC
Peat Moss
Rhyolite Sand
Site Sand
Site Zeolite
SMZ
R-SMZ
R-SMZ-GAC
R-SMZ-GAC-Peat Moss
Site Sand-GAC-Site Zeolite Layered


Manganese, Total
Media Column Depth Tests
Spiked Influent
38"
26"
14"
14" Control
Unspiked Influent
Peat Moss-Sand
μg/L
80
60
40
20
0
0
5
10
15
20
25
30
GAC-Sand
8
6
4
2
0
Cumulative volume (m)
80
70
60
50
40
30
20
SMZ-Sand
30
25
20
15
10
5
0
Cumulative Volumetric Loading (m)
Cumulative Volumetric Loading (m)

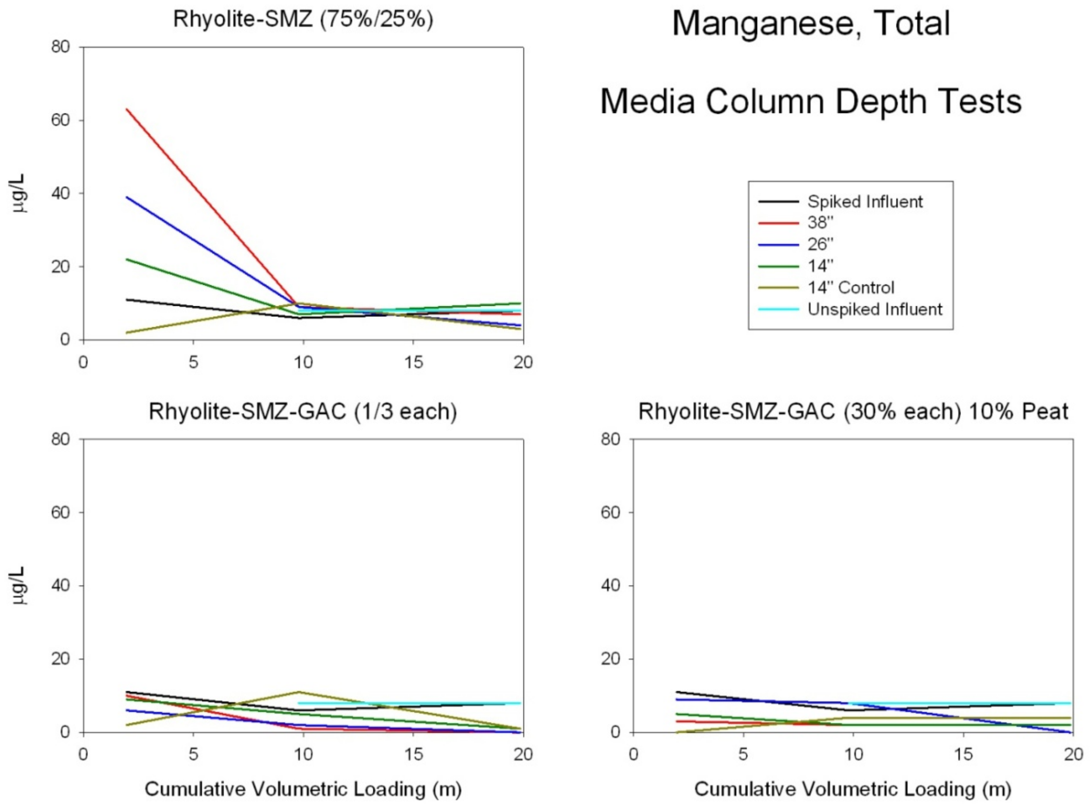


**Figure 4-19. Manganese Removal from Column Tests**

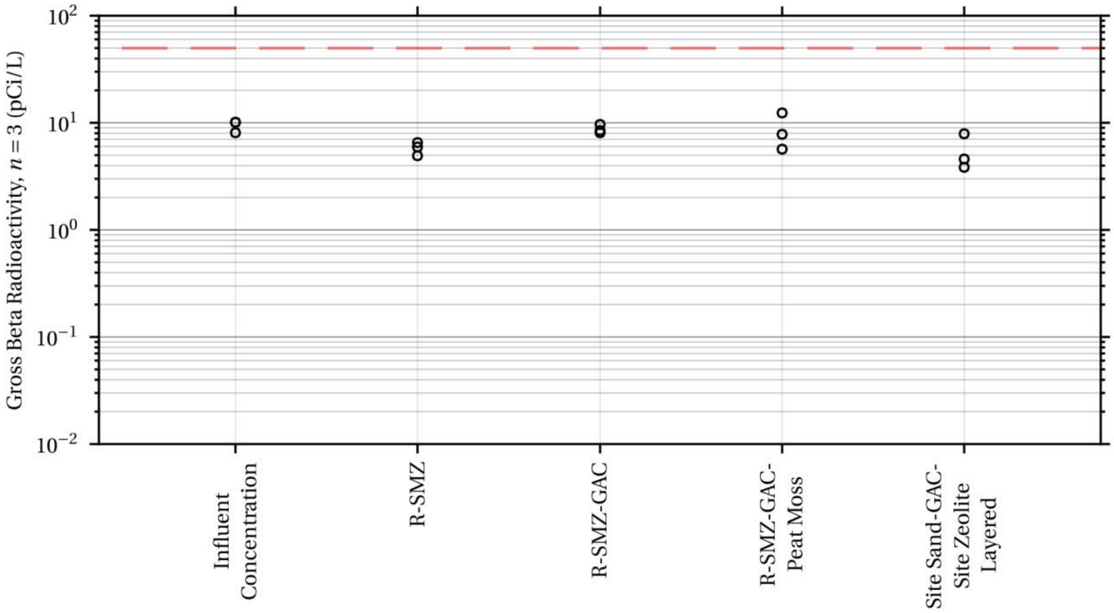
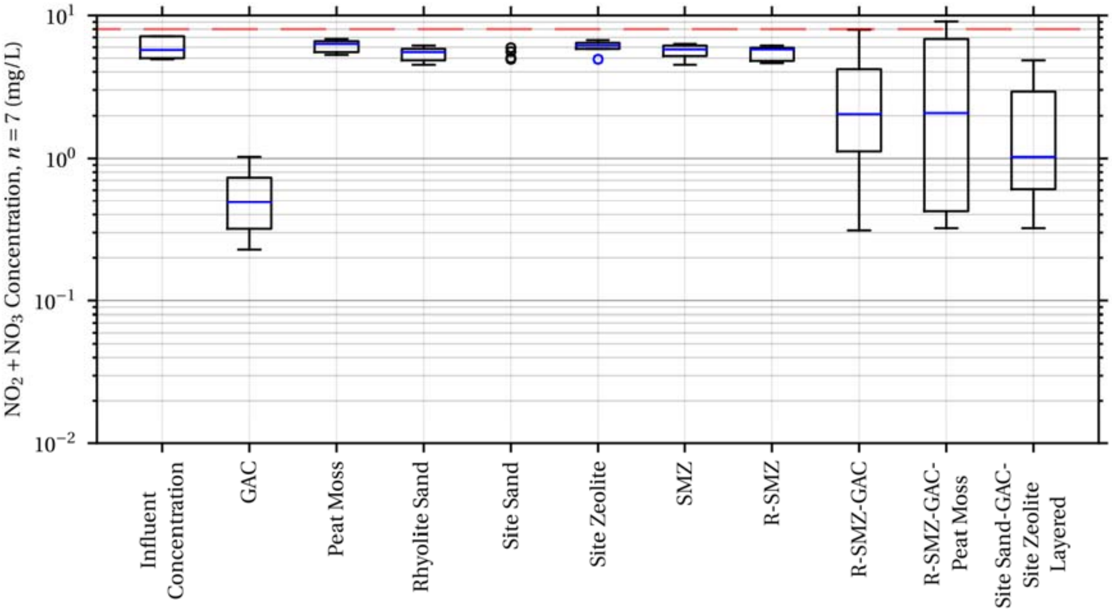
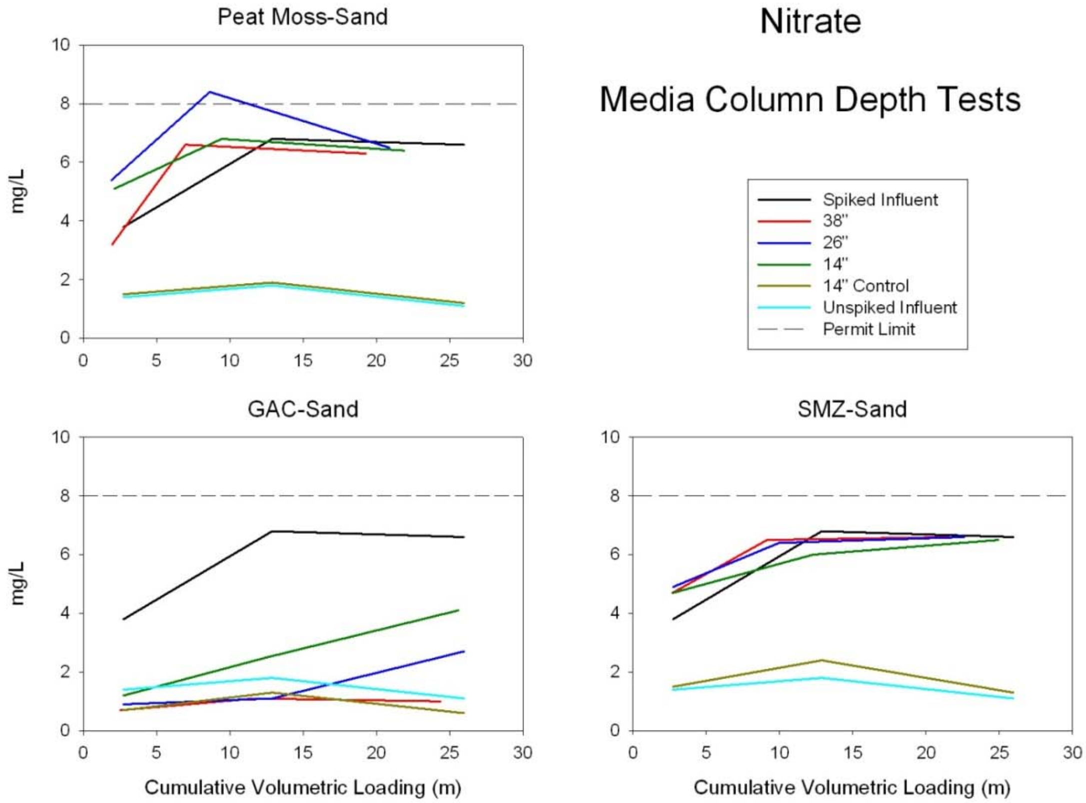
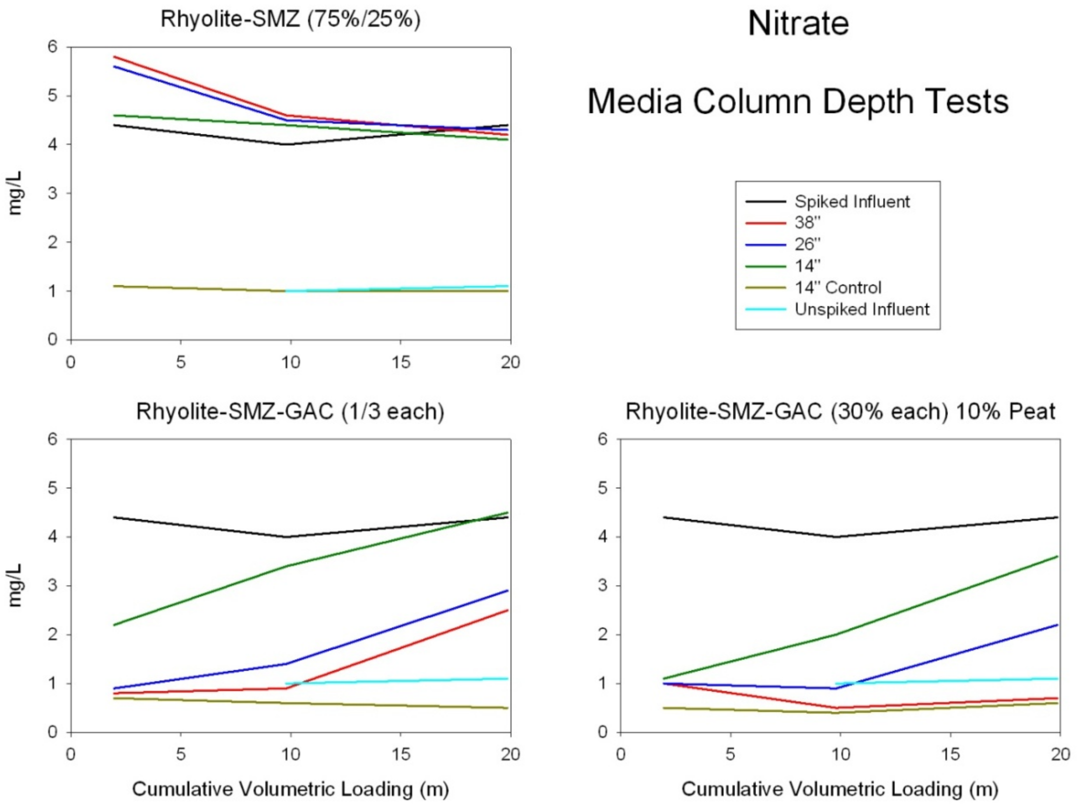


Figure 4-20. Gross Beta Radioactivity Removal from Column Tests


$NO_2 + NO_3$ Concentration, $n = 7$ (mg/L)
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
Influent Concentration
GAC
Peat Moss
Rhyolite Sand
Site Sand
Site Zeolite
SMZ
R-SMZ
R-SMZ-GAC
R-SMZ-GAC-Peat Moss
Site Sand-GAC-Site Zeolite Layered


Nitrate
Media Column Depth Tests
Peat Moss-Sand
GAC-Sand
SMZ-Sand
mg/L
Cumulative Volumetric Loading (m)
0
2
4
6
8
10
0
5
10
15
20
25
30
Spiked Influent
38"
26"
14"
14" Control
Unspiked Influent
Permit Limit



Nitrate

Media Column Depth Tests

Rhyolite-SMZ (75%/25%)

Rhyolite-SMZ-GAC (1/3 each)

Rhyolite-SMZ-GAC (30% each) 10% Peat

**Figure 4-21. Nitrite+Nitrate (and Nitrate) Removal from Column Tests**

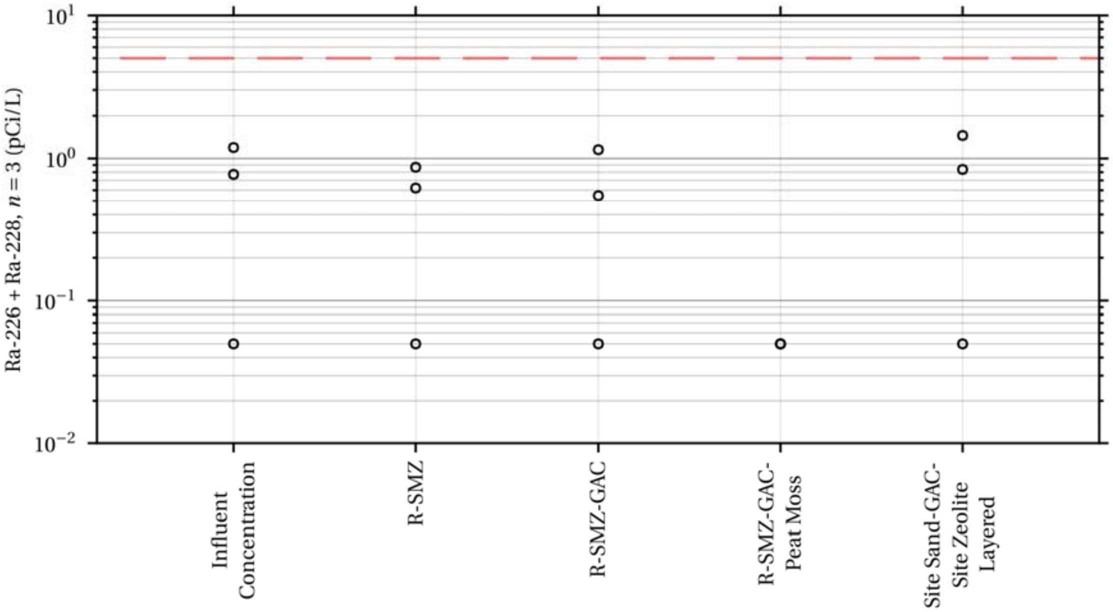
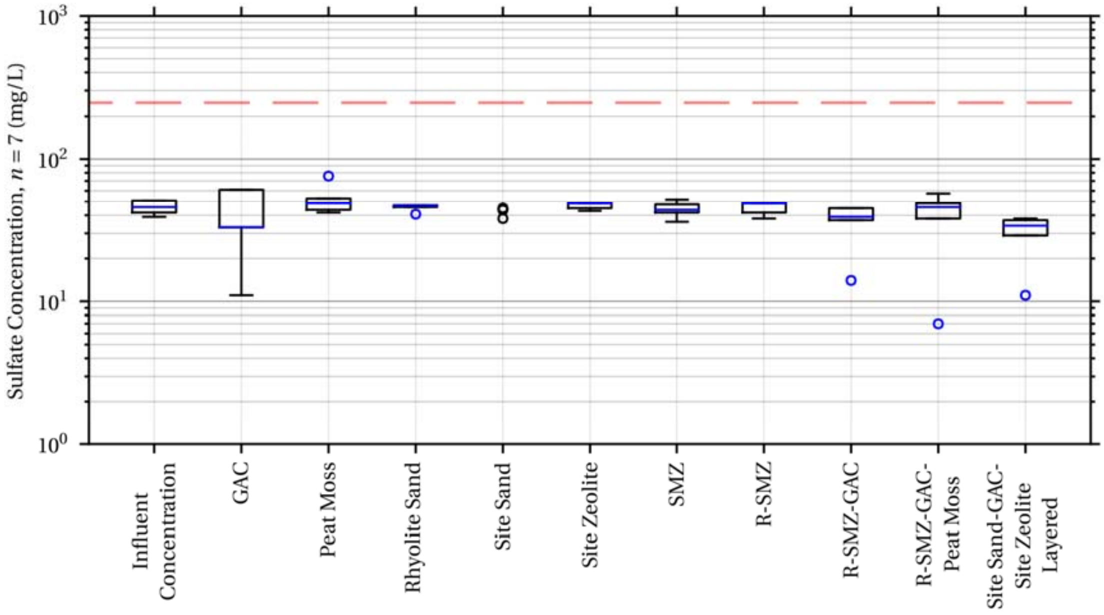
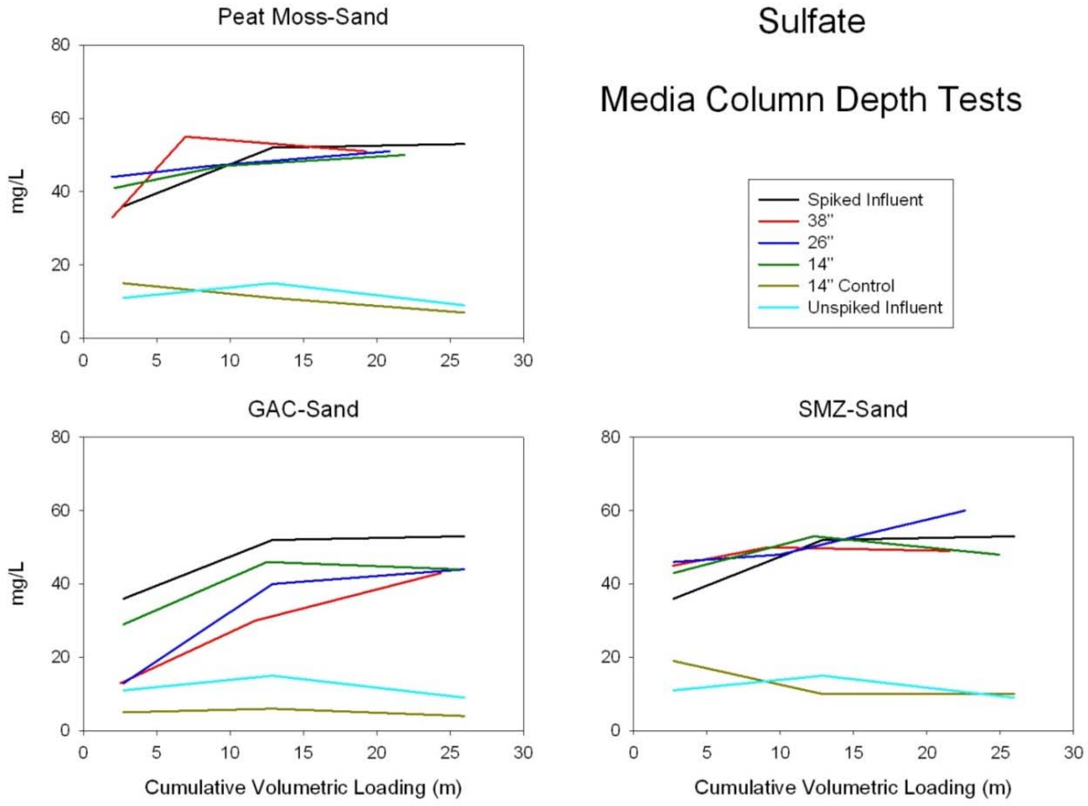


Figure 4-22. Radium 226+228 Removal from Column Tests


Sulfate Concentration, $n$ = 7 (mg/L)
$10^0$
$10^1$
$10^2$
$10^3$
Influent Concentration
GAC
Peat Moss
Rhyolite Sand
Site Sand
Site Zeolite
SMZ
R-SMZ
R-SMZ-GAC
R-SMZ-GAC-Peat Moss
Site Sand-GAC-Site Zeolite Layered


Sulfate
Media Column Depth Tests
Peat Moss-Sand
GAC-Sand
SMZ-Sand
mg/L
0
20
40
60
80
0
5
10
15
20
25
30
Cumulative Volumetric Loading (m)
Spiked Influent
38"
26"
14"
14" Control
Unspiked Influent

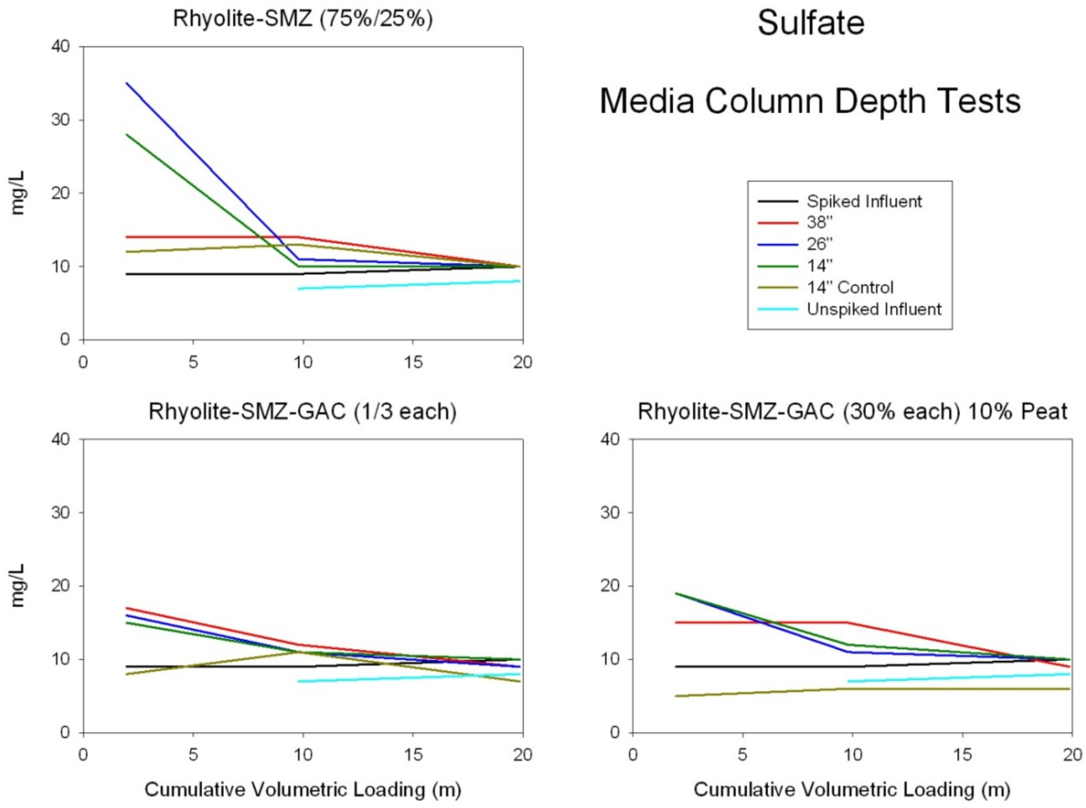
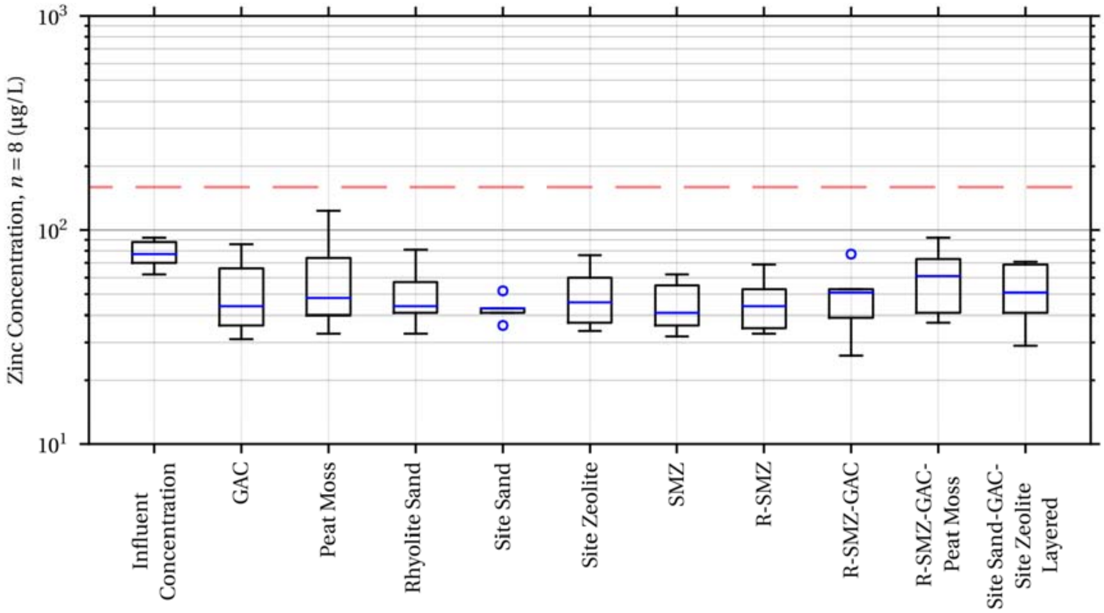
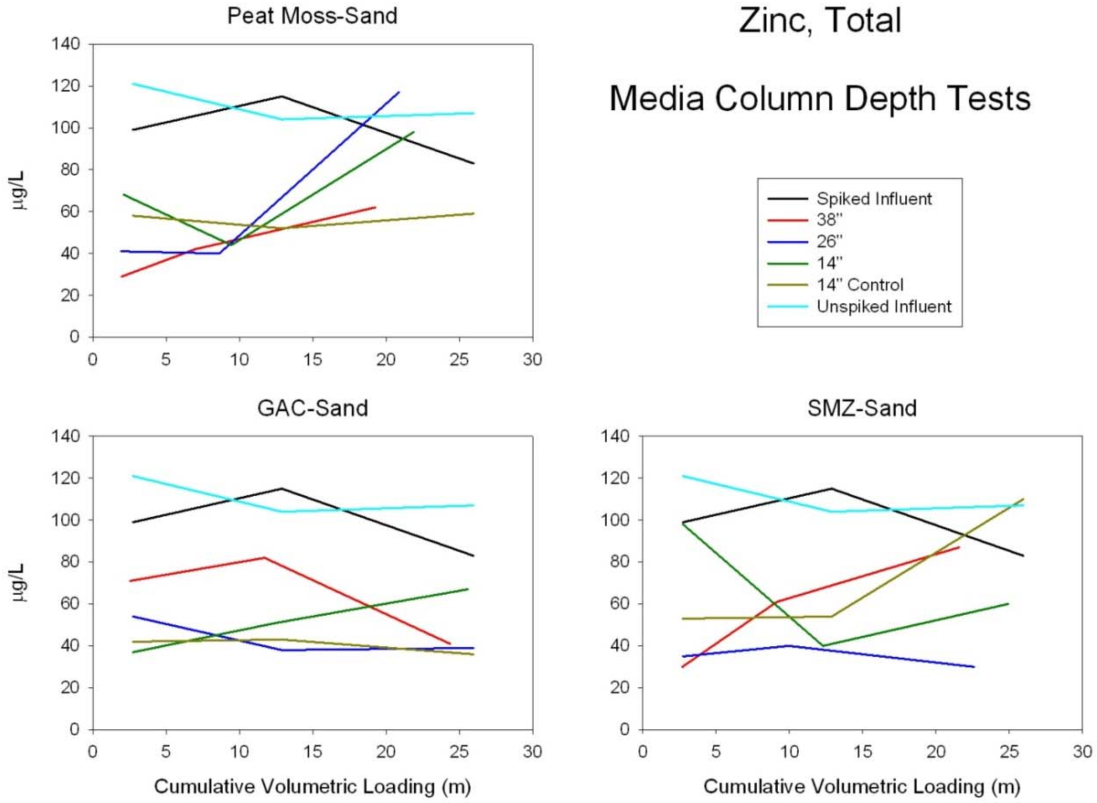


Figure 4-23. Sulfate Removal from Column Tests




Zinc, Total

Media Column Depth Tests

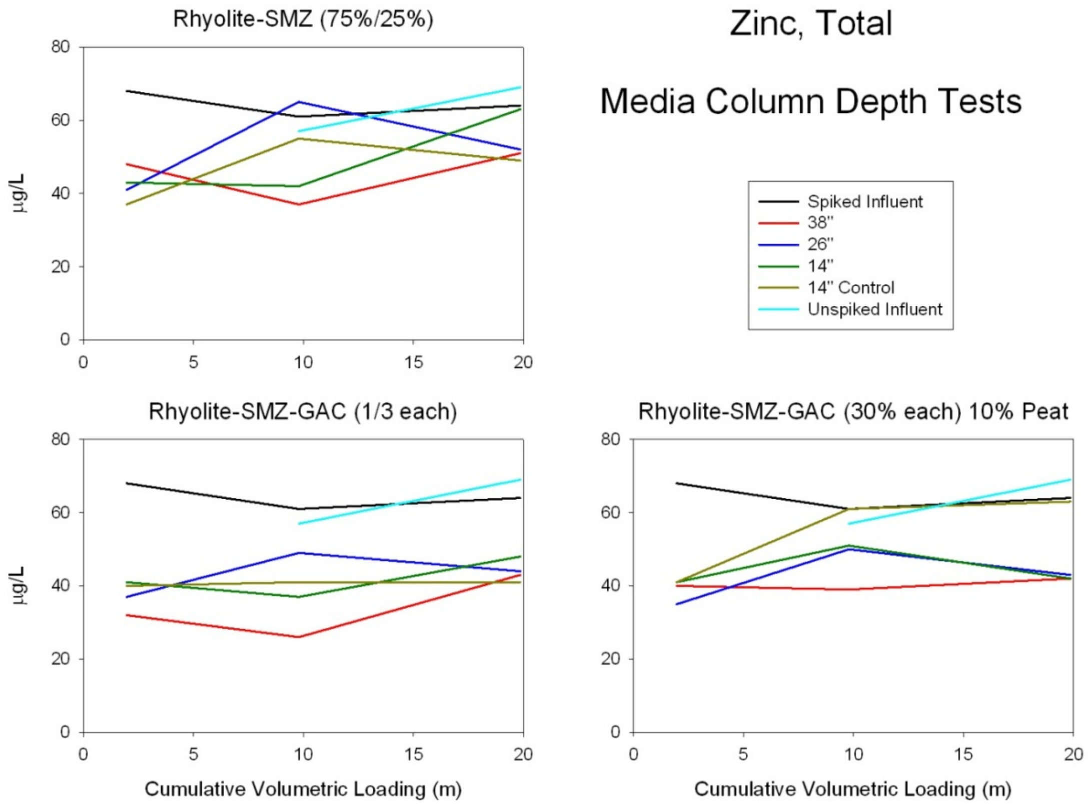


**Figure 4-24. Zinc Removal from Column Tests**

The results shown in Figures 4-9 through 4-24 were used to develop a list of potential problematic media-constituent combinations (Table 4-14). To confirm this list and to improve predictions of effluent concentrations as related to permit limits, influent - effluent concentration scatter plots were prepared for all of the full-depth column tests. The sign test was used to determine if the influent and effluent concentrations differed significantly. If they did, first-order regression equations were fitted to these plots. Tables 4-15 through 4-24 show the fitted equation coefficients for the removal relationships for the full-depth, long-term column tests. The significant equations (based on ANOVA evaluations of the equation coefficients and on the complete equation) were used to calculate the expected effluent concentrations for the different media for the maximum observed site concentrations, within the limitations described above. The results of these equations will not be valid as the media are near the end of their chemical life, but as shown in other calculations in this report, for many pollutants, the design life is substantially shorter than the estimated lifespan for the media. These equations are used with the maximum observed outfall concentrations to predict worst-case effluent concentrations with the results shown on Table 4-25, along with the benchmark permit limits. The combinations of constituents and media that exceed the benchmark values under these worst-case conditions are highlighted in yellow.

### Table 4-14. Filter Media-Constituents Problematic Combinations

| Media | Problematic Constituents |
|---|---|
| GAC | pH |
| Peat moss | pH |
| Rhyolite sand | pH and copper |
| Site filter sand | copper |
| Site zeolite | pH |
| Surface modified zeolite | pH and copper |
| Rhyolite - Surface Modified Zeolite | pH, copper, and mercury |
| Rhyolite - Surface Modified Zeolite - Granulated Activated Carbon | pH, copper, and mercury |
| Rhyolite - Surface Modified Zeolite - Granulated Activated Carbon - Peat Moss | pH, copper, and mercury |
| Layered Site Sand – Site Zeolite – Granular Activated Carbon (SZG) | pH |

### Table 4-15. Removals for Granular Activated Carbon for Full-Depth Column Tests

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration *** | Reduction (%)*** |
|---|---|---|---|---|---|
| pH | 0.063 | Y = X + 0.7 | 7.7 (7.3 to 8.2) | 8.5 | -10 |
| oil and grease | no data | n/a | n/a | n/a | n/a |
| Chloride | 0.344 | Y = X | 18 (1 to 34) | 31 | -74 |
| Fluoride | 0.227 | Y = X | 2.6 (1.7 to 3.1) | 2.2 | 15 |
| Sulfate, as $SO_4$ | 0.227 | Y = X | 45 (39 to 51) | 39 | 15 |
| Boron, µg/L | 0.188 | Y = X | 170 (<LOD to 509) | 68 | 60 |
| Ammonia, as N | 0.008 | Y = 0.27 (2.1) | 2.7 (0.3 to 3.9) | 0.3 | 90 |
| Nitrite + nitrate as N | 0.008 | Y = 0.56 (0.50) | 6.0 (4.9 to 7.1) | 0.6 | 91 |
| nitrite as N | 0.227 | Y = X | 0.03 (0.015 to 0.046) | 0.1 | -255 |
| TDS | 0.500 | Y = X | 199 (80 to 250) | 202 | 0 |
| zinc, µg/L | 0.035 | Y = 48 (0.40) | 77 (62 to 92) | 48 | 38 |
| antimony, µg/L | 0.004 | Y = 28 (0.41) | 68 (47 to 87) | 28 | 60 |
| cadmium, µg/L | 0.004 | all effluents <LOD | 65 (43 to 109) | 1 | 98 |
| Copper, µg/L | 0.004 | Y = 4.5 (0.82) | 125 (76 to 244) | 4 | 97 |
| Mercury, µg/L | no data | n/a | n/a | n/a | n/a |
| Nickel, µg/L | 0.004 | n/a (most effluents <LOD) | 51 (35 to 62) | 4 | 92 |
| Lead, µg/L | 0.063 | all effluents <LOD | 13 (<LOD to 55) | 2 | 84 |
| Thallium, µg/L (LOD>PL) | 0.004 | all effluents <LOD | 79 (46 to 125) | 3 | 96 |
| TCDD, µg/L | no data | n/a | n/a | n/a | n/a |
| Perchlorate, µg/L | no data | n/a | n/a | n/a | n/a |
| Gross alpha radioactivity, pCi/L | no data | n/a | n/a | n/a | n/a |
| Gross beta radioactivity, pCi/L | no data | n/a | n/a | n/a | n/a |
| Tritium, pCi/L | no data | n/a | n/a | n/a | n/a |
| Uranium, pCi/L | no data | n/a | n/a | n/a | n/a |
| Strontium-90, pCi/L | no data | n/a | n/a | n/a | n/a |
| Radium 226 + 228, pCi/L | no data | n/a | n/a | n/a | n/a |
| < 0.45 um particles, mg/L | 0.500 | Y = X | 199 (80 to 250) | 202 | 0 |

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration *** | Reduction (%)*** |
|---|---|---|---|---|---|
| 0.45 to 3 um particles, mg/L | 0.014 | Y = 3.3 (0.62) | 9.9 (3 to 22) | 3.3 | 67 |
| 3 to 12 um particles, mg/L | 0.009 | Y = 1.2 (0.69) | 50.6 (22 to 90) | 1.2 | 98 |
| 12 to 30 um particles, mg/L | 0.009 | Y = 0.71 (0.53) | 54.5 (18 to 90) | 0.62 | 99 |
| 30 to 60 um particles, mg/L | 0.009 | Y = 2.0 (0.73) | 37.4 (3 to 80) | 1.1 | 97 |
| 60 to 120 um particles, mg/L | 0.009 | Y = 0.96 (0.86) | 20.0 (2 to 58) | 0.62 | 97 |
| 120 to 250 um particles, mg/L | 0.009 | Y = 0.44 (1.3) | 5.1 (0 to 17) | 0.3 | 94 |
| 250 to 1180 um particles, mg/L (no particles found >1180) | 0.021 | Y = 2.6 (0.56) | 13.9 (3 to 45) | 2.5 | 82 |
| SSC, mg/L | 0.009 | Y = 10.2 (0.27) | 191 (50 to 400) | 9.7 | 95 |
| TSS (0.45 to 75 µm), mg/L | 0.009 | Y = 6.3 (0.22) | 161 (50 to 310) | 6.5 | 96 |
| Arsenic, µg/L | 0.008 | Y = 10.5 (0.42) | 56 (<LOD to 178) | 13 | 77 |
| Arsenic, filtered, µg/L | 0.016 | Y = 17 (0.31) | 33 (<LOD to 109) | 11 | 68 |
| Aluminum, µg/L | 0.004 | Y = 119 (0.97) | 6140 (2160 to 10,040) | 105 | 98 |
| Aluminum, filtered, µg/L | 0.008 | Y = 38.7 (0.30) | 73 (<LOD to 121) | 34 | 53 |
| Boron, filtered, µg/L | 0.031 | all effluents <LOD | 177 (<LOD to 472) | 45 | 75 |
| Calcium, µg/L | 0.363 | Y = X | 30,100 (23,500 to 36,300) | 34,500 | -8 |
| Calcium, filtered, µg/L | 0.363 | Y = X | 30,400 (22,150 to 42,400) | 30,600 | -1 |
| Cadmium, filtered, µg/L | 0.008 | n/a (most effluents <LOD) | 28 (1 to 54) | 1 | 96 |
| Copper, filtered, µg/L | 0.004 | Y = 6.8 (0.64) | 42 (23 to 69) | 4 | 91 |
| Iron, µg/L | 0.004 | Y = 81 (1.2) | 4830 (1820 to 8620) | 81 | 98 |
| Iron, filtered, µg/L | 0.004 | Y = 14 (0.84) | 63 (44 to 109) | 9 | 85 |
| Magnesium, µg/L | 0.145 | Y = X | 3250 (2710 to 4140) | 4120 | -27 |
| Magnesium, filtered, µg/L | 0.004 | Y = 3820 (0.35) | 2480 (2140 to 3520) | 3820 | -54 |
| Manganese, µg/L | 0.004 | Y = 3.1 (1.5) | 66 (33 to 120) | 3.1 | 95 |
| Manganese, filtered, µg/L | 0.063 | Y = 0.56 (0.31) | 3.4 (<LOD to 13) | 0.6 | 86 |
| Nickel, filtered, µg/L | 0.004 | Y=3.9 (0.32) | 27 (7 to 68) | 3.9 | 85 |
| Lead, filtered, µg/L | 0.500 | all effluents <LOD | 2 (<LOD to 2) | 2 | 0 |
| Zinc, filtered, µg/L | 0.363 | Y = X | 52 (32 to 87) | 46 | 11 |
| Potassium, µg/L | 0.145 | Y = X | 3450 (2650 to 4240) | 11,100 | -220 |
| Potassium, filtered, µg/L | 0.004 | Y = 10,300 (1.52) | 2410 (1960 to 3250) | 10,300 | -330 |
| Sodium, µg/L | 0.004 | Y = 22, 600 (0.27) | 17,000 (15,400 to 19,000) | 21,600 | -27 |
| Sodium, filtered, µg/L | 0.145 | Y = X | 17,200 (14,200 to 27,300) | 19,100 | -11 |
| Chromium, µg/L | 0.004 | Y = 2.8 (0.64) | 64 (48 to 81) | 2 | 97 |
| Chromium, filtered, µg/L | 0.004 | Y = 1.5 (0.38) | 14 (7 to 19) | 1 | 93 |
| Thallium, filtered, µg/L | 0.004 | n/a (most effluents <LOD) | 64 (27 to 94) | 4.8 | 92 |
| Antimony, filtered, µg/L | 0.004 | Y = 29.7 (0.27) | 56 (39 to 86) | 27 | 52 |
| Nitrate, mg/L | 0.008 | Y = 46 (0.63) | 6.0 (4.9 to 7.1) | 0.46 | 92 |
| Phosphorus, mg/L | 0.063 | Y = 1.2 (0.54) | 0.65 (0.42 to 1.28) | 1.2 | -80 |
| COD, mg/L | 0.008 | Y = 7 (1.5) | 72 (32 to 110) | 7 | 90 |
| Conductivity, µS/cm | 0.109 | Y = 410 (0.11) | 337 (179 to 460) | 410 | -21 |

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration *** | Reduction (%)*** |
|---|---|---|---|---|---|
| ORP, mV | 0.344 | Y = X | 187 (161 to 225) | 175 | 6 |
| Color, Pt color units | 0.008 | Y = 20 (1.3) | 212 (108 to 453) | 20 | 91 |
| Phosphate, as P, mg/L | 0.008 | Y = 3.7 (0.62) | 0.90 (0.45 to 1.43) | 1.2 | -330 |
| Nitrogen, Total, mg/L | 0.008 | Y = 0.18 X | 10.9 (4 to 17.7) | 1.6 | 85 |
| UV-254, absorbance units | 0.008 | Y = 0.027 (1.4) | 0.66 (0.23 to 1.08) | 0.027 | 96 |
| Hardness, mg/L | 0.227 | Y = X | 82 (50 to 106) | 98 | -19 |

* calculated using the sign test, ties ignored in the count; "no data" is when no samples were analyzed

** <LOD substituted with half of the detection limits for these calculations; if predicted effluent is > influent, then use influent conc (except for pH, and when significant increases are noted in the % removal column)

*** <LOD substituted with half of the detection limits for these calculations

## Table 4-16. Removals for Peat Moss for Full-Depth Column Tests

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| pH | 0.008 | Y = X - 3.0 | 7.7 (7.3 to 8.2) | 4.7 | 39 |
| oil and grease | no data | no data | no data | no data | no data |
| Chloride | 0.008 | Y = 33 (0.15) | 18 (1 to 34) | 33 | -89 |
| Fluoride | 0.008 | Y = 0.67X | 2.6 (1.7 to 3.1) | 1.7 | 34 |
| Sulfate, as $SO_4$ | 0.344 | Y = X | 45 (39 to 51) | 51 | -13 |
| Boron, µg/L | 0.344 | Y = X | 170 (<LOD to 509) | 202 | -19 |
| Ammonia, as N | 0.227 | Y = X | 2.7 (0.3 to 3.9) | 3.4 | -23 |
| Nitrite + nitrate as N | 0.500 | Y = X | 6.0 (4.9 to 7.1) | 6.2 | -4 |
| nitrite as N | 0.227 | Y = X | 0.03 (0.015 to 0.046) | 0.03 | -13 |
| TDS | 0.120 | Y = X | 199 (80 to 250) | 216 | 0* |
| zinc, µg/L | 0.035 | Y = 57 (0.51) | 77 (62 to 92) | 57 | 26 |
| antimony, µg/L | 0.004 | Y = 8.5 (1.6) | 68 (47 to 87) | 8.5 | 88 |
| cadmium, µg/L | 0.004 | all effluent <LOD | 65 (43 to 109) | 1 | 98 |
| Copper, µg/L | 0.004 | Y = 13 (1.0) | 125 (76 to 244) | 13 | 90 |
| Mercury, µg/L | no data | n/a | n/a | n/a | n/a |
| Nickel, µg/L | 0.004 | Y = 6 (1.0) | 51 (35 to 62) | 6 | 88 |
| Lead, µg/L | 0.063 | all effluent <LOD | 13 (<LOD to 55) | 2 | 84 |
| Thallium, µg/L (LOD>PL) | 0.004 | Y = 8.9 (1.0) | 79 (46 to 125) | 9 | 89 |
| TCDD, µg/L | no data | n/a | n/a | n/a | n/a |
| Perchlorate, µg/L | no data | n/a | n/a | n/a | n/a |
| Gross alpha radioactivity, pCi/L | no data | n/a | n/a | n/a | n/a |
| Gross beta radioactivity, pCi/L | no data | n/a | n/a | n/a | n/a |
| Tritium, pCi/L | no data | n/a | n/a | n/a | n/a |
| Uranium, pCi/L | no data | n/a | n/a | n/a | n/a |
| Strontium-90, pCi/L | no data | n/a | n/a | n/a | n/a |
| Radium 226 + 228, pCi/L | no data | n/a | n/a | n/a | n/a |
| < 0.45 um particles, mg/L | 0.120 | Y = X | 199 (80 to 250) | 216 | 0* |
| 0.45 to 3 um particles, mg/L | 0.310 | Y = X | 10.6 (3 to 22) | 4.7 | 0* |
| 3 to 12 um particles, mg/L | 0.064 | Y = 0.50 (0.7) | 54.9 (22 to 90) | 0.5 | 99 |
| 12 to 30 um particles, mg/L | 0.009 | Y = 1.3 (1.7) | 54.5 (18 to 90) | 1.3 | 98 |
| 30 to 60 um particles, mg/L | 0.009 | Y = 1.6 (0.9) | 37.4 (3 to 80) | 1.6 | 96 |
| 60 to 120 um particles, mg/L | 0.021 | Y = 1.8 (1.4) | 20.0 (2 to 58) | 1 | 95 |
| 120 to 250 um particles, mg/L | 0.014 | Y = 0.27 (1.0) | 5.1 (0 to 17) | 0.27 | 95 |
| 250 to 1180 um particles, mg/L (no particles found >1180) | 0.088 | Y = 4.7 (0.92) | 13.9 (3 to 45) | 3.5 | 75 |
| SSC, mg/L | 0.045 | Y =7.0 (0.3) | 206 (50 to 400) | 9.9 | 94 |
| TSS (0.45 to 75 µm), mg/L | 0.045 | Y = 7.1 (0.5) | 171 (50 to 310) | 7.1 | 96 |
| Arsenic, µg/L | 0.035 | y = 0.086X + 6.19 | 56 (<LOD to 178) | 18 | 68 |
| Arsenic, filtered, µg/L | 0.145 | Y = X | 33 (<LOD to 109) | 15 | 53 |
| Aluminum, µg/L | 0.035 | Y = 4150 (1.9) | 6140 (2160 to 10,040) | 4150 | 32 |
| Aluminum, filtered, µg/L | 0.004 | Y = 778 (0.48) | 73 (<LOD to 121) | 780 | -980 |
| Boron, filtered, µg/L | 0.188 | Y = X | 177 (<LOD to 472) | 175 | 1 |

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| Calcium, µg/L | 0.004 | Y = 11,700 (0.40) | 30,100 (23,500 to 36,300) | 11,700 | 61 |
| Calcium, filtered, µg/L | 0.004 | Y = 0.40 X | 30,400 (22,150 to 42,400) | 11,900 | 61 |
| Cadmium, filtered, µg/L | 0.008 | almost all effluent <LOD | 28 (1 to 54) | 1 | 96 |
| Copper, filtered, µg/L | 0.004 | Y = 12.3 (0.26) | 42 (23 to 69) | 18 | 57 |
| Iron, µg/L | 0.035 | Y = 2800 (2.5) | 4830 (1820 to 8620) | 2800 | 42 |
| Iron, filtered, µg/L | 0.637 | Y = X | 63 (44 to 109) | 110 | -69 |
| Magnesium, µg/L | 0.363 | Y = X | 3250 (2710 to 4140) | 5300 | -63 |
| Magnesium, filtered, µg/L | 0.637 | Y = X | 2480 (2140 to 3520) | 4250 | -71 |
| Manganese, µg/L | 0.035 | Y = 290 (0.56) | 66 (33 to 120) | 290 | -340 |
| Manganese, filtered, µg/L | 0.004 | Y = 230 (0.64) | 3.4 (<LOD to 13) | 230 | -6700 |
| Nickel, filtered, µg/L | 0.035 | Y = 4.8 (0.62) | 27 (7 to 68) | 4.8 | 82 |
| Lead, filtered, µg/L | 0.500 | all <LOD | 2 (<LOD to 2) | 2 | 0 |
| Zinc, filtered, µg/L | 0.145 | Y = X | 52 (32 to 87) | 58 | -11 |
| Potassium, µg/L | 0.145 | Y = X | 3450 (2650 to 4240) | 3360 | 3 |
| Potassium, filtered, µg/L | 0.145 | Y = X | 2410 (1960 to 3250) | 2480 | -3 |
| Sodium, µg/L | 0.035 | Y = 20,000 (0.30) | 17,000 (15,400 to 19,000) | 19,900 | -17 |
| Sodium, filtered, µg/L | 0.363 | Y = X | 17,200 (14,200 to 27,300) | 18,700 | -9 |
| Chromium, µg/L | 0.004 | Y = 10.2 (0.82) | 64 (48 to 81) | 7.8 | 88 |
| Chromium, filtered, µg/L | 0.063 | Y = 3.8 (0.9) | 14 (7 to 19) | 3.8 | 74 |
| Thallium, filtered, µg/L | 0.004 | Y = 13 (0.63) | 64 (27 to 94) | 13 | 80 |
| Antimony, filtered, µg/L | 0.004 | Y = 8.1 (1.7) | 56 (39 to 86) | 8.1 | 86 |
| Nitrate, mg/L | 0.500 | Y = X | 6.0 (4.9 to 7.1) | 6.1 | -2 |
| Phosphorus, mg/L | 0.227 | Y = X | 0.65 (0.42 to 1.28) | 1.7 | -160 |
| COD, mg/L | 0.063 | Y = 36 (1.4) | 72 (32 to 110) | 36 | 50 |
| Conductivity, µS/cm | 0.227 | Y = X | 337 (179 to 460) | 330 | 3 |
| ORP, mV | 0.008 | Y = 270 (0.13) | 187 (161 to 225) | 267 | -43 |
| Color, Pt color units | 0.063 | Y = 180 (1.6) | 212 (108 to 453) | 179 | 16 |
| Phosphate, as P, mg/L | 0.500 | Y = X | 0.90 (0.45 to 1.43) | 5.2 | -480 |
| Nitrogen, Total, mg/L | 0.500 | Y = X | 10.9 (4 to 17.7) | 11 | 1 |
| UV-254, absorbance units | 0.500 | Y = X | 0.66 (0.23 to 1.08) | 0.71 | -8 |
| Hardness, mg/L | 0.031 | Y = 54 (0.51) | 82 (50 to 106) | 54 | 34 |

* calculated using the sign test, ties ignored in the count; "no data" is when no samples were analyzed

** <LOD substituted with half of the detection limits for these calculations; if predicted effluent is > influent, then use influent concentration (except for pH, and when significant increases are noted in the % removal column)

*** <LOD substituted with half of the detection limits for these calculations

## Table 4-17. Removals for Rhyolite Sand for Full-Depth Column Tests

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| pH | 0.109 | Y = X + 0.2 | 7.7 (7.3 to 8.2) | 7.8 | -2 |
| oil and grease | no data | no data | no data | no data | no data |
| Chloride | 0.500 | Y = X | 18 (1 to 34) | 16 | 10 |
| Fluoride | 0.500 | Y = X | 2.6 (1.7 to 3.1) | 2.5 | 1 |
| Sulfate, as $SO_4$ | 0.500 | Y = X | 45 (39 to 51) | 45 | -1 |
| Boron, µg/L | 0.344 | Y = X | 170 (<LOD to 509) | 219 | -28 |
| Ammonia, as N | 0.008 | Y = 0.38 (1.1) | 2.7 (0.3 to 3.9) | 0.4 | 86 |
| Nitrite + nitrate as N | 0.500 | Y = X | 6.0 (4.9 to 7.1) | 5.4 | 10 |
| nitrite as N | 0.344 | Y = X | 0.03 (0.015 to 0.046) | 0.03 | 1 |
| TDS | 0.200 | Y = X | 199 (80 to 250) | 228 | 0* |
| zinc, µg/L | 0.035 | Y = 48.8 (0.31) | 77 (62 to 92) | 49 | 37 |
| antimony, µg/L | 0.035 | Y = 0.834 X | 68 (47 to 87) | 54 | 21 |
| cadmium, µg/L | 0.004 | almost all effluent < LOD | 65 (43 to 109) | 2 | 98 |
| Copper, µg/L | 0.004 | Y = 37.8 (0.33) | 125 (76 to 244) | 42 | 66 |
| Mercury, µg/L | no data | n/a | n/a | n/a | n/a |
| Nickel, µg/L | 0.004 | Y = 6.9 (0.6) | 51 (35 to 62) | 7 | 86 |
| Lead, µg/L | 0.063 | almost all effluent < LOD | 13 (<LOD to 55) | 2 | 83 |
| Thallium, µg/L (LOD>PL) | 0.004 | Y = 6.6 (0.86) | 79 (46 to 125) | 7 | 92 |
| TCDD, µg/L | no data | n/a | n/a | n/a | n/a |
| Perchlorate, µg/L | no data | n/a | n/a | n/a | n/a |
| Gross alpha radioactivity, pCi/L | no data | n/a | n/a | n/a | n/a |
| Gross beta radioactivity, pCi/L | no data | n/a | n/a | n/a | n/a |
| Tritium, pCi/L | no data | n/a | n/a | n/a | n/a |
| Uranium, pCi/L | no data | n/a | n/a | n/a | n/a |
| Strontium-90, pCi/L | no data | n/a | n/a | n/a | n/a |
| Radium 226 + 228, pCi/L | no data | n/a | n/a | n/a | n/a |
| < 0.45 um particles, mg/L | 0.200 | Y = X | 199 (80 to 250) | 228 | 0* |
| 0.45 to 3 um particles, mg/L | 0.250 | Y = X | 10.6 (3 to 22) | 6.1 | 0* |
| 3 to 12 um particles, mg/L | 0.009 | Y = 1.7 (0.7) | 54.9 (22 to 90) | 1.7 | 97 |
| 12 to 30 um particles, mg/L | 0.009 | Y = 1.21 (1.2) | 54.5 (18 to 90) | 1.2 | 98 |
| 30 to 60 um particles, mg/L | 0.009 | Y = 4.1 (1.2) | 37.4 (3 to 80) | 2.4 | 94 |
| 60 to 120 um particles, mg/L | 0.021 | Y = 1.94 (1.5) | 20.0 (2 to 58) | 1.07 | 95 |
| 120 to 250 um particles, mg/L | 0.009 | Y = 0.44 (1.3) | 5.1 (0 to 17) | 0.31 | 94 |
| 250 to 1180 um particles, mg/L (no particles found >1180) | 0.045 | Y = 5.3 (0.90) | 13.9 (3 to 45) | 3.8 | 73 |
| SSC, mg/L | 0.014 | Y = 7.30 (0.5) | 206 (50 to 400) | 13.4 | 93 |
| TSS (0.45 to 75 µm), mg/L | 0.009 | Y = 3.52 (0.6) | 171 (50 to 310) | 10.2 | 94 |
| Arsenic, µg/L | 0.035 | Y = 0.27 X + 5.93 | 56 (<LOD to 178) | 22 | 61 |
| Arsenic, filtered, µg/L | 0.063 | Y = 0.258 X + 9.58 | 33 (<LOD to 109) | 18 | 43 |
| Aluminum, µg/L | 0.035 | Y = 1630 (2.1) | 6140 (2160 to 10,040) | 1630 | 73 |

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| Aluminum, filtered, µg/L | 0.500 | Y = X | 73 (<LOD to 121) | 232 | -220 |
| Boron, filtered, µg/L | 0.500 | Y = X | 177 (<LOD to 472) | 183 | -3 |
| Calcium, µg/L | 0.363 | Y = X | 30,100 (23,500 to 36,300) | 31,200 | -4 |
| Calcium, filtered, µg/L | 0.637 | Y = X | 30,400 (22,150 to 42,400) | 29,300 | 4 |
| Cadmium, filtered, µg/L | 0.008 | almost all effluent < LOD | 28 (1 to 54) | 1 | 95 |
| Copper, filtered, µg/L | 0.363 | Y = X | 42 (23 to 69) | 37 | 13 |
| Iron, µg/L | 0.035 | Y = 1080 (1.9) | 4830 (1820 to 8620) | 1080 | 78 |
| Iron, filtered, µg/L | 0.637 | Y = X | 63 (44 to 109) | 150 | -130 |
| Magnesium, µg/L | 0.637 | Y = X | 3250 (2710 to 4140) | 3300 | -2 |
| Magnesium, filtered, µg/L | 0.145 | Y = X | 2480 (2140 to 3520) | 2770 | -12 |
| Manganese, µg/L | 0.035 | Y = 30 (2.1) | 66 (33 to 120) | 30 | 54 |
| Manganese, filtered, µg/L | 0.500 | Y = X | 3.4 (<LOD to 13) | 4.5 | -33 |
| Nickel, filtered, µg/L | 0.035 | Y = 6 (0.43) | 27 (7 to 68) | 6 | 77 |
| Lead, filtered, µg/L | n/a | almost all influent and effluent < LOD | 2 (<LOD to 2) | 2 | n/a |
| Zinc, filtered, µg/L | 0.363 | Y = X | 52 (32 to 87) | 49 | 7 |
| Potassium, µg/L | 0.004 | Y = 6520 (0.32) | 3450 (2650 to 4240) | 6520 | -89 |
| Potassium, filtered, µg/L | 0.004 | Y = 5420 (0.23) | 2410 (1960 to 3250) | 5350 | -120 |
| Sodium, µg/L | 0.004 | Y = 22,000 (0.17) | 17,000 (15,400 to 19,000) | 22,000 | -30 |
| Sodium, filtered, µg/L | 0.035 | Y = 24,500 (0.13) | 17,200 (14,200 to 27,300) | 19,600 | -14 |
| Chromium, µg/L | 0.035 | Y = 26.8 (0.54) | 64 (48 to 81) | 27 | 58 |
| Chromium, filtered, µg/L | 0.637 | Y = X | 14 (7 to 19) | 18 | -28 |
| Thallium, filtered, µg/L | 0.004 | almost all effluent < LOD | 64 (27 to 94) | 10 | 85 |
| Antimony, filtered, µg/L | 0.145 | Y = X | 56 (39 to 86) | 46 | 18 |
| Nitrate, mg/L | 0.500 | Y = X | 6.0 (4.9 to 7.1) | 5.4 | 11 |
| Phosphorus, mg/L | 0.008 | Y =0.24 (0.19) | 0.65 (0.42 to 1.28) | 0.24 | 63 |
| COD, mg/L | 0.008 | Y = 19 (0.81) | 72 (32 to 110) | 19 | 74 |
| Conductivity, µS/cm | 0.344 | Y = X | 337 (179 to 460) | 370 | -10 |
| ORP, mV | 0.656 | Y = X | 187 (161 to 225) | 185 | 1 |
| Color, Pt color units | 0.227 | Y = X | 212 (108 to 453) | 152 | 28 |
| Phosphate, as P, mg/L | 0.227 | Y = X | 0.90 (0.45 to 1.43) | 0.63 | 31 |
| Nitrogen, Total, mg/L | 0.063 | Y = 7.8 (0.78) | 10.9 (4 to 17.7) | 7.8 | 28 |
| UV-254, absorbance units | 0.227 | Y = X | 0.66 (0.23 to 1.08) | 0.53 | 19 |
| Hardness, mg/L | 0.227 | Y = X | 82 (50 to 106) | 103 | -25 |

* calculated using the sign test, ties ignored in the count; "no data" is when no samples were analyzed

** <LOD substituted with half of the detection limits for these calculations; if predicted effluent is > influent, then use influent concentration (except for pH, and when significant increases are noted in the % removal column)

*** <LOD substituted with half of the detection limits for these calculations

## Table 4-18. Removals for Site Sand for Full-Depth Column Tests

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| pH | 0.688 | Y = X | 7.7 (7.3 to 8.2) | 7.5 | 2 |
| oil and grease | no data | no data | no data | no data | no data |
| Chloride | 0.500 | Y = X | 18 (1 to 34) | 46 | -47 |
| Fluoride | 0.313 | Y = X | 2.6 (1.7 to 3.1) | 2.1 | 17 |
| Sulfate, as $SO_4$ | 0.688 | Y = X | 45 (39 to 51) | 43 | 6 |
| Boron, µg/L | 0.313 | Y = X | 170 (<LOD to 509) | 213 | -25 |
| Ammonia, as N | 0.063 | Y = 54X | 2.7 (0.3 to 3.9) | 1.3 | 54 |
| Nitrite + nitrate as N | 0.313 | Y = X | 6.0 (4.9 to 7.1) | 5.4 | 11 |
| nitrite as N | 0.313 | Y = X | 0.03 (0.015 to 0.046) | 0.1 | -255 |
| TDS | 0.250 | Y = X | 199 (80 to 250) | 202 | 0* |
| zinc, µg/L | 0.188 | Y = 43 (0.13) | 77 (62 to 92) | 43 | 44 |
| antimony, µg/L | 0.031 | Y = 33 (0.69) | 68 (47 to 87) | 27 | 61 |
| cadmium, µg/L | 0.031 | all effluent <LOD | 65 (43 to 109) | 1 | 98 |
| Copper, µg/L | 0.031 | Y = 31.2 (0.34) | 125 (76 to 244) | 31 | 75 |
| Mercury, µg/L | no data | n/a | n/a | n/a | n/a |
| Nickel, µg/L | 0.031 | almost all effluent <LOD | 51 (35 to 62) | 5 | 89 |
| Lead, µg/L | 0.250 | all effluent <LOD | 13 (<LOD to 55) | 2 | 84 |
| Thallium, µg/L (LOD>PL) | 0.031 | Y = 9.6 (0.84) | 79 (46 to 125) | 10 | 88 |
| TCDD, µg/L | no data | n/a | n/a | n/a | n/a |
| Perchlorate, µg/L | no data | n/a | n/a | n/a | n/a |
| Gross alpha radioactivity, pCi/L | no data | n/a | n/a | n/a | n/a |
| Gross beta radioactivity, pCi/L | no data | n/a | n/a | n/a | n/a |
| Tritium, pCi/L | no data | n/a | n/a | n/a | n/a |
| Uranium, pCi/L | no data | n/a | n/a | n/a | n/a |
| Strontium-90, pCi/L | no data | n/a | n/a | n/a | n/a |
| Radium 226 + 228, pCi/L | no data | n/a | n/a | n/a | n/a |
| < 0.45 um particles, mg/L | 0.250 | Y = X | 199 (80 to 250) | 202 | 0* |
| 0.45 to 3 um particles, mg/L | 0.040 | Y = 3.2 (1.0) | 9.9 (3 to 22) | 3.2 | 68 |
| 3 to 12 um particles, mg/L | 0.022 | Y = 1.7 (0.26) | 50.6 (22 to 90) | 2.4 | 95 |
| 12 to 30 um particles, mg/L | 0.022 | Y = 1.6 (1.2) | 54.5 (18 to 90) | 1.6 | 97 |
| 30 to 60 um particles, mg/L | 0.022 | Y = 1.8 (1.1) | 37.4 (3 to 80) | 1.8 | 95 |
| 60 to 120 um particles, mg/L | 0.022 | Y = 0.067X | 20.0 (2 to 58) | 1.3 | 94 |
| 120 to 250 um particles, mg/L | 0.022 | Y = 0.002X | 5.1 (0 to 17) | 0.3 | 94 |
| 250 to 1180 um particles, mg/L (no particles found >1180) | 0.110 | Y = 2.63 (0.53) | 14.4 (3 to 45) | 2.6 | 82 |
| SSC, mg/L | 0.022 | Y =13.3 (0.49) | 191 (50 to 400) | 13.3 | 93 |
| TSS (0.45 to 75 µm), mg/L | 0.022 | Y = 9.5 (0.60) | 161 (50 to 310) | 9.5 | 94 |
| Arsenic, µg/L | 0.063 | Y = 14.3 (0.46) | 56 (<LOD to 178) | 10 | 82 |
| Arsenic, filtered, µg/L | 0.125 | Y = X | 33 (<LOD to 109) | 11 | 65 |
| Aluminum, µg/L | 0.031 | Y = 750 (0.57) | 6140 (2160 to 10,040) | 750 | 88 |
| Aluminum, filtered, µg/L | 0.313 | Y = X | 73 (<LOD to 121) | 52 | 28 |
| Boron, filtered, µg/L | 0.313 | Y = X | 177 (<LOD to 472) | 185 | -4 |

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| Calcium, µg/L | 0.188 | Y = X | 30,100 (23,500 to 36,300) | 25,700 | 15 |
| Calcium, filtered, µg/L | 0.500 | Y = X | 30,400 (22,150 to 42,400) | 30,900 | -1 |
| Cadmium, filtered, µg/L | 0.031 | almost all effluent <LOD | 28 (1 to 54) | 2 | 93 |
| Copper, filtered, µg/L | 0.188 | Y = X | 42 (23 to 69) | 34 | 19 |
| Iron, µg/L | 0.031 | Y = 560 (0.58) | 4830 (1820 to 8620) | 560 | 88 |
| Iron, filtered, µg/L | 0.031 | Y = 41 (0.32) | 63 (44 to 109) | 41 | 35 |
| Magnesium, µg/L | 0.500 | Y = X | 3250 (2710 to 4140) | 3520 | -8 |
| Magnesium, filtered, µg/L | 0.031 | Y = 3590 (0.20) | 2480 (2140 to 3520) | 3590 | -44 |
| Manganese, µg/L | 0.188 | Y = 18 (0.70) | 66 (33 to 120) | 18 | 72 |
| Manganese, filtered, µg/L | 0.125 | almost all effluent <LOD | 3.4 (<LOD to 13) | 1.3 | 61 |
| Nickel, filtered, µg/L | 0.188 | Y = X | 27 (7 to 68) | 17 | 35 |
| Lead, filtered, µg/L | n/a | all influent and effluent <LOD | 2 (<LOD to 2) | 2 | 0 |
| Zinc, filtered, µg/L | 0.500 | Y = X | 52 (32 to 87) | 65 | 25 |
| Potassium, µg/L | 0.188 | Y = X | 3450 (2650 to 4240) | 2710 | 22 |
| Potassium, filtered, µg/L | 0.500 | Y = X | 2410 (1960 to 3250) | 2750 | -14 |
| Sodium, µg/L | 0.188 | Y = X | 17,000 (15,400 to 19,000) | 16,900 | 0 |
| Sodium, filtered, µg/L | 0.500 | Y = X | 17,200 (14,200 to 27,300) | 18,500 | -7 |
| Chromium, µg/L | 0.031 | Y = 19.2 (0.39) | 64 (48 to 81) | 19 | 70 |
| Chromium, filtered, µg/L | 0.500 | Y = X | 14 (7 to 19) | 14 | 2.6 |
| Thallium, filtered, µg/L | 0.031 | Y = 15 (1.0) | 64 (27 to 94) | 15 | 76 |
| Antimony, filtered, µg/L | 0.188 | Y = X | 56 (39 to 86) | 29 | 48 |
| Nitrate, mg/L | 0.313 | Y = X | 6.0 (4.9 to 7.1) | 5.3 | 12 |
| Phosphorus, mg/L | 0.063 | Y = 0.24X | 0.65 (0.42 to 1.28) | 0.19 | 71 |
| COD, mg/L | 0.063 | Y = 0.34X | 72 (32 to 110) | 22 | 70 |
| Conductivity, µS/cm | 0.313 | Y = X | 337 (179 to 460) | 335 | 1 |
| ORP, mV | 0.313 | Y = X | 187 (161 to 225) | 205 | -9 |
| Color, Pt color units | 0.313 | Y = X | 212 (108 to 453) | 138 | 35 |
| Phosphate, as P, mg/L | 0.063 | Y = 0.48X | 0.90 (0.45 to 1.43) | 0.63 | 30 |
| Nitrogen, Total, mg/L | 0.313 | Y = X | 10.9 (4 to 17.7) | 11 | -4 |
| UV-254, absorbance units | 0.313 | Y = X | 0.66 (0.23 to 1.08) | 0.41 | 38 |
| Hardness, mg/L | 0.688 | Y = X | 82 (50 to 106) | 82 | 1 |

* calculated using the sign test, ties ignored in the count; "no data" is when no samples were analyzed

** <LOD substituted with half of the detection limits for these calculations; if predicted effluent is > influent, then use influent concentration (except for pH, and when significant increases are noted in the % removal column)

*** <LOD substituted with half of the detection limits for these calculations

## Table 4-19. Removals for Site Zeolite for Full-Depth Column Tests

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| pH | 0.227 | Y = X | 7.7 (7.3 to 8.2) | 7.6 | 0.5 |
| oil and grease | no data | no data | no data | no data | no data |
| Chloride | 0.008 | Y = 36 (0.10) | 18 (1 to 34) | 36 | -100 |
| Fluoride | 0.227 | Y = X | 2.6 (1.7 to 3.1) | 2.2 | 14 |
| Sulfate, as $SO_4$ | 0.227 | Y = X | 45 (39 to 51) | 47 | -4 |
| Boron, µg/L | 0.500 | Almost all effluent <LOD | 170 (<LOD to 509) | 249 | -46 |
| Ammonia, as N | 0.008 | Y = 0.18 (1.0) | 2.7 (0.3 to 3.9) | 0.2 | 94 |
| Nitrite + nitrate as N | 0.500 | Y = X | 6.0 (4.9 to 7.1) | 6 | 0 |
| nitrite as N | 0.016 | Y = 0.65X | 0.03 (0.015 to 0.046) | 0.02 | 36 |
| TDS | 0.430 | Y = X | 198 (80 to 250) | 183 | 0* |
| zinc, µg/L | 0.035 | Y = 47 (0.31) | 77 (62 to 92) | 47 | 39 |
| antimony, µg/L | 0.004 | Y = 37 (0.41) | 68 (47 to 87) | 37 | 49 |
| cadmium, µg/L | 0.004 | Almost all effluent <LOD | 65 (43 to 109) | 1 | 98 |
| Copper, µg/L | 0.004 | Y = 0.322 X | 125 (76 to 244) | 41 | 67 |
| Mercury, µg/L | no data | n/a | n/a | n/a | n/a |
| Nickel, µg/L | 0.004 | Y = 7.9 (0.5) | 51 (35 to 62) | 8 | 84 |
| Lead, µg/L | 0.063 | all effluent < LOD | 13 (<LOD to 55) | 2 | 84 |
| Thallium, µg/L (LOD>PL) | 0.004 | Y = 8 (0.80) | 79 (46 to 125) | 8 | 90 |
| TCDD, µg/L | no data | n/a | n/a | n/a | n/a |
| Perchlorate, µg/L | no data | n/a | n/a | n/a | n/a |
| Gross alpha radioactivity, pCi/L | no data | n/a | n/a | n/a | n/a |
| Gross beta radioactivity, pCi/L | no data | n/a | n/a | n/a | n/a |
| Tritium, pCi/L | no data | n/a | n/a | n/a | n/a |
| Uranium, pCi/L | no data | n/a | n/a | n/a | n/a |
| Strontium-90, pCi/L | no data | n/a | n/a | n/a | n/a |
| Radium 226 + 228, pCi/L | no data | n/a | n/a | n/a | n/a |
| < 0.45 um particles, mg/L | 0.430 | Y = X | 198 (80 to 250) | 183 | 0* |
| 0.45 to 3 um particles, mg/L | 0.031 | Y = 2.5 (1.1) | 9.9 (3 to 22) | 2.5 | 75 |
| 3 to 12 um particles, mg/L | 0.009 | Y = 1.6 (0.81) | 50.6 (22 to 90) | 1.6 | 97 |
| 12 to 30 um particles, mg/L | 0.009 | Y = 0.78 (1.1) | 54.5 (18 to 90) | 0.78 | 99 |
| 30 to 60 um particles, mg/L | 0.009 | Y = 2.0 (1.3) | 37.4 (3 to 80) | 1 | 97 |
| 60 to 120 um particles, mg/L | 0.014 | Y = 1.3 (1.5) | 20.0 (2 to 58) | 0.73 | 96 |
| 120 to 250 um particles, mg/L | 0.014 | Y = 0.31 (1.5) | 5.1 (0 to 17) | 0.2 | 96 |
| 250 to 1180 um particles, mg/L (no particles found >1180) | 0.064 | Y = 4.0 (0.61) | 13.9 (3 to 45) | 2.9 | 79 |
| SSC, mg/L | 0.009 | Y =12 (0.52) | 191 (50 to 400) | 9.7 | 95 |
| TSS (0.45 to 75 µm), mg/L | 0.009 | Y = 6.1 (0.53) | 161 (50 to 310) | 6.3 | 96 |
| Arsenic, µg/L | 0.035 | Y = 0.11 X + 12.1 | 56 (<LOD to 178) | 20 | 65 |
| Arsenic, filtered, µg/L | 0.016 | Y = 19 (0.43) | 33 (<LOD to 109) | 13 | 59 |
| Aluminum, µg/L | 0.004 | Y = 310 (0.57) | 6140 (2160 to 10,040) | 306 | 95 |
| Aluminum, filtered, µg/L | 0.500 | Y = X | 73 (<LOD to 121) | 56 | 23 |

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| Boron, filtered, µg/L | 0.188 | Y = X | 177 (<LOD to 472) | 232 | -31 |
| Calcium, µg/L | 0.145 | Y = X | 30,100 (23,500 to 36,300) | 29,700 | 1 |
| Calcium, filtered, µg/L | 0.363 | Y = X | 30,400 (22,150 to 42,400) | 28,900 | 5 |
| Cadmium, filtered, µg/L | 0.008 | Almost all effluent <LOD | 28 (1 to 54) | 2 | 92 |
| Copper, filtered, µg/L | 0.035 | Y = 25 (0.26) | 42 (23 to 69) | 31 | 29 |
| Iron, µg/L | 0.004 | Y = 230 (0.78) | 4830 (1820 to 8620) | 230 | 95 |
| Iron, filtered, µg/L | 0.035 | Y = 0.76 X | 63 (44 to 109) | 43 | 32 |
| Magnesium, µg/L | 0.004 | Y = 1280 (0.39) | 3250 (2710 to 4140) | 1280 | 61 |
| Magnesium, filtered, µg/L | 0.004 | Y = 1400 (0.41) | 2480 (2140 to 3520) | 1400 | 44 |
| Manganese, µg/L | 0.004 | Y = 7.4 (0.85) | 66 (33 to 120) | 7 | 89 |
| Manganese, filtered, µg/L | 0.500 | Y = X | 3.4 (<LOD to 13) | 1.1 | 67 |
| Nickel, filtered, µg/L | 0.145 | Y = X | 27 (7 to 68) | 11 | 58 |
| Lead, filtered, µg/L | 0.500 | almost all influent and effluent <LOD | 2 (<LOD to 2) | 2 | 0 |
| Zinc, filtered, µg/L | 0.227 | Y = X | 52 (32 to 87) | 58 | -11 |
| Potassium, µg/L | 0.035 | Y = 4790 (0.17) | 3450 (2650 to 4240) | 4790 | -39 |
| Potassium, filtered, µg/L | 0.004 | Y = 3900 (0.23) | 2410 (1960 to 3250) | 4350 | -81 |
| Sodium, µg/L | 0.004 | Y = 37,600 (0.40) | 17,000 (15,400 to 19,000) | 37,600 | -120 |
| Sodium, filtered, µg/L | 0.004 | Y = 24,800 (0.23) | 17,200 (14,200 to 27,300) | 32,100 | -87 |
| Chromium, µg/L | 0.004 | Y = 20.5 (0.53) | 64 (48 to 81) | 21 | 68 |
| Chromium, filtered, µg/L | 0.004 | Y = 0.86 X | 14 (7 to 19) | 11 | 21 |
| Thallium, filtered, µg/L | 0.004 | Y = 7.5 (0.77) | 64 (27 to 94) | 7.5 | 88 |
| Antimony, filtered, µg/L | 0.035 | Y = 0.72 X | 56 (39 to 86) | 37 | 35 |
| Nitrate, mg/L | 0.500 | Y = X | 6.0 (4.9 to 7.1) | 6 | 0 |
| Phosphorus, mg/L | 0.008 | Y = 0.19 (0.55) | 0.65 (0.42 to 1.28) | 0.19 | 71 |
| COD, mg/L | 0.008 | Y = 14 (0.81) | 72 (32 to 110) | 14 | 81 |
| Conductivity, µS/cm | 0.109 | Y = 420 (0.10) | 337 (179 to 460) | 420 | -23 |
| ORP, mV | 0.227 | Y = X | 187 (161 to 225) | 191 | -2 |
| Color, Pt color units | 0.008 | Y = 55 (0.58) | 212 (108 to 453) | 55 | 74 |
| Phosphate, as P, mg/L | 0.016 | Y = 0.32 (0.60) | 0.90 (0.45 to 1.43) | 0.32 | 65 |
| Nitrogen, Total, mg/L | 0.008 | Y = 0.58X | 10.9 (4 to 17.7) | 6.5 | 41 |
| UV-254, absorbance units | 0.008 | Y = 0.50X | 0.66 (0.23 to 1.08) | 0.34 | 48 |
| Hardness, mg/L | 0.227 | Y = X | 82 (50 to 106) | 79 | 4 |

* calculated using the sign test, ties ignored in the count; "no data" is when no samples were analyzed

** <LOD substituted with half of the detection limits for these calculations; if predicted effluent is > influent, then use influent concentration (except for pH, and when significant increases are noted in the % removal column)

*** <LOD substituted with half of the detection limits for these calculations

### Table 4-20. Removals for Surface Modified Zeolite for Full-Depth Column Tests

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| pH | 0.063 | Y = X + 0.1 | 7.7 (7.3 to 8.2) | 7.7 | -1 |
| oil and grease | no data | no data | no data | no data | no data |
| Chloride | 0.063 | Y = 26 (0.41) | 18 (1 to 34) | 26 | -47 |
| Fluoride | 0.500 | Y = X | 2.6 (1.7 to 3.1) | 2.5 | 3 |
| Sulfate, as $SO_4$ | 0.063 | Y = 45 (0.11) | 45 (39 to 51) | 45 | 1 |
| Boron, µg/L | 0.188 | almost all effluent < LOD | 170 (<LOD to 509) | 156 | 8 |
| Ammonia, as N | 0.008 | Y = 0.10 (0.58) | 2.7 (0.3 to 3.9) | 0.1 | 96 |
| Nitrite + nitrate as N | 0.227 | Y = X | 6.0 (4.9 to 7.1) | 5.9 | 7 |
| nitrite as N | 0.227 | Y = X | 0.03 (0.015 to 0.046) | 0.03 | -2 |
| TDS | n/a | Y = X (by observation) | 199 (80 to 250) | 232 | 0* |
| zinc, µg/L | 0.004 | Y = 44 (0.25) | 77 (62 to 92) | 44 | 43 |
| antimony, µg/L | 0.004 | Y = X - 25 | 68 (47 to 87) | 43 | 37 |
| cadmium, µg/L | 0.004 | almost all effluent < LOD | 65 (43 to 109) | 1 | 98 |
| Copper, µg/L | 0.004 | Y = 43 (0.23) | 125 (76 to 244) | 39 | 68 |
| Mercury, µg/L | no data | n/a | n/a | n/a | |
| Nickel, µg/L | 0.004 | Y = 3.3 (0.51) | 51 (35 to 62) | 3 | 94 |
| Lead, µg/L | 0.063 | almost all effluent < LOD | 13 (<LOD to 55) | 2 | 82 |
| Thallium, µg/L (LOD>PL) | 0.004 | Y = 5.8 (0.77) | 79 (46 to 125) | 6 | 93 |
| TCDD, µg/L | no data | n/a | n/a | n/a | n/a |
| Perchlorate, µg/L | no data | n/a | n/a | n/a | n/a |
| Gross alpha radioactivity, pCi/L | no data | n/a | n/a | n/a | n/a |
| Gross beta radioactivity, pCi/L | no data | n/a | n/a | n/a | n/a |
| Tritium, pCi/L | no data | n/a | n/a | n/a | n/a |
| Uranium, pCi/L | no data | n/a | n/a | n/a | n/a |
| Strontium-90, pCi/L | no data | n/a | n/a | n/a | n/a |
| Radium 226 + 228, pCi/L | no data | n/a | n/a | n/a | n/a |
| < 0.45 um particles, mg/L | n/a | Y = X (by observation) | 199 (80 to 250) | 232 | 0* |
| 0.45 to 3 um particles, mg/L | 0.014 | Y = 0.40X | 9.9 (3 to 22) | 3.8 | 62 |
| 3 to 12 um particles, mg/L | 0.009 | Y = 1.6 (0.56) | 50.6 (22 to 90) | 1.6 | 97 |
| 12 to 30 um particles, mg/L | 0.009 | Y = 0.71 (0.40) | 54.5 (18 to 90) | 0.74 | 99 |
| 30 to 60 um particles, mg/L | 0.009 | Y = 1.9 (0.90) | 37.4 (3 to 80) | 1.3 | 97 |
| 60 to 120 um particles, mg/L | 0.009 | Y = 0.97 (1.1) | 20.0 (2 to 58) | 0.97 | 95 |
| 120 to 250 um particles, mg/L | 0.009 | Y = 0.19 (1.4) | 5.1 (0 to 17) | 0.19 | 96 |
| 250 to 1180 um particles, mg/L (no particles found >1180) | 0.045 | Y = 3.5 (0.52) | 13.9 (3 to 45) | 3.1 | 78 |
| SSC, mg/L | 0.009 | Y = 7.7 (0.35) | 191 (50 to 400) | 11.7 | 94 |
| TSS (0.45 to 75 µm), mg/L | 0.009 | Y = 0.047X | 161 (50 to 310) | 8 | 95 |
| Arsenic, µg/L | 0.063 | Y = 0.17 X + 20 | 56 (<LOD to 178) | 25 | 55 |
| Arsenic, filtered, µg/L | 0.500 | Y = X | 33 (<LOD to 109) | 20 | 38 |

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| Aluminum, µg/L | 0.004 | Y = 200 (0.35) | 6140 (2160 to 10,040) | 274 | 96 |
| Aluminum, filtered, µg/L | 0.008 | Y = 0.65 X | 73 (<LOD to 121) | 48 | 34 |
| Boron, filtered, µg/L | 0.500 | Y = X | 177 (<LOD to 472) | 160 | 10 |
| Calcium, µg/L | 0.363 | Y = 1.2 X | 30,100 (23,500 to 36,300) | 34,800 | -15 |
| Calcium, filtered, µg/L | 0.363 | Y = X | 30,400 (22,150 to 42,400) | 33,000 | -8 |
| Cadmium, filtered, µg/L | 0.008 | almost all effluent < LOD | 28 (1 to 54) | 2 | 95 |
| Copper, filtered, µg/L | 0.227 | Y = X | 42 (23 to 69) | 35 | 18 |
| Iron, µg/L | 0.004 | Y = 180 (0.48) | 4830 (1820 to 8620) | 180 | 96 |
| Iron, filtered, µg/L | 0.004 | Y = 23 (0.30) | 63 (44 to 109) | 36 | 44 |
| Magnesium, µg/L | 0.363 | Y = X | 3250 (2710 to 4140) | 3950 | -21 |
| Magnesium, filtered, µg/L | 0.035 | Y = 3600 (0.39) | 2480 (2140 to 3520) | 3570 | -44 |
| Manganese, µg/L | 0.004 | Y = 4.8 (1.0) | 66 (33 to 120) | 4.9 | 93 |
| Manganese, filtered, µg/L | 0.500 | Y = X | 3.4 (<LOD to 13) | 3.1 | 9 |
| Nickel, filtered, µg/L | 0.035 | Y = 4.8 (0.37) | 27 (7 to 68) | 4.8 | 82 |
| Lead, filtered, µg/L | n/a | almost all influent and effluent < LOD | 2 (<LOD to 2) | 2 | 0 |
| Zinc, filtered, µg/L | 0.227 | Y = X | 52 (32 to 87) | 46 | 12 |
| Potassium, µg/L | 0.637 | Y = X | 3450 (2650 to 4240) | 1050 | -17 |
| Potassium, filtered, µg/L | 0.035 | Y = 4400 (0.32) | 2410 (1960 to 3250) | 3980 | -66 |
| Sodium, µg/L | 0.145 | Y = X | 17,000 (15,400 to 19,000) | 20,200 | -19 |
| Sodium, filtered, µg/L | 0.363 | Y = X | 17,200 (14,200 to 27,300) | 17,500 | -2 |
| Chromium, µg/L | 0.004 | Y = 20 (0.53) | 64 (48 to 81) | 20 | 68 |
| Chromium, filtered, µg/L | 0.035 | Y = 12 (0.87) | 14 (7 to 19) | 12 | 18 |
| Thallium, filtered, µg/L | 0.004 | almost all effluent < LOD | 64 (27 to 94) | 5.5 | 91 |
| Antimony, filtered, µg/L | 0.063 | Y = 39 (0.42) | 56 (39 to 86) | 34 | 39 |
| Nitrate, mg/L | 0.227 | Y = X | 6.0 (4.9 to 7.1) | 5.6 | 7 |
| Phosphorus, mg/L | 0.008 | Y = 0.32 (0.22) | 0.65 (0.42 to 1.28) | 0.32 | 50 |
| COD, mg/L | 0.008 | Y = 27 (0.62) | 72 (32 to 110) | 27 | 62 |
| Conductivity, µS/cm | 0.227 | Y = X | 337 (179 to 460) | 390 | -17 |
| ORP, mV | 0.500 | Y = X | 187 (161 to 225) | 191 | -2 |
| Color, Pt color units | 0.063 | Y = 100 (1.3) | 212 (108 to 453) | 99 | 53 |
| Phosphate, as P, mg/L | 0.063 | Y = 0.68 (0.46) | 0.90 (0.45 to 1.43) | 0.68 | 25 |
| Nitrogen, Total, mg/L | 0.063 | Y = 8.5 (0.67) | 10.9 (4 to 17.7) | 8.5 | 22 |
| UV-254, absorbance units | 0.063 | Y = 0.50 (0.69) | 0.66 (0.23 to 1.08) | 0.5 | 24 |
| Hardness, mg/L | 0.063 | Y = 140 (0.33) | 82 (50 to 106) | 140 | -69 |

* calculated using the sign test, ties ignored in the count; "no data" is when no samples were analyzed

** <LOD substituted with half of the detection limits for these calculations; if predicted effluent is > influent, then use influent concentration (except for pH, and when significant increases are noted in the % removal column)

*** <LOD substituted with half of the detection limits for these calculations

## Table 4-21. Removals for Rhyolite Sand - Surface Modified Zeolite (R-SMZ) Mixture for Full-Depth Column Tests

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| pH | 0.227 | Y = X | 7.7 (7.3 to 8.2) | 7.8 | -2 |
| oil and grease | most infl. < LOD | n/a | 1.4 (<LOD to 2.2) | 1.5 | n/a |
| Chloride | 0.344 | Y = X | 18 (1 to 34) | 17 | 2 |
| Fluoride | 0.227 | Y = X | 2.6 (1.7 to 3.1) | 2.3 | 10 |
| Sulfate, as $SO_4$ | 0.344 | Y = X | 45 (39 to 51) | 45 | -1 |
| Boron, µg/L | 0.500 | Y = X | 170 (<LOD to 509) | 156 | 8 |
| Ammonia, as N | 0.008 | Y = 0.071 (0.57) | 2.7 (0.3 to 3.9) | 0.1 | 97 |
| Nitrite + nitrate as N | 0.227 | Y = X | 6.0 (4.9 to 7.1) | 5.5 | 8 |
| nitrite as N | 0.227 | Y = X | 0.03 (0.015 to 0.046) | 0.04 | -18 |
| TDS | 0.250 | Y = X | 199 (80 to 250) | 202 | 0* |
| zinc, µg/L | 0.004 | Y = 44 (0.28) | 77 (62 to 92) | 44 | 43 |
| antimony, µg/L | 0.035 | Y = 0.75 X | 68 (47 to 87) | 45 | 34 |
| cadmium, µg/L | 0.004 | almost all effluent <LOD | 65 (43 to 109) | 1 | 98 |
| Copper, µg/L | 0.004 | Y = 56 (0.18) | 125 (76 to 244) | 48 | 61 |
| Mercury, µg/L | 0.125 | Y = 13 (0.48) | 63 (43 to 76) | 12 | 80 |
| Nickel, µg/L | 0.004 | Y = 5.4 (0.17) | 51 (35 to 62) | 5 | 89 |
| Lead, µg/L | 0.063 | all effluent <LOD | 13 (<LOD to 55) | 2 | 84 |
| Thallium, µg/L (LOD>PL) | 0.004 | Y = 7.8 (0.77) | 79 (46 to 125) | 8 | 90 |
| TCDD, µg/L | 0.250 | Y = 1.8 X $10^{-8}$ (0.76) | 1.8X$10^{-7}$ (1X$10^{-8}$ to 5X$10^{-7}$) | 1.8 X $10^{-8}$ | 90 |
| Perchlorate, µg/L | all infl. < LOD | n/a | all infl. <LOD | all effl. <LOD | all infl. < LOD |
| Gross alpha radioactivity, pCi/L | 0.125 | Y = 0.8 (0.68) | 5.3 (3.9 to 6.8) | 0.82 | 84 |
| Gross beta radioactivity, pCi/L | 0.125 | Y = 5.8 (0.14) | 9.4 (8.1 to 10.1) | 5.8 | 39 |
| Tritium, pCi/L | all infl. < LOD | n/a | all infl. <LOD | all effl. <LOD | all infl. < LOD |
| Uranium, pCi/L | 0.125 | Y = 0.31 (0.6) | 1.2 (1.1 to 1.5) | 0.31 | 75 |
| Strontium-90, pCi/L | all infl. < LOD | n/a | 0.45 (0.4 to 0.8) | 0.25 | all infl. < LOD |
| Radium 226 + 228, pCi/L | 0.125 | Y = 0.14 (0.5) | 0.92 (0.67 to 1.2) | 0.14 | 84 |
| < 0.45 um particles, mg/L | 0.250 | Y = X | 199 (80 to 250) | 202 | 0* |
| 0.45 to 3 um particles, mg/L | 0.040 | Y = 3.2 (1.0) | 9.9 (3 to 22) | 3.2 | 68 |
| 3 to 12 um particles, mg/L | 0.022 | Y = 1.7 (0.26) | 50.6 (22 to 90) | 2.4 | 95 |
| 12 to 30 um particles, mg/L | 0.022 | Y = 1.6 (1.2) | 54.5 (18 to 90) | 1.6 | 97 |
| 30 to 60 um particles, mg/L | 0.022 | Y = 1.8 (1.1) | 37.4 (3 to 80) | 1.8 | 95 |
| 60 to 120 um particles, mg/L | 0.022 | Y = 0.067X | 20.0 (2 to 58) | 1.3 | 94 |
| 120 to 250 um particles, mg/L | 0.022 | Y = 0.002X | 5.1 (0 to 17) | 0.3 | 94 |
| 250 to 1180 um particles, mg/L (no particles found >1180) | 0.110 | Y = 2.63 (0.53) | 14.4 (3 to 45) | 2.6 | 82 |
| SSC, mg/L | 0.022 | Y =13.3 (0.49) | 191 (50 to 400) | 13.3 | 93 |

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| TSS (0.45 to 75 µm), mg/L | 0.022 | Y = 9.5 (0.60) | 161 (50 to 310) | 9.5 | 94 |
| Arsenic, µg/L | 0.227 | Y = 0.41 X | 56 (<LOD to 178) | 30 | 48 |
| Arsenic, filtered, µg/L | 0.500 | Y = X | 33 (<LOD to 109) | 27 | 18 |
| Aluminum, µg/L | 0.004 | Y = 1070 (0.70) | 6140 (2160 to 10,040) | 1070 | 83 |
| Aluminum, filtered, µg/L | 0.500 | Y = X | 73 (<LOD to 121) | 74 | -2 |
| Boron, filtered, µg/L | 0.188 | Y = X | 177 (<LOD to 472) | 130 | 26 |
| Calcium, µg/L | 0.363 | Y = X | 30,100 (23,500 to 36,300) | 29,400 | 2 |
| Calcium, filtered, µg/L | 0.363 | Y = X | 30,400 (22,150 to 42,400) | 27,900 | 8 |
| Cadmium, filtered, µg/L | 0.008 | almost all effluent <LOD | 28 (1 to 54) | 2 | 94 |
| Copper, filtered, µg/L | 0.500 | Y = X | 42 (23 to 69) | 40 | 6 |
| Iron, µg/L | 0.004 | Y = 460 (0.65) | 4830 (1820 to 8620) | 460 | 91 |
| Iron, filtered, µg/L | 0.004 | Y = 0.79 X | 63 (44 to 109) | 50 | 22 |
| Magnesium, µg/L | 0.637 | Y = X | 3250 (2710 to 4140) | 3230 | 1 |
| Magnesium, filtered, µg/L | 0.035 | Y = 2970 (0.20) | 2480 (2140 to 3520) | 2970 | -20 |
| Manganese, µg/L | 0.004 | Y = 10 (0.68) | 66 (33 to 120) | 10 | 85 |
| Manganese, filtered, µg/L | 0.344 | Y = X | 3.4 (<LOD to 13) | 4.4 | -31 |
| Nickel, filtered, µg/L | 0.035 | Y = 8 (0.82) | 27 (7 to 68) | 8 | 70 |
| Lead, filtered, µg/L | n/a | almost all influent and effluent <LOD | 2 (<LOD to 2) | 2 | 0 |
| Zinc, filtered, µg/L | 0.363 | Y = X | 52 (32 to 87) | 47 | 10 |
| Potassium, µg/L | 0.035 | Y = 4560 (0.07) | 3450 (2650 to 4240) | 4380 | -27 |
| Potassium, filtered, µg/L | 0.004 | Y = 4140 (0.09) | 2410 (1960 to 3250) | 3850 | -66 |
| Sodium, µg/L | 0.004 | Y = 1.2 X | 17,000 (15,400 to 19,000) | 20,100 | -18 |
| Sodium, filtered, µg/L | 0.035 | Y = 1.1 X | 17,200 (14,200 to 27,300) | 18,400 | -7 |
| Chromium, µg/L | 0.035 | Y = 27 (0.58) | 64 (48 to 81) | 27 | 57 |
| Chromium, filtered, µg/L | 0.035 | Y = 0.7 X | 14 (7 to 19) | 16 | -12 |
| Thallium, filtered, µg/L | 0.004 | Y = 8.1 (0.87) | 64 (27 to 94) | 8.1 | 87 |
| Antimony, filtered, µg/L | 0.145 | Y = X | 56 (39 to 86) | 42 | 27 |
| Nitrate, mg/L | 0.227 | Y = X | 6.0 (4.9 to 7.1) | 5.5 | 8 |
| Phosphorus, mg/L | 0.008 | Y = 0.29 (0.12) | 0.65 (0.42 to 1.28) | 0.29 | 56 |
| COD, mg/L | 0.008 | Y = 21 (0.60) | 72 (32 to 110) | 21 | 70 |
| Conductivity, µS/cm | 0.344 | Y = X | 337 (179 to 460) | 390 | -15 |
| ORP, mV | 0.500 | Y = X | 187 (161 to 225) | 181 | 3 |
| Color, Pt color units | 0.063 | Y = 0.59X | 212 (108 to 453) | 117 | 45 |
| Phosphate, as P, mg/L | 0.227 | Y = X | 0.90 (0.45 to 1.43) | 0.74 | 18 |
| Nitrogen, Total, mg/L | 0.227 | Y = X | 10.9 (4 to 17.7) | 8.3 | 24 |
| UV-254, absorbance units | 0.500 | Y = X | 0.66 (0.23 to 1.08) | 0.62 | 6 |
| Hardness, mg/L | 0.063 | Y = 96 (0.15) | 82 (50 to 106) | 96 | -17 |

* calculated using the sign test, ties ignored in the count; "no data" is when no samples were analyzed

** <LOD substituted with half of the detection limits for these calculations; if predicted effluent is > influent, then use influent concentration (except for pH, and when significant increases are noted in the % removal column)

*** <LOD substituted with half of the detection limits for these calculations

## Table 4-22. Removals for Rhyolite Sand - Surface Modified Zeolite - Granular Activated Carbon Mixture (R-SMZ-GAC) for Full-Depth Column Tests

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| pH | 0.227 | Y = X | 7.7 (7.3 to 8.2) | 8.1 | -6 |
| oil and grease | most influ. <LOD | n/a | 1.4 (<LOD to 2.2) | all <LOD | >29 |
| Chloride | 0.063 | Y = 30 (0.18) | 18 (1 to 34) | 30 | -72 |
| Fluoride | 0.063 | Y = 2.2 (0.25) | 2.6 (1.7 to 3.1) | 2.2 | 14 |
| Sulfate, as $SO_4$ | 0.063 | Y = 37 (0.29) | 45 (39 to 51) | 37 | 18 |
| Boron, µg/L | 0.031 | almost all effluent <LOD | 170 (<LOD to 509) | 45 | 75 |
| Ammonia, as N | 0.008 | Y = 0.013 (1.4) | 2.7 (0.3 to 3.9) | 0.01 | 96 |
| Nitrite + nitrate as N | 0.063 | Y = 3.0 (0.84) | 6.0 (4.9 to 7.1) | 3 | 49 |
| nitrite as N | 0.227 | Y = X | 0.03 (0.015 to 0.046) | 0.08 | -180 |
| TDS | 0.250 | Y = X | 199 (80 to 250) | 225 | 0* |
| zinc, µg/L | 0.035 | Y = 48 (0.31) | 77 (62 to 92) | 48 | 37 |
| antimony, µg/L | 0.004 | Y = 35 (0.49) | 68 (47 to 87) | 31 | 55 |
| cadmium, µg/L | 0.004 | almost all effluent <LOD | 65 (43 to 109) | 1 | 98 |
| Copper, µg/L | 0.004 | Y = 16 (0.46) | 125 (76 to 244) | 7 | 94 |
| Mercury, µg/L | 0.125 | Y = 2.4 (0.41) | 63 (43 to 76) | 2 | 96 |
| Nickel, µg/L | 0.004 | Y = 4.3 (0.33) | 51 (35 to 62) | 4 | 92 |
| Lead, µg/L | 0.063 | all effluent <LOD | 13 (<LOD to 55) | 2 | 84 |
| Thallium, µg/L (LOD>PL) | 0.004 | almost all effluent <LOD | 79 (46 to 125) | 4 | 96 |
| TCDD, µg/L | 0.250 | Y = $9.4 \times 10^{-9}$ (0.11) | $1.8 \times 10^{-7}$ ($1 \times 10^{-8}$ to $5 \times 10^{-7}$) | $9.4 \times 10^{-9}$ | 95 |
| Perchlorate, µg/L | all infl. < LOD | n/a | all infl. <LOD | all effl. <LOD | all infl. < LOD |
| Gross alpha radioactivity, pCi/L | 0.125 | all effluent <LOD | 5.3 (3.9 to 6.8) | 0.5 | 90 |
| Gross beta radioactivity, pCi/L | 0.500 | Y = X | 9.4 (8.1 to 10.1) | 8.7 | 7 |
| Tritium, pCi/L | all infl. < LOD | n/a | all infl. <LOD | all effl. <LOD | all infl. < LOD |
| Uranium, pCi/L | 0.125 | all eff. <LOD | 1.2 (1.1 to 1.5) | all eff. <LOD | >80 |
| Strontium-90, pCi/L | all infl. < LOD | n/a | 0.45 (0.4 to 0.8) | all effl. <LOD | all infl. < LOD |
| Radium 226 + 228, pCi/L | 0.125 | Y = 0.31 (1.2) | 0.92 (0.67 to 1.2) | 0.31 | 66 |
| < 0.45 um particles, mg/L | 0.250 | Y = X | 199 (80 to 250) | 225 | 0* |
| 0.45 to 3 um particles, mg/L | 0.160 | Y = X | 9.9 (3 to 22) | 7.2 | 0* |
| 3 to 12 um particles, mg/L | 0.009 | Y = 4.0 (0.5) | 54.9 (22 to 90) | 2.9 | 95 |
| 12 to 30 um particles, mg/L | 0.009 | Y = 0.68 (0.76) | 54.5 (18 to 90) | 0.67 | 99 |
| 30 to 60 um particles, mg/L | 0.009 | Y = 1.1 (0.70) | 37.4 (3 to 80) | 1 | 97 |
| 60 to 120 um particles, mg/L | 0.009 | Y = 0.85 (0.77) | 20.0 (2 to 58) | 0.76 | 96 |
| 120 to 250 um particles, mg/L | 0.009 | Y = 0.08 (1.4) | 5.1 (0 to 17) | 0.08 | 98 |
| 250 to 1180 um particles, mg/L (no particles found >1180) | 0.075 | Y = 5.0 (0.66) | 13.9 (3 to 45) | 4.1 | 71 |

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| SSC, mg/L | 0.009 | Y = 10.2 (0.24) | 206 (50 to 400) | 13.6 | 93 |
| TSS (0.45 to 75 µm), mg/L | 0.009 | Y = 10.2 (0.37) | 171 (50 to 310) | 10.2 | 94 |
| Arsenic, µg/L | 0.016 | Y = 14 (0.33) | 56 (<LOD to 178) | 16 | 72 |
| Arsenic, filtered, µg/L | 0.109 | Y = 14 (0.34) | 33 (<LOD to 109) | 14 | 57 |
| Aluminum, µg/L | 0.004 | Y = 610 (1.3) | 6140 (2160 to 10,040) | 614 | 90 |
| Aluminum, filtered, µg/L | 0.008 | Y = 45 (0.39) | 73 (<LOD to 121) | 39 | 46 |
| Boron, filtered, µg/L | 0.031 | all effluent <LOD | 177 (<LOD to 472) | 45 | 75 |
| Calcium, µg/L | 0.363 | Y = X | 30,100 (23,500 to 36,300) | 37,000 | -23 |
| Calcium, filtered, µg/L | 0.637 | Y = X | 30,400 (22,150 to 42,400) | 35,000 | -15 |
| Cadmium, filtered, µg/L | 0.008 | almost all effluent <LOD | 28 (1 to 54) | 1 | 96 |
| Copper, filtered, µg/L | 0.004 | Y = 13 (0.40) | 42 (23 to 69) | 9 | 80 |
| Iron, µg/L | 0.004 | Y = 210 (1.0) | 4830 (1820 to 8620) | 210 | 96 |
| Iron, filtered, µg/L | 0.008 | Y = 0.37 X | 63 (44 to 109) | 21 | 66 |
| Magnesium, µg/L | 0.145 | Y = X | 3250 (2710 to 4140) | 4570 | -41 |
| Magnesium, filtered, µg/L | 0.004 | Y = 4300 (0.39) | 2480 (2140 to 3520) | 4310 | -74 |
| Manganese, µg/L | 0.004 | Y = 6 (1.1) | 66 (33 to 120) | 5.3 | 92 |
| Manganese, filtered, µg/L | 0.125 | almost all effluent <LOD | 3.4 (<LOD to 13) | 0.6 | 81 |
| Nickel, filtered, µg/L | 0.004 | Y = 0.3 X | 27 (7 to 68) | 7.6 | 71 |
| Lead, filtered, µg/L | n/a | almost all influent and effluent <LOD | 2 (<LOD to 2) | 2 | 0 |
| Zinc, filtered, µg/L | 0.363 | Y = X | 52 (32 to 87) | 44 | 14 |
| Potassium, µg/L | 0.004 | Y = 12,800 (0.23) | 3450 (2650 to 4240) | 8990 | -160 |
| Potassium, filtered, µg/L | 0.004 | Y = 8000 (0.23) | 2410 (1960 to 3250) | 7990 | -230 |
| Sodium, µg/L | 0.145 | Y = X | 17,000 (15,400 to 19,000) | 21,400 | -26 |
| Sodium, filtered, µg/L | 0.145 | Y = X | 17,200 (14,200 to 27,300) | 19,600 | -14 |
| Chromium, µg/L | 0.004 | Y = 6.1 (0.69) | 64 (48 to 81) | 5.4 | 91 |
| Chromium, filtered, µg/L | 0.004 | Y = 0.27 X | 14 (7 to 19) | 2.8 | 80 |
| Thallium, filtered, µg/L | 0.004 | almost all effluent <LOD | 64 (27 to 94) | 5.5 | 91 |
| Antimony, filtered, µg/L | 0.035 | Y = 34 (0.39) | 56 (39 to 86) | 30 | 48 |
| Nitrate, mg/L | 0.063 | Y = 3.0 (0.88) | 6.0 (4.9 to 7.1) | 3.0 | 50 |
| Phosphorus, mg/L | 0.500 | Y = X | 0.65 (0.42 to 1.28) | 0.68 | -4 |
| COD, mg/L | 0.008 | Y = 5.6 (1.4) | 72 (32 to 110) | 5.5 | 92 |
| Conductivity, µS/cm | 0.656 | Y = X | 337 (179 to 460) | 360 | -6 |
| ORP, mV | 0.500 | Y = X | 187 (161 to 225) | 184 | 2 |
| Color, Pt color units | 0.008 | Y = 46 (0.66) | 212 (108 to 453) | 46 | 78 |
| Phosphate, as P, mg/L | 0.500 | Y = X | 0.90 (0.45 to 1.43) | 1.5 | -66 |
| Nitrogen, Total, mg/L | 0.008 | Y = 2.9 (0.88) | 10.9 (4 to 17.7) | 2.9 | 74 |
| UV-254, absorbance units | 0.063 | Y = 0.16 (2.0) | 0.66 (0.23 to 1.08) | 0.16 | 75 |
| Hardness, mg/L | 0.500 | Y = X | 82 (50 to 106) | 102 | -24 |

* calculated using the sign test, ties ignored in the count; "no data" is when no samples were analyzed

** <LOD substituted with half of the detection limits for these calculations; if predicted effluent is > influent, then use influent concentration (except for pH, and when significant increases are noted in the % removal column)

*** <LOD substituted with half of the detection limits for these calculations

## Table 4-23. Removals for Rhyolite Sand - Surface Modified Zeolite - Granular Activated Carbon - Peat Moss (R-SMZ-GAC-PM) for Full-Depth Column Tests

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| pH | 0.227 | Y = X | 7.7 (7.3 to 8.2) | 7.6 | 1 |
| oil and grease | most influ. <LOD | n/a | 1.4 (<LOD to 2.2) | all <LOD | >29 |
| Chloride | 0.109 | Y = 33 (0.39) | 18 (1 to 34) | 33 | -89 |
| Fluoride | 0.344 | Y = X | 2.6 (1.7 to 3.1) | 2.1 | 17 |
| Sulfate, as $SO_4$ | 0.188 | Y = X | 45 (39 to 51) | 42 | 8 |
| Boron, µg/L | 0.031 | almost all effluent <LOD | 170 (<LOD to 509) | 83 | 51 |
| Ammonia, as N | 0.008 | Y = 0.037 (1.0) | 2.7 (0.3 to 3.9) | <0.1 | 99 |
| Nitrite + nitrate as N | 0.227 | Y = X | 6.0 (4.9 to 7.1) | 3.6 | 41 |
| nitrite as N | 0.500 | Y = X | 0.03 (0.015 to 0.046) | 0.13 | -320 |
| TDS | 0.200 | Y = X | 199 (80 to 250) | 205 | 0* |
| zinc, µg/L | 0.145 | Y = X | 77 (62 to 92) | 59 | 23 |
| antimony, µg/L | 0.004 | Y = 32 (0.55) | 68 (47 to 87) | 28 | 59 |
| cadmium, µg/L | 0.004 | almost all effluent <LOD | 65 (43 to 109) | 3 | 96 |
| Copper, µg/L | 0.004 | Y = 21 (0.41) | 125 (76 to 244) | 20 | 84 |
| Mercury, µg/L | 0.125 | Y = 2.2 (0.41) | 63 (43 to 76) | 2 | 96 |
| Nickel, µg/L | 0.004 | Y = 6.3 (0.71) | 51 (35 to 62) | 6 | 88 |
| Lead, µg/L | 0.063 | almost all effluent <LOD | 13 (<LOD to 55) | 2 | 84 |
| Thallium, µg/L (LOD>PL) | 0.004 | Y = 5.6 (0.9) | 79 (46 to 125) | 6 | 93 |
| TCDD, µg/L | 0.250 | Y = 2 X $10^{-8}$ (0.86) | 1.8X$10^{-7}$ (1X$10^{-8}$ to 5X$10^{-7}$) | 2 X $10^{-8}$ | 89 |
| Perchlorate, µg/L | all infl. < LOD | n/a | all infl. <LOD | all effl. <LOD | all infl. < LOD |
| Gross alpha radioactivity, pCi/L | 0.125 | Y = 0.5 (all <LOD) | 5.3 (3.9 to 6.8) | 0.5 (all <LOD) | >90 |
| Gross beta radioactivity, pCi/L | 0.500 | Y = X | 9.4 (8.1 to 10.1) | 8.6 | 9 |
| Tritium, pCi/L | all infl. < LOD | n/a | all infl. <LOD | all effl. <LOD | all infl. < LOD |
| Uranium, pCi/L | 0.500 | Y = X | 1.2 (1.1 to 1.5) | 3 | -160 |
| Strontium-90, pCi/L | all infl. < LOD | n/a | 0.45 (0.4 to 0.8) | all effl. <LOD | all infl. < LOD |
| Radium 226 + 228, pCi/L | 0.125 | Y = 0.18 (0.81) | 0.92 (0.67 to 1.2) | 0.18 | 80 |
| < 0.45 um particles, mg/L | 0.200 | Y = X | 199 (80 to 250) | 205 | 0* |
| 0.45 to 3 um particles, mg/L | 0.031 | Y = 4.8 (0.70) | 9.9 (3 to 22) | 4.8 | 52 |
| 3 to 12 um particles, mg/L | 0.009 | Y = 4.1 (0.86) | 50.6 (22 to 90) | 2.6 | 95 |
| 12 to 30 um particles, mg/L | 0.009 | Y = 0.48 (0.57) | 54.5 (18 to 90) | 0.48 | 99 |
| 30 to 60 um particles, mg/L | 0.009 | Y = 1.3 (0.79) | 37.4 (3 to 80) | 0.97 | 97 |
| 60 to 120 um particles, mg/L | 0.009 | Y = 1.0 (0.71) | 20.0 (2 to 58) | 0.78 | 96 |
| 120 to 250 um particles, mg/L | 0.009 | Y = 0.15 (0.88) | 5.1 (0 to 17) | 0.15 | 97 |
| 250 to 1180 um particles, mg/L (no particles found >1180) | 0.009 | Y = 2.4 (0.33) | 13.9 (3 to 45) | 2.8 | 80 |
| SSC, mg/L | 0.009 | Y =9.2 (0.48) | 191 (50 to 400) | 12.6 | 93 |

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| TSS (0.45 to 75 µm), mg/L | 0.009 | Y = 14.5 (0.82) | 161 (50 to 310) | 14.5 | 91 |
| Arsenic, µg/L | 0.008 | Y = 0.16 X + 14 | 56 (<LOD to 178) | 21 | 64 |
| Arsenic, filtered, µg/L | 0.016 | Y = 0.18 X + 13 | 33 (<LOD to 109) | 15 | 53 |
| Aluminum, µg/L | 0.004 | Y = 440 (0.58) | 6140 (2160 to 10,040) | 437 | 93 |
| Aluminum, filtered, µg/L | 0.008 | Y = 0.69 X | 73 (<LOD to 121) | 50 | 31 |
| Boron, filtered, µg/L | 0.031 | all effluent <LOD | 177 (<LOD to 472) | 45 | 75 |
| Calcium, µg/L | 0.637 | Y = X | 30,100 (23,500 to 36,300) | 30,500 | -1 |
| Calcium, filtered, µg/L | 0.637 | Y = X | 30,400 (22,150 to 42,400) | 29,000 | 5 |
| Cadmium, filtered, µg/L | 0.008 | almost all effluent <LOD | 28 (1 to 54) | 1 | 96 |
| Copper, filtered, µg/L | 0.004 | Y = 21 (0.55) | 42 (23 to 69) | 18 | 57 |
| Iron, µg/L | 0.004 | Y = 200 (0.53) | 4830 (1820 to 8620) | 200 | 96 |
| Iron, filtered, µg/L | 0.004 | Y = 0.65 X | 63 (44 to 109) | 42 | 34 |
| Magnesium, µg/L | 0.145 | Y = X | 3250 (2710 to 4140) | 4040 | -24 |
| Magnesium, filtered, µg/L | 0.004 | Y = 3660 (0.26) | 2480 (2140 to 3520) | 3660 | -47 |
| Manganese, µg/L | 0.004 | Y = 16 (0.34) | 66 (33 to 120) | 16 | 77 |
| Manganese, filtered, µg/L | 0.313 | Y = X | 3.4 (<LOD to 13) | 2.2 | 35 |
| Nickel, filtered, µg/L | 0.004 | Y = 5.1 (0.46) | 27 (7 to 68) | 5.1 | 81 |
| Lead, filtered, µg/L | n/a | almost all influent and effluent <LOD | 2 (<LOD to 2) | 4 | -110 |
| Zinc, filtered, µg/L | 0.637 | Y = X | 52 (32 to 87) | 51 | 1 |
| Potassium, µg/L | 0.004 | Y = 8000 (0.20) | 3450 (2650 to 4240) | 8000 | -130 |
| Potassium, filtered, µg/L | 0.004 | Y = 6700 (0.27) | 2410 (1960 to 3250) | 6700 | -180 |
| Sodium, µg/L | 0.145 | Y = X | 17,000 (15,400 to 19,000) | 20,100 | -18 |
| Sodium, filtered, µg/L | 0.363 | Y = X | 17,200 (14,200 to 27,300) | 18,600 | -8 |
| Chromium, µg/L | 0.004 | Y = 10 (0.42) | 64 (48 to 81) | 10 | 90 |
| Chromium, filtered, µg/L | 0.004 | Y = 9 (0.45) | 14 (7 to 19) | 5.7 | 60 |
| Thallium, filtered, µg/L | 0.004 | Y = 7.4 (0.82) | 64 (27 to 94) | 7.4 | 89 |
| Antimony, filtered, µg/L | 0.035 | Y = 0.33 (0.38) | 56 (39 to 86) | 29 | 49 |
| Nitrate, mg/L | 0.227 | Y = X | 6.0 (4.9 to 7.1) | 3.4 | 43 |
| Phosphorus, mg/L | 0.500 | Y = X | 0.65 (0.42 to 1.28) | 0.62 | 4 |
| COD, mg/L | 0.008 | Y = 8.6 (1.9) | 72 (32 to 110) | 8.6 | 88 |
| Conductivity, µS/cm | 0.344 | Y = X | 337 (179 to 460) | 370 | -10 |
| ORP, mV | 0.500 | Y = X | 187 (161 to 225) | 186 | 0 |
| Color, Pt color units | 0.063 | Y = 66 (0.64) | 212 (108 to 453) | 66 | 69 |
| Phosphate, as P, mg/L | 0.063 | Y = 1.9 (0.64) | 0.90 (0.45 to 1.43) | 1.9 | -110 |
| Nitrogen, Total, mg/L | 0.008 | Y = 2.3 (0.85) | 10.9 (4 to 17.7) | 2.3 | 79 |
| UV-254, absorbance units | 0.008 | Y = 0.09 (0.51) | 0.66 (0.23 to 1.08) | 0.09 | 87 |
| Hardness, mg/L | 0.227 | Y = X | 82 (50 to 106) | 100 | -21 |

* calculated using the sign test, ties ignored in the count; "no data" is when no samples were analyzed

** <LOD substituted with half of the detection limits for these calculations; if predicted effluent is > influent, then use influent concentration (except for pH, and when significant increases are noted in the % removal column)

*** <LOD substituted with half of the detection limits for these calculations

## Table 4-24. Removals for Layered Site Sand - Site Zeolite - Granular Activated Carbon (S-Z-GAC) for Full-Depth Column Tests

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| pH | 0.227 | Y = X | 7.7 (7.3 to 8.2) | 8.1 | -6 |
| oil and grease | most influ. <LOD | most influ. <LOD | 1.4 (<LOD to 2.2) | 1.7 | most infl. <LOD |
| Chloride | 0.008 | Y = 44 (0.64) | 18 (1 to 34) | 44 | -150 |
| Fluoride | 0.227 | Y = X | 2.6 (1.7 to 3.1) | 2.3 | 12 |
| Sulfate, as $SO_4$ | 0.008 | Y = 34 (0.34) | 45 (39 to 51) | 34 | 24 |
| Boron, µg/L | 0.031 | almost all effluent <LOD | 170 (<LOD to 509) | 72 | 58 |
| Ammonia, as N | 0.008 | Y = 0.18 (1.1) | 2.7 (0.3 to 3.9) | 0.2 | 94 |
| Nitrite + nitrate as N | 0.008 | Y = 1.7 (0.98) | 6.0 (4.9 to 7.1) | 1.7 | 72 |
| nitrite as N | 0.227 | Y = X | 0.03 (0.015 to 0.046) | 0.02 | 29 |
| TDS | 0.160 | Y = X | 199 (80 to 250) | 249 | 0* |
| zinc, µg/L | 0.004 | Y = 52 (0.30) | 77 (62 to 92) | 52 | 33 |
| antimony, µg/L | 0.004 | Y = 0.53 X | 68 (47 to 87) | 36 | 48 |
| cadmium, µg/L | 0.004 | almost all effluent <LOD | 65 (43 to 109) | 2 | 98 |
| Copper, µg/L | 0.004 | Y = 8.4 (0.46) | 125 (76 to 244) | 8 | 94 |
| Mercury, µg/L | 0.125 | Y = 0.043X | 63 (43 to 76) | 3 | 96 |
| Nickel, µg/L | 0.004 | almost all effluent <LOD | 51 (35 to 62) | 4 | 92 |
| Lead, µg/L | 0.313 | almost all effluent <LOD | 13 (<LOD to 55) | 3 | 80 |
| Thallium, µg/L (LOD>PL) | 0.004 | all effluent <LOD | 79 (46 to 125) | 3 | 96 |
| TCDD, µg/L | 0.250 | Y = 9.5 X $10^{-9}$ (0.10) | 1.8X$10^{-7}$ (1X$10^{-8}$ to 5X$10^{-7}$) | 9.5 X $10^{-9}$ | 95 |
| Perchlorate, µg/L | all infl. < LOD | n/a | all infl. <LOD | all effl. <LOD | all infl. < LOD |
| Gross alpha radioactivity, pCi/L | 0.125 | Y = 0.009X | 5.3 (3.9 to 6.8) | 0.05 | >90 |
| Gross beta radioactivity, pCi/L | 0.125 | Y = 5.4 (0.40) | 9.4 (8.1 to 10.1) | 5.4 | 42 |
| Tritium, pCi/L | all infl. < LOD | n/a | all infl. <LOD | all effl. <LOD | all infl. < LOD |
| Uranium, pCi/L | 0.500 | Y = X | 1.2 (1.1 to 1.5) | 0.8 | 30 |
| Strontium-90, pCi/L | all infl. < LOD | n/a | 0.45 (0.4 to 0.8) | all effl. <LOD | all infl. < LOD |
| Radium 226 + 228, pCi/L | 0.125 | all effluent <LOD | 0.92 (0.67 to 1.2) | all effl. <LOD | >90 |
| < 0.45 um particles, mg/L | 0.160 | Y = X | 199 (80 to 250) | 249 | 0* |
| 0.45 to 3 um particles, mg/L | 0.014 | Y = 2.3 (0.74) | 9.9 (3 to 22) | 2.3 | 77 |
| 3 to 12 um particles, mg/L | 0.009 | Y = 1.4 (0.61) | 50.6 (22 to 90) | 1.4 | 97 |
| 12 to 30 um particles, mg/L | 0.009 | Y = 0.65 (0.59) | 54.5 (18 to 90) | 0.64 | 99 |
| 30 to 60 um particles, mg/L | 0.009 | Y = 1.1 (0.96) | 37.4 (3 to 80) | 1.1 | 97 |
| 60 to 120 um particles, mg/L | 0.009 | Y = 0.75 (1.1) | 20.0 (2 to 58) | 0.44 | 98 |
| 120 to 250 um particles, mg/L | 0.014 | Y = 0.19 (1.2) | 5.1 (0 to 17) | 0.14 | 97 |
| 250 to 1180 um particles, | 0.009 | Y = 2.5 (0.49) | 13.9 (3 to 45) | 2.2 | 84 |

| Constituent, mg/L unless noted otherwise | p that effluent equals influent* | regression equation (or Y = constant, and COV also shown)** | Mean Influent Concentration (approximate range)*** | Mean Effluent Concentration*** | Reduction (%)*** |
|---|---|---|---|---|---|
| mg/L (no particles found >1180) | | | | | |
| SSC, mg/L | 0.009 | Y = 9.1 (0.25) | 191 (50 to 400) | 8.2 | 96 |
| TSS (0.45 to 75 µm), mg/L | 0.009 | Y = 5.4 (0.33) | 161 (50 to 310) | 5.6 | 97 |
| Arsenic, µg/L | 0.008 | Y = 0.042 X + 18 | 56 (<LOD to 178) | 17 | 71 |
| Arsenic, filtered, µg/L | 0.109 | Y = 13 (14) | 33 (<LOD to 109) | 14 | 58 |
| Aluminum, µg/L | 0.004 | Y = 130 (0.94) | 6140 (2160 to 10,040) | 131 | 98 |
| Aluminum, filtered, µg/L | 0.008 | Y = 0.60 X | 73 (<LOD to 121) | 38 | 48 |
| Boron, filtered, µg/L | 0.031 | all effluent <LOD | 177 (<LOD to 472) | 45 | 75 |
| Calcium, µg/L | 0.637 | Y = X | 30,100 (23,500 to 36,300) | 36,000 | -19 |
| Calcium, filtered, µg/L | 0.637 | Y = X | 30,400 (22,150 to 42,400) | 32,800 | -8 |
| Cadmium, filtered, µg/L | 0.008 | almost all effluent <LOD | 28 (1 to 54) | 1 | 96 |
| Copper, filtered, µg/L | 0.004 | Y = 11 (0.76) | 42 (23 to 69) | 10 | 77 |
| Iron, µg/L | 0.004 | Y = 92 (1.1) | 4830 (1820 to 8620) | 92 | 98 |
| Iron, filtered, µg/L | 0.004 | Y = X -55 | 63 (44 to 109) | 17 | 73 |
| Magnesium, µg/L | 0.145 | Y = X | 3250 (2710 to 4140) | 2740 | 16 |
| Magnesium, filtered, µg/L | 0.363 | Y = X | 2480 (2140 to 3520) | 2650 | -7 |
| Manganese, µg/L | 0.004 | Y = 1.6 (1.2) | 66 (33 to 120) | 1.6 | 98 |
| Manganese, filtered, µg/L | 0.125 | almost all effluent <LOD | 3.4 (<LOD to 13) | 0.6 | 81 |
| Nickel, filtered, µg/L | 0.004 | Y = 6.4 (0.89) | 27 (7 to 68) | 6.4 | 76 |
| Lead, filtered, µg/L | n/a | almost all influent and effluent <LOD | 2 (<LOD to 2) | 2 | 0 |
| Zinc, filtered, µg/L | 0.344 | Y = X | 52 (32 to 87) | 44 | 15 |
| Potassium, µg/L | 0.004 | Y = 7200 (0.52) | 3450 (2650 to 4240) | 7240 | -110 |
| Potassium, filtered, µg/L | 0.004 | Y = 6200 (0.46) | 2410 (1960 to 3250) | 6260 | -160 |
| Sodium, µg/L | 0.004 | Y = 36,700 (0.45) | 17,000 (15,400 to 19,000) | 36,700 | -120 |
| Sodium, filtered, µg/L | 0.035 | Y = 1.8 X | 17,200 (14,200 to 27,300) | 32,200 | -87 |
| Chromium, µg/L | 0.004 | Y = 4.8 (0.62) | 64 (48 to 81) | 4.8 | 92 |
| Chromium, filtered, µg/L | 0.004 | Y = 2 (1.2) | 14 (7 to 19) | 2 | 86 |
| Thallium, filtered, µg/L | 0.004 | almost all effluent <LOD | 64 (27 to 94) | 3.6 | 94 |
| Antimony, filtered, µg/L | 0.035 | Y = 34 (0.42) | 56 (39 to 86) | 33 | 43 |
| Nitrate, mg/L | 0.008 | Y = 1.7 (1.0) | 6.0 (4.9 to 7.1) | 1.7 | 72 |
| Phosphorus, mg/L | 0.500 | Y = X | 0.65 (0.42 to 1.28) | 0.73 | -12 |
| COD, mg/L | 0.008 | Y = 4.4 (2.3) | 72 (32 to 110) | 4.4 | 94 |
| Conductivity, µS/cm | 0.109 | Y = 440 (0.13) | 337 (179 to 460) | 440 | -30 |
| ORP, mV | 0.500 | Y = X | 187 (161 to 225) | 180 | 4 |
| Color, Pt color units | 0.008 | Y = 0.16X | 212 (108 to 453) | 30 | 86 |
| Phosphate, as P, mg/L | 0.227 | Y = X | 0.90 (0.45 to 1.43) | 2 | -120 |
| Nitrogen, Total, mg/L | 0.227 | Y = X | 10.9 (4 to 17.7) | 4.6 | 57 |
| UV-254, absorbance units | 0.008 | Y = 0.030 (0.68) | 0.66 (0.23 to 1.08) | 0.03 | 95 |
| Hardness, mg/L | 0.063 | Y = 97 (0.15) | 82 (50 to 106) | 97 | -17 |

* calculated using the sign test, ties ignored in the count; "no data" is when no samples were analyzed

** <LOD substituted with half of the detection limits for these calculations; if predicted effluent is > influent, then use influent concentration (except for pH, and when significant increases are noted in the % removal column)

*** <LOD substituted with half of the detection limits for these calculations

## Table 4-25. Calculated Treatment Effluent Concentrations for Maximum Observed Site Concentrations Compared to Permit Limits

| | | | Granular Activated Carbon (GAC) | | Peat Moss (PM) | | Rhyolite Sand | |
|---|---|---|---|---|---|---|---|---|
| Constituent, mg/L unless noted otherwise | permit limits (008 and 009) | Maximum observed 008 and 009 concentrations (Geosyntec Feb 2009) | calculated effluent concentrations* | Reduction (%) | calculated effluent concentrations* | Reduction (%) | calculated effluent concentrations* | Reduction (%) |
| pH | between 6.5 and 8.5 | max: 7.75 and **8.80**<br>min: 6.60 and 6.70 | max: 8.45 and **9.50**<br>min: 7.30 and 7.40 | -10 | **max: 4.75 and 5.80**<br>**min: 3.60 and 3.70** | 39 | max: 7.95 and **9.00**<br>min: 6.80 and 6.90 | -2 |
| Chloride | 150 mg/L | 25 and 46 | 25 and 46 | -74 | 25 and 33 | -89 | 25 and 46 | 10 |
| Fluoride | 1.6 mg/L | 0.24 and 0.40 | 0.24 and 0.40 | 15 | 0.24 and 0.40 | 34 | 0.24 and 0.40 | 1 |
| Sulfate, as $SO_4$ | 300/250 mg/L | 21 and 240 | 21 and 240 | 15 | 21 and 240 | -13 | 21 and 240 | -1 |
| Boron, µg/L | 1 mg/L | 0.079 and 0.21 | 0.079 and 0.21 | 60 | 0.079 and 0.21 | -19 | 0.079 and 0.21 | -28 |
| Ammonia, as N | 10.1 mg/L | <0.3 | <0.3 | 90 | <0.3 | -23 | <0.3 | 86 |
| Nitrite + nitrate as N | 8/10 mg/L | 7.7 and 3.6 | 0.56 | 91 | 7.7 and 3.6 | -4 | 7.7 and 3.6 | 10 |
| nitrite as N | 1/na mg/L | <0.06 | <0.06 | -255 | <0.06 | -13 | <0.06 | 1 |
| TDS | 950/850 mg/L | 290 and 570 | 290 and 570 | 0 | 290 and 570 | 0* | 290 and 570 | 0* |
| zinc, µg/L | 159 µg/L | 40 and 88 | 40 and 48 | 38 | 40 and 57 | 26 | 40 and 49 | 37 |
| antimony, µg/L | 6 µg/L | <2.5 and 4.2 | <2.5 and 4.2 | 60 | <2.5 and 4.2 | 88 | <2.5 and 3.5 | 21 |
| cadmium, µg/L | 5 µg/L | 1.5 and **9.2** | <LOD | 98 | <LOD | 98 | <LOD | 98 |
| Copper, µg/L | 14 µg/L | **15 and 39** | 4.5 | 97 | 13 | 90 | **15 and 38** | 66 |
| Nickel, µg/L | 100 µg/L | 7.8 and 10 | <LOD | 92 | 6 | 88 | 6.9 | 86 |
| Lead, µg/L | 5.2 µg/L | **120 and 260** | <LOD | 84 | <LOD | 84 | <LOD | 83 |
| Thallium, µg/L (LOD>PL) | 2 µg/L | <7 | <7 | 96 | <7 | 89 | <7 | 92 |

* if predicted effluent is > influent, then use influent concentration (except for pH, and when significant increases are noted in the % removal column due to washout/leaching)

The highlighted and bold values exceed the permit limits

## Table 4-25. Calculated Treated Effluent Concentrations for Maximum Observed Site Concentrations Compared to Permit Limits (continued)

| | | | Site Sand | | Site Zeolite | | Surface Modified Zeolite (SMZ) | |
|---|---|---|---|---|---|---|---|---|
| Constituent, mg/L unless noted otherwise | permit limits (008 and 009) | Maximum observed 008 and 009 concentrations (Geosyntec Feb 2009) | calculated effluent concentrations* | Reduction (%) | calculated effluent concentrations* | Reduction (%) | calculated effluent concentrations* | Reduction (%) |
| pH | between 6.5 and 8.5 | max: 7.75 and **8.80**<br>min: 6.60 and 6.70 | max: 7.75 and 8.80<br>min: 6.60 and 6.70 | 2 | max: 7.75 and **8.80**<br>min: 6.60 and 6.70 | 0.5 | max: 7.85 and **8.90**<br>min: 6.70 and 6.80 | -1 |
| Chloride | 150 mg/L | 25 and 46 | 25 and 46 | -47 | 25 and 36 | -100 | 25 and 26 | -47 |
| Fluoride | 1.6 mg/L | 0.24 and 0.40 | 0.24 and 0.40 | 17 | 0.24 and 0.40 | 14 | 0.24 and 0.40 | 3 |
| Sulfate, as $SO_4$ | 300/250 mg/L | 21 and 240 | 21 and 240 | 6 | 21 and 240 | -4 | 21 and 45 | 1 |
| Boron, µg/L | 1 mg/L | 0.079 and 0.21 | 0.079 and 0.21 | -25 | <LOD | -46 | <LOD | 8 |
| Ammonia, as N | 10.1 mg/L | <0.3 | <0.3 | 54 | <0.3 | 94 | 0.1 | 96 |
| Nitrite + nitrate as N | 8/10 mg/L | 7.7 and 3.6 | 7.7 and 3.6 | 11 | 7.7 and 3.6 | 0 | 7.7 and 3.6 | 7 |
| nitrite as N | 1/na mg/L | <0.06 | <0.06 | -255 | 0.02 | 36 | <0.06 | -2 |
| TDS | 950/850 mg/L | 290 and 570 | 290 and 570 | 0* | 290 and 570 | 0* | 290 and 570 | 0* |
| zinc, µg/L | 159 µg/L | 40 and 88 | 40 and 43 | 44 | 40 and 47 | 39 | 40 and 44 | 43 |
| antimony, µg/L | 6 µg/L | <2.5 and 4.2 | <2.5 and 4.2 | 61 | <2.5 and 4.2 | 49 | <2.5 | 37 |
| cadmium, µg/L | 5 µg/L | 1.5 and **9.2** | <LOD | 98 | <LOD | 98 | <LOD | 98 |
| Copper, µg/L | 14 µg/L | **15 and 39** | **15 and 31** | 75 | 4.8 and 13 | 67 | **15 and 39** | 68 |
| Nickel, µg/L | 100 µg/L | 7.8 and 10 | <LOD | 89 | 7.8 and 7.9 | 84 | 3.3 | 94 |
| Lead, µg/L | 5.2 µg/L | **120 and 260** | <LOD | 84 | <LOD | 84 | <LOD | 82 |
| Thallium, µg/L (LOD>PL) | 2 µg/L | <7 | <7 | 88 | <7 | 90 | <7 | 93 |

* if predicted effluent is > influent, then use influent concentration (except for pH, and when significant increases are noted in the % removal column)

## Table 4-25. Calculated Treated Effluent Concentrations for Maximum Observed Site Concentrations Compared to Permit Limits (continued)

|  |  |  | Rhyolite - Surface Modified Zeolite |  | Rhyolite - Surface Modified Zeolite - Granulated Activated Carbon |  |
|---|---|---|---|---|---|---|
| Constituent, mg/L unless noted otherwise | permit limits (008 and 009) | Maximum observed 008 and 009 concentrations (Geosyntec Feb 2009) | calculated effluent concentrations* | Reduction (%) | calculated effluent concentrations* | Reduction (%) |
| pH | between 6.5 and 8.5 | max: 7.75 and **8.80**<br>min: 6.60 and 6.70 | max: 7.75 and **8.80**<br>min: 6.60 and 6.70 | -2 | max: 7.75 and **8.80**<br>min: 6.60 and 6.70 | -6 |
| oil and grease | 15 mg/L | 12 and **16** | na | n/a | na | >29 |
| Chloride | 150 mg/L | 25 and 46 | 25 and 46 | 2 | 25 and 30 | -72 |
| Fluoride | 1.6 mg/L | 0.24 and 0.40 | 0.24 and 0.40 | 10 | 0.24 and 0.40 | 14 |
| Sulfate, as $SO_4$ | 300/250 mg/L | 21 and 240 | 21 and 240 | -1 | 21 and 37 | 18 |
| Boron, µg/L | 1 mg/L | 0.079 and 0.21 | 0.079 and 0.21 | 8 | <LOD | 75 |
| Ammonia, as N | 10.1 mg/L | <0.3 | <0.3 | 97 | 0.013 | >99 |
| Nitrite + nitrate as N | 8/10 mg/L | 7.7 and 3.6 | 7.7 and 3.6 | 8 | 3 | 49 |
| nitrite as N | 1/na mg/L | <0.06 | <0.06 | -18 | <0.06 | -180 |
| TDS | 950/850 mg/L | 290 and 570 | 290 and 570 | 0* | 290 and 570 | 0* |
| zinc, µg/L | 159 µg/L | 40 and 88 | 40 and 44 | 43 | 40 and 48 | 37 |
| antimony, µg/L | 6 µg/L | <2.5 and 4.2 | <2.5 and 3.2 | 34 | <2.5 and 4.2 | 55 |
| cadmium, µg/L | 5 µg/L | 1.5 and **9.2** | <LOD | 98 | <LOD | 98 |
| Copper, µg/L | 14 µg/L | **15 and 39** | **15 and 39** | 61 | **15 and 16** | 94 |
| Mercury, µg/L | 0.13 µg/L | **0.17 and 0.21** | **0.17 and 0.21** | 80 | **0.17 and 0.21** | 96 |
| Nickel, µg/L | 100 µg/L | 7.8 and 10 | 5.4 | 89 | 4.3 | 92 |
| Lead, µg/L | 5.2 µg/L | **120 and 260** | <LOD | 84 | <LOD | 84 |
| Thallium, µg/L (LOD>PL) | 2 µg/L | <7 | <7 | 90 | <7 | 96 |
| TCDD, µg/L | 2.8 X $10^{-8}$ µg/L | **3.19 X $10^{-7}$ and 9.1 X $10^{-4}$** | 1.8 X $10^{-8}$ | 90 | 9.4 X $10^{-9}$ | 95 |
| Perchlorate, µg/L | 6 µg/L | <1.5 | na | all infl. < LOD | <1.5 | all infl. < LOD |
| Gross alpha radioactivity, pCi/L | 15 pCi/L | 6.07 and **16.3** | 0.8 | 84 | <LOD | 90 |

|  |  |  | Rhyolite - Surface Modified Zeolite |  | Rhyolite - Surface Modified Zeolite - Granulated Activated Carbon |  |
|---|---|---|---|---|---|---|
| Constituent, mg/L unless noted otherwise | permit limits (008 and 009) | Maximum observed 008 and 009 concentrations (Geosyntec Feb 2009) | calculated effluent concentrations* | Reduction (%) | calculated effluent concentrations* | Reduction (%) |
| Gross beta radioactivity, pCi/L | 50 pCi/L | 23.7 and 21.8 | 5.8 | 39 | 23.7 and 21.8 | 7 |
| Tritium, pCi/L | 20,000 pCi/L | <50 | <50 | all infl. < LOD | <50 | all infl. < LOD |
| Uranium, pCi/L | 20 pCi/L | 0.68 and 0.52 | 0.31 | 75 | <LOD | >80 |
| Strontium-90, pCi/L | 300 pCi/L | 0.21 and 0.29 | na | all infl. < LOD | na | all infl. < LOD |
| Radium 226 + 228, pCi/L | 5 pCi/L | 0.50 and 1.88 | 0.14 | 84 | 0.31 | 66 |

## Table 4-25. Calculated Treated Effluent Concentrations for Maximum Observed Site Concentrations Compared to Permit Limits (continued)

| | | | Rhyolite - Surface Modified Zeolite - Granulated Activated Carbon - Peat Moss | | Layered Site Sand – Site Zeolite – Granular Activated Carbon (SZG) | |
|---|---|---|---|---|---|---|
| Constituent, mg/L unless noted otherwise | permit limits (008 and 009) | Maximum observed 008 and 009 concentrations (Geosyntec Feb 2009) | calculated effluent concentrations* | Reduction (%) | calculated effluent concentrations* | Reduction (%) |
| pH | between 6.5 and 8.5 | max: 7.75 and **8.80**<br>min: 6.60 and 6.70 | max: 7.75 and **8.80**<br>min: 6.60 and 6.70 | 1 | max: 7.75 and **8.80**<br>min: 6.60 and 6.70 | -6 |
| oil and grease | 15 mg/L | 12 and **16** | na | >29 | na | most influ. <LOD |
| Chloride | 150 mg/L | 25 and 46 | 25 and 33 | -89 | 25 and 44 | -150 |
| Fluoride | 1.6 mg/L | 0.24 and 0.40 | 0.24 and 0.40 | 17 | 0.24 and 0.40 | 12 |
| Sulfate, as $SO_4$ | 300/250 mg/L | 21 and 240 | 21 and 240 | 8 | 21 and 30 | 33 |
| Boron, µg/L | 1 mg/L | 0.079 and 0.21 | <LOD | 51 | <LOD | 58 |
| Ammonia, as N | 10.1 mg/L | <0.3 | 0.037 | 99 | 0.18 | 94 |
| Nitrite + nitrate as N | 8/10 mg/L | 7.7 and 3.6 | 7.7 and 3.6 | 41 | 1.7 | 72 |
| nitrite as N | 1/na mg/L | <0.06 | <0.06 | -320 | <0.06 | 29 |
| TDS | 950/850 mg/L | 290 and 570 | 290 and 570 | 0* | 290 and 570 | 0* |
| zinc, µg/L | 159 µg/L | 40 and 88 | 40 and 88 | 23 | 40 and 52 | 33 |
| antimony, µg/L | 6 µg/L | <2.5 and 4.2 | <2.5 and 4.2 | 59 | <2.5 and 2.2 | 48 |
| cadmium, µg/L | 5 µg/L | 1.5 and **9.2** | <LOD | 96 | <LOD | 98 |
| Copper, µg/L | 14 µg/L | **15 and 39** | **15 and 21** | 84 | 8.4 | 94 |
| Mercury, µg/L | 0.13 µg/L | **0.17 and 0.21** | **0.17 and 0.21** | 96 | 0.007 and 0.009 | 96 |
| Nickel, µg/L | 100 µg/L | 7.8 and 10 | 6.3 | 88 | <LOD | 92 |
| Lead, µg/L | 5.2 µg/L | **120 and 260** | <LOD | 84 | <LOD | 80 |
| Thallium, µg/L (LOD>PL) | 2 µg/L | <7 | <7 | 93 | <7 | 96 |
| TCDD, µg/L | 2.8 X $10^{-8}$ µg/L | **3.19 X $10^{-7}$ and 9.1 X $10^{-4}$** | 2 X $10^{-8}$ | 89 | 9.5 X $10^{-9}$ | 95 |
| Perchlorate, µg/L | 6 µg/L | <1.5 | <1.5 | all infl. < LOD | <1.5 | all infl. < LOD |

|  |  |  | Rhyolite - Surface Modified Zeolite - Granulated Activated Carbon - Peat Moss |  | Layered Site Sand – Site Zeolite – Granular Activated Carbon (SZG) |  |
|---|---|---|---|---|---|---|
| Constituent, mg/L unless noted otherwise | permit limits (008 and 009) | Maximum observed 008 and 009 concentrations (Geosyntec Feb 2009) | calculated effluent concentrations* | Reduction (%) | calculated effluent concentrations* | Reduction (%) |
| Gross alpha radioactivity, pCi/L | 15 pCi/L | 6.07 and **16.3** | 0.5 | >90 | 0.055 and 0.15 | >90 |
| Gross beta radioactivity, pCi/L | 50 pCi/L | 23.7 and 21.8 | 23.7 and 21.8 | 9 | 5.4 | 42 |
| Tritium, pCi/L | 20,000 pCi/L | <50 | <50 | all infl. < LOD | <50 | all infl. < LOD |
| Uranium, pCi/L | 20 pCi/L | 0.68 and 0.52 | 0.68 and 0.52 | -160 | 0.68 and 0.52 | 30 |
| Strontium-90, pCi/L | 300 pCi/L | 0.21 and 0.29 | na | all infl. < LOD | na | all infl. < LOD |
| Radium 226 + 228, pCi/L | 5 pCi/L | 0.50 and 1.88 | 0.18 | 80 | <LOD | >90 |

The most common exceedence during maximum site conditions is for pH, where it may be slightly high (up to 9 compared to permit limit of 8.5) or too low (as low of 4.75 compared to 6.6 for initial flushing flows). Lead and copper were also periodic exceedences as some of the media were not effective in reducing very low copper and lead influent concentrations to the even lower permit limits. Similar issues occur with mercury; the levels are already low and some media cannot reduce it further. Table 4-26 through 4-31 summarize the constituent-media combinations that had significant removals and significant increases in constituent concentrations (Tables 4-26 through 4-28 for the media components and 4-29 through 4-31 for the mixtures). Most of the constituents and media combinations that had statistically significant decreases had decreases in the range of at least 25 to 50%. Exceptions are some of the major ions (Mg, K, and Na, for example) that participate in ion exchange reactions. Percent reductions were calculated, although their use is questionable since they are dependent on the influent water chemistry and concentration.

**Table 4-26. Significant Decreases: Media Components (generally greater than at least 25 to 50%)**

| Constituent | Granular Activated Carbon | Peat Moss | Rhyolite sand | Site sand | Site Zeolite | Surface Modified Zeolite |
|---|---|---|---|---|---|---|
| SSC, mg/L | X | X | X | X | X | X |
| Antimony, filtered, µg/L | X | X |  |  | X | X |
| Antimony, µg/L | X | X | X | X | X | X |
| Arsenic, filtered, µg/L | X |  | X |  | X |  |
| Arsenic, µg/L | X | X | X | X | X | X |
| Boron, filtered, µg/L | X |  |  |  |  |  |
| Boron, µg/L |  |  |  |  |  |  |
| Cadmium, filtered, µg/L | X | X | X | X | X | X |
| Cadmium, µg/L | X | X | X | X | X | X |
| Chromium, filtered, µg/L | X | X |  |  | X | X |
| Chromium, µg/L | X | X | X | X | X | X |
| Copper, filtered, µg/L | X | X |  |  | X |  |
| Copper, µg/L | X | X | X | X | X | X |
| Lead, filtered, µg/L |  |  |  |  |  |  |
| Lead, µg/L | X | X | X |  | X | X |
| Manganese, filtered, µg/L | X |  |  |  |  |  |
| Manganese, µg/L | X |  | X |  | X | X |
| Nickel, filtered, µg/L | X | X | X |  |  | X |
| Nickel, µg/L | X | X | X | X | X | X |
| Thallium, filtered, µg/L | X | X | X | X | X | X |
| Thallium, µg/L (LOD>PL) | X | X | X | X | X | X |
| Zinc, filtered, µg/L |  |  |  |  |  |  |

| Constituent | Granular Activated Carbon | Peat Moss | Rhyolite sand | Site sand | Site Zeolite | Surface Modified Zeolite |
|---|---|---|---|---|---|---|
| Zinc, µg/L | X | X | X |  | X | X |
| Aluminum, filtered, µg/L | X |  |  |  |  | X |
| Aluminum, µg/L | X | X | X | X | X | X |
| Calcium, filtered, µg/L |  | X |  |  |  |  |
| Calcium, µg/L |  | X |  |  |  |  |
| Iron, filtered, µg/L | X |  |  | X | X | X |
| Iron, µg/L | X | X | X | X | X | X |
| Magnesium, filtered, µg/L |  |  |  |  | X |  |
| Magnesium, µg/L |  |  |  |  | X |  |
| Potassium, filtered, µg/L |  |  |  |  |  |  |
| Potassium, µg/L |  |  |  |  |  |  |
| Sodium, filtered, µg/L |  |  |  |  |  |  |
| Sodium, µg/L |  |  |  |  |  |  |
| Ammonia, as N, mg/L | X |  | X | X | X | X |
| Chloride, mg/L |  |  |  |  |  |  |
| COD, mg/L | X | X | X | X | X | X |
| Color, Pt color units | X | X |  |  | X | X |
| Conductivity, µS/cm |  |  |  |  |  |  |
| Fluoride, mg/L |  | X |  |  |  |  |
| Hardness, mg/L |  | X |  |  |  |  |
| Nitrate, mg/L | X |  |  |  |  |  |
| Nitrite + nitrate as N, mg/L | X |  |  |  |  |  |
| Nitrite as N. mg/ |  |  |  |  | X |  |
| Nitrogen, Total, mg/L | X |  | X |  | X | X |
| ORP, mV |  |  |  |  |  |  |
| pH |  | X |  |  |  |  |
| Phosphate, as P, mg/L |  |  |  | X | X | X |
| Phosphorus, mg/L |  |  | X | X | X | X |
| Sulfate, as $SO_4$, mg/L |  |  |  |  |  | X |
| UV-254, absorbance units | X |  |  |  | X | X |

**Table 4-27. Significant Increases: Media Components (generally at least 25% to 50% or greater)**

| Constituent | Granular Activated Carbon | Peat Moss | Rhyolite sand | Site sand | Site Zeolite | Surface Modified Zeolite |
|---|---|---|---|---|---|---|
| SSC, mg/L | | | | | | |
| Antimony, filtered, µg/L | | | | | | |
| Antimony, µg/L | | | | | | |
| Arsenic, filtered, µg/L | | | | | | |
| Arsenic, µg/L | | | | | | |
| Boron, filtered, µg/L | | | | | | |
| Boron, µg/L | | | | | | |
| Cadmium, filtered, µg/L | | | | | | |
| Cadmium, µg/L | | | | | | |
| Chromium, filtered, µg/L | | | | | | |
| Chromium, µg/L | | | | | | |
| Copper, filtered, µg/L | | | | | | |
| Copper, µg/L | | | | | | |
| Lead, filtered, µg/L | | | | | | |
| Lead, µg/L | | | | | | |
| Manganese, filtered, µg/L | | X | | | | |
| Manganese, µg/L | | X | | | | |
| Nickel, filtered, µg/L | | | | | | |
| Nickel, µg/L | | | | | | |
| Thallium, filtered, µg/L | | | | | | |
| Thallium, µg/L (LOD>PL) | | | | | | |
| Zinc, filtered, µg/L | | | | | | |
| Zinc, µg/L | | | | | | |
| Aluminum, filtered, µg/L | | X | | | | |
| Aluminum, µg/L | | | | | | |
| Calcium, filtered, µg/L | | | | | | |
| Calcium, µg/L | | | | | | |
| Iron, filtered, µg/L | | | | | | |
| Iron, µg/L | | | | | | |
| Magnesium, filtered, µg/L | X | | | X | | X |
| Magnesium, µg/L | | | | | | |
| Potassium, filtered, µg/L | X | | X | | X | X |
| Potassium, µg/L | | | X | | X | |
| Sodium, filtered, µg/L | | | X | | X | |
| Sodium, µg/L | X | X | | | X | |
| Ammonia, as N, mg/L | | | | | | |
| Chloride, mg/L | | X | | | X | X |

| Constituent | Granular Activated Carbon | Peat Moss | Rhyolite sand | Site sand | Site Zeolite | Surface Modified Zeolite |
|---|---|---|---|---|---|---|
| COD, mg/L | | | | | | |
| Color, Pt color units | | | | | | |
| Conductivity, µS/cm | X | | | | X | |
| Fluoride, mg/L | | | | | | |
| Hardness, mg/L | | | | | | X |
| Nitrate, mg/L | | | | | | |
| Nitrite + nitrate as N, mg/L | | | | | | |
| Nitrite as N. mg/ | | | | | | |
| Nitrogen, Total, mg/L | | | | | | |
| ORP, mV | | X | | | | |
| pH | X | | X | | | X |
| Phosphate, as P, mg/L | X | | | | | |
| Phosphorus, mg/L | X | | | | | |
| Sulfate, as $SO_4$, mg/L | | | | | | |
| UV-254, absorbance units | | | | | | |

**Table 4-28. Insufficient Data to Show Significant Change: Media Components (Minimum change detected is 25 to 50%)**

| Constituent | Granular Activated Carbon | Peat Moss | Rhyolite sand | Site sand | Site Zeolite | Surface Modified Zeolite |
|---|---|---|---|---|---|---|
| SSC, mg/L | | | | | | |
| Antimony, filtered, µg/L | | | X | X | | |
| Antimony, µg/L | | | | | | |
| Arsenic, filtered, µg/L | | X | | X | | X |
| Arsenic, µg/L | | | | | | |
| Boron, filtered, µg/L | | X | X | X | X | X |
| Boron, µg/L | X | X | X | X | X | X |
| Cadmium, filtered, µg/L | | | | | | |
| cadmium, µg/L | | | | | | |
| Chromium, filtered, µg/L | | | X | X | | |
| Chromium, µg/L | | | | | | |
| Copper, filtered, µg/L | | | X | X | | X |
| Copper, µg/L | | | | | | |
| Lead, filtered, µg/L | X | X | | | X | X |
| Lead, µg/L | | | | X | | |
| Manganese, filtered, µg/L | | | X | X | X | X |
| Manganese, µg/L | | | | X | | |

| Constituent | Granular Activated Carbon | Peat Moss | Rhyolite sand | Site sand | Site Zeolite | Surface Modified Zeolite |
|---|---|---|---|---|---|---|
| Nickel, filtered, µg/L |  |  |  | X | X |  |
| Nickel, µg/L |  |  |  |  |  |  |
| Thallium, filtered, µg/L |  |  |  |  |  |  |
| Thallium, µg/L (LOD>PL) |  |  |  |  |  |  |
| Zinc, filtered, µg/L | X | X | X | X | X | X |
| Zinc, µg/L |  |  |  | X |  |  |
| Aluminum, filtered, µg/L |  |  | X | X | X |  |
| Aluminum, µg/L |  |  |  |  |  |  |
| Calcium, filtered, µg/L | X |  | X | X | X | X |
| Calcium, µg/L | X |  | X | X | X | X |
| Iron, filtered, µg/L |  | X | X |  |  |  |
| Iron, µg/L |  |  |  |  |  |  |
| Magnesium, filtered, µg/L |  | X | X |  |  |  |
| Magnesium, µg/L | X | X | X | X |  | X |
| Potassium, filtered, µg/L |  | X |  | X |  |  |
| Potassium, µg/L | X | X |  | X |  | X |
| Sodium, filtered, µg/L | X | X |  | X |  | X |
| Sodium, µg/L |  |  |  | X |  | X |
| Ammonia, as N, mg/L |  | X |  |  |  |  |
| Chloride, mg/L | X |  | X | X |  |  |
| COD, mg/L |  |  |  |  |  |  |
| Color, Pt color units |  |  | X | X |  |  |
| Conductivity, µS/cm |  | X | X | X |  | X |
| Fluoride, mg/L | X |  | X | X | X | X |
| Hardness, mg/L | X |  | X | X | X |  |
| Nitrate, mg/L |  | X | X | X | X | X |
| Nitrite + nitrate as N, mg/L |  | X | X | X | X | X |
| Nitrite as N. mg/ | X | X | X | X |  | X |
| Nitrogen, Total, mg/L |  | X |  | X |  |  |
| ORP, mV | X |  | X | X | X | X |
| pH |  |  |  | X | X |  |
| Phosphate, as P, mg/L |  | X | X |  |  |  |
| Phosphorus, mg/L |  | X |  |  |  |  |
| Sulfate, as $SO_4$, mg/L | X | X | X | X | X |  |
| UV-254, absorbance units |  | X | X | X |  |  |

### Table 4-29. Significant Decreases: Media Mixtures (generally greater than 25% to 50%)

| Constituent | Rhyolite Sand – Surface Modified Zeolite | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon – Peat Moss | Layered Site Sand – Site Zeolite – Granular Activated Carbon |
|---|---|---|---|---|
| SSC, mg/L | X | X | X | X |
| Antimony, filtered, µg/L |  | X | X | X |
| antimony, µg/L | X | X | X | X |
| Arsenic, filtered, µg/L |  | X | X | X |
| Arsenic, µg/L |  | X | X | X |
| Boron, filtered, µg/L |  | X | X | X |
| Boron, µg/L |  | X | X | X |
| Cadmium, filtered, µg/L | X | X | X | X |
| Cadmium, µg/L | X | X | X | X |
| Chromium, filtered, µg/L |  | X | X | X |
| Chromium, µg/L | X | X | X | X |
| Copper, filtered, µg/L |  | X | X | X |
| Copper, µg/L | X | X | X | X |
| Lead, filtered, µg/L |  |  |  |  |
| Lead, µg/L | X | X | X |  |
| Manganese, filtered, µg/L |  | X |  | X |
| Manganese, µg/L | X | X | X | X |
| Nickel, filtered, µg/L | X | X | X | X |
| Nickel, µg/L | X | X | X | X |
| Thallium, filtered, µg/L | X | X | X | X |
| Thallium, µg/L (LOD>PL) | X | X | X | X |
| Zinc, filtered, µg/L |  |  |  |  |
| Zinc, µg/L | X | X |  | X |
| Aluminum, filtered, µg/L |  | X | X | X |
| Aluminum, µg/L | X | X | X | X |
| Calcium, filtered, µg/L |  |  |  |  |
| Calcium, µg/L |  |  |  |  |
| Iron, filtered, µg/L | X | X | X | X |
| Iron, µg/L | X | X | X | X |
| Magnesium, filtered, µg/L |  |  |  |  |
| Magnesium, µg/L |  |  |  |  |
| Potassium, filtered, µg/L |  |  |  |  |
| Potassium, µg/L |  |  |  |  |
| Sodium, filtered, µg/L |  |  |  |  |

| Constituent | Rhyolite Sand – Surface Modified Zeolite | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon – Peat Moss | Layered Site Sand – Site Zeolite – Granular Activated Carbon |
|---|---|---|---|---|
| Sodium, µg/L | | | | |
| Ammonia, as N, mg/L | X | X | X | X |
| Chloride, mg/L | | | | |
| COD, mg/L | X | X | X | X |
| Color, Pt color units | X | X | X | X |
| Conductivity, µS/cm | | | | |
| Fluoride, mg/L | | X | | |
| Hardness, mg/L | | | | |
| Nitrate, mg/L | | X | | X |
| Nitrite + nitrate as N, mg/L | | X | | X |
| Nitrite as N, mg/L | | | | |
| Nitrogen, Total, mg/L | | X | X | |
| ORP, mV | | | | |
| pH | | | | |
| Phosphate, as P, mg/L | | | | |
| Phosphorus, mg/L | X | | | |
| Sulfate, as $SO_4$, mg/L | | X | | X |
| UV-254, absorbance units | | X | X | X |
| Gross alpha radioactivity, pCi/L | X | X | X | X |
| Gross beta radioactivity, pCi/L | X | | | X |
| Mercury, µg/L | X | X | X | X |
| Radium 226 + 228, pCi/L | X | X | X | X |
| TCDD, µg/L | | X | X | X |
| Uranium, pCi/L | X | X | | |

## Table 4-30. Significant Increases: Media Mixtures (Generally greater than 25% to 50%)

| Constituent | Rhyolite Sand – Surface Modified Zeolite | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon – Peat Moss | Layered Site Sand – Site Zeolite – Granular Activated Carbon |
|---|---|---|---|---|
| SSC, mg/L | | | | |
| Antimony, filtered, µg/L | | | | |
| Antimony, µg/L | | | | |
| Arsenic, filtered, µg/L | | | | |
| Arsenic, µg/L | | | | |
| Boron, filtered, µg/L | | | | |
| Boron, µg/L | | | | |
| Cadmium, filtered, µg/L | | | | |
| Cadmium, µg/L | | | | |
| Chromium, filtered, µg/L | X | | | |
| Chromium, µg/L | | | | |
| Copper, filtered, µg/L | | | | |
| Copper, µg/L | | | | |
| Lead, filtered, µg/L | | | | |
| Lead, µg/L | | | | |
| Manganese, filtered, µg/L | | | | |
| Manganese, µg/L | | | | |
| Nickel, filtered, µg/L | | | | |
| Nickel, µg/L | | | | |
| Thallium, filtered, µg/L | | | | |
| Thallium, µg/L (LOD>PL) | | | | |
| Zinc, filtered, µg/L | | | | |
| Zinc, µg/L | | | | |
| Aluminum, filtered, µg/L | | | | |
| Aluminum, µg/L | | | | |
| Calcium, filtered, µg/L | | | | |
| Calcium, µg/L | | | | |
| Iron, filtered, µg/L | | | | |
| Iron, µg/L | | | | |
| Magnesium, filtered, µg/L | X | X | X | |
| Magnesium, µg/L | | | | |
| Potassium, filtered, µg/L | X | X | X | X |
| Potassium, µg/L | X | X | X | X |
| Sodium, filtered, µg/L | X | | | X |

| Constituent | Rhyolite Sand – Surface Modified Zeolite | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon – Peat Moss | Layered Site Sand – Site Zeolite – Granular Activated Carbon |
|---|---|---|---|---|
| Sodium, µg/L | X | | | X |
| Ammonia, as N, mg/L | | | | |
| Chloride, mg/L | | X | X | X |
| COD, mg/L | | | | |
| Color, Pt color units | | | | |
| Conductivity, µS/cm | | | | X |
| Fluoride, mg/L | | | | |
| Hardness, mg/L | X | | | X |
| Nitrate, mg/L | | | | |
| Nitrite + nitrate as N, mg/L | | | | |
| Nitrite as N, mg/L | | | | |
| Nitrogen, Total, mg/L | | | | |
| ORP, mV | | | | |
| pH | | | | |
| Phosphate, as P, mg/L | | | X | |
| Phosphorus, mg/L | | | | |
| Sulfate, as $SO_4$, mg/L | | | | |
| UV-254, absorbance units | | | | |
| Gross alpha radioactivity, pCi/L | | | | |
| Gross beta radioactivity, pCi/L | | | | |
| Mercury, µg/L | | | | |
| Radium 226 + 228, pCi/L | | | | |
| TCDD, µg/L | | | | |
| Uranium, pCi/L | | | | |

### Table 4-31. Insufficient Data to Show Significant Change: Media Mixtures (Minimum change detected is 25% to 50%)

| Constituent | Rhyolite Sand – Surface Modified Zeolite | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon – Peat Moss | Layered Site Sand – Site Zeolite – Granular Activated Carbon |
|---|---|---|---|---|
| SSC, mg/L | | | | |
| Antimony, filtered, µg/L | X | | | |
| Antimony, µg/L | | | | |
| Arsenic, filtered, µg/L | X | | | |
| Arsenic, µg/L | X | | | |
| Boron, filtered, µg/L | X | | | |
| Boron, µg/L | X | | | |
| Cadmium, filtered, µg/L | | | | |
| Cadmium, µg/L | | | | |
| Chromium, filtered, µg/L | | | | |
| Chromium, µg/L | | | | |
| Copper, filtered, µg/L | X | | | |
| Copper, µg/L | | | | |
| Lead, filtered, µg/L | X | X | X | X |
| Lead, µg/L | | | | X |
| Manganese, filtered, µg/L | X | | X | |
| Manganese, µg/L | | | | |
| Nickel, filtered, µg/L | | | | |
| Nickel, µg/L | | | | |
| Thallium, filtered, µg/L | | | | |
| Thallium, µg/L (LOD>PL) | | | | |
| Zinc, filtered, µg/L | X | X | X | X |
| Zinc, µg/L | | | X | |
| Aluminum, filtered, µg/L | X | | | |
| Aluminum, µg/L | | | | |
| Calcium, filtered, µg/L | X | X | X | X |
| Calcium, µg/L | X | X | X | X |
| Iron, filtered, µg/L | | | | |
| Iron, µg/L | | | | |
| Magnesium, filtered, µg/L | | | | X |
| Magnesium, µg/L | X | X | X | X |
| Potassium, filtered, µg/L | | | | |
| Potassium, µg/L | | | | |
| Sodium, filtered, µg/L | | X | X | |

| Constituent | Rhyolite Sand – Surface Modified Zeolite | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon | Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon – Peat Moss | Layered Site Sand – Site Zeolite – Granular Activated Carbon |
|---|---|---|---|---|
| Sodium, µg/L | | X | X | |
| Ammonia, as N, mg/L | | | | |
| Chloride, mg/L | X | | | |
| COD, mg/L | | | | |
| Color, Pt color units | | | | |
| Conductivity, µS/cm | X | X | X | |
| Fluoride, mg/L | X | | X | X |
| Hardness, mg/L | | X | X | |
| Nitrate, mg/L | X | | X | |
| Nitrite + nitrate as N, mg/L | X | | X | |
| Nitrite as N, mg/L | X | X | X | X |
| Nitrogen, Total, mg/L | X | | | X |
| ORP, mV | X | X | X | X |
| pH | X | X | X | X |
| Phosphate, as P, mg/L | X | X | | X |
| Phosphorus, mg/L | | X | X | X |
| Sulfate, as $SO_4$, mg/L | X | | X | |
| UV-254, absorbance units | X | | | |
| Gross alpha radioactivity, pCi/L | | | | |
| Gross beta radioactivity, pCi/L | | X | X | |
| Mercury, µg/L | | | | |
| Radium 226 + 228, pCi/L | | | | |
| TCDD, µg/L | X | | | |
| Uranium, pCi/L | | | X | X |

### 4.3.2 Obvious Contaminant Changes Observed during the Full-Depth Column Tests

The following list shows the major changes in constituent concentrations identified for the different individual media and combinations of media during these column studies. For the individual media, these are based on the effluent behavior, which reflects the contribution of both the medium and the site sand, which was mixed 50/50 (v/v) with the media. The sand was added to improve the hydraulic retention time for the larger media and to prevent compaction and washout of the smaller media. The sand also was likely responsible for most of the excellent particle retention and removal of particulate-bound pollutants. The site sand is listed first below so that its removal ability can be highlighted separate from the individual media.

Site Sand (S):

- Filtering significantly reduced particulate forms
- Small manganese (filtered) increase indicating some CEC (similar to prior testing, sand has poor removal ability, but it is not inert)
- Phosphorus and phosphate reductions

Granular Activated Carbon (GAC):

- Filtering significantly reduced particulate forms
- Very large potassium (filtered) increase indicating significant cation exchange (some filtered manganese increase)
- Some phosphorus leaching
- Small pH drop
- Very large nitrate decrease

Peat Moss (P):

- Filtering significantly reduced particulate forms
- Very large manganese and aluminum (filtered forms) increases indicating significant cation exchange
- Very large pH decrease indicating large $H^+$ ($H_3O+$) releases

Rhyolite Sand:

- Filtering significantly reduced particulate forms
- Some potassium and small sodium increases indicating some possible cation exchange
- Small pH increase

Site Zeolite (Z):

- Filtering significantly reduced particulate forms
- Large potassium and sodium increases indicating cation exchange removal
- Phosphorus and phosphate reductions

Surface Modified Zeolite (SMZ):

- Filtering significantly reduced particulate forms
- Some manganese and potassium increases indicating some cation exchange
- Phosphate and phosphorus reductions

Rhyolite Sand – Surface Modified Zeolite (R – SMZ) Mixed Media:

- Filtering significantly reduced particulate forms

- Filtered potassium increase (small increases for filtered sodium and magnesium) showing some cation exchange

Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon (R – SMZ – G) Mixed Media:

- Filtering significantly reduced particulate forms
- Filtered potassium increase (small increases for filtered magnesium) showing some cation exchange

Rhyolite Sand – Surface Modified Zeolite – Granular Activated Carbon – Peat Moss (R – SMZ – G - P) Mixed Media:

- Filtering significantly reduced particulate forms
- Filtered potassium increase (small increases for filtered magnesium) showing some cation exchange

Layered Site Sand – Site Zeolite – Granular Activated Carbon (SZG) Mixed Media:

- Filtering significantly reduced particulate forms
- Filtered potassium and sodium increase showing cation exchange

### 4.3.3 Long-Term Removal as a Function of Pollutant Form

All of the individual media and mixtures demonstrated excellent removals of solids and particulate-associated pollutants. However, the removal of dissolved, colloidal, or complexed components varied greatly by media type. For example, Figure 4-25 shows the removal of total and filtered forms of copper for the different media. The primary removal mechanism in the media is physical straining/removal of particulate-associated copper. The best removal of copper was by GAC, followed by peat, which may be related to organic complexation of copper in the influent water or complexation with the organic content of the media. Poorer removal of filtered copper was observed by zeolites (typically associated with CEC removal mechanisms) and sands (only physical straining mechanisms).

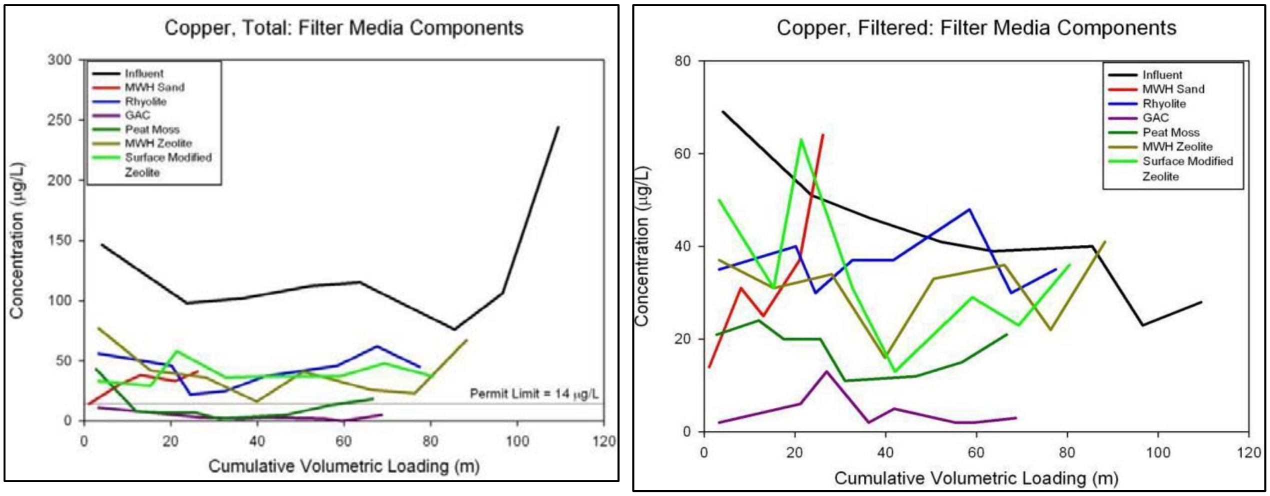


**Figure 4-25. Changes in Pollutant Removal with Treatment Loading for Filtered and Total Forms of Copper**

Of the individual media types studied, peat and the GAC demonstrated the best removals for total and dissolved copper, even with the relatively high influent concentrations.

It may be asked if the zeolite and sand contact times were too low to allow for substantial removals of filtered copper by CEC. This is not thought to be an issue for these tests. Copper complexes likely formed which are not readily removed by cation exchange, but sorption by the GAC was effective. However, peat moss was also reasonably effective, which offers high CEC capacity, but possibly also destabilized the complexes with the pH drop in the media, or the copper formed complexes with the organics in the peat. The filtered copper includes colloids and organometallic complexes also, plus copper readily forms amalgams with zinc; it is possible that only small fractions of the filtered copper were in ionic forms and therefore amenable for cation exchange.

### 4.3.4 Long-Term Removal: Effects of Media Mixtures on Pollutant Removals and Breakthrough

Figure 4-26 shows that nitrate removal is excellent in mixtures containing GAC. However, breakthrough occurs more rapidly as the fraction of GAC in the media mix decreases. Similar trends were noted for the removal of zinc in mixtures containing SMZ, although it is not as pronounced. In general, the media mixtures resulted in more consistent removals for a broader range of constituents compared to the individual media.

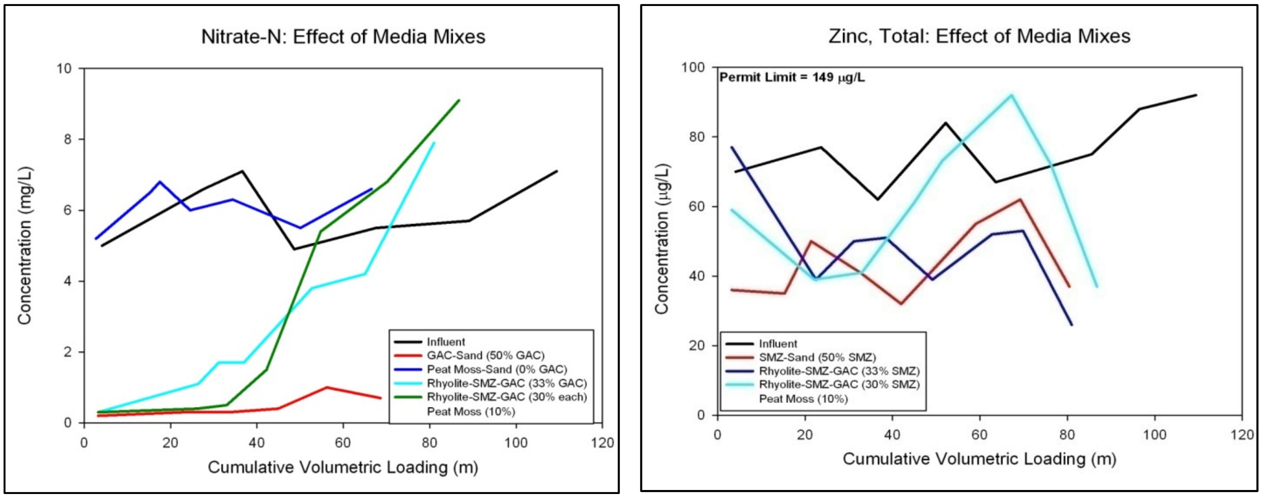


**Figure 4-26. Changes in the Removal of Constituents as the Amount of Water Treated Increases for Different Media Mixtures**

### 4.3.5 Ion-Exchanging Media: Trade-Offs between Pollutant Removals and Releases

With ion-exchange, ions must be released as other ions are retained. In the example shown in Figure 4-27, retention of nitrates occurs in the GAC throughout the testing, phosphates are released early, and chlorides are released later in the filter run after a slight retention early in the filter life.

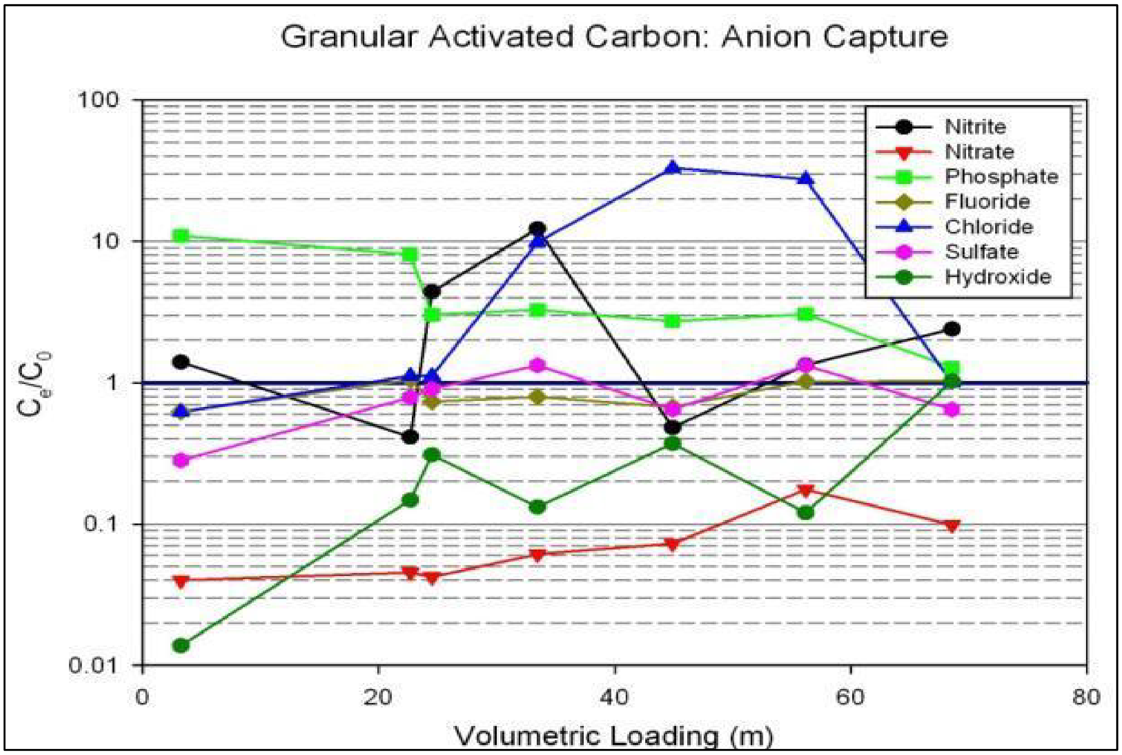


**Figure 4-27. Trade-Offs Between Pollutant Removals and Releases**

### 4.3.6 *E. coli* Retention by Potential Media

On bacterial spiking days, samples were collected from the columns both before and after spiked stormwater had passed through the filters and the results are shown in Figure 4-28. The “pre” designation per week indicates the treated spiked stormwater prior to the addition of *E. coli* and represents the “first flush” through the column. *E. coli* in this effluent would indicate bacteria retention in the column and subsequent release with the next storm. The “post” designation indicates the treatment of stormwater that has been spiked both with the chemicals and the *E. coli*. The *E. coli* spikes were larger than those typically seen in runoff from the site in order to test whether the columns were capable of meeting recreational water quality guidelines under high influent conditions.

The results showed that the peat and compost columns did not contain a residual load of *E. coli* prior to the start of testing. During the first week, both media were capable of removing the *E. coli* to below the recreational water quality standards. In addition, the performance of compost and peat were statistically identical. During the second week, *E. coli* was flushed from the previously-spiked column prior to treating the bacterially-spiked stormwater, indicating a release of a portion of retained *E. coli*. The effluent concentrations from the treatment of the bacterially-spiked stormwater during week 2 indicated that approximately a 2-log removal of *E. coli* was achieved, but the effluent was near (and likely not different from) the recreational water quality standard. Again, the performance of peat and compost was similar. During week 3, the pre-spiked samples showed release of previously-trapped *E. coli*, and at this point, the first flush pre-treatment from the peat media violates the recreational water quality standard. The compost does not, based on these observations; however, there is insufficient data to determine whether these media performances are statistically different from each other. The effluent from treating bacterially-spiked stormwater shows concentrations that are greater than the recreational water quality standard and, for the peat column, may be approaching the influent concentration, indicating no removal.

These results overall show that *E. coli* removal can occur in an organic-based media but, in areas with frequent rainfall where the loading is likely to be greater and more frequent, regrowth and subsequent release are likely. This is less likely to be as great a concern in drier climates where media drying between storms should be more pronounced.

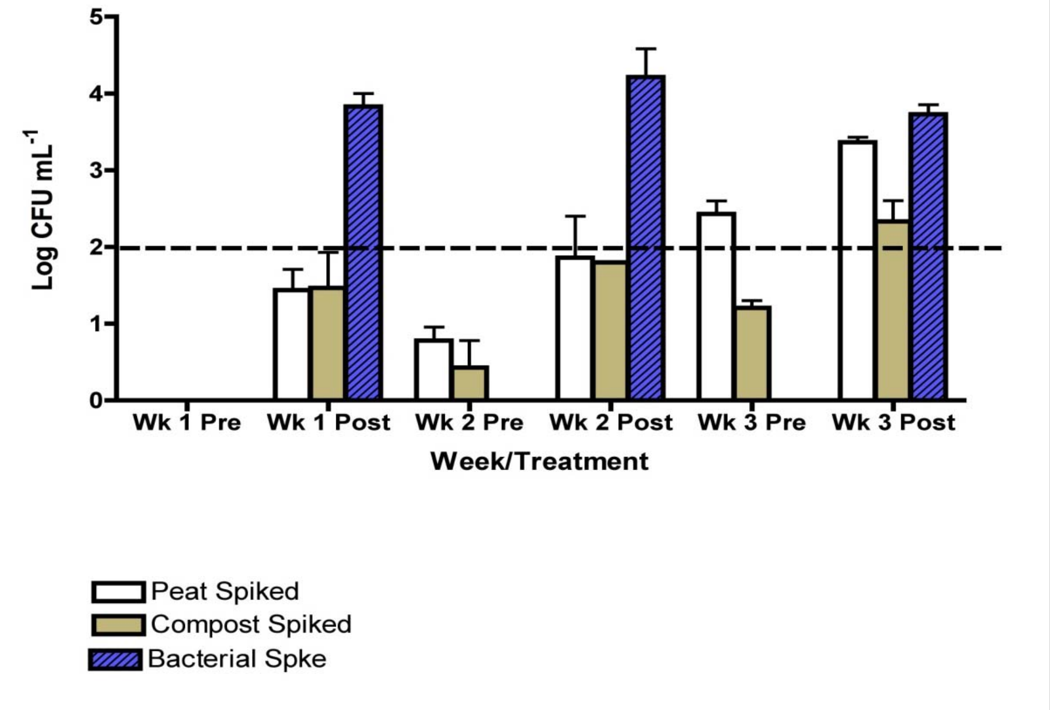


**Figure 4-28.** ***E. coli*** **Removals in Compost and Peat Media.**

## 4.4 Contact Time Effects on Contaminant Removal

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 because the likelihood of making a favorable contact with the media increases. 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.

Figure 4-29 shows that cadmium was effectively removed for all media depths in all media types. Low cadmium effluent concentrations were observed for all tests, irrespective of influent concentrations.

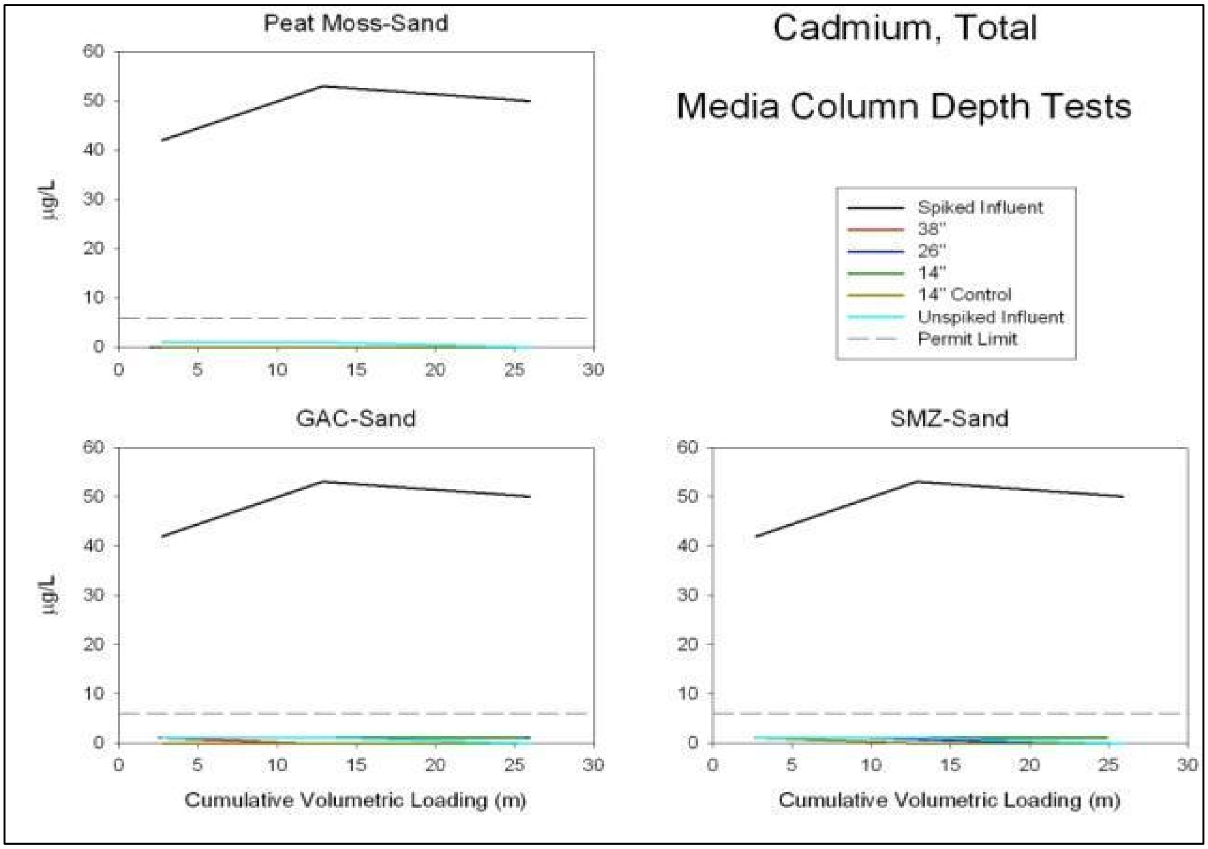


Figure 4-29. Contact Time Effects on Cadmium Removal

However, as shown in Figure 4-30, there was more of a pronounced effect of residence time (media depth) for nitrate removal for some media types. In these plots, the “unspiked influent” data represent unspiked stormwater with low concentrations, and the “14 inch control” data represent the column effluent for these unspiked influent conditions (the 14 inch columns were the only ones tested for these conditions). As expected, low effluent concentrations for ineffective media only occurred concurrently with these low influent concentrations, and should not be interpreted as removal by the media. Similar results were seen for media with poor removal ability (in this case, SMZ and peat moss). Only the GAC showed good removals, with the removal ability being best with the deepest column. This indicates that GAC has a limited capacity for nitrate and increasing the amount of GAC in contact with the passing influent water increases the length of time (shown as volumetric loading) that excellent removals occur.

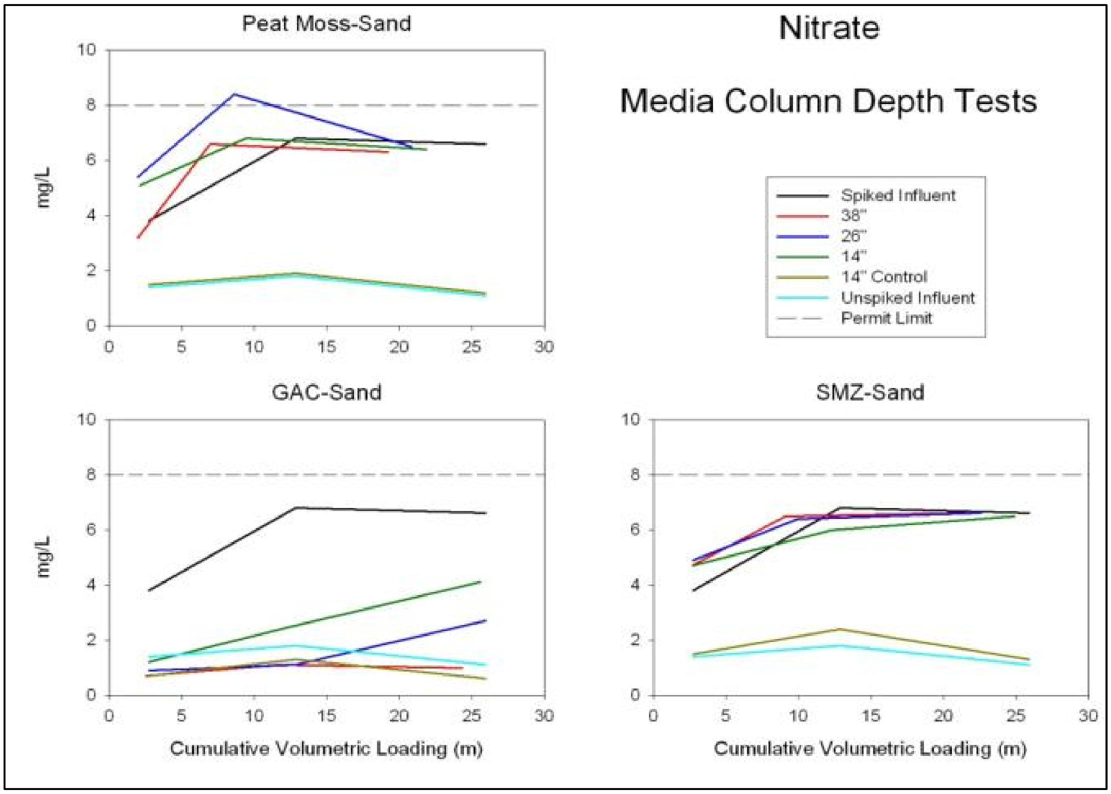


**Figure 4-30. Nitrate Removal with Varying Depth Column during Media Component Testing**

Figures 4-31 and 4-32 show removals of nitrate and phosphate during the mixed media tests as a function of column depth. Deeper GAC columns and higher concentrations of GAC in the media resulted in slightly better nitrate removals, while the longer columns and higher concentration resulted in greater leaching of the phosphate from the media.

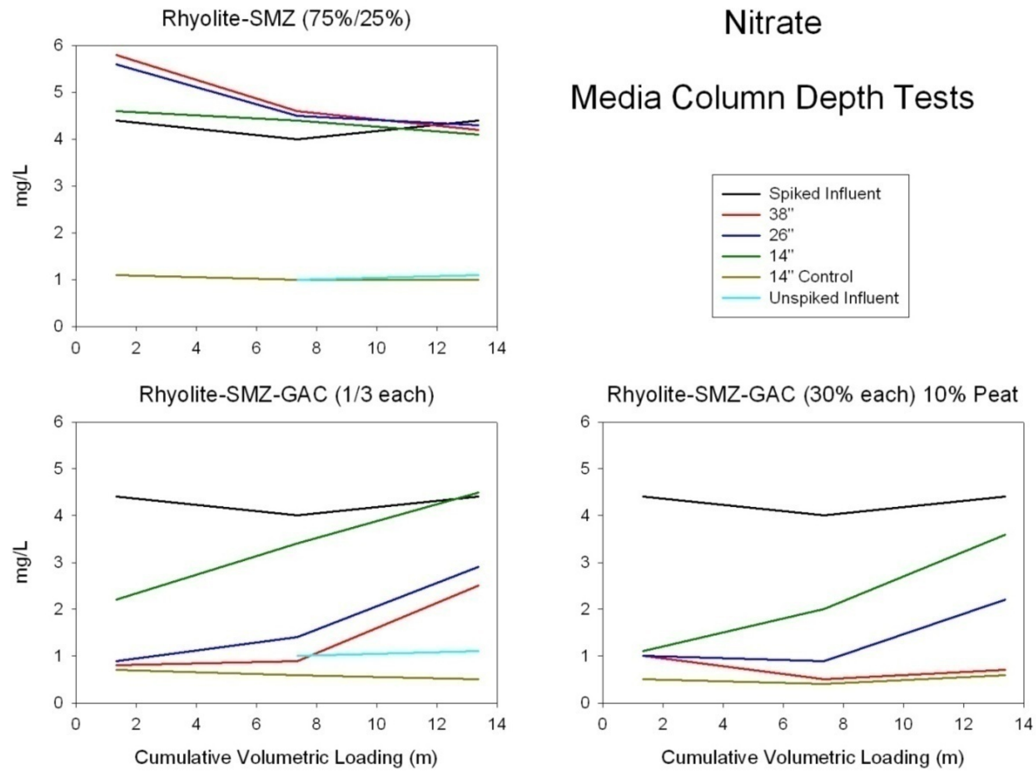


**Figure 4-31. Nitrate Removal with Varying Column Depth for Mixed Media Columns**

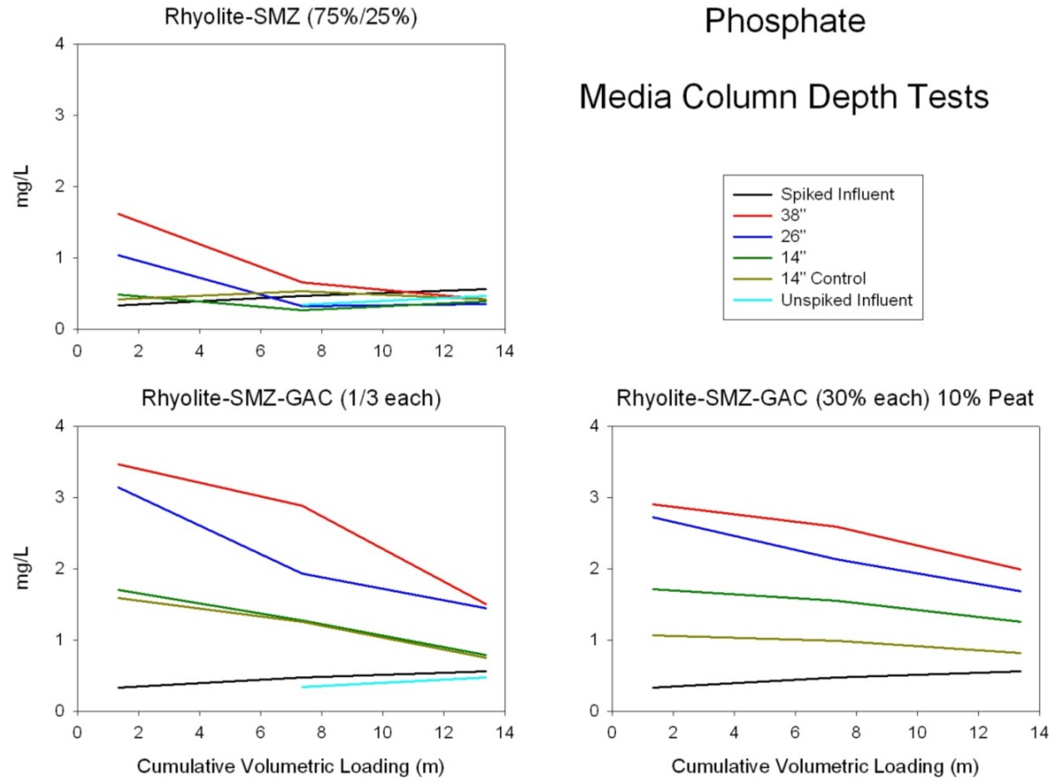


**Figure 4-32. Phosphate Removal with Varying Columns Depth for Mixed Media Columns**

Substantial data has been collected for these tests and these are only examples with further data shown in Appendix B. The following subsections further discuss the effects of varying contact times on contaminant removals for different column conditions, and also present the kinetics data from the batch tests to support these observations.

### 4.4.1 Contact Time from Batch Kinetics Tests

Appendices B and C contain the basic data plots showing the effects of contact time on the contaminant removal. The purpose of these tests is to determine the amount of contaminant that can be retained by the potential component media for the final mix, 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 as the basis for these tests 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 as 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 well to most low-concentration stormwater treatment observations. Isotherms that indicated favorable adsorption, for example, may become unfavorable at low concentrations.

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, as is traditionally-predicted. 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. At some point, however, increasing contact time provided little increase in removal. In design, these results, especially when combined with data from the variable-depth columns, indicate the optimal contact time for substantial removal. Figure 4-33 for peat moss and ammonia removal is an example where very little ammonia was removed until after about one day of contact.

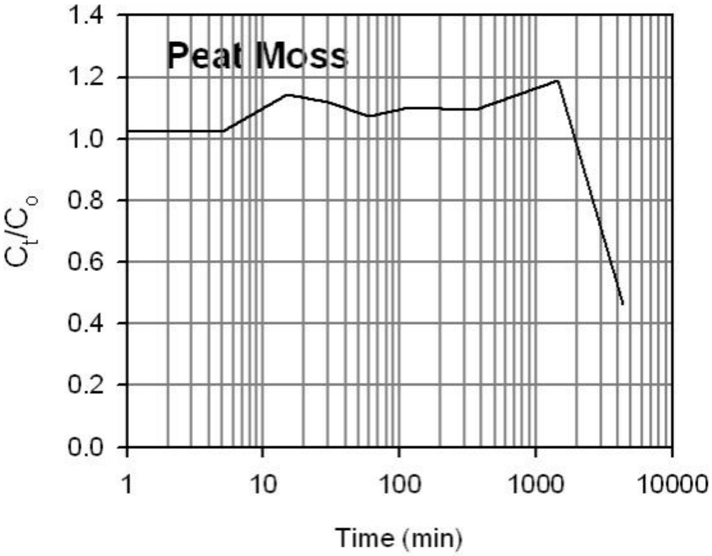


**Figure 4-33. Uptake of Ammonia by Peat Moss during Batch Kinetics Tests**

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 and the data could be fit to a traditional exponential decay equation to determine the rate constant for removal. The lag time before removal, however, complicates the traditional exponential decay equation. 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 Figure 4-34 showing lead uptake versus time, a more traditional, relatively constant removal is seen for the GAC material indicating that increasing contact time beyond 3 days may result in increased removal of lead. Therefore, during field operation of these units, assuming the pore water remains aerobic, lead removal may continue during quiescent times between storms. In contrast, the peat moss data indicates a leveling off of removals after a period of time and that additional removals may not occur during quiescent times. The site zeolite test indicates the delay, then the rapid removal, as described above and lead removal may continue after the storm ends.

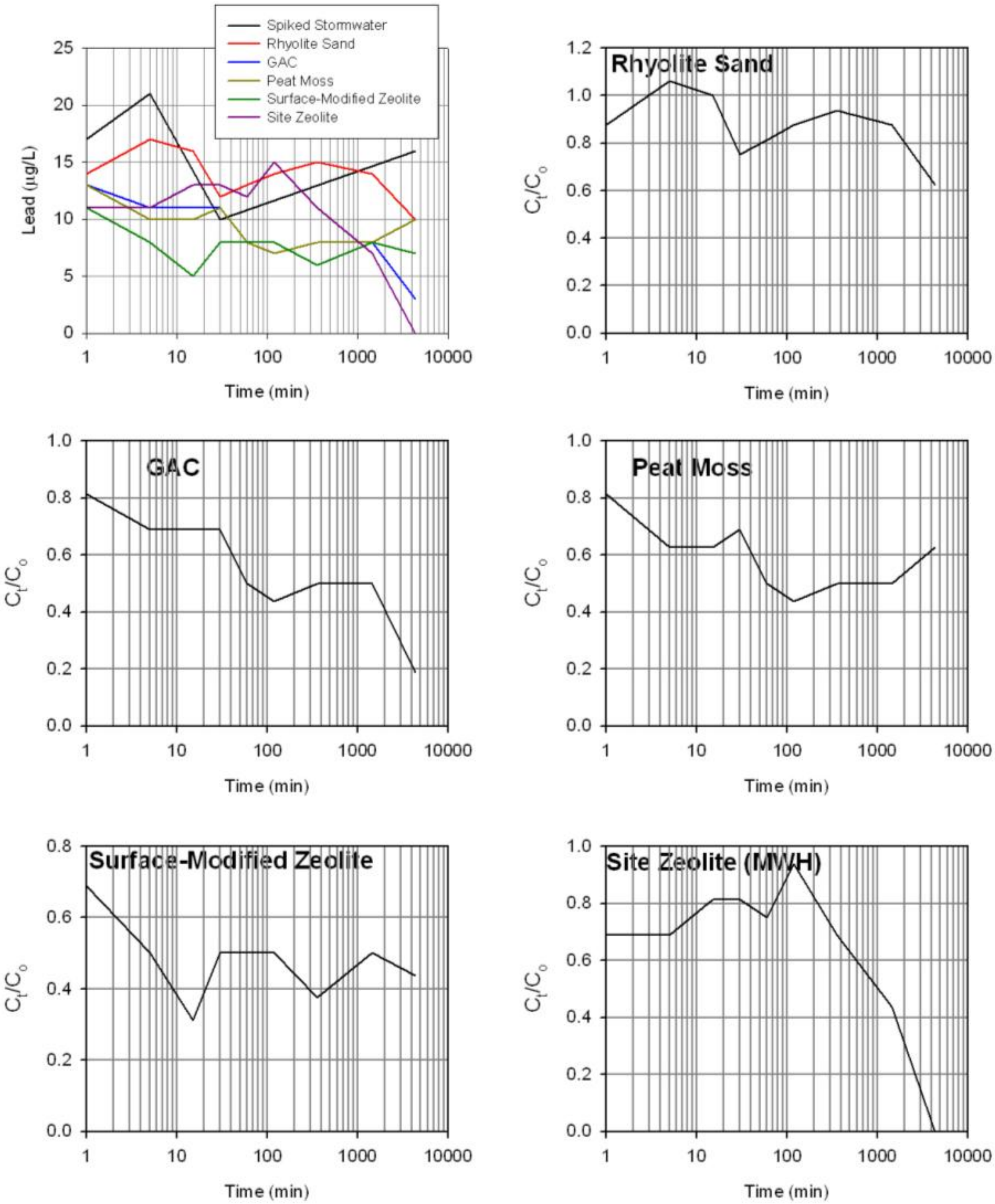


**Figure 4-34. Lead Removal by Contact Time during Batch Tests**

Figure 4-35 shows the effects of different contact times on the removal of nickel from stormwater for the different media. As shown here, the uptake was most significant and rapid for peat moss and GAC. The optimal contact times for most metals removal ranged from 10 to 1,000 minutes, depending on the metal and the media type. When the contact time was less than 10 minutes, the metal removals were much less than for the longer contact time periods.

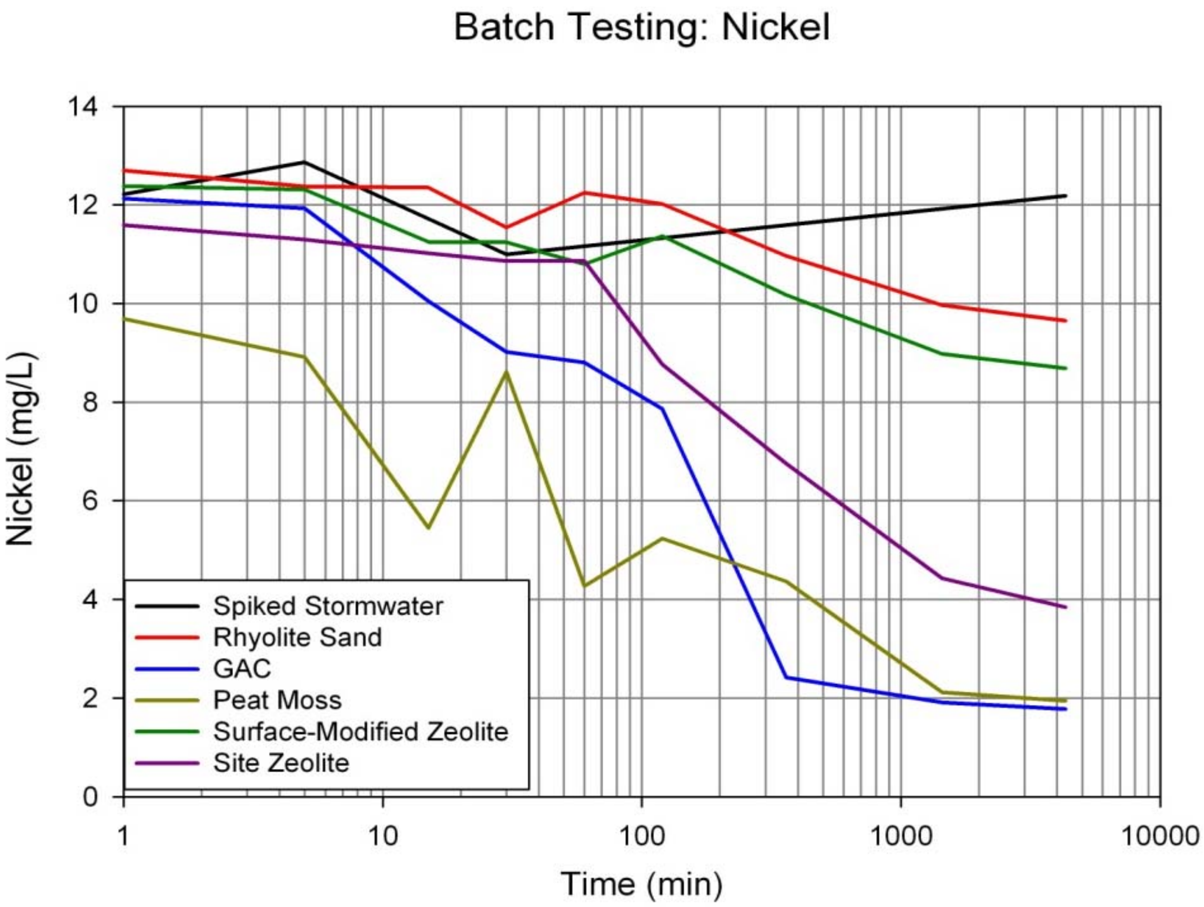


**Figure 4-35. Batch Kinetics Tests for Nickel**

Figure 4-36 are similar plots for antimony and sulfate showing that the antimony was similar to the nickel (except for the GAC), while the sulfate results were more constant with time and were more limited for all media. This was not surprising since anion removal is more difficult since most media have much lower anion exchange capacities than cation exchange capacities.

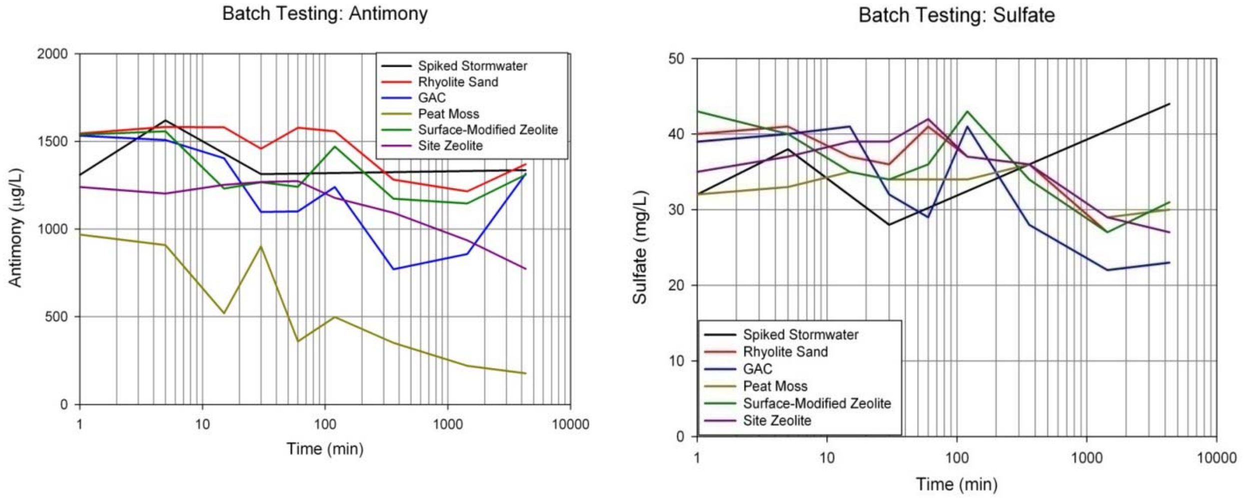


**Figure 4-36. Batch Kinetics Tests for Antimony and Sulfate**

Tables 4-32 and 4-33 summarize the data presented in Appendix C on the batch kinetic tests. Table 4-32 shows the period of time in minutes over which uptake by the media was observed. The time is given as a range, with the initial value showing the lag period before the uptake began, and the final value being when the water concentration leveled off, indicating maximum removal had occurred, or the test was ended. The "decrease" fractions are the resultant Ce/Co ratios ("effluent" concentration/starting concentration). In some cases, these ratios are greater than 1.0, indicating release of the constituent from the media during the test. This was most common for constituents involved in ion-exchange reactions and usually included the major ions. In other cases, such as for peat, increased color, COD, and UV-254 indicates leaching of organic materials during exposure. Table 4-33 summarizes the average initial lag period before removal for the different classes of constituents for each media. In all cases, the blanks indicate that no obvious uptake or release of the constituents was observed.

## Table 4-32. Batch Kinetics Tests (Summarized from Appendix C)

| | Granular Activated Carbon | | Surface Modified Zeolite | | Rhyolite Sand | | Peat Moss | | Site Zeolite | |
|---|---|---|---|---|---|---|---|---|---|---|
| | time (min.) | decrease | time (min.) | decrease | time (min.) | decrease | time (min.) | decrease | time (min.) | decrease |
| **Common Constituents** | | | | | | | | | | |
| Conductivity | | | | | | | 100 to 1000 | 0.6 | | |
| Hardness | 80 to 1000 | 0.5 | | | | | | | | |
| ORP | 10 to 1000 | 0.8 | | | | | | | | |
| pH | 10 to 1000 | 1.3 | | | | | | | | |
| **Carbon Behavior Indicators** | | | | | | | | | | |
| Color | 10 to 5,000 | 0 | 3000 to 5000 | 0.1 | 300 to 1000 | 2.5 | 3 to 5,000 | 3 | | |
| UV-254 | 5 to 5,000 | 0.1 | 5 to 5,000 | 0.9 | | | 10 to 5,000 | 2.5 | 1 to 5,000 | 0.6 |
| COD | | | | | 10 to 5,000 | 2 | 20 to 1000 | 4 | | |
| **Major Ions** | | | | | | | | | | |
| Calcium | 100 to 1000 | 0.6 | | | | | | | | |
| Magnesium | 100 to 5,000 | 1.6 | 100 to 5,000 | 1.3 | 500 to 5,000 | 1.2 | 30 to 1000 | 2.5 | 100 to 3,000 | 0.6 |
| Sodium | 1000 to 5,000 | 1.4 | | | | | | | 1 to 5,000 | 2.8 |
| Potassium | 1 to 5,000 | 16 | 100 to 5,000 | 1.3 | 100 to 5,000 | 1.2 | | | 1 to 5,000 | 1.6 |
| Sulfate | 200 to 1000 | 0.6 | 300 to 1000 | 0.8 | 300 to 1000 | 0.6 | | | 100 to 5,000 | 0.8 |
| Fluoride | | | 1 to 1000 | 0.8 | 1 to 1000 | 0.8 | 100 to 1000 | 0.6 | 200 to 2000 | 0.7 |
| **Nutrients** | | | | | | | | | | |
| Ammonia | 200 to 1000 | 0.8 | 100 to 5,000 | 0.5 | 20 to 5,000 | 0.4 | 2,000 to 5,000 | 0.5 | 1 to 1000 | 0.1 |
| Nitrate | 20 to 1000 | 0.4 | | | | | | | | |
| Total Nitrogen | | | 20 to 5,000 | 3 | | | 50 to 1000 | 2.5 | 3 to 100 | 3 |
| Total Phosphorus | 10 to 5,000 | 10 | | | 20 to 1000 | 0.7 | 10 to 2000 | 1.5 | | |
| Phosphate | 1 to 5,000 | 3 | | | 1 to 5,000 | 0.7 | 1000 to 5,000 | 0.4 | | |
| **Heavy Metals and Trace Constituents** | | | | | | | | | | |
| Aluminum | | | 100 to 1000 | 0.5 | | | | | 10 to 3,000 | 0.3 |
| Antimony | 10 to 1000 | 0.5 | 10 to 1000 | 0.8 | | | 1 to 5,000 | 0.1 | 100 to 5,000 | 0.6 |
| Arsenic | 10 to 100 | 0.8 | | | | | 1 to 1000 | 0.4 | 1 to 1000 | 3.5 |

|  | **Granular Activated Carbon** |  | **Surface Modified Zeolite** |  | **Rhyolite Sand** |  | **Peat Moss** |  | **Site Zeolite** |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | time (min.) | decrease | time (min.) | decrease | time (min.) | decrease | time (min.) | decrease | time (min.) | decrease |
| Boron | 30 to 5,000 | 0.2 | 30 to 1000 | 0.6 | 100 to 1000 | 0.4 |  |  |  |  |
| Cadmium | 5 to 1,000 | 0.2 | 100 to 5,000 | 0.7 | 100 to 5,000 | 0.6 | 1 to 5,000 | 0.1 | 100 to 5,000 | 0.2 |
| Chromium | 1 to 100 | 0 | 50 to 1000 | 0.6 | 100 to 5,000 | 0.2 | 1 to 1000 | 0.4 | 30 to 5,000 | 0 |
| Copper | 1 to 1000 | 0.2 | 100 to 1000 | 0.6 | 100 to 1000 | 0.6 | 1 to 1000 | 0.2 | 10 to 1000 | 0.3 |
| Iron |  |  |  |  |  |  |  |  |  |  |
| Lead | 1 to 5,000 | 0.2 | 1 to 10 | 0.5 |  |  | 1 to 100 | 0.5 | 100 to 5,000 | 0 |
| Manganese | 10 to 300 | 0 | 100 to 5,000 | 2 |  |  |  |  | 100 to 1000 | 0.6 |
| Nickel | 5 to 5,000 | 0.2 | 100 to 1000 | 0.8 | 100 to 5,000 | 0.8 | 1 to 5,000 | 0.2 | 50 to 5,000 | 0.3 |
| Thallium | 5 to 5,000 | 0.1 | 5 to 1000 | 0.2 | 30 to 5,000 | 0.1 |  |  | 10 to 1000 | 0 |
| Zinc |  |  |  |  |  |  |  |  |  |  |

time (minutes) for departure from Ce/Co ratio of 1 to stable conditions
fraction is final Ce/Co ratio
blank cells correspond to no obvious removal trend with time

**Table 4-33. Time Needed before Removal Started (minutes) (# of constituents having removal of # measured)**

| | GAC | SMZ | Rhyolite | Peat | Site Zeolite |
|---|---|---|---|---|---|
| Common Constituents | 45 (2 of 4) | | | 100 (1 of 4) | |
| Carbon Behavior | 8 (2 of 3) | 1500 (2 of 3) | | | 1 (1 of 3) |
| Major Ions | 150 (2 of 6) | 150 (2 of 6) | 150 (2 of 6) | 100 (1 of 6) | 130 (3 of 6) |
| Nutrients | 110 (2 of 5) | 100 (1 of 5) | 14 (3 of 5) | 1500 (2 of 5) | 1 (1 of 5) |
| Heavy Metals | 8 (10 of 14) | 60 (9 of 14) | 88 (6 of 14) | 1 (7 of 14) | 57 (9 of 14) |

The following summarizes the most apparent findings for these batch kinetic tests:

- GAC has both consistent removal and short contact times (10 min) for carbon behavior constituents and metals. Rapid (6 min) leaching of nutrients and slow leaching (>6 hrs) for major ions.
- SMZ removals are relatively slow (at least an hour) and less consistent. Leaching (20 min) for nutrients and metals (2 hrs).
- Rhyolite uptake is fast (about 15 min) for nutrients and slow for major ions and metals (>1.5 to 2.5 hrs). No leaching observed.
- Peat uptake is very fast (1 min) for metals, but very slow and inconsistent for others. Leaching for all carbon-related constituents occurred after 10 minutes and for some major ions and nutrients after 30 minutes.
- Site Zeolite has very fast removals (1 min) for some carbon-behavior constituents and nutrients, but slow (>1 to 2 hrs) for major ions and metals. Rapid leaching (after 1 min) for some major ions and metals.

### 4.4.2 Optimal Contact Time for Removal from Varying Depth Column Tests

Table 4-34 summarizes the removal of various constituents from the varying-depth media columns. Appendix B contains the suite of plots of these observations. The taller media depths have a longer contact time between the stormwater and media compared to the shorter columns, and should provide higher levels of treatment for those constituents whose removal is not immediate and rapid. Increased media in the treatment devices also increases the overall capacity before maintenance is needed. The yellow high-lighted cells indicate media and constituent combinations that had obvious benefits with taller media depths, compared to shorter column depths. Leaching was observed for some combinations and was also noted. In some cases, the taller media columns were associated with increased leaching, very likely due to the longer contact times and increased media masses. Blank cells indicate conditions where no obvious effects or inconsistent effects occurred.

### Table 4-34. Summary of Observed Removal Trends for Varying Media Height Column Tests (from Appendix B)

| Constituent | | Peat moss | GAC | SMZ | Rhyolite-SMZ | Rhyolite-SMZ-GAC | Rhyolite-SMZ-GAC-peat |
|---|---|---|---|---|---|---|---|
| Aluminum | total | no difference with column depths | no difference with column depths | 38" columns had better removal with large loading | major leaching with 38" columns at low loadings, little effect seen at high loadings | large leaching with 38" columns at low loadings, little effect seen at high loadings | |
| | filtered | major leaching | leaching at low loads, uptake at high loadings | uptake for all conditions | more leaching with deeper columns | minor leaching at all conditions | minor leaching at all conditions |
| Ammonia | total | large leaching for tall columns at low loads | better removal with 38" columns | good removal for all columns | very large removals for all columns | very large removals for all columns | very large removals for all columns |
| Antimony | total | 38" best, then 26". 14" OK | all poor removal | all slight removal | 38 and 26" better than 14" | all the same removal | all the same removal |
| | filtered | 38" best, then 26". 14" OK | all poor removal | all slight removal | 38 and 26" better than 14" | all the same removal | all the same removal |
| Arsenic | total | all good removal until highest loads | all good removal until highest loads | all good removal until highest loads | | | taller columns better slightly at higher loads |
| | filtered | all good removal until highest loads | all good removal until highest loads | all removals good | | | |
| Boron | total | no removals | 38" very good removals 26" also very good until high loads, 14" less effective | no removals | no removals | 38" very good removals 26" also very good , 14" less effective; all decrease with high loads | 38" very good removals 26" also very good , 14" less effective; all decrease with high loads |

| Constituent | | Peat moss | GAC | SMZ | Rhyolite-SMZ | Rhyolite-SMZ-GAC | Rhyolite-SMZ-GAC-peat |
|---|---|---|---|---|---|---|---|
| | filtered | no removals | 38" very good removals 26" also very good until high loads, 14" less effective | no removals | no removals | 38" very good removals 26" also very good , 14" less effective; all decrease with high loads | 38" very good removals 26" also very good , 14" less effective; all decrease with high loads |
| Cadmium | total | all very high removals | all very high removals | all very high removals | all very high removals | all very high removals | all very high removals |
| | filtered | all very high removals | all very high removals | all very high removals | all very high removals | all very high removals | all very high removals |
| Calcium | total | all very good at very low loads, then poor at moderate and high loads | 38" best, then 26" with 14" poor, all poor at high loads | no removals | no removals | no removals | all moderate removals |
| Chloride | total | no removals | no removals | no removals | no removals | no removals | no removals |
| Chromium | total | 38, 26, 14 removals in order of depth, but all close with very high removals | 38, 26, 14 removals in order of depth, but all close with very high removals | 38 and 26 removals much better than 14" column removals | all about the same with slight removal | 38" best and 26" next best removals, but 14" removal only moderate | all about the same with good removals |
| | filtered | | all excellent removals | about the same with poor removals | | 38" best and 26" next best removals, but 14" removal poor, especially at high load | in order of column depth, but only slight removals |
| COD | total | | | | | | |

| **Constituent** | | **Peat moss** | **GAC** | **SMZ** | **Rhyolite-SMZ** | **Rhyolite-SMZ-GAC** | **Rhyolite-SMZ-GAC-peat** |
|---|---|---|---|---|---|---|---|
| Color | total | all good removals, no real difference with depth | all good removals, no real difference with depth | all very good removals, with 38" best | | | |
| Conductivity | | no removals | no removals | no removals | no removals | no removals | no removals |
| Copper | total | all very high removals, 38" and 26" in order and best (< permit limits), 14" also very good (but not < permit limits) | all very high removals, 38" and 26" in order and best (but only 38" < permit limits), 14" also very good (but not < permit limits) | all very good, with 14" not as good | all very high removals, 38" and 26" in order and best, 14" also very good (but none are < permit limits) | all very high removals, 38" and 26" in order and best, 14" also very good (but none are < permit limits, but 38" quite close) | all very high removals, 38" and 26" in order and best, 14" also very good (but none are < permit limits, but 38" quite close) |
| | filtered | all very high removals | all very high removals | all very high removals | all moderate removals | all very high removals, 38" and 26" in order and best , 14" also very good | all very high removals, 38" and 26" in order and best , 14" also very good |
| Fluoride | total | 38" and 26" columns very good removals at low loads, not as good at high loads, 14" column slight removal | all slight removals, better for longer columns | no removals | all slight removals, better for longer columns | all slight removals, better for longer columns | all slight removals, better for longer columns |

| **Constituent** | | **Peat moss** | **GAC** | **SMZ** | **Rhyolite-SMZ** | **Rhyolite-SMZ-GAC** | **Rhyolite-SMZ-GAC-peat** |
|---|---|---|---|---|---|---|---|
| Hardness | total | all high removal for low loads and then moderate removal for large load | removal in order of column depth for small loads, then no removal after large load | no removals | moderate removal in order of column depths, but quite close | all moderate removal | all moderate removal |
| Iron | total | very high removals by all | very high removals by all | very high removals by all | | | |
| | filtered | | | | | | |
| Lead | total | very high removals by all | very high removals by all | very high removals by all | high removals, best with 38, then 26, and 14 more moderate removals | high removals, best with 38, then 26, and 14 more moderate removals | high removals, best with 38, then 26, and 14 more moderate removals |
| | filtered | high removals by all | high removals by all | high removals by all | moderate removals by all | moderate removals by all | moderate removals by all |
| Magnesium | total | all large amounts of leaching | taller columns leaching more | taller columns leaching more | moderate leaching | leaching increased with increased loads | leaching increased with increased loads |
| | filtered | all large amounts of leaching | taller columns leaching more | taller columns leaching more | moderate leaching | leaching increased with increased loads | leaching increased with increased loads |
| Manganese | total | all slight removal | all very large removals | all large removals | deeper columns leach more at low loads, then no removal | all slight to moderate removals | all slight to moderate removals |
| | filtered | all slight removal | all large removals | all large removals | 38 and 26 columns moderate removal. 14" columns leaching | all large removals | all large removals |

| **Constituent** | | **Peat moss** | **GAC** | **SMZ** | **Rhyolite-SMZ** | **Rhyolite-SMZ-GAC** | **Rhyolite-SMZ-GAC-peat** |
|---|---|---|---|---|---|---|---|
| Mercury | total | not tested | not tested | not tested | all complete removals (effluent to nd) | all complete removals (effluent to nd) | all complete removals (effluent to nd) |
| Nickel | total | all very large removals | all very large removals | all very large removals | all very large removals | all very large removals | all very large removals |
| | filtered | all very large removals | all very large removals | all very large removals | all very large removals | all very large removals | all very large removals |
| Nitrate | total | no removals | deeper columns better than others at high loads | no removals | no removals | deeper columns better than others at high loads | deeper columns better than others at high loads |
| Nitrite | total | moderate removals | moderate to good removals | leaching | deeper columns leach more at low loads, then no removal | deeper columns leach more at low loads, then no removal | deeper columns leach more at low loads, then no removal |
| Oil and Grease | total | not tested | not tested | not tested | all complete removals (effluent to nd) | all complete removals (effluent to nd) | all complete removals (effluent to nd) |
| ORP | | all increased | 38 and 26 moderate reductions; 14 slight reductions | all slight reductions | all slight increases | all moderate reductions | no changes |
| pH | | 14" columns slight increase, 38 and 26" columns slight decrease | 38 and 26 moderate increases; 14 slight increase | all slight increase | no changes | all slight increase | all slight increase |

| Constituent | | Peat moss | GAC | SMZ | Rhyolite-SMZ | Rhyolite-SMZ-GAC | Rhyolite-SMZ-GAC-peat |
|---|---|---|---|---|---|---|---|
| Perchlorate | total | not tested | not tested | not tested | all complete removals (effluent to nd) | 38 and 26 complete removals (effluent to nd); 14I columns moderate removal | no removals |
| Total Phosphorus | total | all moderate removals | taller columns leaching more | increased removals with increased loading | | taller columns leaching more | all leaching |
| Phosphate | total | slight removals | taller columns leaching more | increased removals with increased loading | | taller columns leaching more | taller columns leaching more |
| Potassium | total | taller columns leaching more | taller columns leaching more | taller columns leaching more | all leaching | all leaching | all leaching |
| | filtered | taller columns leaching more | taller columns leaching more | all leaching | all leaching | all leaching | all leaching |
| Sodium | total | | tall column leaching more | | tall column leaching more | tall column leaching more | tall column leaching more |
| | filtered | tall column leaching more | tall column leaching more | | tall column leaching more | tall column leaching more | tall column leaching more |
| SSC | | all very high removals | all very high removals | all very high removals, with moderate to high loads | initial flushing with low concentration tests and tall columns | initial flushing with low concentration tests and tall columns | initial flushing with low concentration tests and tall columns |

| Constituent | | Peat moss | GAC | SMZ | Rhyolite-SMZ | Rhyolite-SMZ-GAC | Rhyolite-SMZ-GAC-peat |
|---|---|---|---|---|---|---|---|
| Sulfate | total | | all moderate removals; 38" best, 14" only slight removals | | | | |
| Thallium | total | 38" very good removals, 14" slight removals | 38" very good removals, 14" slight removals | 38" very good removals, 14" slight removals | 38" very high removals, 14" also very good removals | 38" very high removals, 14" also very good removals | 38" very high removals, 14" also very good removals |
| | filtered | all very high removals | all very high removals | all very high removals | all moderate removals | 38 very good removals; 26 and 14 moderate removals | 38 very good removals; 26 and 14 moderate removals |
| Total Nitrogen | total | | all very good removals | all slight removals | all moderate removals | all moderate removals | all moderate removals |
| UV-254 | | | all very good removals | all moderate removals after high load | | all very good removals | all very good removals |
| Zinc | total | all moderate removals at low loads, then only slight removals | all slight to moderate removals | all slight to moderate removals | 38" and 26" columns moderate removal; 14 slight removal | 38" and 26" columns moderate removal; 14 slight removal | 38" and 26" columns moderate removal; 14 slight removal |
| | filtered | all moderate removals | all moderate removals | all moderate removals | all slight removals | all slight removals | all slight removals |

Table 4-35 summarizes the observations shown in Table 4-34 and lists the minimum depth, in inches, for which the best removal was observed (based on 18-20 m of stormwater loading). Blanks indicate limited treatment or release for possible ion exchange constituents. If no difference was observed for the three columns, then 14 inches is shown for the optimal minimum media depth. For some media-constituent combinations, the shallower columns provided good treatment, but deeper columns provided slightly better treatment. Besides the increasing level of treatment provided, additional media increases the chemical capacity, increasing maintenance intervals. The limitation is the same as noted above. For those constituents that are released from the media, deeper columns have increased releases.

**Table 4-35. Minimal Column Depth for Observed Best Treatment (inches)**

| | | **Peat moss** | **GAC** | **SMZ** | **Rhyolite-SMZ** | **Rhyolite-SMZ-GAC** | **Rhyolite-SMZ-GAC-peat** |
|---|---|---|---|---|---|---|---|
| Aluminum | total | 14 | 14 | 38 | | | |
| | filtered | | | 14 | | | |
| Ammonia | total | | 38 | 14 | 14 | 14 | 14 |
| Antimony | total | 38 | | | 38 | 14 | 14 |
| | filtered | 38 | | | 38 | 14 | 14 |
| Arsenic | total | 14 | 14 | 14 | | | 26 |
| | filtered | 14 | 14 | 14 | | | |
| Boron | total | | 26 | | | 26 | 26 |
| | filtered | | 26 | | | 26 | 26 |
| Cadmium | total | 14 | 14 | 14 | 14 | 14 | 14 |
| | filtered | 14 | 14 | 14 | 14 | 14 | 14 |
| Calcium | total | 36 | | | | | 14 |
| Chloride | total | | | | | | |
| Chromium | total | 14 | 14 | 14 | 14 | 26 | 14 |
| | filtered | | 14 | | | 26 | |
| COD | total | | | | | | |
| Color | total | 14 | 14 | 14 | | | |
| Conductivity | | | | | | | |
| Copper | total | 26 | 26 | 26 | 26 | 26 | 26 |
| | filtered | 14 | 14 | 14 | 14 | 26 | 26 |
| Fluoride | total | 26 | 26 | | 26 | 26 | 26 |
| Hardness | total | 14 | | | 14 | 14 | 14 |
| Iron | total | 14 | 14 | 14 | | | |
| | filtered | | | | | | |
| Lead | total | 14 | 14 | 14 | 38 | 38 | 38 |
| | filtered | 14 | 14 | 14 | 14 | 14 | 14 |
| Magnesium | total | | | | | | |
| | filtered | | | | | | |
| Manganese | total | | 14 | 14 | | 14 | 14 |
| | filtered | | 14 | 14 | 26 | 14 | 14 |
| Mercury | total | | | | 14 | 14 | 14 |
| Nickel | total | 14 | 14 | 14 | 14 | 14 | 14 |

|  |  | Peat moss | GAC | SMZ | Rhyolite-SMZ | Rhyolite-SMZ-GAC | Rhyolite-SMZ-GAC-peat |
|---|---|---|---|---|---|---|---|
|  | filtered | 14 | 14 | 14 | 14 | 14 | 14 |
| Nitrate | total | 38 |  |  |  | 38 | 38 |
| Nitrite | total | 14 | 14 |  |  |  |  |
| Oil and Grease | total |  |  |  | 14 | 14 | 14 |
| ORP |  |  | 26 |  |  | 14 |  |
| pH |  | 14 | 14 | 14 |  | 14 | 14 |
| Perchlorate | total |  |  |  | 14 | 26 |  |
| Total Phosphorus | total | 14 |  | 14 |  |  |  |
| Phosphate | total |  |  | 38 |  |  |  |
| Potassium | total |  |  |  |  |  |  |
|  | filtered |  |  |  |  |  |  |
| Sodium | total |  |  |  |  |  |  |
|  | filtered |  |  |  |  |  |  |
| SSC |  | 14 | 14 | 14 | 14 | 14 | 14 |
| Sulfate | total |  | 38 |  |  |  |  |
| Thallium | total | 38 | 38 | 38 | 38 | 38 | 38 |
|  | filtered | 14 | 14 | 14 | 14 | 38 | 38 |
| Total Nitrogen | total |  | 14 |  | 14 | 14 | 14 |
| UV-254 |  |  | 14 | 14 |  | 14 | 14 |
| Zinc | total | 14 | 14 | 14 | 26 | 26 | 26 |
|  | filtered | 14 | 14 | 14 |  |  |  |

### 4.4.3 Contact Time for Different Media Types and Depths

The contact time was calculated for the varying depth column tests based on the measured treatment flow rates (in units of m/day), the depths of the media, and the porosity of the media mixture in the column. Figure 4-37 shows the observed treatment flow rates for the six sets of varying depth columns. As indicated, most of the treatment flow rates are larger for the shorter columns at the beginning of the test run, and for the tests that did not have additional particulates added. Figure 4-38 shows the typical contact times, in minutes, for each of the media combinations tested for different column media depths. For instances where some of the treatment flow rates were not available, values from the long-term, tall column tests were used. As indicated earlier, the single media column preparations were mixtures of 50/50 media and site sand. The column mixture tests did not have any sand added. The sand was added for the single medium tests to better moderate the flows. Some of the coarser media (the GAC and site zeolite, for example) would have very high treatment flow rates if used alone, resulting in very short contact times. The fine grain or fibrous media (especially the peat) would likely fail early in the filter runs due to media compression. The sand added a supporting material that helped moderate the flows. The site sand was very fine grained itself and had very low treatment flow rates.

Overall, the treatment flow rates for the 14” columns resulted in residence times of about 4 to 30 minutes. The media mixtures had much faster flow rates and reduced contact times compared to the single-media columns that contained large fractions of the site filter sand. The 38” columns had contact times of about 10 to 90 minutes. The media mixture having the best overall control as noted earlier (R-SMZ-GAC-PM) had short contact times (4 minutes for 14”, 10 minutes for 26”, and 16 minutes for 38”). To be conservative, the overall slower treatment flow rates observed during the long-term column tests are recommended for final control practice designs - treatment flow rates of about 15 m/day and corresponding contact times of about 10 minutes. The batch kinetics tests indicated generally longer contact times should be used, but the column tests are more representative of actual field conditions. Combining the column results with the batch results indicates that 10 minutes should be considered as a minimum contact time, with optimal contact times possibly being as great as ten times this value.

Therefore, the 38” media depth would be indicative of the most suitable operational conditions. There are other options to control flows through the media filters, but slow draining underdrains with these low drainage rates would be very difficult to control due to clogging. Newly developed foundation drain material is being investigated at the University of Alabama and would likely be a superior method for controlling the discharge rate from the biofilter components of the ENTS.

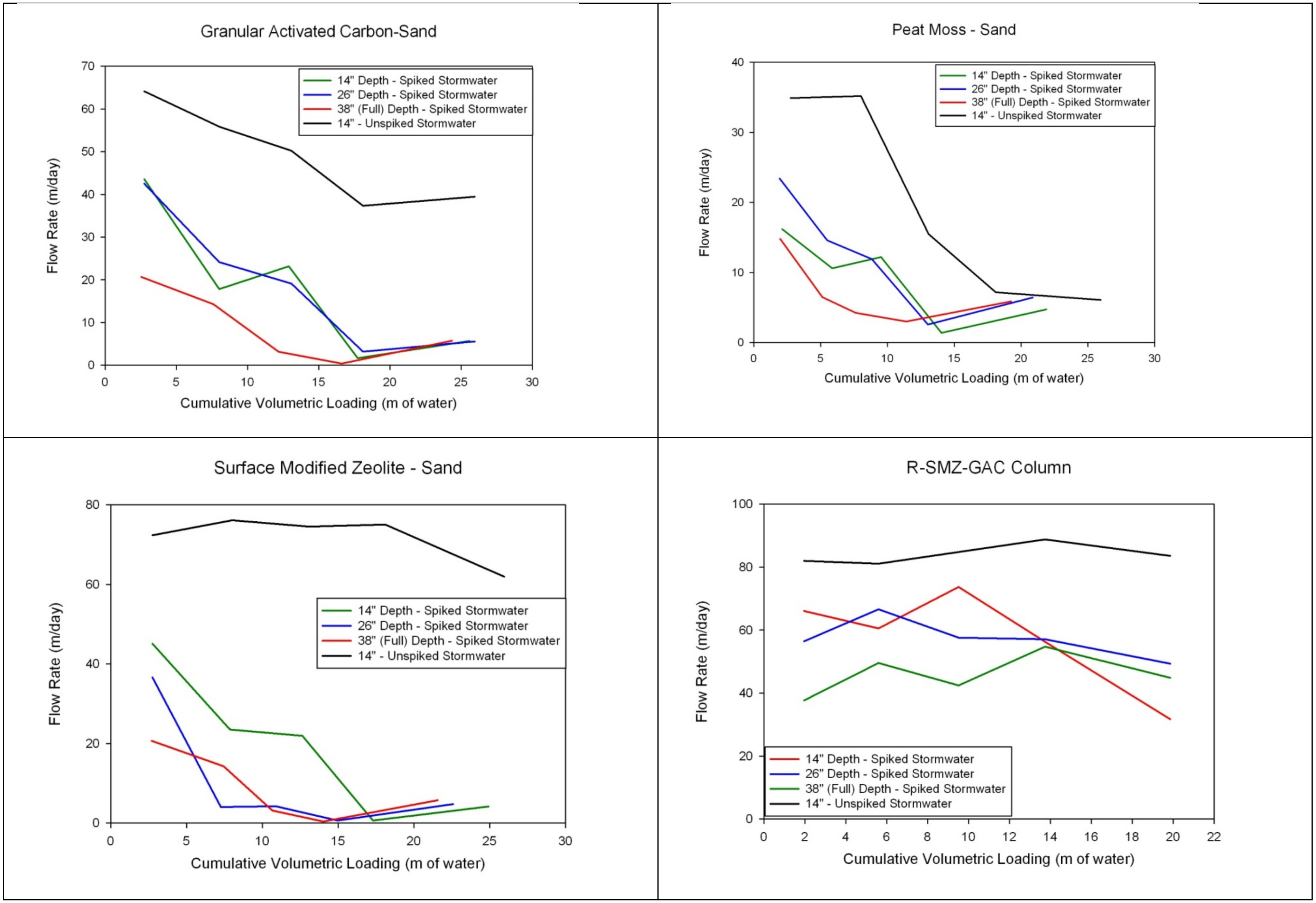


**Figure 4-37. Column Depth and Residence Time Effects on Flow Rate for Varying Depth Columns**

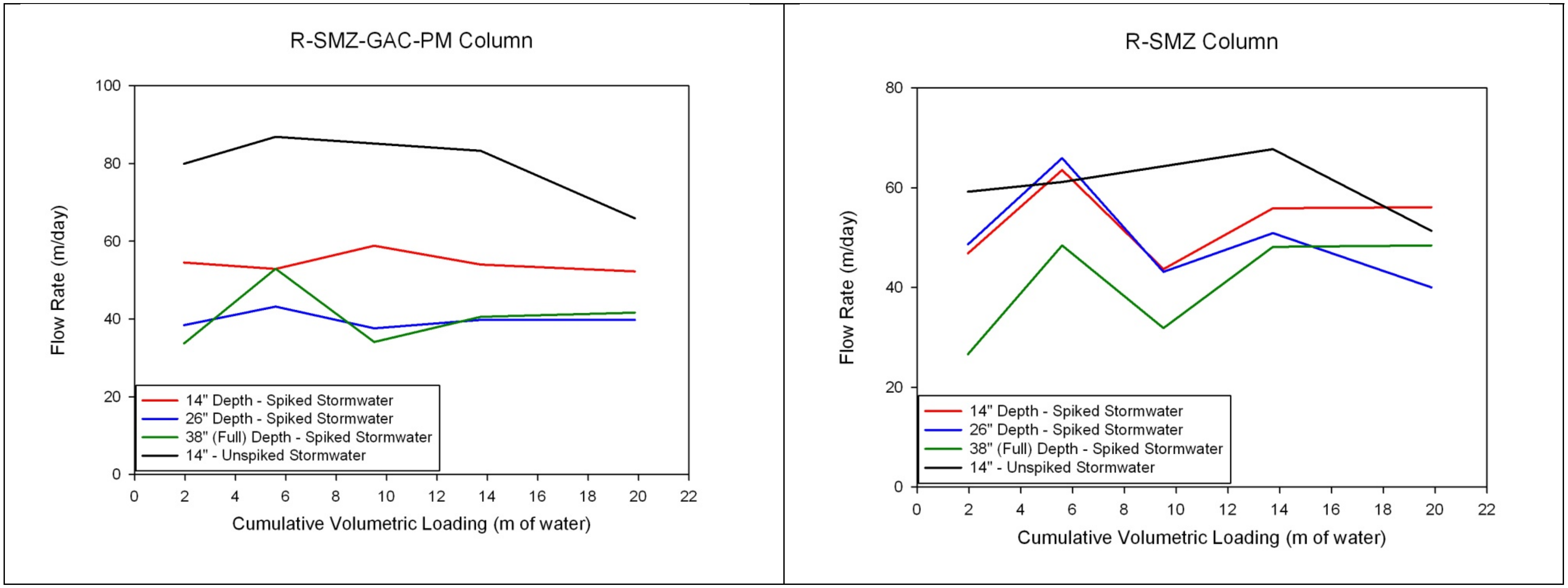


**Figure 4-37. Column Depth and Residence Time Effects on Flow Rate for Varying Depth Columns (cont.).**

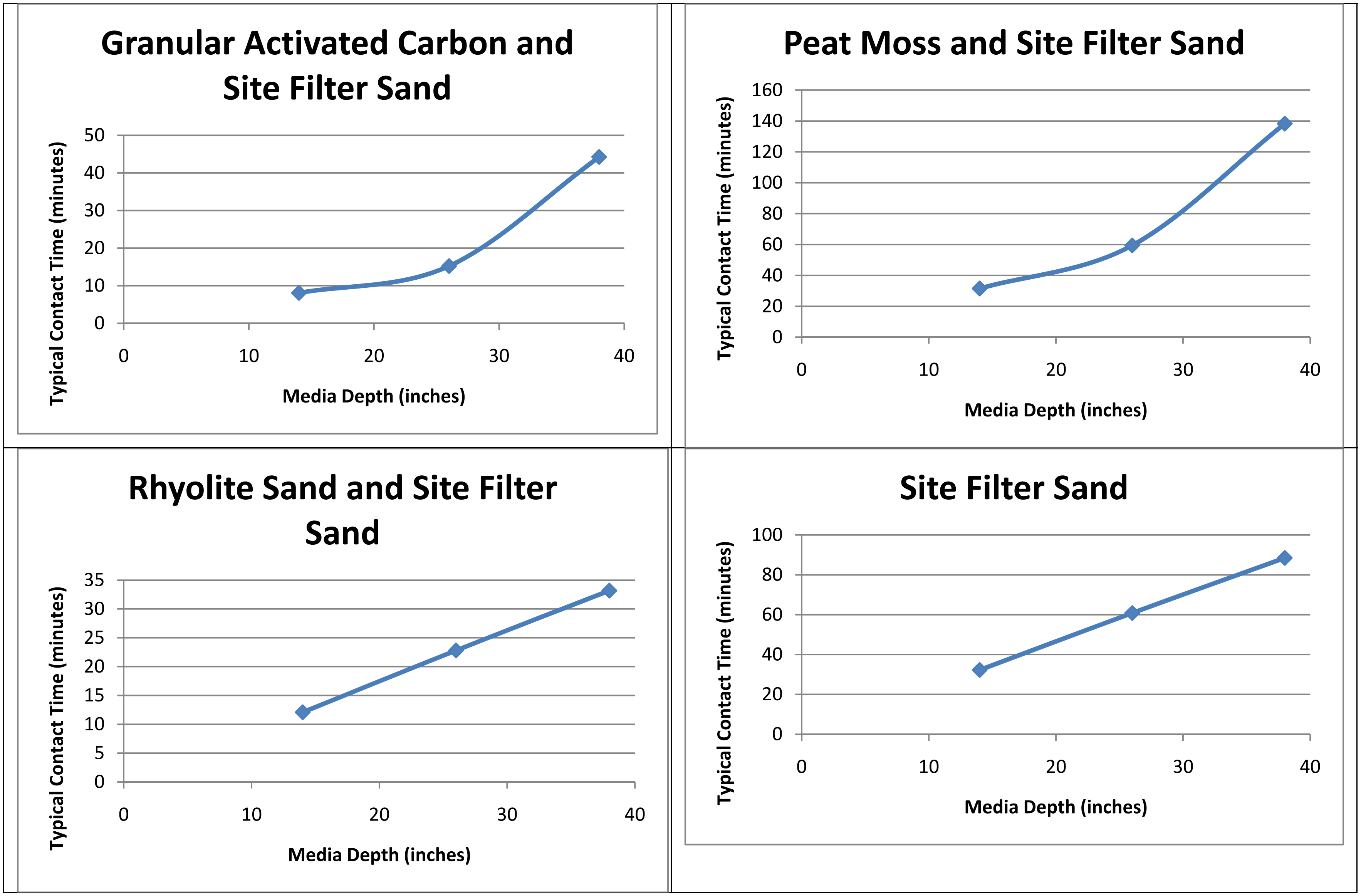


**Figure 4-38. Contact Time Associated with Varying Depth Column Tests**

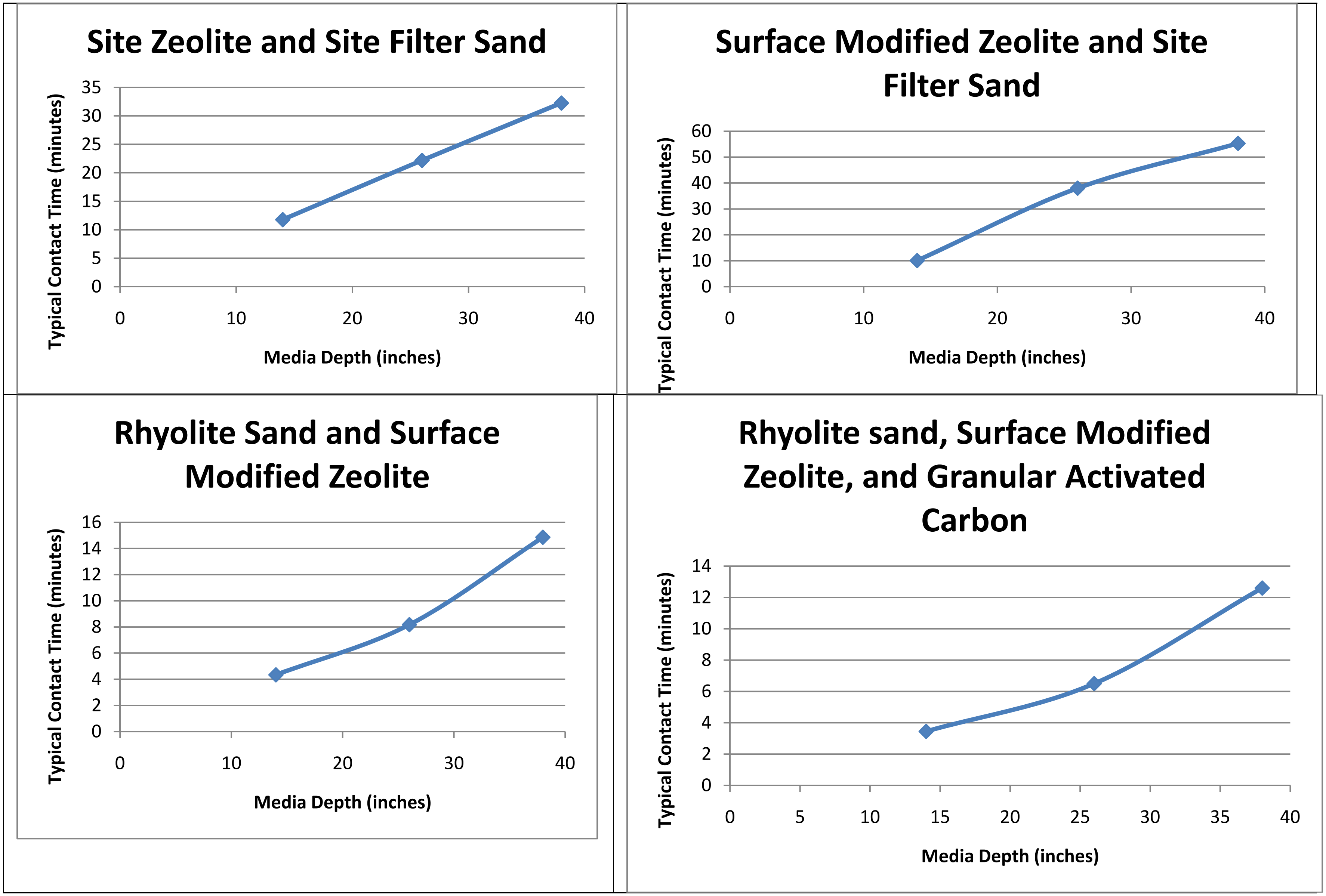


**Figure 4-38. Contact Time Associated with Varying Depth Column Tests (cont.).**

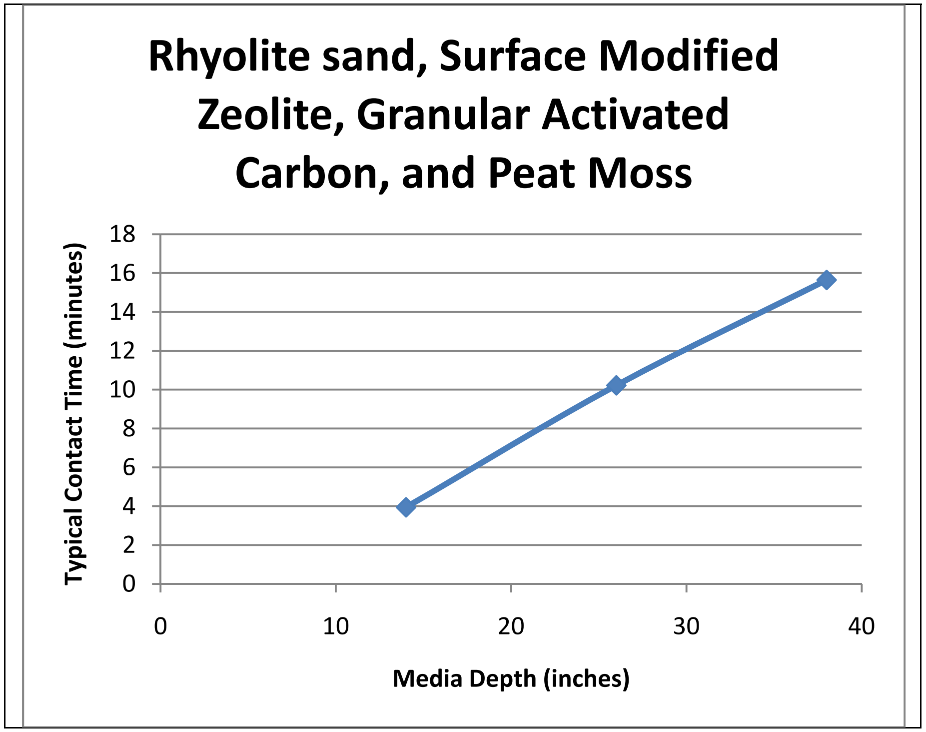


Figure 4-38. Contact Time Associated with Varying Depth Column Tests (cont.).

## *4.5 Anaerobic and Aerobic Long-Term Retention of Captured Contaminants during Interevent Periods*

Prior research has shown that some media tend to lose previously-captured material if interevent periods are long. During even lengthy inter-event periods, some of the pore water will drain from the media, but the media will remain moist. Because the oxygen is not replaced in the media depths and because these filters are not sterile, micro-anaerobic conditions are likely to develop on the media surface. These anaerobic conditions affect pollutant uptake and retention. Continued uptake may occur given the very long exposure periods; however, for many pollutants, previously-captured pollutants will be released. Estimating the losses due to anaerobic exposure conditions can be used to predict the potential for and quantity of a “first-flush” of very elevated concentrations at the beginning of subsequent events.

Appendix D contains plots of the changes in the media content of the different constituents after prolonged exposure to stormwater under aerobic and anaerobic conditions, with the exception of arsenic. Arsenic is not shown because all results were below the detection limit. As described in the methods section, a pre-weighed portion of the media was subjected to high concentrations of the stormwater for several hours to load the material with the stormwater constituents. The slurry was then filtered and the filtrate was analyzed to determine how much of the material was sorbed to the media. This loaded material was then split with portions placed in two containers with typical stormwater. One of the containers was sealed while the other was aerated. They were kept in these conditions for several weeks, and then these slurries were filtered and the filtrates analyzed to determine the amount of sorbed material still on the media after the exposure periods.

These media loadings are plotted as ratios of the amount taken up by the media during the initial loading. These ratios indicate release or capture of material as a result of prolonged aerobic and anaerobic exposure. Figures 4-39 and 4-40 are examples showing the behavior of retained sulfate and ammonia on the media during long-term storage tests under both anaerobic and aerobic storage conditions. An example nutrient and a major ion, both of which are on the permit, are shown here since those constituents that readily participate in ion-exchange are less likely to be retained on the media during long-term exposures. The figures also provide the measured uptake of the constituent by the media.

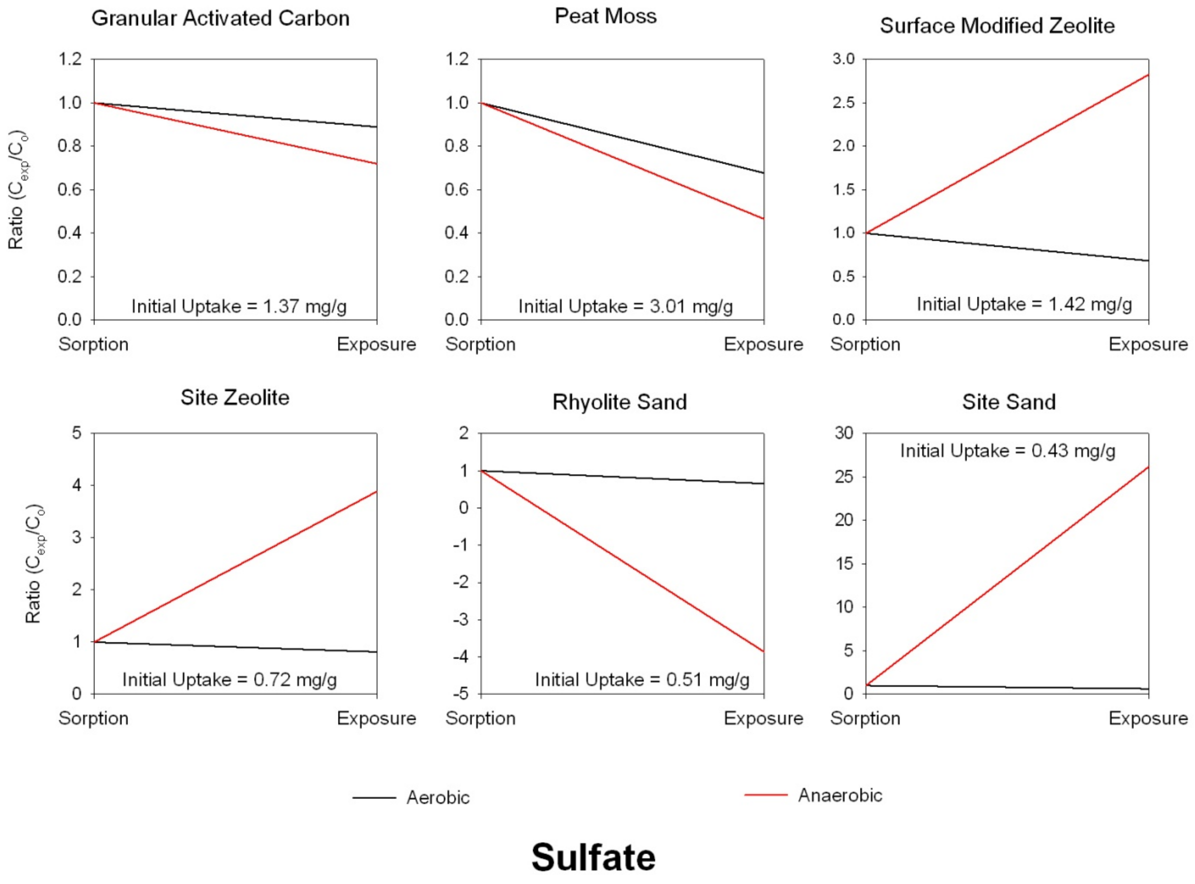


**Figure 4-39. Aerobic and Anaerobic Exposure Results for Media Components and Sulfate**

Initially, sulfate was retained by all media. As a result of the long-term exposure times in these tests, GAC, peat moss and rhyolite had slight to moderate releases, with those releases being greater if the water went anaerobic. However, anaerobic conditions increased the uptake of sulfate by the site sand, site zeolite and SMZ. Sulfides were not measured during any of these tests so it is unknown if sulfate was reduced to sulfide during the tests either chemically or microbially. If sulfate was reduced to sulfide, this may have freed surface sites for further sulfate uptake. All media also took up ammonia during the initial loading (Figure 4-40). For all media except peat moss and site sand, ammonia retention was equivalent for both aerobic and anaerobic exposure, indicating minimal potential losses during lengthy interevent periods. For peat moss and site sand, total retention during anaerobic conditions would be positive after a lengthy interevent period; however, some of the retained ammonia would be lost to the porewater and likely would show up in the first flush from the next storm. The remaining figures are in Appendix D.

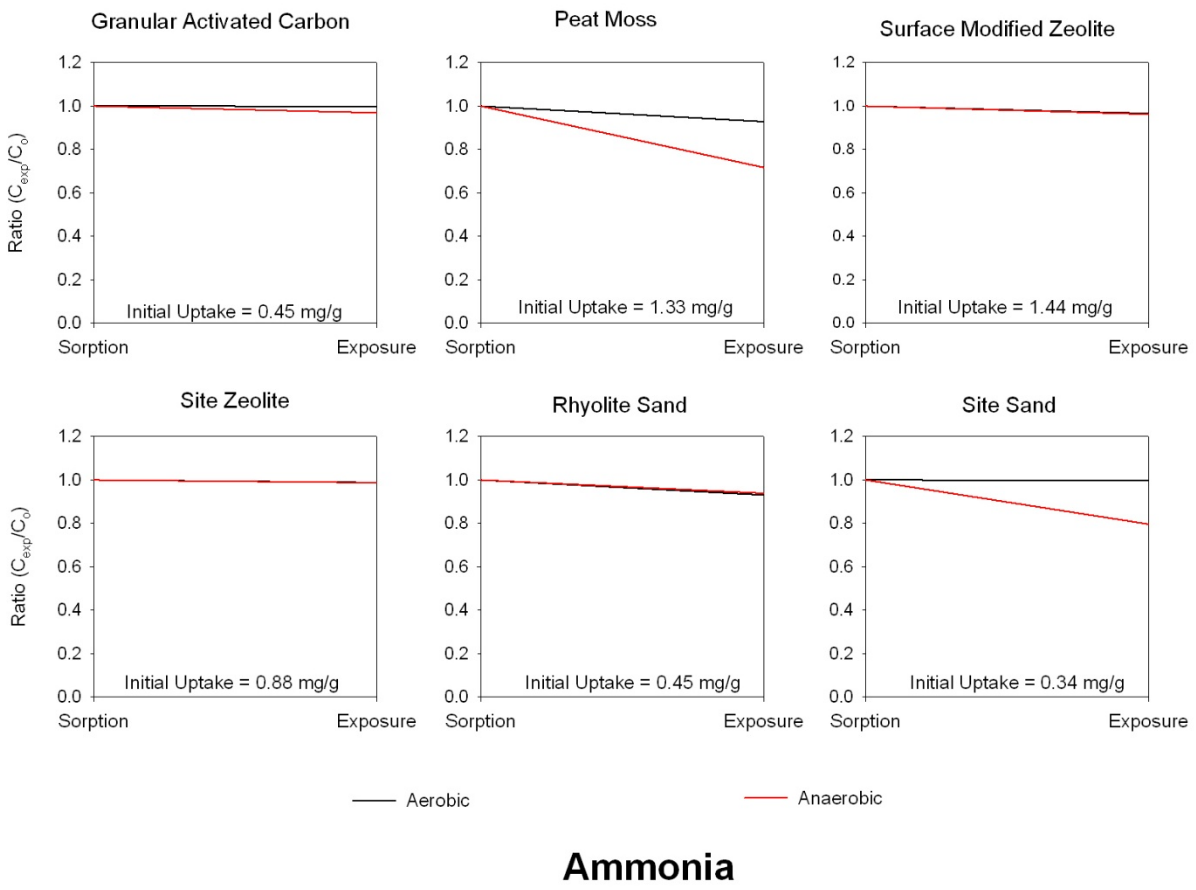


**Figure 4-40. Aerobic and Anaerobic Exposure Results for Media Components and Ammonia**

Table 4-36 is a summary of the different constituent and media combinations that were examined under aerobic and anaerobic exposures. The cells that are highlighted in yellow indicated conditions that had at least a 20% continued removal of the constituent during the exposure, while the red high-lighted cells indicate conditions where losses of >20% were observed. When the initial capacity was less than 0 (indicating releases during the sorption phase of the test), it is noted in the table. The combinations that showed releases during the long-term exposures are listed in Table 4-37, while combinations that experiences continued uptakes during these exposures are listed in Table 4-38. These releases and uptakes need to be considered simultaneously with the media's ability to remove the constituents. As an example, the site filter sand shows relatively little release potential, but it has a relatively poor ability to remove constituents.

## Table 4-36. Review of Aerobic and Anaerobic Retention Tests (from Appendix D)

| Cexp/Co* | Granular Activated Carbon | Peat Moss | Surface Modified Zeolite | Site Zeolite | Rhyolite Sand | Site Filter Sand |
|---|---|---|---|---|---|---|
| **Common Constituents** | | | | | | |
| Hardness | Initial Capacity < 0 | Initial Capacity < 0 | Initial Capacity < 0 | Initial Capacity < 0 | Initial Capacity < 0 | Initial Capacity < 0 |
| aerobic | 1.35 | 1.38 | 1.30 | 1.03 | 1.37 | 17.1 |
| anaerobic | 1.29 | 1.04 | 1.12 | 1.01 | 1.20 | 1.58 |
| pH | | | | | | |
| aerobic | 1.21 | 1.18 | 1.26 | 1.22 | 1.32 | 1.32 |
| anaerobic | 0.94 | 1.25 | 1.22 | 1.21 | 1.33 | 1.42 |
| COD | | Initial Capacity < 0 | Initial Capacity < 0 | | | |
| aerobic | 0.48 | -0.29 | -0.54 | 0.81 | 0.26 | 0.01 |
| anaerobic | 0.84 | -2.03 | 0.74 | 0.21 | 0.36 | 1.64 |
| **Major Ions** | | | | | | |
| Calcium | | | Initial Capacity < 0 | Initial Capacity < 0 | | |
| aerobic | 0.50 | 0.50 | 2.11 | 1.01 | 0.03 | -0.23 |
| anaerobic | 1.79 | 1.06 | 1.12 | 1.01 | 1.14 | 1.56 |
| Chloride | | | | | | |
| aerobic | 0.97 | 0.98 | 0.99 | 0.99 | 0.99 | 0.99 |
| anaerobic | 1.65 | 1.04 | 1.10 | 1.03 | 1.11 | 1.16 |
| Fluoride | Initial Capacity < 0 | Initial Capacity < 0 | Initial Capacity < 0 | Initial Capacity < 0 | Initial Capacity < 0 | Initial Capacity < 0 |
| aerobic | 1.18 | 1.19 | 1.28 | 1.18 | 1.25 | 1.69 |
| anaerobic | 1.10 | 1.71 | 1.17 | 1.40 | 1.11 | 1.23 |
| Magnesium | | | | | | |
| aerobic | 0.86 | 0.84 | 0.95 | 1.00 | 0.93 | 0.87 |
| anaerobic | 1.25 | 1.05 | 1.35 | 1.00 | 1.51 | 1.26 |
| Sodium | | | | Initial Capacity < 0 | | |
| aerobic | 0.87 | 0.86 | 0.81 | 1.90 | 0.48 | 0.86 |
| anaerobic | 1.09 | 1.28 | 1.14 | 1.20 | 1.40 | 1.34 |
| Potassium | Initial Capacity < 0 | | | | | |
| aerobic | 1.05 | 0.90 | 0.91 | 0.96 | 0.80 | 0.93 |
| anaerobic | 1.02 | 1.08 | 1.18 | 0.86 | 1.23 | 1.18 |

| Cexp/Co* | Granular Activated Carbon | Peat Moss | Surface Modified Zeolite | Site Zeolite | Rhyolite Sand | Site Filter Sand |
|---|---|---|---|---|---|---|
| Sulfate | | | | | | |
| aerobic | 0.89 | 0.68 | 0.68 | 0.81 | 0.65 | 0.63 |
| anaerobic | 0.72 | 0.47 | 2.83 | 3.89 | -3.86 | 26.2 |
| **Nutrients** | | | | | | |
| Ammonia | | | | | | |
| aerobic | 1.00 | 0.93 | 0.97 | 0.99 | 0.93 | 1.00 |
| anaerobic | 0.97 | 0.72 | 0.96 | 0.99 | 0.94 | 0.80 |
| Nitrate | | | | | | |
| aerobic | 0.88 | 0.02 | -1.95 | 0.69 | -3.11 | -0.05 |
| anaerobic | 0.84 | 2.50 | 1.98 | 1.95 | 2.16 | 1.19 |
| Nitrite | | | | | Initial Capacity < 0 | Initial Capacity < 0 |
| aerobic | 0.56 | 0.54 | -3.05 | 0.64 | 2.31 | 13.5 |
| anaerobic | 0.55 | 0.74 | 0.83 | 0.78 | -6.64 | 0.71 |
| Total Nitrogen | | | | | | |
| aerobic | 0.95 | 0.80 | 0.95 | 0.97 | 0.92 | 0.82 |
| anaerobic | 0.94 | 1.32 | 0.90 | 1.00 | 0.66 | -1.94 |
| Total Phosphorus | | | | | | |
| aerobic | -0.46 | 0.37 | 0.17 | 0.63 | 0.48 | 0.36 |
| anaerobic | 2.63 | -8.38 | -0.14 | -0.75 | -6.60 | 11.0 |
| Phosphate | | | | | | |
| aerobic | 0.59 | 0.78 | 0.28 | 0.85 | 0.97 | 0.51 |
| anaerobic | 0.51 | 0.16 | 0.58 | 0.34 | 0.36 | -3.01 |
| **Heavy Metals and Trace Constituents** | | | | | | |
| Aluminum | | | | Initial Capacity < 0 | | |
| aerobic | 1.0 | -9.36 | 0.99 | 1.02 | 0.99 | 1.0 |
| anaerobic | 0.87 | 1.05 | 1.01 | 1.12 | 1.01 | 1.01 |
| Antimony | | | | | | |
| aerobic | 1.0 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 |
| anaerobic | 1.0 | 0.99 | 0.98 | 0.98 | 0.96 | 0.91 |
| Arsenic | | | | | | |
| aerobic | n/a | n/a | n/a | n/a | n/a | n/a |
| anaerobic | n/a | n/a | n/a | n/a | n/a | n/a |
| Boron | | | | | | |
| aerobic | 0.95 | 0.96 | 0.94 | 0.94 | 0.93 | 0.92 |
| anaerobic | 1.78 | 1.23 | 1.42 | 1.97 | 1.62 | 1.34 |
| Cadmium | | | | | | |
| aerobic | 0.99 | 0.97 | 0.99 | 1.00 | 1.00 | 1.00 |
| anaerobic | 0.90 | 0.98 | 0.77 | 1.00 | 0.96 | 1.01 |
| Chromium | | | | | | |
| aerobic | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 |

| Cexp/Co* | Granular Activated Carbon | Peat Moss | Surface Modified Zeolite | Site Zeolite | Rhyolite Sand | Site Filter Sand |
|---|---|---|---|---|---|---|
| anaerobic | 0.98 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 |
| Copper | | | | | | |
| aerobic | 1.00 | 0.99 | 0.97 | 0.99 | 0.98 | 0.97 |
| anaerobic | 0.99 | -1.07 | 1.92 | 1.05 | 2.16 | 1.23 |
| Iron | | | | | | |
| aerobic | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| anaerobic | 1.00 | 0.98 | 0.98 | 1.00 | 0.95 | -0.87 |
| Lead | | | | | | |
| aerobic | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| anaerobic | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Manganese | Initial Capacity < 0 | Initial Capacity < 0 | Initial Capacity < 0 | Initial Capacity < 0 | Initial Capacity < 0 | Initial Capacity < 0 |
| aerobic | 16.6 | 1.11 | 1.34 | 1.02 | 1.14 | 1.02 |
| anaerobic | 1.48 | 1.01 | 1.12 | 1.01 | 1.07 | 1.02 |
| Nickel | | | | | | |
| aerobic | 0.99 | 0.97 | 0.99 | 1.00 | 1.00 | 1.00 |
| anaerobic | 0.86 | 0.99 | 0.72 | 0.99 | 0.57 | 1.02 |
| Thallium | | | | | | |
| aerobic | 0.99 | 0.94 | 0.99 | 0.99 | 0.99 | 0.99 |
| anaerobic | 0.94 | 0.62 | 0.98 | 0.98 | 0.98 | 3.51 |
| Zinc | | | | | | |
| aerobic | 0.98 | 0.94 | 0.98 | 1.00 | 0.98 | 0.98 |
| anaerobic | 0.83 | 0.95 | 0.44 | 1.00 | 0.61 | 1.05 |

*constituent contained in the media after the exposure, Cexp, compared to the amount contained in the media after the initial constituent loading at the start of the tests, Co. Cexp/Co ratios >1.2 indicate continued uptake of the constituent by the media during the test (yellow high-lighted cells), while ratios <1.2 indicate losses from the loaded media during aerobic or anaerobic exposures (red high-lighted cells)

**Table 4-37. Constituent and Media Combinations that Experienced Releases during Long-Term Exposure**

| Releases (Cexp/Co ratios <=0.8) | Granular Activated Carbon | Peat Moss | Surface Modified Zeolite | Site Zeolite | Rhyolite Sand | Site Filter Sand |
|---|---|---|---|---|---|---|
| **Common Constituents (3: COD, hardness and pH)** | | | | | | |
| aerobic | COD | COD | COD | none | COD | COD |
| anaerobic | none | COD | COD | COD | COD | none |
| **Major Ions (7: Ca, Cl, F, Mg, Na, K, and $SO_4$)** | | | | | | |
| aerobic | Ca | Ca, $SO_4$ | $SO_4$ | none | Ca, Na, $SO_4$ | Ca |
| anaerobic | $SO_4$ | $SO_4$ | none | none | K, $SO_4$ | none |
| **Nutrients (6: $NH_3$, $NO_3$, $NO_2$, TN, TP, and $PO_4$)** | | | | | | |
| aerobic | $NO_2$, TP, $PO_4$ | $NO_2$, $NO_3$, TP, $PO_4$ | $NO_2$, $NO_3$, TP, $PO_4$ | $NO_2$, $NO_3$, TP | $NO_3$, TP | $NO_3$, TP, $PO_4$ |
| anaerobic | $NO_2$, $PO_4$ | $NH_3$, $NO_2$, TP, $PO_4$ | TP, $PO_4$ | $NO_2$, TP, $PO_4$ | $NO_2$, TN, TP, $PO_4$ | $NO_2$, TN, $PO_4$ |
| **Heavy Metals and Trace Constituents (13: Al, Sb, As, B, Cd, Cr, Cu, Fe, Pb, Mn, Ni, Tl, and Zn)** | | | | | | |
| aerobic | none | Al | none | none | none | none |
| anaerobic | none | Cu, Tl | Ni, Zn | none | Ni, Zn | Fe |

**Table 4-38. Constituent and Media Combinations that Experienced Uptake during Long-Term Exposures**

| Uptake (Cexp/Co ratios >=1.2) | Granular Activated Carbon | Peat Moss | Surface Modified Zeolite | Site Zeolite | Rhyolite Sand | Site Filter Sand |
|---|---|---|---|---|---|---|
| **Common Constituents (3: COD, hardness and pH)** | | | | | | |
| aerobic | hardness, pH | hardness | hardness, pH | pH | hardness, pH | hardness, pH |
| anaerobic | hardness | pH | pH | pH | pH | hardness, pH |
| **Major Ions (7: Ca, Cl, F, Mg, Na, K, and $SO_4$)** | | | | | | |
| aerobic | none | none | Ca, F | Na | F | F |
| anaerobic | Ca, Cl, Mg, | F, Na | Mg, $SO_4$ | F, $SO_4$ | Mg, Na | F, Mg, Na, $SO_4$ |
| **Nutrients (6: $NH_3$, $NO_3$, $NO_2$, TN, TP, and $PO_4$)** | | | | | | |
| aerobic | none | none | none | none | $NO_2$ | $NO_2$ |
| anaerobic | TP | $NO_3$, TN | $NO_3$ | $NO_3$ | $NO_3$ | TP |
| **Heavy Metals and Trace Constituents (13: Al, Sb, As, B, Cd, Cr, Cu, Fe, Pb, Mn, Ni, Tl, and Zn)** | | | | | | |
| aerobic | Mn | none | Mn | none | none | none |
| anaerobic | B | B | B, Cu | B | B, Cu | B, Cu, Tl |

MWH conducted leaching tests for some of the treatment media to identify possible contaminant sources associated with their use in treatment systems. These were generally conducted as standard, or modified, TCLP leaching tests where a known quantity of new media was placed in a container having a leaching solution (from DI water to acetic acid). The mixture was agitated for a set time (usually 48 hours), and then the mixture was filtered and the liquid analyzed for the constituents of interest (many of the constituents that have listed permit limits for 008 and 009). The media tested included: Rhyolite sand, Surface Modified Zeolite, site Zeolite, and site filter sand. The GAC and peat were not investigated. Few leached constituents were expected to exceed the permit limits, as shown in Table 4-39.

**Table 4-39. Leaching Tests Results for Selected Media that May Exceed Permit Limits Using TCLP Tests (observed filtrate concentrations vs. permit limits) (MWH May 2009) (maximum concentration observed and the site permit limits for 008/009)**

| Surface Modified Zeolite | Site Zeolite | Rhyolite Sand | Site Filter Sand |
|---|---|---|---|
| TDS (1,000 mg/L vs. 950/850 mg/L) | TDS (1,500 mg/L vs. 950/850 mg/L) | Lead (11 µg/L vs. 5.2 µg/L) | No exceedences identified due to leaching of media |
| Chloride (430 mg/L vs. 150 mg/L) | Lead (62 µg/L vs. 5.2 µg/L) | Mercury (0.24 µg/L vs. 0.13 µg/L) | |
| | Gross alpha radioactivity (96 pCi/L vs. 15 pCi/L) | | |
| | Gross beta radioactivity (86 pCi/L vs. 50 pCi/L) | | |

The zeolites leached elevated salts, while the zeolite currently used for stormwater treatment on site also leached elevated lead, and gross alpha and beta radioactivity. The Rhyolite sand leached elevated lead and mercury, while the filter sand currently used on site for stormwaters treatment did not indicate any leaching problems.

## *4.6 Chemical Capacity of Media and Replacement Requirements*

The ability of the treatment media to remove contaminants may be limited by their maximum operational capacities for the constituents, among other factors. It can be assumed that each removal mechanism has a physical or chemical limit. Physical limits are normally associated with clogging, as discussed as part of the flow rate discussions. Particulate matter accumulating on or in the media matrix eventually prevents any movement of the water through the material, causing bypassing of the water around the treatment media and resulting in little to no treatment. Chemical limits relate to the mechanisms involved in the removal processes of the “filterable” (including colloidal and chemically-complexed) pollutant forms. Many complementary processes occur in the media, but the complex nature of the water (numerous constituents, at varying concentrations, under varying environmental conditions of flow rate or residence time, pH, and temperature, multiple types of media reaction sites, for example) prevents accurate theoretical calculations of the chemical removal capacities. Traditionally, chemical capacities have been estimated from empirical equations without concern for the site-specific mechanisms simply because of the variety of potential mechanisms operating in a heterogeneous media. Traditional capacity testing typically is done using controlled tests conducted under idealized (but unrealistically simple) conditions (single constituents, high concentrations, controlled pH and temperature, etc.). These results can indicate capacity, but extrapolating these types of results to actual field conditions remains problematic. These types of tests are best at providing rankings of media, as opposed to design capacities. As an example, cation exchange capacity (CEC) has been used to calculate the removal capacity of stormwater treatment media. Similarly, specifications for the organic matter content of biofiltration soils are also used by many states. While a gross indicator of removal potential under some conditions, CEC falls far short in being a quantitative and simple measure of overall removal capacity. Increased organic matter content also appears to benefit the removal of some pollutants; however, it is also a source of other potential pollutants that can readily leach from the media during the treatment process.

Therefore, the likely removal capacities of the treatment media were examined using several methods of batch testing and of column testing. The column tests should give the best estimate of operational capacity, while the batch testing will indicate ultimate capacity. The difference between the two capacities can be attributed to very slow removal processes and to pollutants moving from readily-available media surface sites to interior retention sites. This diffusion typically is a very slow process and can be rate limiting. This diffusion also may explain the further removal of pollutants during the long-term exposure tests. The operational capacity determined from the column tests should be used in design since they were conducted under dynamic flow conditions over a long period of study with intermittent flows, with multiple data observations. They reflect many of the actual conditions of full-scale installations. The rationale for using the batch data for some pollutants is that many constituents did not break through during the study duration, resulting in uncertainties in their operational capacities. The results from all capacity-estimating tests were compared to these full-column test results. The results are summarized in the rest of this section, while the detailed data and all of the plots are presented in Appendix A10.

### 4.6.1 Chemical Capacity based on Full-Depth Column Tests

Tables 4-40 and 4-41 summarize the operational capacities of the media test columns, expressed as mass of pollutant removed per unit area of filter (based on the 3-foot deep, 3.5-inch inside diameter columns of media). Since these columns are close to the full-depth of the media planned for the site treatment facilities, these unit area loadings can be used to estimate the maintenance interval for the different media, based on different sized biofiltration units. These capacities were calculated using normalized data for breakthrough analyses (effluent concentration/influent concentration or Ce/Co).

Breakthrough was assumed at the first point on the curve of Ce/Co versus cumulative volume loading where Ce/Co = 1. If the capacity listed in the table is 0, then the media provided no measureable removal for the test conditions (some of the constituents were at very low concentrations which hindered removal, for example). Constituent category relates to past or expected permit limit exceedences, as described in the footnotes. Many of the values have a > indication showing that breakthrough was never observed during the testing period, and the value shown is the maximum loading placed onto the column during the long-term tests. Because the capacities are expressed as mg pollutant/m2 filter surface area and not in the traditional form of mg pollutant/g media, they are not translatable to filters of similar composition but different depths or to filters with different composition.

Appendix A10, Figures A10-1 through A10-60, present the complete set of breakthrough curves, starting with line graphs showing the Ce/Co ratios for different treatment volumes plotted for all tested media and then multiple miniature plots for each medium, for all of the constituents for which full-column data are available.

### Table 4-40. Capacity of Filter Columns for Retention of Contaminants (mg/m$^2$ of filter surface)

| Constituent | Constituent Category** | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium, Total | A | > 4,380 | > 4,250 | > 4,890 | > 1,660 | > 5,590 | > 5,110 | > 5,120 | > 5,160 | > 5,420 | > 3,900 |
| Copper, Total | A | > 8,280 | > 7,440 | > 6,390 | > 2,450 | > 7,400 | > 6,880 | > 6,180 | > 9,490 | > 9,140 | > 7,210 |
| Lead, Total | A | > 729 | > 707 | > 803 | > 275 | > 938 | > 824 | > 857 | >860 | > 911 | > 631 |
| Mercury | A | not tested | not tested | not tested | not tested | not tested | not tested | > 4,120 | > 4,960 | > 5,330 | > 3,760 |
| Oil and Grease | A | not tested | not tested | not tested | not tested | not tested | not tested | 16,700 | > 32,400 | > 34,700 | 0 |
| TCDD | A | not tested | not tested | not tested | not tested | not tested | not tested | > 1.27E-5 | > 1.35E-5 | > 1.35E-5 | > 1.02E-5 |
| Antimony, Total | B | > 2,790 | > 3,840 | 673 | > 1,060 | > 2,740 | 572 | 1,260 | > 3,010 | 1,610 | 784 |
| Iron, Total | B | > 327,000 | Flush | Flush | > 112,000 | > 407,000 | > 374,000 | > 353,000 | > 375,000 | > 402,000 | > 292,000 |
| Manganese, Total | B | > 4,290 | Washout | Flush | > 1,250 | > 5,060 | > 4,890 | > 4,510 | > 4,830 | > 4,400 | > 3,930 |
| Nitrate | B | > 379,000 | 2,150 | 17,800 | > 13,300 | 3,510 | 11,200 | 14,500 | 251,000 | 239,000 | > 267,000 |
| Sulfate | B | 461,000 | Washout | 44,300 | > 61,500 | 69,400 | 117,000 | 154,000 | > 683,000 | 126,000 | > 739,000 |
| Zinc, Total | B | Flush | Flush | Flush | > 885 | > 2,650 | > 2,680 | > 2,650 | Flush | 1,080 | > 1,540 |
| Aluminum, Filtered |  | > 2,660 | Washout | 370 | 443 | 81.9 | 235 | 141 | > 2,700 | 229 | 69.4 |
| Aluminum, Total |  | > 410,000 | Flush | Flush | > 140,000 | > 512,000 | > 469,000 | > 407,000 | > 445,000 | > 493,000 | > 369,000 |
| Ammonia |  | > 169,000 | 10,900 | > 183,000 | > 2,890 | > 226,000 | > 212,000 | > 215,000 | > 221,000 | > 234,000 | > 158,000 |
| Antimony, Filtered |  | > 1,960 | > 3,100 | 900 | 653 | 1,160 | 675 | 1,110 | 909 | > 2,350 | > 1,490 |
| Arsenic, Filtered |  | >1,530 | Flush | 1,020 | 569 | > 1,720 | > 985 | 654 | > 1,520 | 1,360 | > 1,190 |
| Arsenic, Total |  | > 3,010 | > 2,580 | 2,360 | > 1,220 | > 3,260 | 2,200 | 1,820 | > 3,300 | > 3,150 | > 2,490 |
| Boron, Filtered |  | > 7,680 | 2,170 | Washout | 1,000 | 573 | Washout | 2,310 | > 9,000 | > 9,700 | > 6,840 |
| Boron, Total |  | Flush | 1,140 | Washout | 939 | Washout | 1,790 | 2,600 | > 8,190 | 39,006 | 2470 |
| Cadmium, Filtered |  | > 1,800 | >1,740 | > 2,010 | > 667 | > 2,210 | > 2,070 | > 2,070 | > 2,130 | > 2,270 | > 1,620 |
| Calcium, Filtered |  | 269,000 | > 1.24E6 | 183,000 | 69,000 | 263,300 | 105,000 | 182,000 | 180,000 | 316,000 | 192,000 |
| Calcium, Total |  | 300,000 | 1.25E+06 | 102,000 | 81,400 | 207,000 | 116,000 | 213,000 | 220,000 | 412,000 | 169,000 |

| Constituent | Constituent Category** | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Chloride | | 7,150 | Washout | Washout | Washout | Washout | Washout | Washout | Washout | 15,200 | Washout |
| Chromium, Filtered | | > 883 | > 682 | 68 | 52.5 | 5.74 | 44 | 1,21 | > 906 | > 721 | 731 |
| Chromium, Total | | > 4,200 | > 3,700 | > 2,870 | > 1,170 | > 3,830 | > 3,510 | > 2,510 | > 4,710 | > 4,650 | > 3,620 |
| COD | | > 4,47E6 | Washout | > 415,000 | > 918,000 | > 5.13E6 | > 3.62E6 | > 4.09E6 | > 5.39E6 | > 5.51E6 | > 4.17E6 |
| Copper, Filtered | | > 2,570 | > 1,610 | 290 | 207 | > 1,010 | Washout | Washout | > 2,680 | > 2,070 | > 1,990 |
| Fluoride | | 18,700 | > 59,200 | 23,600 | 9,910 | 32,200 | 16,000 | 20,600 | 19,400 | 21,900 | 18,700 |
| Hardness | | 262,000 | > 267,000 | 75,200 | 15,100 | 883,000 | 17,100 | 72,00 | 98,000 | 647,000 | 193,000 |
| Iron, Filtered | | > 3,660 | Flush | Flush | > 583 | Flush | Flush | Flush | > 3,390 | Flush | > 2,820 |
| Lead, Filtered (very low influent conc.)* | | Flush | Flush | Flush | Flush | Flush | Flush | Flush | Flush | Flush | Flush |
| Magnesium, Filtered | | 764 | 1,560 | Washout | Washout | > 95,500 | Washout | Washout | Washout | Washout | 13,900 |
| Magnesium, Total | | 2,850 | Washout | Washout | Washout | > 174,000 | Washout | Washout | 453 | 1,880 | 21,800 |
| Manganese, Filtered | | > 197 | Washout | Washout | Flush | > 97.2 | Washout | Washout | > 223 | Flush | > 169 |
| Nickel, Filtered | | > 1,660 | >1,520 | >1,620 | 417 | > 1,410 | > 1,880 | > 1,560 | > 1,620 | >1,970 | > 1,340 |
| Nickel, Total | | > 3,330 | > 3,060 | > 3,420 | > 1,210 | > 3,780 | > 3,860 | > 3,680 | > 3,940 | > 4,000 | > 3,000 |
| Nitrite | | 138 | Flush | Washout | 12.2 | 184 | 140 | 14.8 | 385 | 185 | 673 |
| Perchlorate | | not tested | not tested | not tested | not tested | not tested | not tested | 0 | 0 | 0 | 0 |
| Phosphate | | Washout | Washout | Flush | > 8,060 | > 51,800 | 1,140 | 401 | Washout | Washout | Washout |
| Potassium, Filtered | | Washout | 413 | Washout | 194 | Washout | Washout | Washout | Washout | Washout | Washout |
| Potassium, Total | | Washout | Washout | Washout | > 19,500 | Washout | Washout | Washout | Washout | Washout | Washout |
| Sodium, Filtered | | 24,000 | Washout | Washout | 31,200 | Washout | 31,100 | Washout | Washout | Washout | Washout |
| Sodium, Total | | Washout | Washout | Washout | Washout | Washout | 7,610 | Washout | Washout | Washout | Washout |
| Thallium, | | > 4,040 | > 3,450 | > 4,560 | > 1,290 | > 4,960 | > 4,690 | > 4,500 | > 4,720 | > 4,900 | > 3,700 |

| Constituent | Constituent Category** | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Filtered | | | | | | | | | | | |
| Thallium, Total | | > 5,160 | > 4,620 | > 4,820 | > 1,810 | > 6,220 | > 5,000 | > 5,010 | > 6,060 | > 6,310 | > 4,640 |
| TN | | > 634,000 | 12,500 | 237,000 | 7,350 | 21,200 | 17,300 | Washout | > 620,000 | > 746,000 | Flush |
| TP | | Washout | Flush | > 31,600 | > 8,350 | > 40,500 | > 26,174 | > 29,100 | Washout | Washout | Washout |
| Zinc, Filtered | | Flush | washout | Flush | Washout | Washout | Washout | Washout | > 8.43 | Washout | > 116 |

* The very low influent concentrations likely adversely affected the removals of these constituents.

** “A” are constituents that have exceeded current benchmark limits at Outfalls 008 or 009. “B” are constituents that have a high likelihood of exceeding benchmark limits at Outfalls 008 or 009 during extended future monitoring based on observations elsewhere on the site or through probability analyses.

### Table 4-41. Capacity of Filter Columns for Retention of Radioactive Contaminants (pCi/$m^2$ of filter surface)

| Constituent | Constituent Category** | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Gross Alpha | A | not tested | not tested | not tested | not tested | not tested | not tested | > 316,000 | > 337,000 | > 358,000 | > 249,000 |
| Gross Beta | B | not tested | not tested | not tested | not tested | not tested | not tested | >120,000 | 38,300 | 182,000 | > 148,000 |
| Radium-226 | B | not tested | not tested | not tested | not tested | not tested | not tested | > 13,400 | Flush | > 15,400 | > 11,200 |
| Radium-228 | B | not tested | not tested | not tested | not tested | not tested | not tested | Washout | 12,600 | > 17,200 | Washout |
| Alpha Radium | | not tested | not tested | not tested | not tested | not tested | not tested | > 54,200 | > 40,700 | > 54,400 | > 40,800 |
| Strontium-90 (very low influent)* | | not tested | not tested | not tested | not tested | not tested | not tested | 0 | 0 | 0 | 0 |
| Tritium (very low influent)* | | not tested | not tested | not tested | not tested | not tested | not tested | 0 | 0 | 0 | 0 |
| Uranium | | not tested | not tested | not tested | not tested | not tested | not tested | > 77,000 | > 87,300 | > 93,600 | Flush |

* The very low influent concentrations likely adversely affected the removals of these constituents.

** “A” are constituents that have exceeded current benchmark limits at Outfalls 008 or 009. “B” are constituents that have a high likelihood of exceeding benchmark limits at Outfalls 008 or 009 during extended future monitoring based on observations elsewhere on the site or through probability analyses.

Figure 4-41 is an example line plot for filtered arsenic showing how removal performance generally decreased over time (increased stormwater volumetric loading); initially, the Ce/Co values were quite small indicating high removals, however, the ratios increased with subsequent loading, with several of the media indicating eventual breakthrough.

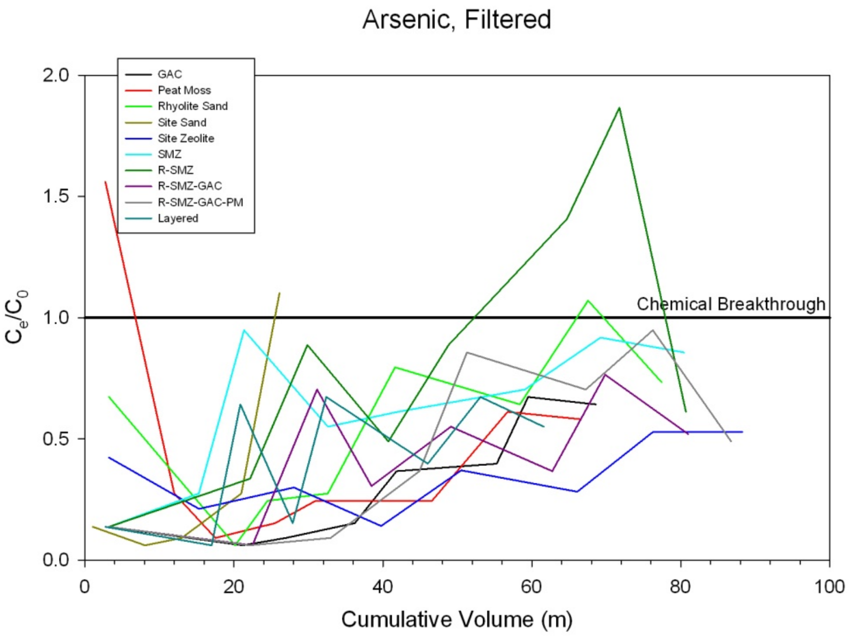


**Figure 4-41. Breakthrough Plots for Filtered Arsenic Full-Depth Column Tests Showing Both Flushing for Peat Moss and Breakthrough for Several Media**

Designations of “flush” or “washout” are also shown on the table when observed. “Flush” indicates that the first sample from the column had Ce/Co > 1, but that the remaining samples in the testing for that media-pollutant combination had Ce/Co < 1. In the example shown previously in Figure 4-41, the peat moss initial Ce/Co ratio was >1, but then decreased and followed the general trend of the other media, indicating an initial flush of arsenic from the peat moss material. This high initial result may indicate that the media was contaminated before use (likely at the manufacture/generation location) or that the pollutant was very loosely bound and easily displaced from the media). Once the initial flushing of the media occurs, the media may provide removal, as indicated for the peat moss in this example. Results such as this may indicate that washing of the media and then redirecting the washwater to further treatment (or recycling through the treatment media) may be necessary to meet performance guidelines.

For the media-pollutant combinations designated as “washout,” Ce/Co remained above 1 for most of the sampling periods, indicating that the media was likely a constant source of the pollutant. Figure 4-42 shows this behavior for many of the media for chloride, with most of the Ce/Co ratio values greater than 1 for all of the observations, indicating that chloride was released almost continuously, likely as part of an anion exchange reaction.

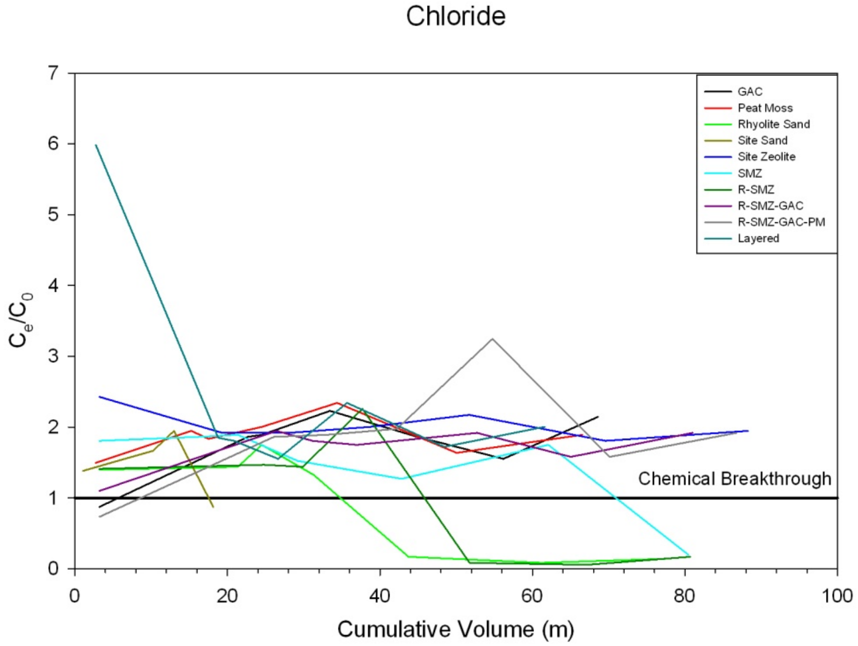


**Figure 4-42. Breakthrough Plots for Chloride Full-Depth Column Tests Showing Washout (Continuous Release) during Most Observations**

In addition, many of the tests did not indicate any breakthrough of the contaminants, even considering the long duration of the tests and the large amount of stormwater treated. These constituent-media combinations therefore show the maximum amount of the pollutant used, with a greater than sign (>) indicating that breakthrough would potentially occur for larger constituent loadings beyond the range of the tests. Figure 4-43 is an example for filtered thallium where all of the effluent samples had concentrations less than the influent sample concentrations for all testing periods. In this case, it was not possible to determine an expected removal capacity for filtered thallium, but it was certainly greater than the total amount of filtered thallium applied to the columns during the tests. For those constituents where some movement toward breakthrough occurs during the testing, traditional fixed-bed sorption models could be used to predict capacity. However, capacities calculated using these methods, like all empirical single-component sorption models, are not transferable to other conditions because the removals are influenced by the influent concentration of each constituent and the competition for removal sites.

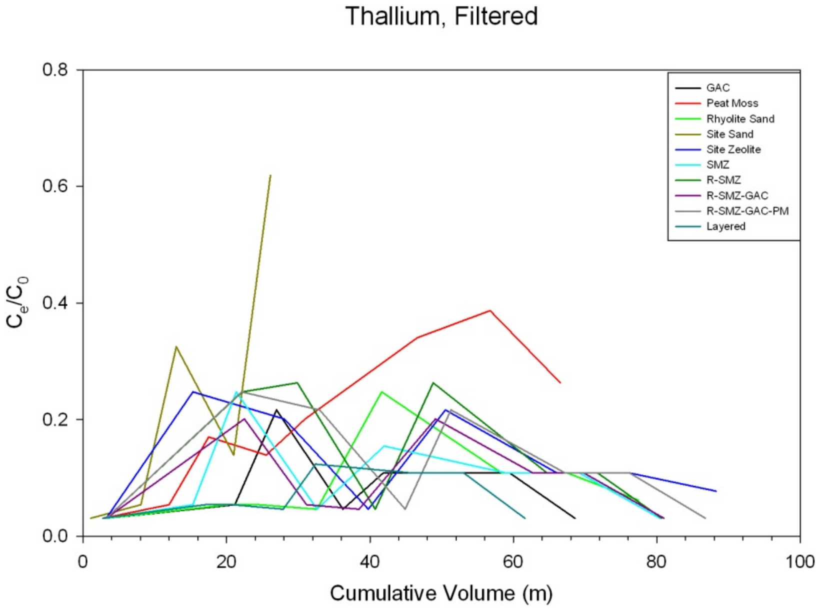


**Figure 4-43. Breakthrough Plots for Filtered Thallium Full-Depth Column Tests, Indicating No Observed Breakthrough for Any Media**

As the loadings increase, even for constituents that did not show any breakthrough, the potential for media clogging by particulate matter also increases. Therefore, there is a practical upper limit to the chemical capacity estimates based on likely premature failure due to clogging. In fact, unless supported by extensive pre-treatment to remove the particulates most likely to cause clogging (typically those smaller than 10 – 25 µm), it is very likely that most stormwater treatment media will have chemical removal capacity remaining when the system fails due to clogging. This may not necessarily be a problem, as extra treatment capacity offers a margin of safety during periods of unusually high contaminant concentrations. Also, completely “saturated” media may potentially present disposal problems. During TCLP leaching tests of saturated treatment media, Johnson, *et al.* (2003) identified potential TCLP leaching problems associated only with cadmium (of the heavy metals analyzed). However, they found that clogging most likely would occur well before the cadmium could reach problematic levels in the different treatment media, indicating that using all of the chemical capacity can generate unanticipated problems.

The prior pollutant removal discussion of this report summarizes the significant pollutant removals based on statistical evaluations of all sampling pairs (untreated vs. treated water) for each treatment media. During the statistical tests, a medium may be considered not to provide significant removal if several of the sampling events demonstrate no pollutant removal. The “sign test” is a simple non-parametric statistical test that indicates the confidence level that two sets of paired data are different. As an example, for eight pairs of observations (the typical number of observations for these column tests), the sign test requires that at least seven of the effluent samples must be smaller than the influent samples, for a commonly accepted significance level of less than 0.05 (less than a 1 in 20 chance of being incorrect). The sign test only indicates the statistical significance of the likelihood that the two sets of paired data come from different populations, with the stated confidence. The sign test does not consider the magnitude of the differences in the values. Therefore, any breakthrough (defined as when the effluent and influent are the "same," or when the effluent was degraded) decreased the confidence that the effluent concentrations are less than the influent. Therefore, the significance results presented earlier are therefore conservative because fluctuations around the Ce/Co = 1 line (limited removals/exchanges), flushing, and washout will affect the number of events where Ce/Co < 1. In addition, in many cases, as noted above, breakthrough was not observed during the maximum period of the tests, so the upper limits of the media capacities are shown with greater than signs (>) in Tables 4-40 and 4-41. This is especially true for the metals because the influent concentrations were kept low to better reflect site conditions.

The amount of the different media in each test column obviously affects these unit area treatment capacity calculations. Table 4-42 lists the amount of each media type used in the full-depth columns. The columns were constructed using mixtures created on a volume basis; however, treatment capacities depend on the mass of the different materials. In the single medium tests, the test medium was mixed with an approximate equal volume of the site filter sand to moderate flows. As found during prior filter media research (Clark 2000 and Clark and Pitt 1999), coarse material results in very high treatment flows, which causes very low residence time in the filters, and, thus, reduced performance. For fine or organic material (such as the peat moss), the mixtures had very low flow rates, causing premature clogging. The organic material would compress and dramatically restrict flows. By mixing these with a filter sand (or the rhyolite sand), the organic material was supported by the sand grains reducing compaction problems and providing structure for flow paths for the water around the sand and organic material. This basic mixture resulted in a much more balanced flow rate for the different media types, along with reasonable contact times for treatment.

**Table 4-42. Medium Masses Used in Full-Depth Column Tests (grams of media per column)**

| Total media depth in column (inches) | Mixture Testes | Filter site sand | Surface Modified Zeolite (SMZ) | Rhyolite sand ( R) | Peat Moss (PM) | Granular activated carbon (GAC) | Site Zeolite (Z) |
|---|---|---|---|---|---|---|---|
| 36 | SMZ – Filter Sand (50-50) | 4700 | 2900 | | | | |
| 33 | R – Filter Sand (50-50) | 4310 | | 3380 | | | |
| 33 | PM – Filter Sand (50-50) | 4310 | | | 441 | | |
| 38 | GAC – Filter Sand (50-50) | 4960 | | | | 1620 | |
| 36 | Z– Filter Sand (50-50) | 4700 | | | | | 2340 |
| 34 | Filter Site Sand (100%) | 8890 | | | | | |
| 38 | R-SMZ (75-25) | | 1530 | 5840 | | | |
| 38 | R-SMZ-G (1/3) | | 2040 | 2590 | | 1010 | |
| 38 | R-SMZ-G-PM (30-30-30-10) | | 1840 | 2330 | 102 | 910 | |
| 34 | Sand-Z-GAC (1/3) - Layered | 2960 | | | | 905 | 1480 |

### 4.6.2 Capacity of Media Compared to Expected Clogging

As noted previously, maximum particulate loadings before clogging varied by media type. The maximum runoff volume that can be treated per unit area of filter before clogging was calculated using an assumed annual flow-weighted particulate solids concentration of about 50 mg/L for the water entering the stormwater biofilter (after partial treatment in the sedimentation basin). The corresponding constituent unit area loading was also calculated using the annual flow-weighted constituent concentrations (based on site measurements, or estimated for some of the constituents that have not been monitored on site). Tables 4-43 through 4-45 show the ratios of these calculated media chemical capacities to the clogging capacities for each media type and constituent, with both chemical and clogging capacity calculated as years to failure. Table 4-43 lists constituents that have exceeded the current site benchmark limits for Outfalls 008 and 009 samples. Table 4-44 lists constituents that have a high likelihood of exceeding the benchmark limits during extended future monitoring (determined by data from other site open space outfall samples, or from probability analyses of available Outfall 008 and 009 data). Table 4-45 lists other site constituents of interest (as indicated earlier in the discussion on the selection of constituents to monitor); these constituents include other parameters that have benchmark limits and those that may affect operation of the filters). The green highlighted cells indicate the constituent and medium combinations that have excess removal capacity (clogging by particulates is likely to occur before the removal capacity is met). The yellow highlighted cells indicate those combinations where the upper limits of the removal capacities were uncertain and may have excess removal capacity before clogging. Red highlighted cells indicate combinations where the removal capacity for the constituent may be exceeded before the filter is clogged.

**Table 4-43. Ratios of Media Capacity to Clogging (ratio of years to failure) for Constituents that Have Exceeded the Current Benchmark Limits at Outfalls 008 and 009**

| Ratios of Media Capacity to Clogging Period | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium, Total | >140 | >270 | >180 | >210 | >420 | >120 | >230 | >170 | >130 | >150 |
| Copper, Total | >2.2 | >3.7 | >18 | >2.5 | >4.2 | >1.2 | >22 | >2.4 | >1.8 | >2.2 |
| Gross Alpha radioactivity | not tested | not tested | not tested | not tested | not tested | not tested | >0.3 | >0.2 | >0.2 | >0.2 |
| Lead, Total | >1.0 | >1.7 | >1.1 | >1.4 | >2.8 | >0.8 | >1.9 | >1.1 | >0.9 | >0.9 |
| Mercury | not tested | not tested | not tested | not tested | not tested | not tested | >180 | >160 | >130 | >140 |
| Oil and Grease | not tested | not tested | not tested | not tested | not tested | not tested | 0.3 | >0.4 | >0.3 | <0.1 |
| TCDD | not tested | not tested | not tested | not tested | not tested | not tested | >20 | >17 | >12 | >16 |

Green cells indicate conditions where media chemical capacity (in years to failure) exceeds the expected clogging time period

Yellow cells are uncertain, and may have excess media capacity

Red cells indicate conditions where the media chemical capacity would likely be exceeded before the expected clogging period

**Table 4-44. Ratios of Media Capacity to Clogging (ratio of years to failure) for Constituents that Have a High Likelihood of Exceeding Benchmark Limits during Extended Future Monitoring**

| Ratios of Media Capacity to Clogging Period | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|
| Antimony, Total | >19 | >50 | 4.9 | >27 | >39 | 2.6 | 11 | >19 | 7.6 | 6.0 |
| Gross Beta radioactivity | not tested | not tested | not tested | not tested | not tested | not tested | >0.1 | <0.1 | <0.1 | >0.1 |
| Iron, Total | >0.2 | Flush | Flush | >0.3 | >0.6 | >0.2 | >3.0 | >2.4 | >0.2 | >0.2 |
| Manganese, Total | >0.1 | Washout | Flush | >0.1 | >0.1 | >0.1 | >0.1 | >0.1 | >0.1 | >0.1 |
| Nitrate | >0.2 | <0.1 | <0.1 | >0.1 | <0.1 | <0.1 | <0.1 | >0.2 | <0.1 | >0.2 |
| Radium 226+228 | not tested | not tested | not tested | not tested | not tested | not tested | >0.3 | 0.2 | >0.2 | >0.2 |
| Sulfate | 0.1 | Washout | <0.1 | >0.0 | <0.1 | <0.1 | <0.1 | >0.1 | <0.1 | >0.1 |
| Zinc, Total | Flush | Flush | Flush | >0.2 | >0.4 | >0.1 | >0.2 | Flush | <0.1 | >0.1 |

Green cells indicate conditions where media chemical capacity (in years to failure) exceeds the expected clogging time period
Yellow cells are uncertain, and may have excess media capacity
Red cells indicate conditions where the media chemical capacity would likely be exceeded before the expected clogging period

## Table 4-45. Ratios of Media Capacity to Clogging (Ratio of Years to Failure) for Other Site Constituents of Interest

| Ratios of Media Capacity to Clogging Period | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|
| Aluminum, Filtered | >0.3 | Washout | 0.1 | 0.2 | <0.0 | <0.0 | <0.0 | >0.4 | <0.0 | <0.0 |
| Aluminum, Total | >11 | Flush | Flush | >14 | >30 | >8.5 | >14 | >12 | >9.4 | >11 |
| Ammonia | >0.4 | 0.1 | >0.5 | >0.1 | >1.3 | >0.4 | >0.8 | >0.6 | >0.5 | >0.5 |
| Antimony, Filtered | >10 | >31 | 5.1 | >13 | >14 | 2.4 | 7.9 | 4.8 | >9.0 | >9.0 |
| Arsenic, Filtered | >2.1 | Flush | 1.5 | 2.9 | >5.0 | >0.9 | 1.2 | >2.1 | 1.3 | >1.8 |
| Arsenic, Total | >0.8 | >1.3 | 0.7 | 1.3 | 1.9 | 3.9 | 0.7 | >0.9 | >0.6 | >0.8 |
| Boron, Filtered | >0.2 | 0.1 | Washout | 0.1 | <0.1 | Washout | 0.1 | >0.2 | >0.2 | >0.2 |
| Boron, Total | Flush | <0.1 | Washout | 0.1 | Washout | <0.1 | 0.1 | >1.7 | 0.6 | 0.1 |
| Cadmium, Filtered | >79 | >150 | >96 | >110 | >220 | >63 | >120 | >93 | >73 | >82 |
| Calcium, Filtered | <0.1 | >0.2 | <0.1 | <0.1 | 0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Calcium, Total | <0.1 | 0.2 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Chloride | <0.1 | Washout | Washout | Washout | Washout | Washout | Washout | Washout | <0.1 | Washout |
| Chromium, Filtered | >0.6 | >0.9 | <0.1 | 0.1 | <0.1 | <0.1 | <0.1 | >0.6 | >0.6 | 0.6 |
| Chromium, Total | >1.1 | >1.9 | >0.8 | >1.2 | >2.2 | >0.6 | >0.9 | >1.2 | >0.9 | >1.1 |
| COD | >0.1 | Washout | >0.1 | >0.1 | >0.4 | >0.1 | >0.2 | >1.7 | >0.1 | >0.2 |
| Copper, Filtered | >0.8 | >1.0 | 0.1 | 0.3 | >0.7 | Washout | Washout | >1.2 | >0.7 | >1.0 |
| Fluoride | 0.1 | >0.6 | 0.1 | 0.2 | 0.4 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Hardness | <0.1 | >0.1 | <0.1 | <0.1 | 0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Iron, Filtered | >0.1 | Flush | Flush | >0.1 | Flush | Flush | Flush | >0.1 | Flush | >0.1 |
| Magnesium, Total | <0.1 | Washout | Washout | Washout | >0.1 | Washout | Washout | <0.1 | <0.1 | <0.1 |
| Magnesium, Filtered | >0.1 | >0.1 | Washout | Washout | >0.1 | Washout | Washout | Washout | Washout | >0.1 |
| Manganese, filtered | >0.1 | Washout | Washout | Flush | >0.1 | Washout | Washout | >0.1 | Flush | >0.1 |
| Nickel, Filtered | >2.2 | >4.0 | >2.3 | 2.1 | >4.2 | >1.7 | >2.8 | >2.1 | >1.9 | >2.0 |
| Nickel, Total | >2.2 | >3.8 | >2.4 | >3.1 | >5.6 | >1.8 | >3.3 | >2.6 | >1.9 | >2.3 |
| Nitrite | <0.1 | Flush | Washout | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Perchlorate | not tested | not tested | not tested | not tested | not tested | not tested | <0.1 | <0.1 | <0.1 | <0.1 |

| Ratios of Media Capacity to Clogging Period | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|
| Phosphate | Washout | Washout | Flush | >0.4 | >1.5 | <0.1 | <0.1 | Washout | Washout | Washout |
| Potassium, Filtered | Washout | <0.1 | Washout | <0.1 | Washout | Washout | Washout | Washout | Washout | Washout |
| Potassium, Total | Washout | Washout | Washout | >0.1 | Washout | Washout | Washout | Washout | Washout | Washout |
| Sodium, filtered | <0.1 | Washout | Washout | <0.1 | Washout | <0.1 | Washout | Washout | Washout | Washout |
| Sodium, Total | Washout | Washout | Washout | Washout | Washout | <0.1 | Washout | Washout | Washout | Washout |
| Thallium, Filtered | >53 | >87 | >66 | >65 | >150 | >43 | >79 | >62 | >46 | >56 |
| Thallium, Total | >69 | >120 | >70 | >93 | >180 | >45 | >88 | >79 | >60 | >70 |
| TN | >0.4 | <0.1 | 0.2 | <0.1 | <0.1 | <0.1 | Washout | >0.4 | >3.5 | Flush |
| TP | Washout | Flush | >0.1 | >0.1 | >0.3 | >0.1 | >0.1 | Washout | Washout | Washout |

Green cells indicate conditions where media chemical capacity (in years to failure) exceeds the expected clogging time period

Yellow cells are uncertain, and may have excess media capacity

Red cells indicate conditions where the media chemical capacity would likely be exceeded before the expected clogging period

These calculations are based on the full-depth column tests, which are similar to the expected depth of the media in the site filters. If the values indicated in the tables are much larger than 1, then it would be possible to use less material in the constructed filters, reflected as either smaller surface areas at the same depth or as shallower filters, or a combination of the two. However, that could cause effluent concentrations of other constituents to be exceeded before clogging. The red cells on the tables have ratios less than one and additional media could be used to increase the ratio values, such as by increasing the volumetric content of the medium providing the best removal for the pollutant of interest, or the media would need replacing before clogging occurred. Table 4-43 shows that the filters would clog before the removal capacity is exceeded for most media-critical pollutant combinations. The exceptions are for two test columns for oil and grease (R-SMZ and the layered media). The other two mixed media tests for oil and grease are uncertain, as the chemical capacity was not reached during the tests, but their failure ratios to >0.3, indicating that they had greater removal capacity than the R-SMZ and layered. This is expected since the R-SMZ-GAC, with and without PM, has a substantial organic-based content, which should provide good removal of organic pollutants. While the layered column was comprised of 1/3 GAC, it was not mixed and the flow rate through the GAC layer may have been too high to allow good removal of oil and grease. The gross alpha results also are unable to predict clogging versus capacity because the maximum capacities were not determined, as the influent concentrations were very low. Three of the total lead tests (SMZ, R-SMZ-GAC-PM and the layered media) also had uncertain predictive results for the same reason, but the ratios are quite high (>0.8), indicating that they are likely to have excess capacity when the filter clogs. None of these measurements indicated initial flushing or washout. The next set of constituents (Table 4-44) has many more uncertain results and likely premature failures, especially for sulfate and nitrate, plus some combinations showing initial flushing or washout. As expected, the third set of constituents of interest (Table 4-45) has many more premature capacity, initial flushing, and washout conditions. This is because most of the constituents associated with ion exchange are in this third group. As some constituents are removed from the water, ion exchange processes release others. This would be indicated by washout notations and by very low removal capacities.

In order to understand how these treatment capacities relate to site conditions, the following sections discuss how the main advanced treatment systems in the watersheds above Outfalls 008 and 009 compare to these data.

### 4.6.4 Site ENTS Designs and Maintenance Expected Requirements

#### *Site Hydrologic Factors*

The final draft *Hydrology Report* (Geosyntec Aug 2008) was reviewed to obtain information pertaining to the watersheds and associated flows expected in the drainage areas above Outfalls 008 and 009. The Outfall 008 watershed is comprised of 62 acres, and is primarily open space with no anthropogenic impervious surfaces (covered with chaparral and grassland vegetation, and bedrock outcrops). The soils are predominately associated with sedimentary rock land (88%) and Gaviota rocky sandy loam (12%), having a NRCS hydrologic soil group D. The Outfall 009 watershed has 536 acres, is primarily (90%) open space (chaparral and grassland vegetation, and bedrock outcrops) and developed areas (about 55 acres of buildings and other impervious surfaces and dirt roads). The soils are associated with sedimentary rock land (61%), Gaviota rocky sandy loam (32%) and Saugus sandy loam (7%), being predominately hydrologic soil group D.

Tables 4-46 and 4-47 summarize the drainage area and expected discharges to the advanced treatment systems (engineered natural treatment systems, or ENTS) that were originally proposed for the Outfall 008 and 009 watersheds, based on data from the *Hydrology Report*. Table 4-48 and 4-49 show the calculated annual unit area discharges to the sedimentation basin portions and to the biofilter portions of these treatment systems.

The water balance analysis presented in the *Hydrology Report* is based on a total rainfall depth of 928 inches (16 inches per year on average) recorded over the 58-year simulation period. For both Outfall 008 and 009 watersheds, the expected annual surface runoff is 17.9% of the rainfall total. As indicated in Table 4-50, the expected annual runoff is about 10,400 $ft^3$/acre (820,000 L/ha) for both watershed areas.

## Table 4-46. Initial Advanced Treatment Area Description (Outfall 009 Watershed) (Geosyntec 2008)

| ENTS ID | ENTS Type | Location | Drainage Area (ac) | Cumulative Drainage Area (ac) | Annual Discharge to ENTS ($ft^3$/year) |
|---|---|---|---|---|---|
| GC4 | Grade Control | Area I Building 402 | 9.3 | 9.3 | 96683 |
| TT5 | Treatment Train | Lower Parking Lot | 31.9 | 41.1 | 427276 |
| TT6 | Treatment Train | Sage Ranch Trail Head | 2.5 | 2.5 | 25990 |
| TT4 | Treatment Train | Area I landfill | 4.8 | 4.8 | 49901 |
| BIO7 | Bioretention | Roadway ENT | 3.9 | 3.9 | 40544 |
| TT3 | Treatment Train | LOX | 129.9 | 342.5 | 3560630 |
| BIO6 | Bioretention | Roadway ENT | 1.3 | 1.3 | 13515 |
| BIO5 | Bioswale | Area II Landfill | 5.9 | 5.9 | 61336 |
| GC3 | Grade Control | Area II Landfill | 2.6 | 2.6 | 27030 |
| GC2 | Grade Control | Area II Landfill | 2.8 | 2.8 | 29109 |
| BIO4 | Bioswale | Area II Landfill | 1.4 | 1.4 | 14554 |
| BIO2 | Bioswale | Ashpile | 5.7 | 5.7 | 59257 |
| BIO1 | Bioretention | Ashpile | 28.5 | 34.2 | 355543 |
| TT1 | Treatment Train | Fire Station | 9.7 | 9.7 | 100841 |
| TT2 | Treatment Train | Helipad | 3.5 | 3.5 | 36386 |
| BIO3 | Bioretention | Roadway ENT | 3.3 | 47.1 | 489652 |
| GC1 | Grade Control | Area 2 at Outfall 009 | 66.6 | 536.3 | 5575375 |

## Table 4-47. Initial Advanced Treatment Area Description (Outfall 008 Watershed) (Geosyntec 2008)

| ENTS ID | ENTS Type | Location | Drainage Area (ac) | Cumulative Drainage Area (ac) | Annual Discharge to ENTS (ft3/year) |
|---|---|---|---|---|---|
| TT7 | Treatment Train | Outfall 008 | 62.2 | 62.2 | 646631 |

**Table 4-48. Initial Treatment Train Details (Outfall 009 Watershed) (Geosyntec 2008)**

| ENTS ID | Location | Drainage Area (ac) | % Imperv. | Sed. Basin (ac-ft) | Biofilter ($ft^2$) | Annual Discharge ($ft^3$/yr) | Annual Discharge to Sed. Basin ($ft^3$/ac-ft) | Annual Loading to Biofilter ($ft^3/ft^2$) |
|---|---|---|---|---|---|---|---|---|
| TT6 | Sage Ranch Trail Head | 2.5 | 76 | FS/NA | 21,780 | 26,000 |  | 1.19 |
| TT5 | Lower Parking Lot | 31.9 | 42 | 4.5 | 24,588 | 333,000 | 73696 | 13.5 |
| TT4 | Area I Landfill | 4.8 | 76 | FS/NA | 7,800 | 50,000 |  | 6.40 |
| TT3 | LOX | 129.9 | 16 | 14 | 66,286 | 1,350,000 | 96460 | 20. 4 |
| TT1 | Fire Station | 9.7 | 45 | 0.95 | 5,558 | 100,000 | 106149 | 18.1 |
| TT2 | Helipad | 3.5 | 90 | 0.5 | 2,207 | 36,400 | 72772 | 16.5 |

**Table 4-49. Initial Treatment Train Details (Outfall 008 Watershed) (Geosyntec 2008)**

| ENTS ID | Location | Drainage Area (ac) | % Imperv. | Sed. Basin (ac-ft) | Biofilter ($ft^2$) | Annual Discharge ($ft^3$/yr) | Annual Discharge to Sed. Basin ($ft^3$/ac-ft) | Annual Loading to Biofilter ($ft^3/ft^2$) |
|---|---|---|---|---|---|---|---|---|
| TT7 | 3201 to 3200 | 62.2 | 12 | 4.28 | 15,000 | 650,000 | 150,000 | 43.1 |

**Table 4-50. Expected Annual Runoff from Outfall 008 and 009 Watersheds (Geosyntec 2008)**

| Area | Area (acres) | Annual Rainfall (inches) | Fraction of Annual Rainfall as Runoff | Annual Runoff (acre-ft) | Annual Runoff ($ft^3$) | Annual Runoff ($ft^3$/acre) |
|---|---|---|---|---|---|---|
| Outfall 8 watershed | 62 | 16 | 0.179 | 14.8 | 644,000 | 10,400 |
| Outfall 9 watershed | 536 | 16 | 0.179 | 127 | 5,570,000 | 10,400 |

This site hydrology information is used in the following discussions to calculate the expected unit area treatment capabilities for the different media options before the chemical removal capacity is exceeded. In addition, the expected maintenance intervals for the initial advanced treatment designs in both watershed areas are calculated.

### *Area Treated by Media Filtration*

The above information can be used to calculate the expected time before the biofiltration media capacity would be exceeded and therefore would need replacement. Table 4-51 summarizes these loading factors expressed as the area of the biofilter as a percentage of the drainage area, per year of operation before replacement. The constituents are arranged by category, with those that have been shown to exceed current benchmark limits at either Outfalls 008 or 009 first (the “A” category), followed by those constituents that are likely to exceed the benchmark limits with extended monitoring (the “B” category), and then the other constituents that have benchmark limits, or were evaluated due to their effects on the operation of the treatment device. Some of the constituents were not analyzed for all samples and these are indicated. Many did not indicate any breakthrough during the duration of the tests, so the loading factors are shown as “<” the value. As an example, total copper had a loading factor of 0.006% of the drainage area per year if using the layered media mixture. If the media is to be used for 10 years before replacement, then the biofilter surface area would need to be at least 0.06% of the drainage area. For a 10 acre drainage area (435,600 $ft^2$), the biofilter surface area would therefore need to be at least 261 $ft^2$ in area. The gross beta loading factor for the rhyolite sand-surface modified zeolite-granular activated carbon (R-SMZ-GAC) mixture is 1.1%. For the same desired 10 year life and 10 acre drainage area, the biofilter area would need to be at least 47,900 $ft^2$ in area, or more than an acre, or about 10% of the total drainage area. The advanced treatment systems would be assumed to have the same vertical dimensions and media amounts as the full-depth test columns. This information then is used to demonstrate the chemical capacity for the initial advanced treatment system designs included in the Outfall 008 and 009 watersheds.

## Table 4-51. Percentage of Drainage Area per Year of Operation before Chemical Capacity Would Be Exceeded

| Constituent | Constituent Category* | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium, Total | A | <0.000075 | <0.000077 | <0.000067 | <0.00020 | <0.000059 | <0.000064 | <0.000064 | <0.000064 | <0.000061 | <0.000084 |
| Copper, Total | A | <0.0050 | <0.00550 | <0.0064 | <0.017 | <0.0055 | <0.0060 | <0.0066 | <0.0043 | <0.0045 | 0.006 |
| Gross Alpha radioactivity | A | not analyzed | not analyzed | not analyzed | not analyzed | not analyzed | not analyzed | <0.052 | <0.049 | <0.046 | <0.066 |
| Lead, Total | A | <0.034 | <0.035 | <0.031 | <0.089 | <0.026 | <0.030 | <0.029 | <0.029 | <0.027 | <0.039 |
| Mercury | A | not analyzed | not analyzed | not analyzed | not analyzed | not analyzed | not analyzed | <0.000080 | <0.000066 | <0.000062 | <0.000087 |
| Oil and Grease | A | not analyzed | not analyzed | not analyzed | not analyzed | not analyzed | not analyzed | 0.05 | 0.025 | 0.024 | n/a |
| TCDD | A | not analyzed | not analyzed | not analyzed | not analyzed | not analyzed | not analyzed | <0.00065 | <0.00061 | <0.00061 | <0.00080 |
| Antimony, Total | B | <0.00059 | <0.00043 | 0.002 | <0.0015 | <0.00060 | 0.003 | 0.001 | <0.00055 | 0.001 | 0.002 |
| Gross Beta radioactivity | B | not analyzed | not analyzed | not analyzed | not analyzed | not analyzed | not analyzed | <0.34 | 1.1 | 0.23 | <0.28 |
| Iron, Total | B | <0.050 |  |  | <0.15 | <0.040 | <0.044 | <0.046 | <0.044 | <0.041 | <0.056 |
| Manganese, Total | B | <9.6 |  |  | <33 | <8.1 | <8.4 | <9.1 | <8.5 | <9.3 | <10 |
| Nitrate | B | <0.043 | 7.6 | 0.92 | <1.2 | <4.7 | <1.5 | <1.1 | <0.065 | <0.069 | <0.061 |
| Radium 226+228 | B | not analyzed | not analyzed | not analyzed | not analyzed | not analyzed | not analyzed | <0.049 | 0.052 | <0.038 | <0.059 |
| Sulfate | B | 0.14 |  | 1.5 | <1.1 | 0.95 | 0.56 | 0.43 | <0.096 | 0.52 | <0.089 |
| Zinc, Total | B |  |  |  | <0.19 | <0.062 | <0.061 | <0.062 |  | 0.15 | <0.11 |
| Aluminum, Filtered |  | <0.031 |  | 0.22 | 0.19 | 1.0 | 0.35 | 0.58 | <0.030 | 0.36 | 1.2 |
| Aluminum, Total |  | <0.0010 |  |  | <0.0029 | <0.00080 | <0.00087 | <0.0010 | <0.00092 | <0.00083 | <0.0011 |
| Ammonia |  | <0.024 | 0.38 | <0.022 | <1.4 | <0.018 | <0.019 | <0.019 | <0.019 | <0.018 | <0.026 |
| Antimony, Filtered |  | <0.0010 | <0.00066 | 0.002 | 0.003 | 0.002 | 0.003 | 0.002 | 0.002 | <0.00087 | <0.0014 |
| Arsenic, Filtered |  | <0.0054 |  | 0.008 | 0.014 | <0.0048 | <0.0083 | <0.013 | <0.0054 | <0.0060 | <0.0069 |
| Arsenic, Total |  | <0.014 | <0.016 | 0.017 | <0.034 | <0.013 | <0.019 | <0.023 | <0.012 | <0.013 | <0.016 |
| Boron, Filtered |  | <0.053 | 0.19 |  | 0.41 | 0.72 |  | 0.18 | <0.046 | <0.042 | <0.060 |
| Boron, Total |  |  | 0.43 |  | 0.52 |  | 0.28 | 0.19 | <0.060 | 0.013 | 0.20 |
| Cadmium, Filtered |  |  | <0.00014 | <0.00012 | <0.00037 | <0.00011 | <0.00012 | <0.00012 | <0.00012 | <0.00011 | <0.00015 |
| Calcium, Filtered |  | 0.46 | <0.010 | 0.67 | 1.8 | 0.47 | 1.2 | 0.68 | 0.68 | 0.39 | 0.64 |
| Calcium, Total |  | 0.55 | 0.13 | 1.6 | 2.0 | 0.79 | 1.4 | 0.77 | 0.75 | 0.40 | 0.97 |
| Chloride |  | 10 |  |  |  |  |  |  |  | 4.9 |  |
| Chromium, Filtered |  | <0.019 | <0.024 | 0.24 | 0.31 | <2.9 | <0.37 | <14 | <0.018 | <0.023 | 0.022 |

| Constituent | Constituent Category* | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Chromium, Total |  | <0.0098 | <0.011 | <0.014 | <0.035 | <0.011 | <0.012 | <0.016 | <0.0087 | <0.0088 | <0.011 |
| COD |  | <0.073 |  | <0.79 | <0.36 | <0.064 | <0.091 | <0.080 | <0.061 | <0.060 | <0.079 |
| Copper, Filtered |  | <0.013 | <0.020 | 0.11 | 0.16 | <0.032 |  |  | <0.012 | <0.016 | <0.016 |
| Fluoride |  | 0.11 | <0.035 | 0.087 | 0.21 | 0.064 | 0.13 | 0.10 | 0.11 | 0.094 | 0.11 |
| Hardness |  | 1.6 | <1.5 | 5.5 | 27 | 0.46 | 24 | 5,600 | 4.2 | 0.63 | 2.1 |
| Iron, Filtered |  | <0.90 |  |  | <5.6 |  |  |  | <1.0 |  | <1.2 |
| Magnesium, Filtered |  | 54 | 26 |  |  | <0.43 |  |  |  |  | 3.0 |
| Magnesium, Total |  | 29 |  |  |  | <0.47 |  |  | 180 | 44 | 3.8 |
| Manganese, filtered |  | <83 |  |  |  | <170 |  |  | <74 |  | <97 |
| Nickel, Filtered |  | <0.0049 | <0.0054 | <0.0051 | 0.020 | <0.0058 | <0.0044 | <0.0053 | <0.0051 | <0.0042 | <0.0061 |
| Nickel, Total |  | <0.015 | <0.016 | <0.014 | <0.041 | <0.013 | <0.013 | <0.013 | <0.012 | <0.012 | <0.016 |
| Nitrite |  | 5.9 |  |  | 67 | 4.5 | 5.9 | 55 | 2.1 | 4.4 | 1.2 |
| Phosphate |  |  |  |  | <0.10 | <0.016 | <0.72 | <2.0 |  |  |  |
| Potassium, Filtered |  |  | 20 |  | 42 |  |  |  |  |  |  |
| Potassium, Total |  |  |  |  | <0.84 |  |  |  |  |  |  |
| Sodium, filtered |  | 5.1 |  |  | 3.9 |  | 3.9 |  |  |  |  |
| Sodium, Total |  |  |  |  |  |  | 22 |  |  |  |  |
| Thallium, Filtered |  | <0.00020 | <0.00024 | <0.00018 | <0.00064 | <0.00017 | <0.00017 | <0.00018 | <0.00017 | <0.00017 | <0.00022 |
| Thallium, Total |  | <0.00016 | <0.00018 | <0.00017 | <0.00045 | <0.00013 | <0.00016 | <0.00016 | <0.00014 | <0.00013 | <0.00018 |
| TN |  | <0.026 | 1.313 | 0.069 | 2.232 | <0.77 | <0.95 |  | <0.026 | <0.022 |  |
| TP |  |  |  | <0.091 | <0.35 | <0.071 | <0.11 | <0.10 |  |  |  |

* "A" are constituents that have exceeded current benchmark limits at Outfall 008 or 009. "B" are constituents that have a possible likelihood of exceeding benchmark limits at Outfall 008 or 009 during extended future monitoring.

***Site Maintenance Intervals for Proposed Advanced Treatment Systems***

This section summarizes the calculated durations for the initial designs of the advanced treatment systems (ENTS) for the Outfall 008 and 009 watersheds based on the chemical and clogging capacities calculated/demonstrated during the testing of the full-depth columns. These are compared (by color-coding) to an expected ten year desired life of the devices before media replacement or decommissioning. The red combinations would have the chemical capacities exceeded before ten years, while the green combinations would have an expected operation life beyond ten years. The yellow cells indicate combinations where the expected durations are uncertain, but are possible to have at least a ten year operational lifetime. Each table has the constituents sorted, with those that have exceeded the current benchmark limits in the associated outfall listed first, then those that may exceed the benchmark limits with extended monitoring, and then the other constituents of interest. The tables associated with each ENT are listed in Table 4-52.

**Table 4-52. Table Directory for Each ENT Evaluation**

| Outfall Watershed | ENTS | Table number |
|---|---|---|
| Outfall 008 | TT7 | Table 4-53 |
| Outfall 009 | TT6 | Table 4-54 |
| Outfall 009 | TT5 | Table 4-55 |
| Outfall 009 | TT4 | Table 4-56 |
| Outfall 009 | TT3 | Table 4-57 |
| Outfall 009 | TT1 | Table 4-58 |
| Outfall 009 | TT2 | Table 4-59 |

The drainage areas and the sizes of the treatment systems were described previously. As shown on these tables, all of the media combinations would likely have an operational life of at least 10 years for the constituents of greatest concern (those that have exceeded the current benchmark values), with the exception of oil and grease for the layered media, and potentially a slightly shorter service life for the oil and grease for the rhyolite sand-surface modified zeolite combination. The ENTS at Outfall 008 also has a potentially shorter service life (>7 years) for lead for the site sand medium. There are more potential service life problems with the second set of constituents that may show exceedences with extended monitoring. Gross beta radioactivity and nitrate may have service lives less than 10 years for some media in the watershed 008 ENTS and for sulfate, radium 226+228, and zinc for some media for the watershed 009 ENTS. There are many other calculated service lives shorter than 10 years for other constituents, but they are not likely to exceed the benchmark limits, and many of the major ions monitored were measured not for removal, but as exchange ions.

The most robust media, as far as service life is concerned based on these full-depth column tests, were the mixed media, especially those having the largest variety of materials (R-SMZ-GAC; R-SMZ-GAC-PM; and site sand-GAC-site zeolite). The R-SMZ-GAC-PM mixture was slightly more consistent in the service life expectations. The site sand-GAC-site zeolite combination was tested as a layered combination and may perform better if mixed rather than separated by layer because the contact time with the zeolite and GAC media then would be greater. It is important that mixtures be used to treatment to provide redundancy in removal for likely varying conditions. Also, the treatment capacity and uptake values for these tests are for relatively higher concentrations compared to the benchmark permit limits. As the concentrations approach the low permit limits, the effectiveness of some of the media decrease. Having combinations of media in the treatment mixture, these problems are minimized.

## Table 4-53. Expected Maintenance to Replace Media before the 10-Year Life of the Site Advanced Treatment Systems (008 Watershed TT7)

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Copper, Total | A | 0.005 | >130 | >110 | >970 | >37 | >110 | >100 | >940 | >140 | >140 | 110.0 |
| TCDD | A | 1E-12 | | | | | | | >970 | >1000 | >1000 | >780 |
| Lead, Total | A | 0.003 | >18 | >18 | >20 | >7.0 | >24 | >21 | >22 | >22 | >23 | >16 |
| Mercury | A | 0.00004 | | | | | | | >7800 | >9400 | >10,000 | >7200 |
| Cadmium, Total | B | 0.00004 | >8300 | >8100 | >9300 | >3200 | >11,000 | >9700 | >9700 | >9820 | >10,000 | >7400 |
| Iron, Total | B | 2 | >12 | | | >4.3 | >15 | >14 | >130 | >140 | >15 | >11 |
| Gross Beta radioactivity | B | 5 | | | | | | | >1.8 | 0.6 | 2.8 | >2.3 |
| Manganese, Total | B | 5 | >0.065 | | | >0.0190 | >0.077 | >0.074 | >0.069 | >0.074 | >0.067 | >0.060 |
| Nitrate | B | 2 | >14 | 0.1 | 0.7 | >0.51 | >0.14 | >0.43 | >0.550 | >9.6 | >9.1 | >10 |
| Radium 226+228 | B | 0.08 | | | | | | | >13 | 12.0 | >16 | >11 |
| Aluminum, Filtered | | 0.01 | >20 | | 2.8 | 3.4 | 0.6 | 1.8 | 1.1 | >21 | 1.7 | 0.5 |
| Aluminum, Total | | 0.05 | >620 | | | >210 | >780 | >710 | >620 | >680 | >750 | >560 |
| Ammonia | | 0.5 | >26 | 1.7 | >28 | >0.44 | >34 | >32 | >33 | >34 | >36 | >24 |
| Antimony, Filtered | | 0.00025 | >600 | >940 | 270 | 200.0 | 350.0 | 200.0 | 340.0 | 280.0 | >720 | >450 |
| Antimony, Total | | 0.0002 | >1100 | >1500 | 260.0 | >400 | >1000 | 220.0 | 480.0 | >1100 | 610.0 | 300.0 |
| Arsenic, Filtered | | 0.001 | >120 | | 78.0 | 43.3 | >130 | >75 | >50 | >120 | >100 | >91 |
| Arsenic, Total | | 0.005 | >46 | >39 | 36.0 | >19 | >50 | >330 | >28 | >50 | >48 | >38 |
| Boron, Filtered | | 0.05 | >12 | 3.3 | | 1.5 | 0.9 | | 3.5 | >14 | >15 | >10 |
| Boron, Total | | 0.06 | | 1.4 | | 1.2 | | 2.3 | 3.3 | >100 | 50.0 | 3.1 |
| Cadmium, Filtered | | 0.00003 | >4600 | >4400 | >5100 | >1700 | >5600 | >5300 | >5300 | >5400 | >5800 | >4100 |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Calcium, Filtered | | 15 | 1.4 | >6.3 | 0.9 | 0.4 | 1.3 | 0.5 | 0.9 | 0.9 | 1.6 | 1.0 |
| Calcium, Total | | 20 | 1.1 | 4.8 | 0.4 | 0.3 | 0.8 | 0.4 | 0.8 | 0.8 | 1.6 | 0.6 |
| Chloride | | 9 | 0.1 | | | | | | | | 0.1 | |
| Chromium, Filtered | | 0.002 | >34 | >26 | 2.6 | 2.0 | >0.22 | >1.7 | >0.046 | >35 | >270 | 27.8 |
| Chromium, Total | | 0.005 | >64 | >56 | >44 | >18 | >58 | >53 | >38 | >72 | >71 | >55 |
| COD | | 40 | >8.5 | | >0.79 | >1.7 | >9.8 | >6.9 | >7.8 | >100 | >10 | >7.9 |
| Copper, Filtered | | 0.004 | >49 | >31 | 5.5 | 3.9 | >19 | | | >51 | >40 | >38 |
| Fluoride | | 0.25 | 5.7 | >18 | 7.2 | 3.0 | 9.8 | 4.9 | 6.3 | 5.9 | 6.7 | 5.7 |
| Gross Alpha radioactivity | | 2 | | | | | | | >12 | >13 | >14 | >9.5 |
| Hardness | | 50 | 0.4 | >0.41 | 0.1 | 0.0 | 1.3 | 0.0 | 0.0 | 0.1 | 1.0 | 0.3 |
| Iron, Filtered | | 0.4 | >0.70 | | | >0.11 | | 0.0 | 0.0 | >0.640 | | >0.54 |
| Magnesium, Total | | 10 | 0.0 | | | | >1.30 | | | 0.0 | 0.0 | 0.2 |
| Magnesium, Filtered | | 5 | 0.0 | 0.0 | | | >1.5 | | | | | 0.2 |
| Manganese, filtered | | 2 | >0.0075 | | | | >0.0037 | | | >0.0085 | | >0.0064 |
| Nickel, Filtered | | 0.001 | >130 | >120 | >120 | 31.7 | >110 | >140 | >120 | >120 | >150 | >100 |
| Nickel, Total | | 0.006 | >42 | >39 | >430 | >150 | >48 | >49 | >47 | >50 | >51 | >38 |
| Nitrite | | 0.1 | 0.1 | | | 0.0 | 0.1 | 0.1 | 0.0 | 0.3 | 0.1 | 0.5 |
| Oil and Grease | | 0.1 | | | | | | | 12.7 | 24.7 | 26.4 | 0.0 |
| Perchlorate | | 0.0006 | | | | | | | 0.0 | 0.0 | 0.0 | 0.0 |
| Phosphate | | 0.1 | | | | >6.1 | >39 | >0.87 | >0.31 | | | |
| Potassium, Filtered | | 1 | | 0.0 | | 0.0 | | | | | | |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Potassium, Total | | 2 | | | | >0.74 | | | | | | |
| Sodium, filtered | | 15 | 0.1 | | | 0.2 | | 0.2 | | | | |
| Sodium, Total | | 20 | | | | | | 0.0 | | | | |
| Sulfate | | 8 | 4.4 | | 0.4 | >0.59 | 0.7 | 1.1 | 1.5 | >6.5 | 1.2 | >7.0 |
| Thallium, Filtered | | 0.0001 | >3100 | >2600 | >3500 | >980 | >3800 | >3600 | >3400 | >3600 | >3700 | >2800 |
| Thallium, Total | | 0.0001 | >4000 | >3500 | >3700 | >1400 | >4700 | >3800 | >3800 | >4600 | >4800 | >3500 |
| TN | | 2 | >24 | 0.5 | 9.0 | 0.3 | >0.81 | >0.66 | >0 | >24 | >280 | |
| TP | | 0.35 | | | >6.9 | >1.8 | >8.8 | >5.7 | >6.3 | | | |
| Zinc, Total | | 0.02 | | | | >3.4 | >10 | >10 | >10 | | 4.1 | >5.9 |

* “A” are constituents that have exceeded current benchmark limits at Outfall 008. “B” are constituents that have a possible likelihood of exceeding benchmark limits at Outfall 008 during extended future monitoring

red: capacity exceeded before 10 years
green: capacity exceeded after 10 years
yellow: uncertain if capacity exceeded before or after 10 years

### Table 4-54. Expected Maintenance to Replace Media before the 10-Year Life of the Site Advanced Treatment Systems (009 Watershed TT6)

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium, Total | A | 0.00004 | >300,000 | >290,000 | >340,000 | >110,000 | >380,000 | >350,000 | >350,000 | >350,000 | >370,000 | >270,000 |
| Copper, Total | A | 0.005 | >4500 | >4100 | >3500 | >1300 | >4000 | >3800 | >3400 | >5200 | >5000 | 4000 |
| TCDD | A | 1E-11 | | | | | | | >3500 | >3700 | >3700 | >2800 |
| Gross Alpha radioactivity | A | 1 | | | | | | | >870 | >930 | >980 | >680 |
| Lead, Total | A | 0.001 | >2000 | >1900 | >2200 | >760 | >2600 | >2300 | >2900 | >2400 | >2500 | >1700 |
| Mercury | A | 0.00004 | | | | | | | >280,000 | >340,000 | >370,000 | >260,000 |
| Oil and Grease | A | 0.4 | | | | | | | 115 | 223 | 239 | 0 |
| Antimony, Total | B | 0.00041 | >19,000 | >25,000 | 4513 | >7100 | >18,000 | 3836 | 8450 | >20,000 | 11000 | 5300 |
| Iron, Total | B | 2 | >450 | | | >150 | >560 | >510 | >490 | >520 | >550 | >400 |
| Manganese, Total | B | 5 | >2.4 | | | >0.69 | >2.8 | >2.7 | >2.5 | >2.7 | >2.4 | >2.2 |
| Radium 226+228 | B | 0.08 | | | | | | | >37 | 35 | >47 | >31 |
| Sulfate | B | 25 | 51 | | 5 | >6.8 | 8 | 13 | 17 | >750 | 14 | >810 |
| Zinc, Total | B | 0.03 | | | | >81 | >240 | >250 | >240 | | 99 | >140 |
| Aluminum, Filtered | | 0.01 | >730 | | 102 | 122 | 23 | 65 | 39 | >740 | 63 | 19 |
| Aluminum, Total | | 0.05 | >22,000 | | | >7700 | >28,000 | >26,000 | >22,000 | >24,000 | >27,000 | >20,000 |
| Ammonia | | 0.5 | >930 | 60 | >1000 | >16 | >1200 | >1200 | >1200 | >1200 | >1300 | >870 |
| Antimony, Filtered | | 0.00065 | >8300 | >13,000 | 3807 | 2800 | 4900 | 2855 | 4695 | 3845 | >9900 | >6300 |
| Arsenic, Filtered | | 0.001 | >4200 | | 2805 | 1564 | >4700 | >2700 | >1800 | >4200 | >3700 | >3300 |
| Arsenic, Total | | 0.005 | >1700 | >1400 | 1298 | >670 | >1800 | >1200 | >1000 | >1800 | >1700 | >1400 |
| Boron, Filtered | | 0.05 | >420 | 119 | | 55 | 32 | | 127 | >490 | >530 | >380 |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boron, Total | | 0.07 | | 45 | | 37 | | 70 | 102 | >320 | 1532 | 97 |
| Cadmium, Filtered | | 0.00003 | >165,000 | >160,000 | >180,000 | >61,000 | >200,000 | >190,000 | >190,000 | >200,000 | >210,000 | >150,000 |
| Calcium, Filtered | | 15 | 49 | >230 | 34 | 13 | 48 | 19 | 33 | 33 | 58 | 35 |
| Calcium, Total | | 20 | 41 | 172 | 14 | 11 | 28 | 16 | 29 | 30 | 57 | 23 |
| Chloride | | 10 | 2 | | | | | | | | 4 | |
| Chromium, Filtered | | 0.002 | >1200 | >940 | 93 | 72 | >7.9 | >60 | >1.7 | >1200 | >990 | 1005 |
| Chromium, Total | | 0.005 | >2300 | >2000 | >1600 | >640 | >2100 | >1900 | >1400 | >2600 | >2600 | >2000 |
| COD | | 40 | >310 | | >29 | >630 | >350 | >250 | >280 | >3700 | >380 | >290 |
| Copper, Filtered | | 0.003 | >2400 | >1500 | 266 | 190 | >930 | | | >2500 | >1900 | >1800 |
| Fluoride | | 0.25 | 210 | >650 | 260 | 109 | 354 | 176 | 227 | 213 | 241 | 200 |
| Gross Beta radioactivity | | 3 | | | | | | | >330 | 105 | 500 | >410 |
| Hardness | | 50 | 14 | >15 | 4 | 1 | 49 | 1 | 0 | 5 | 36 | 11 |
| Iron, Filtered | | 0.4 | >25 | | | >4.0 | | >0 | >0 | >23 | | >19 |
| Magnesium, Filtered | | 5 | 0 | 1 | | | >52 | | | | | 8 |
| Magnesium, Total | | 10 | 1 | | | | >47 | | | 0 | 1 | 6 |
| Manganese, filtered | | 2 | >0.270 | | | | >0.13 | | | >0.31 | | >0.23 |
| Nickel, Filtered | | 0.001 | >4600 | >4200 | >4500 | 1100 | >3900 | >5200 | >4300 | 500454 | >5400 | >3700 |
| Nickel, Total | | 0.002 | >4600 | >4200 | >4700 | >1700 | >5200 | >5300 | >5100 | >5400 | >5500 | >4100 |
| Nitrate | | 0.7 | >1500 | 8 | 70 | >52 | >14 | >44 | >57 | >990 | >940 | >1000 |
| Nitrite | | 0.1 | 4 | | | 0 | 5 | 4 | 0 | 11 | 5 | 19 |
| Phosphate | | 0.1 | | | | >220 | >1400 | >310 | >11 | | | |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Potassium, Filtered | | 1 | | 1 | | 1 | | | | | | |
| Potassium, Total | | 2 | | | | >27 | | | | | | |
| Sodium, filtered | | 15 | 4 | | | 6 | | 6 | | | | |
| Sodium, Total | | 20 | | | | | | 1 | | | | |
| Thallium, Filtered | | 0.0001 | >110,000 | >95,000 | >125,000 | >35,000 | >140,000 | >130,000 | >120,000 | >130,000 | >130,000 | >100,000 |
| Thallium, Total | | 0.0001 | >140,000 | >130,000 | >130,000 | >50,000 | >170,000 | >140,000 | >140,000 | >170,000 | >170,000 | >130,000 |
| TN | | 2 | >870 | 17 | 326 | 10 | >290 | >24 | | >850 | >1000 | |
| TP | | 0.35 | | | >250 | >66 | >320 | >200 | >230 | | | |

* "A" are constituents that have exceeded current benchmark limits at Outfall 009. "B" are constituents that have a possible likelihood of exceeding benchmark limits at Outfall 009 during extended future monitoring

red: capacity exceeded before 10 years
green: capacity exceeded after 10 years
yellow: uncertain if capacity exceeded before or after 10 years

## Table 4-55. Expected Maintenance to Replace Media before 10-Year Life of Site Advanced Treatment Systems (009 Watershed TT5)

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium, Total | A | 0.00004 | >27,000 | >26,000 | >30,000 | >10,000 | >34,000 | >31,000 | >31,000 | >31,000 | >33,000 | >24,000 |
| Copper, Total | A | 0.005 | >400 | >360 | >310 | >120 | >3600 | >330 | >3000 | >460 | >440 | 350.77 |
| TCDD | A | 1E-11 | | | | | | | >310 | >330 | >330 | >250 |
| Gross Alpha radioactivity | A | 1 | | | | | | | >77 | >82 | >870 | >61 |
| Lead, Total | A | 0.001 | >180 | >170 | >200 | >67 | >230 | >200 | >210 | >210 | >220 | >150 |
| Mercury | A | 0.00004 | | | | | | | >25,000 | >30,000 | >32,000 | >23,000 |
| Oil and Grease | A | 0.4 | | | | | | | 10.16 | 19.70 | 21.10 | 0.00 |
| Iron, Total | B | 2 | >40 | | | >14 | >50 | >45 | >43 | >46 | >49 | >36 |
| Manganese, Total | B | 5 | >0.21 | | | >0.061 | >0.25 | >0.24 | >0.22 | >0.23 | >0.21 | >0.19 |
| Radium 226+228 | B | 0.08 | | | | | | | >3.3 | 3.06 | >4.2 | >2.7 |
| Sulfate | B | 25 | 4.49 | | 0.43 | >0.60 | 0.68 | 1.14 | 1.50 | >6.6 | 1.23 | >7.2 |
| Zinc, Total | B | 0.03 | | | | >7.2 | >210 | >22 | >21 | | 8.76 | >12 |
| Aluminum, Filtered | | 0.01 | >61 | | 9.00 | 10.78 | 1.99 | 5.72 | 3.43 | >66 | 5.57 | 1.69 |
| Aluminum, Total | | 0.05 | >2000 | | | >680 | >2500 | >2300 | >2000 | >2200 | >2400 | >1800 |
| Ammonia | | 0.5 | >820 | 5.30 | >89 | >1.4 | >110 | >100 | >100 | >110 | >110 | >77 |
| Antimony, Filtered | | 0.00065 | >730 | >1200 | 340.00 | 244.37 | 434.11 | 250.00 | 415.40 | 340.18 | >880 | >560 |
| Arsenic, Filtered | | 0.001 | >370 | | 250.00 | 138.41 | >420 | >240 | >160 | >370 | >330 | >290 |
| Arsenic, Total | | 0.005 | >150 | >130 | 110.00 | >590 | >160 | >110 | >89 | >160 | >150 | >120 |
| Boron, Filtered | | 0.05 | >370 | 10.56 | | 4.86 | 2.79 | | 11.24 | >44 | >470 | >33 |
| Boron, Total | | 0.07 | | 3.96 | | 3.26 | | 6.22 | 9.03 | >28 | 135.55 | 8.58 |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium, Filtered | | 0.00003 | >15,000 | >14,000 | >16,000 | >5400 | >18,000 | >17,000 | >17,000 | >17,000 | >18,000 | >13,000 |
| Calcium, Filtered | | 15 | 4.36 | >20 | 3.00 | 1.12 | 4.27 | 1.70 | 2.95 | 2.92 | 5.12 | 3.11 |
| Calcium, Total | | 20 | 3.65 | 15.20 | 1.20 | 0.99 | 2.52 | 1.41 | 2.59 | 2.68 | 5.01 | 2.06 |
| Chloride | | 10 | 0.17 | | | | | | | | 0.37 | |
| Chromium, Filtered | | 0.002 | >110 | >83 | 8.30 | 6.39 | >0.70 | >5.4 | >0.15 | >110 | >88 | 88.91 |
| Chromium, Total | | 0.005 | >200 | >180 | >140 | >57 | >190 | >1700 | >120 | >230 | >230 | >180 |
| COD | | 40 | >270 | | >2.5 | >5.6 | >310 | >220 | >25 | >33 | >34 | >25 |
| Copper, Filtered | | 0.003 | >210 | >130 | 23.51 | 17.00 | >82 | | | >220 | >170 | >160 |
| Fluoride | | 0.25 | 18.20 | >58 | 22.96 | 9.64 | 31.33 | 15.57 | 20.04 | 18.88 | 21.31 | 18.20 |
| Gross Beta radioactivity | | 3 | | | | | | | >290 | 9.32 | 44.27 | >36 |
| Hardness | | 50 | 1.27 | >1.3 | 0.37 | 0.07 | 4.30 | 0.08 | 0.00 | 0.48 | 3.15 | 0.94 |
| Iron, Filtered | | 0.4 | >2.2 | | | >0.350 | | >0 | >0 | >2.1 | 0.00 | >1.7 |
| Lead, filtered | | 0.0002 | | | | | | | | | | |
| Magnesium, Filtered | | 5 | 0.04 | 0.08 | | | >4.60 | | | | | 0.68 |
| Magnesium, Total | | 10 | 0.07 | | | | >4.20 | | Rhyolite Sand | 0.01 | 0.05 | 0.53 |
| Manganese, filtered | | 2 | >0.024 | | | | >0.012 | | | >0.027 | | >0.021 |
| Nickel, Filtered | | 0.001 | >400 | >370 | >390 | 101.44 | >340 | >460 | >380 | >390 | >480 | >330 |
| Nickel, Total | | 0.002 | >410 | >370 | >420 | >150 | >460 | >470 | >450 | >480 | >490 | >360 |
| Nitrate | | 0.7 | >130 | 0.75 | 6.19 | >4.60 | >1.20 | >3.9 | >5.00 | >870 | >83 | >93 |
| Nitrite | | 0.1 | 0.34 | | | 0.03 | 0.45 | 0.34 | 0.04 | 0.94 | 0.45 | 1.64 |
| Phosphate | | 0.1 | | | | >20 | >130 | >2.8 | >0.98 | | | |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Potassium, Filtered | | 1 | | 0.10 | | 0.05 | | | | | | |
| Potassium, Total | | 2 | | | | >2.4 | | | | | | |
| Sodium, filtered | | 15 | 0.39 | | | 0.51 | | 0.50 | | | | |
| Sodium, Total | | 20 | | | | | | 0.09 | | | | |
| Thallium, Filtered | | 0.0001 | >9800 | >8400 | >11,000 | >3100 | >12,000 | >11,000 | >11,000 | >11,000 | >12,000 | >9000 |
| Thallium, Total | | 0.0001 | >13,000 | >11,000 | >12,000 | >4400 | >15,000 | >12,000 | >12,000 | >15,000 | >15,000 | >11,000 |
| TN | | 2 | >77 | 1.52 | 28.83 | 0.89 | >2.6 | >2.10 | | >75 | >97 | |
| TP | | 0.35 | | | >22 | >5.8 | >280 | >180 | >20 | | | |

* “A” are constituents that have exceeded current benchmark limits at Outfall 009. “B” are constituents that have a possible likelihood of exceeding benchmark limits at Outfall 009 during extended future monitoring

red: capacity exceeded before 10 years
green: capacity exceeded after 10 years
yellow: uncertain if capacity exceeded before or after 10 years

### Table 4-56. Expected Maintenance to Replace Media before 10-Year Life of Site Advanced Treatment Systems (009 Watershed TT4)

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium, Total | A | 0.00004 | >56,000 | >54,000 | >63,000 | >21,000 | >72,000 | >66,000 | >65,000 | >66,000 | >69,000 | >50000 |
| Copper, Total | A | 0.005 | >850 | >760 | >660 | >250 | >760 | >710 | >630 | >970 | >940 | 739.49 |
| TCDD | A | 1E-11 | | | | | | | >650 | >690 | >690 | >520 |
| Gross Alpha radioactivity | A | 1 | | | | | | | >160 | >170 | >180 | >130 |
| Lead, Total | A | 0.001 | >370 | >360 | >410 | >140 | >480 | >420 | >440 | >440 | >470 | >320 |
| Mercury | A | 0.00004 | | | | | | | >53,000 | >63,000 | >68,000 | >48,000 |
| Oil and Grease | A | 0.4 | | | | | | | 21.41 | 41.54 | 44.49 | 0.00 |
| Antimony, Total | B | 0.00041 | >3500 | >4800 | 841.78 | >1300 | >3400 | 715.45 | 1575.98 | >3800 | 2013.76 | 980.61 |
| Iron, Total | B | 2 | >84 | | | >29 | >100 | >96 | >91 | >96 | >100 | >75 |
| Manganese, Total | B | 5 | >0.44 | | | >0.13 | >0.52 | >0.50 | >0.46 | >0.50 | >0.45 | >0.40 |
| Radium 226+228 | B | 0.08 | | | | | | | >6.9 | 6.46 | >8.80 | >5.70 |
| Sulfate | B | 25 | 9.46 | | 0.91 | >1.3 | 1.42 | 2.40 | 3.16 | >14 | 2.58 | >15 |
| Zinc, Total | B | 0.03 | | | | >15 | >45 | >46 | >45 | | 18.46 | >26 |
| Aluminum, Filtered | | 0.01 | >140 | | 18.97 | 22.72 | 4.20 | 12.00 | 7.23 | >140 | 11.74 | 3.56 |
| Aluminum, Total | | 0.05 | >4200 | | | >1400 | >5300 | >4800 | >4200 | >4600 | >5000 | >3800 |
| Ammonia | | 0.5 | >170 | 11.18 | >190 | >3.0 | >230 | >220 | >220 | >230 | >240 | >160 |
| Antimony, Filtered | | 0.00065 | >1500 | >2400 | 710.06 | 515.19 | 915.19 | 532.54 | 880.00 | 720.00 | >1900 | >1200 |
| Arsenic, Filtered | | 0.001 | >780 | | 523.08 | 291.79 | >880 | >500 | >340 | >780 | >700 | >6100 |
| Arsenic, Total | | 0.005 | >310 | >260 | 242.05 | >130 | >330 | >230 | >190 | >340 | >320 | >260 |
| Boron, Filtered | | 0.05 | >79 | 22.26 | | 10.26 | 5.88 | | 23.69 | >92 | >990 | >700 |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boron, Total | | 0.07 | | 8.35 | | 6.88 | | 13.11 | 19.05 | >60 | 285.76 | 180.00 |
| Cadmium, Filtered | | 0.00003 | >30.000 | >30,000 | >34,000 | >11,000 | >38,000 | >35,000 | >35,000 | >36,000 | >39,000 | >27,000 |
| Calcium, Filtered | | 15 | 9.20 | >42 | 6.26 | 2.36 | 9.00 | 3.59 | 6.22 | 6.15 | 10.80 | 6.56 |
| Calcium, Total | | 20 | 7.69 | 32.05 | 2.62 | 2.09 | 5.31 | 2.97 | 5.46 | 5.64 | 10.56 | 4.33 |
| Chloride | | 10 | 0.37 | | | | | | | | 0.78 | |
| Chromium, Filtered | | 0.002 | >230 | >170 | 17.44 | 13.46 | >1.5 | >11 | >0.31 | >230 | >180 | 187.44 |
| Chromium, Total | | 0.005 | >430 | >380 | >290 | >120 | >390 | >360 | >260 | >480 | >480 | >370 |
| COD | | 40 | >57 | | >5.3 | >12 | >66 | >46 | >52 | >690 | >71 | >53 |
| Copper, Filtered | | 0.003 | >440 | >280 | 49.57 | 35.38 | >170 | 0.00 | | >460 | >350 | >340 |
| Fluoride | | 0.25 | 38.00 | >120 | 48.41 | 20.33 | 66.05 | 32.82 | 42.26 | 39.79 | 44.92 | 38.36 |
| Gross Beta radioactivity | | 3 | | | | | | | >62 | 19.64 | 93.33 | >76 |
| Hardness | | 50 | 2.69 | >2.7 | 0.77 | 0.15 | 9.06 | 0.18 | 0.00 | 1.01 | 6.64 | 1.98 |
| Iron, Filtered | | 0.4 | >4.7 | | | >0.75 | | >0 | >0 | >4.3 | | >3.6 |
| Lead, filtered | | 0.0002 | | | | | | | | | 0.00 | |
| Magnesium, Filtered | | 5 | 0.08 | 0.16 | | | >9.8 | | | | | 1.43 |
| Magnesium, Total | | 10 | 0.15 | | | | >8.9 | | | 0.02 | 0.10 | 1.12 |
| Manganese, filtered | | 2 | >0.051 | | | | >0.025 | | | >0.057 | | >0.043 |
| Nickel, Filtered | | 0.001 | >850 | >780 | >830 | 213.85 | >720 | >960 | >800 | >830 | >1000 | >690 |
| Nickel, Total | | 0.002 | >850 | >780 | >880 | >310 | >970 | >990 | >940 | >1000 | >1000 | >770 |
| Nitrate | | 0.7 | >280 | 1.58 | 13.04 | >9.7 | >2.6 | >8.2 | >11 | >180 | >180 | >200 |
| Nitrite | | 0.1 | 0.71 | | | 0.06 | 0.94 | 0.72 | 0.08 | 1.97 | 0.95 | 3.45 |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phosphate | | 0.1 | | | | 🟩 >41 | 🟩 >270 | 🟨 >5.8 | 🟨 >2.1 | | | |
| Potassium, Filtered | | 1 | | 🟥 0.21 | | 🟥 0.10 | | | | | | |
| Potassium, Total | | 2 | | | | 🟨 >5 | | | | | | |
| Sodium, filtered | | 15 | 🟥 0.82 | | | 🟥 1.07 | | 🟥 1.06 | | | | |
| Sodium, Total | | 20 | | | | | | 🟥 0.20 | | | | |
| Thallium, Filtered | | 0.0001 | 🟩 >20,000 | 🟩 >17,000 | 🟩 >23,000 | 🟩 >6600 | 🟩 >25,000 | 🟩 >24000 | 🟩 >23,000 | 🟩 >24,000 | 🟩 >25,000 | 🟩 >19,000 |
| Thallium, Total | | 0.0001 | 🟩 >26,000 | 🟩 >24,000 | 🟩 >25,000 | 🟩 >9300 | 🟩 >32,000 | 🟩 >26,000 | 🟩 >26,000 | 🟩 >31,000 | 🟩 >32,000 | 🟩 >24,000 |
| TN | | 2 | 🟩 >160 | 🟥 3.21 | 🟩 60.77 | 🟥 1.88 | 🟨 >5.4 | 🟨 >4.4 | | 🟩 >160 | 🟩 >190 | |
| TP | | 0.35 | | | 🟩 >460 | 🟩 >12 | 🟩 >59 | 🟩 >38 | 🟩 >43 | | | |

* “A” are constituents that have exceeded current benchmark limits at Outfall 009. “B” are constituents that have a possible likelihood of exceeding benchmark limits at Outfall 009 during extended future monitoring

red: capacity exceeded before 10 years
green: capacity exceeded after 10 years
yellow: uncertain if capacity exceeded before or after 10 years

## Table 4-57. Expected Maintenance to Replace Media before 10-Year Life of Site Advanced Treatment Systems (009 Watershed TT3)

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium, Total | A | 0.00004 | >1800 | >17,000 | >20,000 | >6700 | >22,000 | >20,000 | >20,000 | >21,000 | >22,000 | >16,000 |
| Copper, Total | A | 0.005 | >270 | >240 | >200 | >79 | >240 | >220 | >200 | >310 | >290 | 232.22 |
| TCDD | A | 1E-11 | | | | | | | >200 | >220 | >220 | >160 |
| Gross Alpha radioactivity | A | 1 | | | | | | | >51 | >540 | >58 | >400 |
| Lead, Total | A | 0.001 | >120 | >110 | >130 | >44 | >150 | >130 | >140 | >140 | >150 | >100 |
| Mercury | A | 0.00004 | | | | | | | >17,000 | >20,000 | >21,000 | >15,000 |
| Oil and Grease | A | 0.4 | | | | | | | 6.72 | 13.04 | 13.97 | 0.00 |
| Antimony, Total | B | 0.00041 | >1100 | >1500 | 264.34 | >420 | >1100 | 224.67 | 494.90 | >1200 | 632.37 | 307.94 |
| Iron, Total | B | 2 | >26 | | | >9.0 | >33 | >30 | >28 | >30 | >33 | >24 |
| Manganese, Total | B | 5 | >0.14 | | | >0.040 | >0.16 | >0.16 | >0.15 | >0.16 | >0.15 | >0.13 |
| Radium 226+228 | B | 0.08 | | | | | | | >2.2 | 2.03 | >2.8 | >1.80 |
| Sulfate | B | 25 | 2.97 | | 0.29 | >0.40 | 0.45 | 0.75 | 0.99 | >4.4 | 0.81 | >4.8 |
| Zinc, Total | B | 0.03 | | | | >4.8 | >14 | >14 | >14 | | 5.80 | >8.3 |
| Aluminum, Filtered | | 0.01 | >43 | | 5.96 | 7.13 | 1.32 | 3.78 | 2.27 | >43 | 3.69 | 1.12 |
| Aluminum, Total | | 0.05 | >1300 | | | >450 | >1600 | >1500 | >1300 | >1400 | >1600 | >1200 |
| Ammonia | | 0.5 | >540 | 3.51 | >59 | >0.93 | >73 | >68 | >69 | >71 | >75 | >51 |
| Antimony, Filtered | | 0.00065 | >490 | >770 | 222.98 | 160.00 | 287.39 | 170.00 | 275.00 | 225.21 | >580 | >370 |
| Arsenic, Filtered | | 0.001 | >250 | | 164.26 | 91.63 | >280 | >160 | >100 | >240 | >220 | >190 |
| Arsenic, Total | | 0.005 | >97 | >83 | 76.01 | >40 | >100 | >71 | >59 | >110 | >100 | >800 |
| Boron, Filtered | | 0.05 | >25 | 6.99 | | 3.22 | 1.85 | | 7.44 | >29 | >31 | >220 |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boron, Total | | 0.07 | | 2.62 | | 2.16 | | 4.12 | 5.98 | >19 | 89.74 | 5.68 |
| Cadmium, Filtered | | 0.00003 | >9700 | >9300 | >11,000 | >3600 | >12,000 | >11,000 | >11,000 | >11,000 | >12,000 | >8700 |
| Calcium, Filtered | | 15 | 2.89 | >13 | 1.96 | 0.74 | 2.83 | 1.13 | 1.95 | 1.93 | 3.39 | 2.06 |
| Calcium, Total | | 20 | 2.42 | 10.06 | 0.82 | 0.66 | 1.67 | 0.93 | 1.72 | 1.77 | 3.32 | 1.36 |
| Chloride | | 10 | 0.12 | | | | | | | | 0.24 | |
| Chromium, Filtered | | 0.002 | >710 | >55 | 5.48 | 4.23 | >0.46 | >3.5 | >0.097 | >73 | >58 | 58.86 |
| Chromium, Total | | 0.005 | >140 | >120 | >92 | >38 | >120 | >110 | >80 | >150 | >150 | >120 |
| COD | | 40 | >18 | | >1.7 | >4.0 | >21 | >15 | >16 | >22 | >22 | >17 |
| Copper, Filtered | | 0.003 | >140 | >86 | 15.57 | 11.11 | >54 | | | >140 | >110 | >110 |
| Fluoride | | 0.25 | 12.05 | >38 | 15.20 | 6.38 | 20.74 | 10.31 | 13.27 | 12.50 | 14.11 | 12.05 |
| Gross Beta radioactivity | | 3 | | | | | | | >190 | 6.17 | 29.31 | >24 |
| Hardness | | 50 | 0.84 | >0.86 | 0.24 | 0.05 | 2.84 | 0.06 | 0.00 | 0.32 | 2.08 | 0.62 |
| Iron, Filtered | | 0.4 | >1.5 | | | >0.23 | | >0 | >0 | >1.4 | | >1.1 |
| Lead, filtered | | 0.0002 | | | | | | | | | | 0.00 |
| Magnesium, Filtered | | 5 | 0.02 | 0.05 | | | >3.1 | | | | | 0.45 |
| Magnesium, Total | | 10 | 0.05 | | | | >2.8 | | | 0.01 | 0.03 | 0.35 |
| Manganese, filtered | | 2 | >0.016 | | | | >0.0078 | | | >0.018 | | >0.014 |
| Nickel, Filtered | | 0.001 | >270 | >240 | >2600 | 67.15 | >230 | >300 | >250 | >260 | >320 | >220 |
| Nickel, Total | | 0.002 | >270 | >250 | >280 | >97 | >300 | >310 | >300 | >320 | >320 | >240 |
| Nitrate | | 0.7 | >87 | 0.49 | 4.09 | >3.1 | >0.81 | >2.6 | >3.3 | >58 | >55 | >61 |
| Nitrite | | 0.1 | 0.22 | | | 0.02 | 0.30 | 0.23 | 0.02 | 0.62 | 0.30 | 1.08 |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phosphate | | 0.1 | | | | 🟩 >13 | 🟩 >83 | 🟨 >1.8 | 🟨 >0.65 | | | |
| Potassium, Filtered | | 1 | | 🟥 0.07 | | 🟥 0.03 | | | | | | |
| Potassium, Total | | 2 | | | | >1.6 | | | | | | |
| Sodium, filtered | | 15 | 🟥 0.26 | | | 🟥 0.33 | | 🟥 0.33 | | | | |
| Sodium, Total | | 20 | | | | | | 🟥 0.06 | | | | |
| Thallium, Filtered | | 0.0001 | 🟥 5.95 | 🟩 >5600 | 🟩 >7300 | 🟩 >2100 | 🟩 >8000 | 🟩 >7600 | 🟩 >7200 | 🟩 >7600 | 🟩 >7900 | 🟩 >6000 |
| Thallium, Total | | 0.0001 | 🟩 >8300 | 🟩 >7400 | 🟩 >7800 | 🟩 >2900 | 🟩 >10,000 | 🟩 >8000 | 🟩 >8100 | 🟩 >9800 | 🟩 >10,000 | 🟩 >7500 |
| TN | | 2 | 🟩 >510 | 🟥 1.01 | 🟩 19.08 | 🟥 0.59 | 🟨 >1.7 | 🟨 >1.4 | | 🟩 >50 | 🟩 >60 | |
| TP | | 0.35 | | | 🟩 >15 | 🟨 >3.80 | 🟩 >19 | 🟩 >12 | 🟩 >13 | | | |

* “A” are constituents that have exceeded current benchmark limits at Outfall 009. “B” are constituents that have a possible likelihood of exceeding benchmark limits at Outfall 009 during extended future monitoring

red: capacity exceeded before 10 years
green: capacity exceeded after 10 years
yellow: uncertain if capacity exceeded before or after 10 years

## Table 4-58. Expected Maintenance to Replace Media before 10-Year Life of Site Advanced Treatment Systems (009 Watershed TT1)

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium, Total | A | 0.00004 | >20,000 | >19,000 | >22,000 | >7500 | >25,000 | >23,000 | >23,000 | >23,000 | >24,000 | >18,000 |
| Copper, Total | A | 0.005 | >300 | >270 | >230 | >89 | >270 | >250 | >220 | >340 | >330 | 260.8 |
| TCDD | A | 1E-11 | | | | | | | >230 | >240 | >240 | >180 |
| Gross Alpha radioactivity | A | 1 | | | | | | | >57 | >61 | >65 | >45 |
| Lead, Total | A | 0.001 | >130 | >130 | >150 | >50 | >170 | >150 | >150 | >160 | >160 | >110 |
| Mercury | A | 0.00004 | | | | | | | >18,000 | >22,000 | >24,000 | >17,000 |
| Oil and Grease | A | 0.4 | | | | | | | 7.5 | 14.6 | 15.7 | 0.0 |
| Antimony, Total | B | 0.00041 | >1200 | >1700 | 296.8 | >470 | >120 | 252.3 | 555.7 | >1300 | 710.1 | 345.8 |
| Iron, Total | B | 2 | >30 | | | >10 | >37 | >34 | >32 | >34 | >36 | >26 |
| Manganese, Total | B | 5 | >0.16 | | | >0.045 | >0.18 | >0.18 | >0.160 | >0.17 | >0.16 | >0.14 |
| Radium 226+228 | B | 0.08 | | | | | | | >2.40 | 2.3 | >3.1 | >2.1 |
| Sulfate | B | 25 | 3.3 | | 0.3 | >0.45 | 0.5 | 0.8 | 1.1 | >4.9 | 0.9 | >5.3 |
| Zinc, Total | B | 0.03 | | | | >5.3 | >16 | >16 | >16 | | 6.5 | >9.3 |
| Aluminum, Filtered | | 0.01 | >48 | | 6.7 | 8.0 | 1.5 | 4.2 | 2.5 | >49 | 4.1 | 1.3 |
| Aluminum, Total | | 0.05 | >1500 | | | >510 | >1900 | >1700 | >1500 | >1600 | >1800 | >1300 |
| Ammonia | | 0.5 | >61 | 3.9 | >66 | >1.0 | >82 | >77 | >78 | >80 | >85 | >57 |
| Antimony, Filtered | | 0.00065 | >550 | >860 | 250.0 | 181.7 | 322.7 | 187.8 | 308.8 | 250.0 | >650 | >410 |
| Arsenic, Filtered | | 0.001 | >280 | | 184.4 | 102.9 | >310 | >180 | >120 | >270 | >250 | >220 |
| Arsenic, Total | | 0.005 | >110 | >93 | 85.4 | >44 | >120 | >80 | >66 | >120 | >110 | >90 |
| Boron, Filtered | | 0.05 | >28 | 7.8 | | 3.6 | 2.1 | | 8.4 | >33 | >35 | >25 |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boron, Total | | 0.07 | | 2.9 | | 2.4 | | 4.6 | 6.7 | >21 | 100.8 | 6.4 |
| Cadmium, Filtered | | 0.00003 | >11,000 | >10,000 | >12,000 | >4000 | >13,000 | >12,000 | >12,000 | >13,000 | >14,000 | >9800 |
| Calcium, Filtered | | 15 | 3.2 | >15 | 2.2 | 0.8 | 3.2 | 1.3 | 2.2 | 2.2 | 3.8 | 2.3 |
| Calcium, Total | | 20 | 2.7 | 11.3 | 0.9 | 0.7 | 1.9 | 1.0 | 1.9 | 2.0 | 3.7 | 1.5 |
| Chloride | | 10 | 0.1 | | | | | | | | 0.3 | |
| Chromium, Filtered | | 0.002 | >80 | >62 | 6.1 | 4.7 | >0.52 | >4.0 | >0.11 | >82 | >65 | 66.1 |
| Chromium, Total | | 0.005 | >150 | >130 | >100 | >42 | >140 | >130 | >91 | >170 | >170 | >130 |
| COD | | 40 | >200 | | >1.9 | >4.2 | >23 | >16 | >18 | >24 | >25 | >19 |
| Copper, Filtered | | 0.003 | >150 | >97 | 17.5 | 12.5 | >61 | | | >160 | >120 | >120 |
| Fluoride | | 0.25 | 13.5 | >43 | 17.1 | 7.2 | 23.3 | 11.6 | 14.9 | 14.0 | 15.8 | 13.5 |
| Gross Beta radioactivity | | 3 | | | | | | | >22 | 6.9 | 32.9 | >27 |
| Hardness | | 50 | 0.9 | >0.97 | 0.3 | 0.1 | 3.2 | 0.1 | 0.0 | 0.4 | 2.3 | 0.7 |
| Iron, Filtered | | 0.4 | >1.7 | | | >0.26 | | >0 | >0 | >1.5 | | >1.3 |
| Lead, filtered | | 0.0002 | | | | | | | | | | |
| Magnesium, Filtered | | 5 | 0.0 | 0.1 | | | >3.5 | | | | | 0.5 |
| Magnesium, Total | | 10 | 0.1 | | | | >3.1 | | | 0.0 | 0.0 | 0.4 |
| Manganese, filtered | | 2 | >0.018 | | | | >0.0088 | | 0.0 | >0.020 | | >0.015 |
| Nickel, Filtered | | 0.001 | >300 | >270 | >290 | 75.4 | >250 | >340 | >280 | >290 | >360 | >240 |
| Nickel, Total | | 0.002 | >300 | >280 | >310 | >110 | >340 | >350 | >330 | >360 | >360 | >270 |
| Nitrate | | 0.7 | >98 | 0.6 | 4.6 | >3.4 | >0.91 | >2.9 | >3.70 | >65 | >62 | >69 |
| Nitrite | | 0.1 | 0.2 | | | 0.0 | 0.3 | 0.3 | 0.0 | 0.7 | 0.3 | 1.2 |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phosphate | | 0.1 | | | | >15 | >94 | >2.1 | >0.73 | | | |
| Potassium, Filtered | | 1 | | 0.1 | | 0.0 | | | | | | |
| Potassium, Total | | 2 | | | | >1.8 | | | | | | |
| Sodium, filtered | | 15 | 0.3 | | | 0.4 | | 0.4 | | | | |
| Sodium, Total | | 20 | | | | | | 0.1 | | | | |
| Thallium, Filtered | | 0.0001 | >7300 | >6200 | >8200 | >2300 | >9000 | >8500 | >8100 | >8500 | >8900 | >6700 |
| Thallium, Total | | 0.0001 | >9300 | >8400 | >8700 | >3300 | >11,000 | >9000 | >9100 | >11,000 | >11,000 | >8400 |
| TN | | 2 | >57 | 1.1 | 21.4 | 0.7 | >1.9 | >1.6 | | >56 | >67 | |
| TP | | 0.35 | | | >16 | >4.3 | >21 | >14 | >15 | | | |

* “A” are constituents that have exceeded current benchmark limits at Outfall 009. “B” are constituents that have a possible likelihood of exceeding benchmark limits at Outfall 009 during extended future monitoring

red: capacity exceeded before 10 years
green: capacity exceeded after 10 years
yellow: uncertain if capacity exceeded before or after 10 years

## Table 4-59. Expected Maintenance to Replace Media before 10-Year LIfe of Site Advanced Treatment Systems (009 Watershed TT2)

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium, Total | A | 0.00004 | >22,000 | >21,000 | >24,000 | >8300 | >28,000 | >25,000 | >25,000 | >26,000 | >27,000 | >19,000 |
| Copper, Total | A | 0.005 | >330 | >300 | >250 | >98 | >290 | >270 | >250 | >380 | >360 | 286.97 |
| TCDD | A | 1E-11 |  |  |  |  |  |  | >250 | >270 | >270 | >200 |
| Gross Alpha radioactivity | A | 1 |  |  |  |  |  |  | >63 | >670 | >710 | >50 |
| Lead, Total | A | 0.001 | >150 | >140 | >160 | >55 | >190 | >160 | >170 | >170 | >180 | >130 |
| Mercury | A | 0.00004 |  |  |  |  |  |  | >20,000 | >25,000 | >26,000 | 18706.47 |
| Oil and Grease | A | 0.4 |  |  |  |  |  |  | 8.31 | 16.12 | 17.26 | 0.00 |
| Antimony, Total | B | 0.00041 | >1400 | >1900 | 326.66 | >510 | >1300 | 277.64 | 611.58 | >1500 | 781.46 | 380.54 |
| Iron, Total | B | 2 | >33 |  |  | >11 | >400 | >37 | >35 | >37 | >40 | >29 |
| Manganese, Total | B | 5 | >0.17 |  |  | >0.050 | >0.20 | >0.20 | >0.18 | >0.19 | >0.18 | >0.16 |
| Radium 226+228 | B | 0.08 |  |  |  |  |  |  | >2.7 | 2.51 | >3.40 | >2.20 |
| Sulfate | B | 25 | 3.67 |  | 0.35 | >0.49 | 0.55 | 0.93 | 1.23 | >5.4 | 1.00 | >5.9 |
| Zinc, Total | B | 0.03 |  |  |  | >5.9 | >18 | >18 | >18 |  | 7.16 | >10 |
| Aluminum, Filtered |  | 0.01 | >53 |  | 7.36 | 8.82 | 1.63 | 4.68 | 2.81 | >54 | 4.56 | 1.38 |
| Aluminum, Total |  | 0.05 | >1600 |  |  | >560 | >2000 | >1900 | >1600 | >1800 | >2000 | >1500 |
| Ammonia |  | 0.5 | >67 | 4.34 | >73 | >1.2 | >90 | >84 | >86 | >88 | >93 | >63 |
| Antimony, Filtered |  | 0.00065 | >600 | >950 | 275.55 | 199.92 | 355.15 | 206.66 | 339.84 | 278.30 | >720 | >460 |
| Arsenic, Filtered |  | 0.001 | >300 |  | 202.99 | 113.23 | >340 | >200 | >130 | >300 | >270 | >240 |
| Arsenic, Total |  | 0.005 | >120 | >100 | 93.93 | >49 | >130 | >88 | >72 | >130 | >120 | >99 |
| Boron, Filtered |  | 0.05 | >31 | 8.64 |  | 3.98 | 2.28 |  | 9.19 | >36 | 38.61 | >27 |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boron, Total | | 0.07 | | 3.24 | | 2.67 | | 5.09 | 7.39 | >23 | 110.89 | 7.02 |
| Cadmium, Filtered | | 0.00003 | >12,000 | >11,000 | >13,000 | >4400 | >15,000 | >14,000 | >14,000 | >14,000 | >15,000 | >11,000 |
| Calcium, Filtered | | 15 | 3.57 | >16 | 2.43 | 0.92 | 3.49 | 1.39 | 2.41 | 2.39 | 4.19 | 2.55 |
| Calcium, Total | | 20 | 2.99 | 12.44 | 1.01 | 0.81 | 2.06 | 1.15 | 2.12 | 2.19 | 4.10 | 1.68 |
| Chloride | | 10 | 0.14 | | | | | | | | 0.30 | |
| Chromium, Filtered | | 0.002 | >88 | >68 | 6.77 | 5.22 | >0.57 | >4.4 | >0.12 | >90 | >71 | 72.74 |
| Chromium, Total | | 0.005 | >170 | >150 | >110 | >47 | >150 | >140 | >100 | >190 | >190 | >140 |
| COD | | 40 | >22 | | >2.1 | >4.6 | >26 | >18 | >20 | >27 | >27 | >21 |
| Copper, Filtered | | 0.003 | >170 | >110 | 19.24 | 13.73 | >67 | | | >180 | >140 | >130 |
| Fluoride | | 0.25 | 14.89 | >47 | 18.79 | 7.89 | 25.63 | 12.74 | 16.40 | 15.44 | 17.43 | 14.89 |
| Gross Beta radioactivity | | 3 | | | | | | | >24 | 7.62 | 36.22 | >290 |
| Hardness | | 50 | 1.04 | >1.1 | 0.30 | 0.06 | 3.51 | 0.07 | 0.00 | 0.39 | 2.58 | 0.77 |
| Iron, Filtered | | 0.4 | >1.8 | | | >0.290 | | >0 | >0 | >1.7 | | >1.4 |
| Lead, filtered | | 0.0002 | | | | | | | | | | |
| Magnesium, Filtered | | 5 | 0.03 | 0.06 | | | >3.8 | | | | | 0.55 |
| Magnesium, Total | | 10 | 0.06 | | | | >3.5 | | | 0.01 | 0.04 | 0.43 |
| Manganese, filtered | | 2 | >0.020 | | | | >0.0097 | | | >0.022 | | >0.017 |
| Nickel, Filtered | | 0.001 | >330 | >300 | >320 | 82.99 | >280 | >370 | >310 | >320 | >390 | >270 |
| Nickel, Total | | 0.002 | >330 | >300 | >340 | >120 | >380 | >380 | >370 | >390 | >400 | >300 |
| Nitrate | | 0.7 | >110 | 0.61 | 5.06 | >3.8 | >1.0 | >3.2 | >4.1 | >71 | >68 | >76 |

| Capacity (years to capacity) | Constituent Category* | expected median site concentration (mg/L) | GAC | Peat Moss | Rhyolite Sand | Site Sand | Site Zeolite | SMZ | R-SMZ | R-SMZ-GAC | R-SMZ-GAC-PM | Site Sand-GAC-Site Zeolite Layered |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nitrite | | 0.1 | 🟥 0.27 | | | 🟥 0.02 | 🟥 0.37 | 🟥 0.28 | 🟥 0.03 | 🟥 0.77 | 🟥 0.37 | 🟥 1.34 |
| Phosphate | | 0.1 | | | | 🟩 >16 | 🟩 >100 | 🟨 >2.3 | 🟨 >0.80 | | | |
| Potassium, Filtered | | 1 | | 🟥 0.08 | | 🟥 0.04 | | | | | | |
| Potassium, Total | | 2 | | | | >1.9 | | | | | | |
| Sodium, filtered | | 15 | 🟥 0.32 | | | 🟥 0.41 | | 🟥 0.41 | | | | |
| Sodium, Total | | 20 | | | | | | 🟥 0.08 | | | | |
| Thallium, Filtered | | 0.0001 | 🟩 >8040 | 🟩 >6900 | 🟩 >9100 | 🟩 >2600 | 🟩 >9900 | 🟩 >9300 | 🟩 >9000 | 🟩 >9400 | 🟩 >9800 | 🟩 >7400 |
| Thallium, Total | | 0.0001 | 🟩 >10,000 | 🟩 >9200 | 🟩 >9600 | 🟩 >3600 | 🟩 >12,000 | 🟩 >10,000 | 🟩 >10,000 | 🟩 >12,000 | 🟩 >12,000 | 🟩 >9200 |
| TN | | 2 | 🟩 >63 | 🟥 1.24 | 🟩 23.58 | 🟥 0.73 | 🟨 >2.1 | 🟨 >1.7 | | 🟩 >62 | 🟩 74.23 | |
| TP | | 0.35 | | | 🟩 >18 | 🟨 >4.7 | 🟩 >23 | 🟩 >15 | 🟩 >17 | | | |

* “A” are constituents that have exceeded current benchmark limits at Outfall 009. “B” are constituents that have a possible likelihood of exceeding benchmark limits at Outfall 009 during extended future monitoring

red: capacity exceeded before 10 years
green: capacity exceeded after 10 years
yellow: uncertain if capacity exceeded before or after 10 years

### 4.6.4 Treatment Capacities Measured during Batch Tests Compared to Column Test Results

Results from other tests conducted during these media evaluation studies were examined to verify the media chemical capacities for the different constituents calculated from the long-term, full-depth column tests, especially for those media that had negative capacities based on the calculations and those media where the tests did not achieve breakthrough. The data that were examined for chemical capacity included the series of varying depth columns that were studied for a short period to determine the effects of residence time on contaminant removal, the aerobic and anaerobic batch tests that were studied to examine contaminant releases during interevent periods, and the traditional capacity tests where varying masses of media were exposed to spiked stormwater for a pre-determined period of time. The traditional capacity tests used concentrations only slightly greater than those used in the full-column tests, but used much smaller masses of media, and, therefore, their results can provide estimates of ultimate chemical capacity. The task results pertaining to chemical capacity for the different media are discussed in the following subsections.

#### *Varying Depth Column Tests for Chemical Capacity of Treatment Media*

The varying depth tests were described earlier in this report. Table 4-60 shows the amounts of the different media in each of these columns. Tables A10-4 through A10-6 in Appendix A10 summarize and compare the unit mass chemical capacities observed during the different column tests. These calculations are based on the filtered concentrations for the metals since only the filtered portion will participate in chemical removal reactions. Because of the short durations of these tests, few breakthrough observations were obtained, although the values obtained are usually in the same range/order of magnitude as observed during the full depth long-term column tests. The primary differences are where negative capacities were calculated during the full-column tests. Many of these negative capacities occurred due to the calculation method used. The capacities were determined by first determining the capacity of the site sand only column for the pollutants on a per mass basis. Then the per-mass capacity was used to determine the capacity of the site sand in the other columns. If additional pollutant removal occurred, it was attributed to the media mixed into the column. If the sand removal capacity exceeded the mass of pollutant removed, then the media mixed into the column was calculated as negative. A similar procedure was used for the short-column/contact-time tests. The batch tests for the aerobic-anaerobic exposure series and for the capacity tests did not use mixed media, just the individual components and, therefore, the capacities calculated there can be associated directly with the medium.

**Table 4-60. Medium Masses Used in Varying-Depth Column Tests (g media per column)***

| Total media depth in column (inches) | Mixture Tests (v/v measurements, expressed as percentages or fractions) | Site Filter Sand | Surface Modified Zeolite (SMZ) | Rhyolite Sand ( R) | Peat Moss (PM) | Granular Activated Carbon (GAC) |
|---|---|---|---|---|---|---|
| 14 | R-SMZ-G (1/3-1/3-1/3) | | 753 | 956 | | 372 |
| 26 | R-SMZ-G (1/3-1/3-1/3) | | 1400 | 1780 | | 692 |
| 38 | R-SMZ-G (1/3-1/3-1/3) | | 2040 | 2590 | | 1010 |
| 14 | R-SMZ-G-PM (30-30-30-10) | | 677 | 860 | 38 | 335 |
| 26 | R-SMZ-G-PM (30-30-30-10) | | 1260 | 1600 | 70 | 622 |
| 38 | R-SMZ-G-PM (30-30-30-10) | | 1840 | 2330 | 102 | 910 |
| 14 | R-SMZ (75-25) | | 564 | 2150 | | |
| 26 | R-SMZ (75-25) | | 1050 | 4000 | | |
| 38 | R-SMZ (75-25) | | 1530 | 5840 | | |
| 14 | GAC-Site filter sand (1/3-2/3) | 2350 | | | | 413 |
| 26 | GAC-Site filter sand (1/3-2/3) | 4370 | | | | 768 |
| 38 | GAC-Site filter sand (1/3-2/3) | 6390 | | | | 1120 |
| 14 | SMZ-Site filter sand (50-50) | 1870 | 1130 | | | |
| 26 | SMZ-Site filter sand (50-50) | 3470 | 2100 | | | |
| 38 | SMZ-Site filter sand (50-50) | 5070 | 3060 | | | |
| 14 | PM-Site filter sand (50-50) | 1870 | | | 187 | |
| 26 | PM-Site filter sand (50-50) | 3470 | | | 348 | |
| 38 | PM-Site filter sand (50-50) | 5070 | | | 508 | |

*The site zeolite was not tested during these varying column tests

The SMZ-sand, peat-sand, and GAC-sand varying depth columns are directly compared to the full-depth, long-duration column test results on Table 4-61 for a subset of the tested constituents. Only those constituents that had treatment capacity measurements within an order of magnitude for the different column tests are shown. The yellow highlighted columns are the ratios of the chemical treatment capacity values for the long-term full depth columns to the chemical capacity values obtained from the varying depth column tests. The ratios for these selected media and constituent combinations from the different column tests are relatively close to 1. Combinations with very large or very small ratios are not shown on the table, as previously described. The variabilities of the treatment capacities from all of the column tests was relatively low, with coefficients of variation (the standard deviation divided by the average) values mostly in the range of about 0.3 to 1 for these constituents and media.

Given these relatively consistent results for the different column tests, the longer-term full-depth column test chemical capacity values are assumed to be reliable for constituents that had chemical breakthrough or that approached chemical breakthrough. For the other constituents, especially those where the anticipated capacity was substantial, the short-column or batch tests may provide a better estimate of capacity because the smaller amounts of media in these short columns were more likely to become chemically saturated.

## Table 4-61. Comparisons of Long-Term Column with Varying-Depth Column Chemical Capacity Results (mg constituent/g medium)

| **Constituent** | Long-Term Column Breakthrough Testing (SMZ) | Varying Depth Column Average (SMZ) | Long-Term to Varying Depth Column Capacity Ratio (SMZ) | Long-Term Column Breakthrough Testing (GAC) | Varying Depth Column Average (GAC) | Long-Term to Varying Depth Column Capacity Ratio (GAC) | Long-Term Column Breakthrough Testing (PM) | Varying Depth Column Average (PM) | Long-Term to Varying Depth Column Capacity Ratio (PM) |
|---|---|---|---|---|---|---|---|---|---|
| Aluminum | | | | > 0.0125 | > 0.00781 | 1.60 | | | |
| Boron | | | | | | | 0.03 | 0.0174 | 1.72 |
| Calcium | 0.185 | 0.0814 | 2.27 | 1.19 | 1.85 | 0.64 | > 21.4 | > 9.43 | 2.27 |
| Cadmium | > 0.00464 | > 0.00347 | 1.34 | > 0.00735 | > 0.0140 | 0.52 | > 0.0253 | > 0.0186 | 1.36 |
| Copper | | | | > 0.0127 | > 0.0707 | 0.18 | > 0.0268 | > 0.093 | 0.29 |
| Iron | | | | > 0.0172 | > 0.0161 | 1.07 | | | |
| Magnesium | 0.00449 | 0.00350 | 1.28 | 0.00739 | 0.01413 | 0.53 | 0.0235 | 0.0188 | 1.25 |
| Chromium | 0.0000438 | > 0.0000163 | 2.69 | > 0.00441 | > 0.00152 | 2.89 | > 0.0117 | > 0.00143 | 8.18 |
| Thallium | > 0.0108 | > 0.00379 | 2.85 | > 0.0171 | > 0.0166 | 1.03 | > 0.0502 | > 0.0122 | 4.12 |
| Antimony | 0.000891 | > 0.00159 | 0.56 | > 0.00826 | > 0.00109 | 7.55 | > 0.0495 | > 0.0186 | 2.67 |
| Nitrite | 0.000363 | 0.000354 | 1.03 | 0.000676 | 0.00626 | 0.11 | | | |
| Nitrate | | | | > 1.92 | > 1.55 | 1.24 | | | |
| Ammonia | > 0.57 | > 0.179 | 3.18 | > 0.866 | > 0.303 | 2.85 | 0.169 | 0.0386 | 4.37 |
| COD | > 8.49 | > 4.42 | 1.92 | > 20.4 | > 21.3 | 0.96 | | | |
| Fluoride | | | | 0.0678 | 0.0318 | 2.13 | 0.969 | > 0.645 | 1.50 |
| Sulfate | | | | 2.2 | > 5.00 | 0.44 | | | |
| TN | 0.0363 | > 0.272 | 0.13 | > 3.25 | > 2.67 | 1.22 | 0.159 | 0.060 | 2.65 |
| Chloride | | | | 0.0369 | 0.239 | 0.15 | | | |
| Hardness | | | | 1.31 | > 11.8 | 0.11 | > 47.4 | > 27.9 | 1.70 |

### *Aerobic-Anaerobic Initial Loadings as an Estimate of Chemical Capacity and Traditionally-Measured Chemical Capacity of Treatment Media*

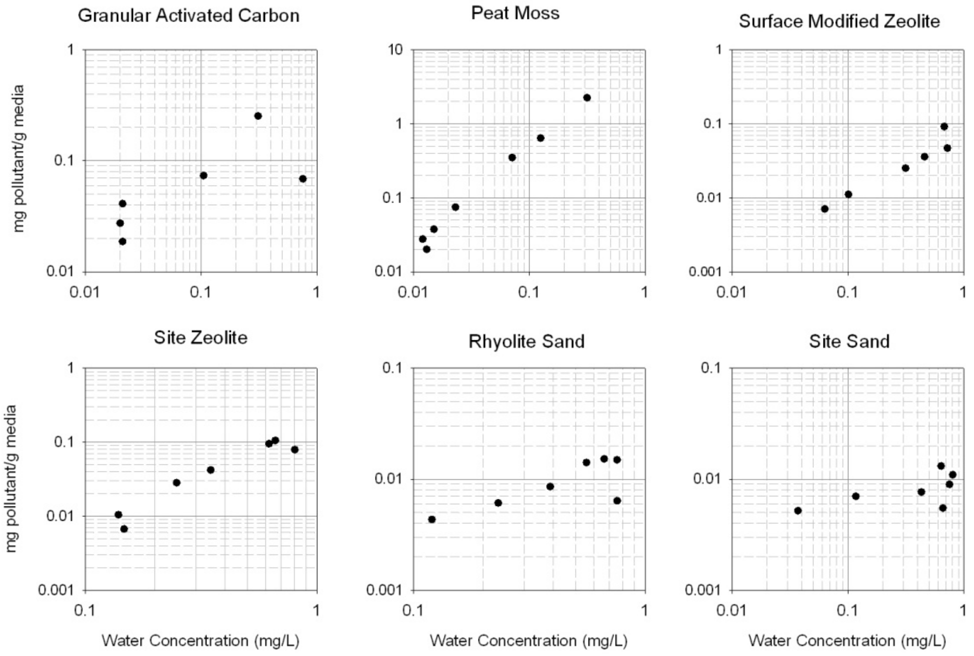
As noted earlier, while the traditional batch capacity testing has limits, it is useful to predict service life for constituents whose breakthrough was not reached during the long-term full column tests. Graphs from traditional capacity tests, e.g., isotherm tests, show the predicted relationship between the mass of a constituent retained on the media to the effluent water concentration. An example of this type of result is given in Figure 4-44 for cadmium. Operational capacities can be estimated from the data set as the maximum capacity reported in a media-constituent combination. Ultimate capacity, which is not likely to be achieved during filter operation, can be estimated from the constants in the Freundlich isotherm. The equation for the Freundlich isotherm is as follows:

$$q_s = a_F C_s^{b_F}$$

Where $q_s$ = amount of pollutant retained by the media (mg/g), $C_s$ = water concentration (mg/L), $a_F$ = adsorbent capacity, and $b_F$ = heterogeneity factor (McKay 1996). Those media-constituent combinations that follow Freundlich-type behavior are those that plot as a straight line on log-log paper.

Table 4-62 compares the batch capacity estimates from the traditional testing to the capacities estimated from the aerobic-anaerobic tests, while Table 4-63 compares the long-term column testing estimates with the traditional capacity testing estimates. As shown in Table 4-62, the capacities for several parameters, especially ones such as chromium, are substantially different (several orders of magnitude) for those media expected to provide excellent metals removal. This likely is a result of the differing starting recipes for the spiked stormwater. For the aerobic-anaerobic testing, the spiked stormwater concentrations were substantially higher than they were for the column and capacity testing activities. The purpose was to load the media to the maximum extent possible in a short time frame. In addition to the higher concentrations, several constituents in that recipe had higher starting concentrations compared to the other constituents. Lead, for example, was spiked an order of magnitude higher than most other metals because of the challenges seen in the column tests with recovering lead as a soluble metal/complex after passing through a 0.45-μm filter. Table 4-63 compares the long-term column testing and traditional capacity testing, where the starting spiked stormwater concentrations were similar. For many media-constituent combinations, if capacity was reached during the testing, the capacities are within an order of magnitude, indicating potential comparability between the results. For several constituent-media combinations, where breakthrough was not reached in the long-term column testing, these capacity results may provide an estimate of the field media capacity after applying a safety factor to the batch capacity estimate.

Freundlich estimates of capacity represent ultimate capacity and assume sufficient time and agitation of the sample and media to ensure successful interactions that lead to pollutant retention. Comparing Freundlich and data listed capacities shows that several media had not reached ultimate capacity; however, it is unlikely that this ultimate capacity will be reached in the field. Future estimations of media capacity should use a testing method similar to that for Freundlich isotherms but where the media mass and not concentration are varied. When this type of test is run for a period of time that mimics slow-flowing conditions in the field, an approximation of the field capacity can be achieved and can be seen readily in the data set generated.



**Cadmium**

**Figure 4-44. Cadmium Capacity Test Results for Media Components**

## Table 4-62. Comparison of Capacities Calculated from Aerobic and Capacity Testing (mg constituent/g medium)

| Constituent | GAC | | Peat | | Rhyolite | | Site Sand | | Site Zeolite | | SMZ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aerobic | Capacity | Aerobic | Capacity | Aerobic | Capacity | Aerobic | Capacity | Aerobic | Capacity | Aerobic | Capacity |
| Arsenic | <0 | 2.50 | <0 | 0.479 | <0 | 0.414 | <0 | 0.220 | <0 | 5.74 | <0 | 5.81 |
| Aluminum | 0.0468 | 0.143 | 0.00395 | <0 | 0.00982 | 0.0169 | 0.0191 | 0.00448 | <0 | 0.0889 | 0.0234 | 0.0842 |
| Boron | 0.156 | 0.851 | 0.286 | 0.422 | 0.0605 | 0.156 | 0.0622 | 0.127 | 0.0632 | 0.0551 | 0.228 | 0.156 |
| Cadmium | 0.0483 | 0.253 | 0.108 | 2.26 | 0.0191 | 0.0152 | 0.0192 | 0.0131 | 0.0230 | 0.106 | 0.0701 | 0.0919 |
| Calcium | 0.648 | 1.65 | 0.942 | 10.7 | 0.0720 | 0.233 | 0.211 | 0.312 | <0 | <0 | <0 | 0.663 |
| Copper | 0.0480 | 0.0538 | 0.110 | 0.120 | 0.0151 | 0.00154 | 0.0158 | 0.001 | 0.0205 | 0.00847 | 0.0535 | 0.00799 |
| Chromium | 6.77 | 0.0172 | 17.2 | <0 | 2.41 | 0.00255 | 2.28 | 0.00185 | 3.21 | 0.0114 | 9.32 | 0.0160 |
| Iron | 1.15 | 0.0961 | 2.44 | 0.00025 | 0.351 | 0.00673 | 0.309 | 2.5E-05 | 0.460 | 0.0137 | 1.34 | 0.0105 |
| Lead | 2.35 | 0.0513 | 5.94 | 0.00125 | 0.986 | 0.00414 | 0.861 | 0.00174 | 1.19 | 0.0259 | 3.35 | 0.0384 |
| Nickel | 0.0212 | 0.116 | 0.0523 | 1.42 | 0.00818 | 0.00934 | 0.00853 | 0.0175 | 0.0107 | 0.0457 | 0.0308 | 0.0360 |
| Magnesium | 0.818 | 0.576 | 1.46 | 2.49 | 0.426 | 0.178 | 0.441 | 0.263 | 0.544 | 1.25 | 1.57 | 0.985 |
| Manganese | <0 | 0.00175 | <0 | 0.105 | <0 | 7.33E-05 | <0 | 0.0017 | <0 | 0.0199 | <0 | 0.00990 |
| Zinc | 0.300 | 0.237 | 0.638 | 0.763 | 0.119 | 0.00969 | 0.120 | 0.0120 | 0.161 | 0.0616 | 0.445 | 0.0604 |
| Potassium | <0 | <0 | 1.82 | 0.115 | 0.369 | 0.00145 | 0.475 | <0 | 0.701 | 0.0300 | 1.41 | 0.0299 |
| Sodium | 0.897 | 0.0714 | 2.46 | 0.272 | 0.349 | <0 | 0.516 | 0.0786 | <0 | <0 | 1.19 | 0.188 |
| Thallium | 0.0287 | 0.337 | 0.0621 | 0.736 | 0.0146 | 0.214 | 0.0105 | 0.0132 | 0.0173 | 0.350 | 0.0532 | 0.301 |
| Antimony | 0.163 | 0.108 | 0.408 | 0.113 | 0.0609 | 0.0149 | 0.0550 | 0.0201 | 0.0774 | 0.0865 | 0.229 | 0.111 |
| COD | 2.41 | 46.8 | <0 | <0 | 0.417 | 5.48 | 0.0160 | 2.949351 | 2.45 | 111 | <0 | 61.9 |
| Nitrite | 0.000665 | | 0.00188 | | <0 | | <0 | | 0.00038 | | 0.000186 | |
| Nitrate | 0.381 | 1.72 | 0.229 | 3.49 | 0.0117 | 0.149 | 0.0281 | 0.597134 | 0.134 | 2.72 | 0.0724 | 2.72 |
| Ammonia | 0.452 | 0.139 | 1.33 | 0.0998 | 0.449 | 0.0957 | 0.340 | 0.121978 | 0.879 | 0.397 | 1.44 | 0.155 |
| Phosphate | 0.0356 | <0 | 0.102 | 0.0998 | 0.0159 | 0.00996 | 0.0124 | 0.064689 | 0.0183 | 0.0497 | 0.0460 | 0.0300 |
| TN | 1.96 | | 1.47 | | 0.884 | | 0.815 | | 1.47 | | 3.15 | |
| TP | 0.00391 | 0.886 | 0.0196 | <0 | 0.00438 | 0.199 | 0.00326 | 0.089847 | 0.00611 | 2.45 | 0.0130 | 2.55 |
| Fluoride | <0 | 5.17 | <0 | 1.55 | <0 | 1.35 | <0 | 2.438296 | <0 | 6.92 | <0 | 0.846 |
| Chloride | 31.8 | | 76.7 | | 15.9 | | 16.0 | | 16.3 | | 53.6 | |
| Sulfate | 1.37 | 0.249 | 3.01 | 0.125 | 0.515 | 0.491 | 0.435 | 0 | 0.724 | 14.8 | 1.42 | <0 |
| Hardness | <0 | 12.3 | <0 | 74.9 | <0 | 2.49 | <0 | 0.500 | <0 | 4.97 | <0 | 2.50 |

## Table 4-63. Comparison of Capacities Calculated from Long-Term Column Breakthrough and Capacity Testing (mg constituent/g medium)

| Constituent | GAC | | Peat | | Rhyolite | | Site Sand | | Site Zeolite | | SMZ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Long-Term Column | Capacity | Long-Term Column | Capacity | Long-Term Column | Capacity | Long-Term Column | Capacity | Long-Term Column | Capacity | Long-Term Column | Capacity |
| Arsenic | >0.00629 | 2.50 | 0 | 0.479 | 0.00173 | 0.414 | 0.000503 | 0.220 | >0.00476 | 5.74 | >0.00185 | 5.81 |
| Aluminum | >0.0125 | 0.143 | 0 | 0 | 0.000361 | 0.0169 | 0.000392 | 0.00448 | 0 | 0.0889 | 1.30E-06 | 0.0842 |
| Boron | >0.0368 | 0.851 | 0.0300 | 0.422 | 0 | 0.156 | 0.000884 | 0.127 | 0.000148 | 0.0551 | 0 | 0.156 |
| Calcium | 1.19 | 1.65 | >21.4 | 10.7 | 0.347 | 0.233 | 0.0610 | 0.312 | 0.761 | 0 | 0.185 | 0.663 |
| Cadmium | >0.00735 | 0.253 | >0.0253 | 2.26 | >0.00392 | 0.0152 | >0.000590 | 0.0131 | >0.00624 | 0.106 | >0.00464 | 0.0919 |
| Copper | >0.0127 | 0.0538 | >0.0268 | 0.120 | 0.000440 | 0.00154 | 0.000183 | 0.001 | >0.00304 | 0.00847 | 0 | 0.00799 |
| Iron | >0.0172 | 0.0961 | 0 | 0.00025 | 0 | 0.00673 | >0.000516 | 2.5E-05 | 0 | 0.0137 | 0 | 0.0105 |
| Magnesium | 0.00739 | 0.576 | 0.0235 | 2.49 | 0.00328 | 0.178 | 0.000369 | 0.263 | 0.00400 | 1.25 | 0.00449 | 0.985 |
| Manganese | 0 | 0.00175 | 0 | 0.105 | 0 | 7.33E-05 | 0 | 0.0017 | 0 | 0.0199 | 0 | 0.00990 |
| Nickel | >0.00102 | 0.116 | 0 | 1.42 | 0 | 0.00934 | 0 | 0.0175 | >0.000326 | 0.04568 | 0 | 0.0360 |
| Lead | 0.00395 | 0.0513 | 0.0278 | 0.00125 | 0 | 0.00414 | 0 | 0.00174 | 0.321 | 0.0259 | 0 | 0.0384 |
| Zinc | 0 | 0.237 | 0 | 0.763 | 0 | 0.00969 | 0 | 0.0120 | 0 | 0.0616 | 0 | 0.0604 |
| Potassium | 0 | 0 | 0.00567 | 0.115 | 0 | 0.00145 | 0.000172 | 0 | 0 | 0.0300 | 0 | 0.0299 |
| Sodium | 0.0337 | 0.0714 | 0 | 0.272 | 0 | 0 | 0.0276 | 0.0786 | 0 | 0 | 0.0395 | 0.188 |
| Chromium | >0.00441 | 0.0172 | >0.0117 | 0 | 9.89E-05 | 0.00255 | 4.64E-05 | 0.00185 | 0 | 0.0114 | 4.38E-05 | 0.0160 |
| Thallium | >0.0171 | 0.337 | >0.0502 | 0.736 | >0.00913 | 0.214 | >0.00114 | 0.0132 | >0.0144 | 0.350 | >0.0108 | 0.301 |
| Antimony | >0.00826 | 0.108 | >0.0495 | 0.112 | 0.00135 | 0.0149 | 0.000578 | 0.0200 | 0.00273 | 0.0865 | 0.000891 | 0.111 |
| Nitrite | 0.000676 | | 0 | | 0 | | 1.08E-05 | | 0.000597 | | 0.000363 | |
| Nitrate | >1.92 | 1.72 | 0 | 3.49 | 0.0264 | 0.149 | >0.0118 | 0.597 | 0 | 2.72 | 0.0112 | 2.72 |
| Ammonia | >0.866 | 0.139 | 0.169 | 0.0998 | >0.421 | 0.0957 | >0.00256 | 0.122 | >0.754 | 0.397 | >0.570 | 0.155 |
| TP | 0 | 0.886 | 0 | 0 | >0.0641 | 0.199 | >0.00738 | 0.0898 | >0.121 | 2.45 | >0.0589 | 2.55 |
| COD | >20.42 | 46.8 | 0 | 0 | >8.60 | 5.48 | >0.812 | 2.95 | >15.6 | 111 | >8.49 | 61.9 |
| Fluoride | 0.0678 | 5.17 | 0.969 | 1.55 | 0.0438 | 1.35 | 0.00877 | 2.44 | 0.0905 | 6.92 | 0.0292 | 0.846 |
| Sulfate | 2.20 | 0.249 | 0 | 0.125 | 0.0336 | 0.491 | >0.0544 | 0 | 0.124 | 14.8 | 0.227 | 0 |
| Phosphate | 0 | 0 | 0 | 0.0998 | 0 | 0.00996 | >0.00713 | 0.0647 | >0.160 | 0.0497 | 0 | 0.0300 |
| TN | >3.25 | | 0.159 | | 0.542 | | 0.00650 | | 0.0580 | | 0.0363 | |
| Chloride | 0.0369 | | 0 | | 0 | | 0 | | 0 | | 0 | |
| Hardness | 1.31 | 12.3 | >47.4 | 74.9 | 0.158 | 2.49 | 0.0133 | 0.500 | 2.94 | 4.97 | 0.0246 | 2.50 |

## 5.0 Likely Mechanisms and Reactions during Media Treatment

Many research studies have been published regarding the treatment efficiency of bioretention for a wide variety of pollutants found in urban stormwater runoff. Some of the past studies that have contained major literature reviews of biofiltration treatment media include Clark et al. (2010); Clark and Pitt (1999); Clark (2000), and Johnson, *et al.* (2003). Predicting the treatment ability of (bio)(in)filtration media is a function of both media and water chemistry. This section begins that meta-analysis of pollutant removal as a function of chemistry.

The water chemistry greatly affects the forms of the pollutants, and many metals that are in the dissolved phase have been shown not to be ionic. These complexed metals have valence charges that may make their treatment more difficult. The preliminary results for soil chemistry effects indicate that the media that appear to have the best removal ability for a wide range of metallic pollutants are those that have both cation exchange ability and comparatively high organic matter content; however these chemical characteristics cannot be used to measure media exhaustion, except for the pure ion exchange resins and possibly for ionic forms of the cations, and then only for relatively high concentrations for single-component systems. For the removal of the dissolved fraction of metals, this also may require a neutral to acidic media pH because of the generally increased solubility of metals at lower pHs. Lower pHs and higher organic matter contents, however, must be evaluated further if phosphorus removal is also desired since phosphorus is removed better at higher pHs and lower organic matter content (organic matter is a source of P). These results also highlight the trade-offs in pollutant capture versus cation/mineral/pollutant export when using ion-exchange media. Design of bioretention devices for effective treatment, and especially to meet permit limits, requires a greater understanding of the interaction of water and soil chemistry on a site, with a focus on the chemistry of the dissolved fraction.

### *5.1 Introduction*

Many guidance documents, published studies, and online performance databases list percent removal rates and effluent concentrations for different stormwater controls. For filtration, infiltration, and biofiltration/bioretention treatment devices, these efficiencies (often extracted from the literature) may range from <30% to almost 100% for pollutants such as metals and phosphorus. While numeric effluent limits for metals may be presented as total recoverable (total) metal concentrations in the effluent water (often based on wastewater total-to-dissolved fractions and not reflecting the greater fraction of particulate-bound metals in untreated stormwater), achieving those concentrations may require removal of both particulate-associated and filtered (“dissolved”) pollutants.

“Dissolved” pollutants are defined traditionally as the total pollutant quantity that is measured after the water has passed through a 0.45-μm membrane filter. These are the pollutants that are considered to be the most bioavailable to the aquatic biota and therefore the greatest toxicity/bioaccumulation concern when they are discharged to receiving waters. For some pollutants, such as the nutrients and many of the major cations and anions in water, the majority of the pollutant is considered to be “dissolved.” For example, nitrates and chlorides are mostly, if not all, found in the filtered fraction. However, for metals, the fraction of a certain metal that passes through the 0.45-µm filter is dependent on the metal and other constituents in the source water, so a consistent ratio of filtered to total metals is generally not observed (Figure 5-1). For metals such as copper and cadmium in the data set below, much of the total metals concentration can be particulate-associated (not filtered through a 0.45-µm membrane filter), while for others, such as thallium and antimony, most of the total concentration was associated with the filtered fraction, although the range of the filtered fraction can be highly variable, even for the same sampling location.

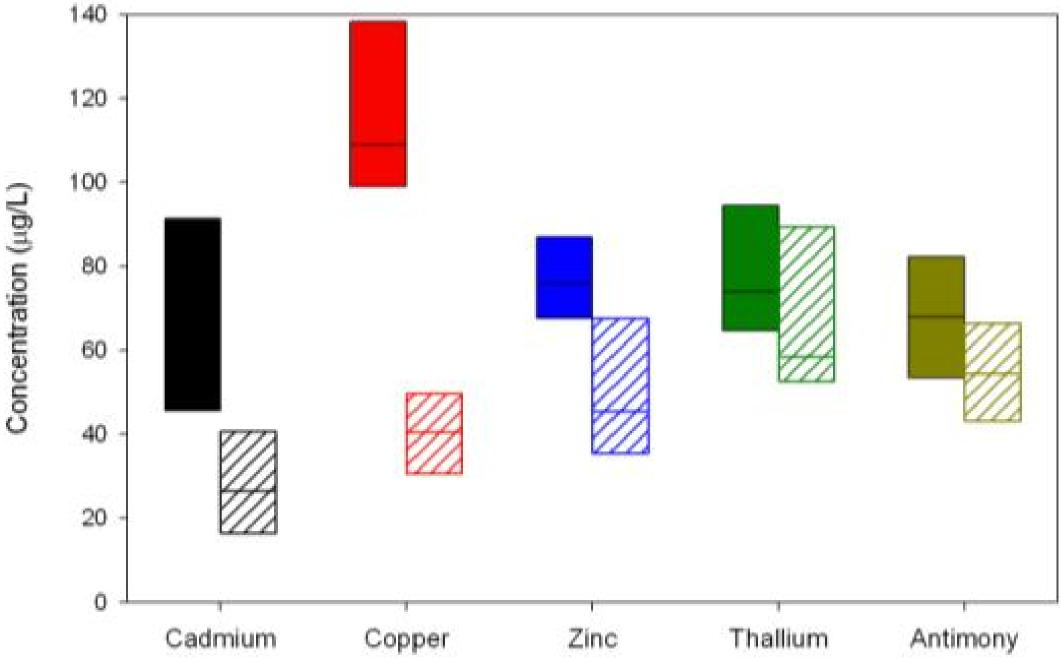


**Figure 5-1. Total (solid fill) versus filtered (striped fill) metals concentrations in spiked stormwater influent**

Compared to the removal of “dissolved” pollutants, particulate-associated pollutant removal is easy in (bio)(in)filtration systems. As the water passes through the pores, the larger particulates are strained out and trapped in the pore spaces of the media. Assuming that pore-water chemistry does not affect this binding, this removal does not depend on the chemistry of the water and media, but on the pore size and the particle diameters. The removal of filtered pollutants, though, is dependent on the chemistry of the influent water and of the media. Laboratory testing and ranking of media has often been based on “synthetic” stormwater where the pollutants, particularly the metals, are in ionic form and performance rankings have been developed based on these tests. However, researchers such as Morquecho, *et al*. (2005) have shown that metals that pass through these filters are not just ionic, but also can be associated with colloidal particles (both organic and inorganic complexes) (Table 5-1). These complexes have different charge states than the original metal ions and therefore will react differently than the metal ion by itself. A media's ability to remove "dissolved" pollutants thus should be expressed not in generic terms but instead as a function of both the soil and water chemistry.

**Table 5-1. Fraction Ionic vs. Bound Metals in Filtered Fraction from Source Area Stormwater (Morquecho 2005)**

| | % Ionic | % Bound |
|---|---|---|
| Zinc | 15 | 85 |
| Copper | 70 | 30 |
| Cadmium | 10 | 90 |
| Lead | 12 | 88 |

## 5.2 Effects of Influent Water Chemistry

This effect of influent chemistry can be seen when comparing the removals of various filtered metals for a single media, for example, a peat-moss sand mixture (50/50 v/v) compared to a natural zeolite (50/50 v/v with sand) (Figure 5-2). The three metals shown in the graph (antimony, copper, and zinc) all should have a preferred charge of +2 and should be equally removed by a medium if the primary removal mechanism is only ion exchange. However, the removals of these metals are different both within a single filter medium and when comparing removals between two or more media. Each of these metals can complex with both organic and inorganic material in water and their charge state after complexation may affect the preferential binding ability of the media for a particular metal. Removal of copper was slightly greater with peat moss than with zeolite, while antimony removals were better and occurred at higher volumetric loadings in the peat moss. This is likely due to peat moss's complex chemical nature which offers a variety of potential sorption/ion exchange sites. Another interesting note is the release of zinc from the media. Zinc may be participating in an ion exchange reaction on these media and therefore, zinc is released as copper or antimony is removed.

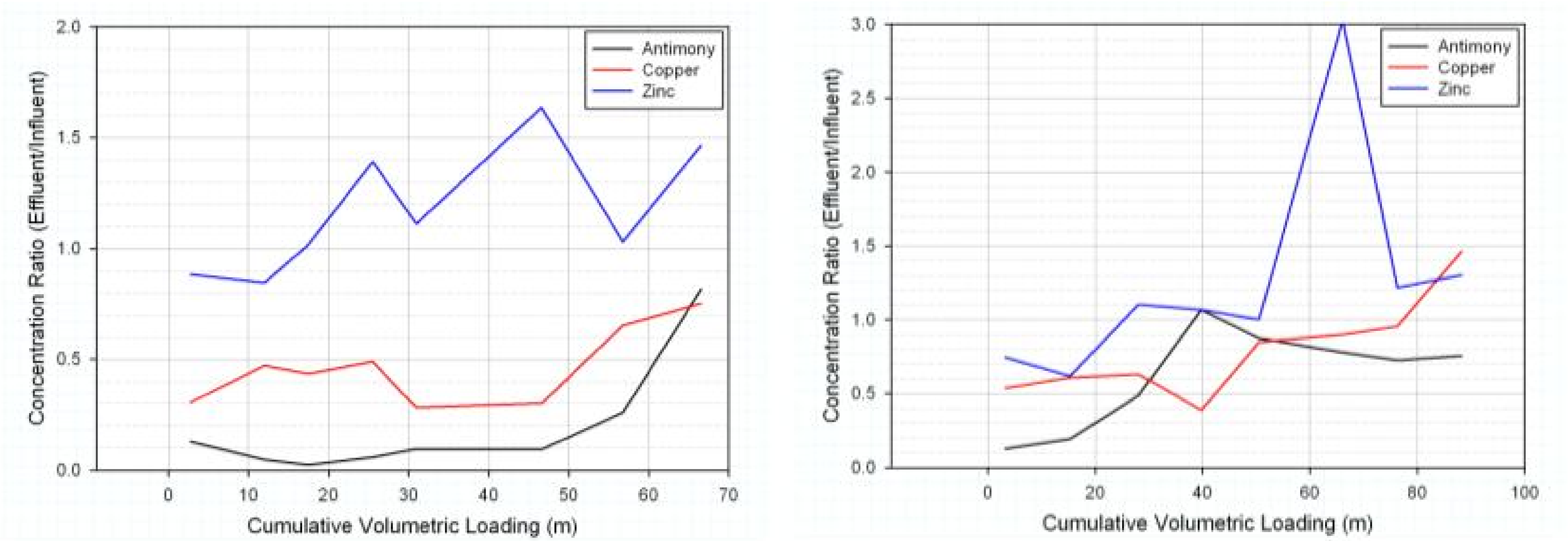


**Figure 5-2. Removal of Dissolved Antimony, Copper, and Zinc by Peat Moss-Sand (left) and by Zeolite-Sand (right)**

Zeolite's primary removal mechanism is ion exchange of a loosely-bound cation (such as calcium, magnesium, and potentially aluminum or other polyvalent ion) with the metal of interest that is in solution. Zeolite retains these metals until a metal/cation that is more strongly attached to the charged lattice structure attempts to bind to the zeolite. At that point, previously captured metals may be released. Peat moss is a complex mixture of organic matter with a variety of organic acids available to participate in ion exchange. However, peat generally is low in divalent major cations such as calcium and magnesium and tries to scavenge calcium as a preferential exchange. The similarities in removals between the zeolite and the peat moss indicate that ion exchange is likely occurring in the media as a dominant mechanism. The lower effluent concentrations of antimony and copper with peat moss indicate that peat moss has the potential to participate in other binding reactions, such as those with the organic part of the complex. These are not reaction sites that are available on a zeolite.

In contrast to the zeolite, activated carbon's removal mechanisms tend to bind organic molecules. The removals of metals by peat moss and a virgin coconut hull-based granular activated carbon (GAC) are shown on Figure 5-3. The peat has approximately 40% of the carbon content of the GAC, and the data shows that the GAC has much poorer removals of antimony compared to the peat, but better removal of copper. Copper is more likely to complex with organic matter than antimony, the reduction of removal efficiency for antimony is not surprising in a media that is not known for substantial ion exchange of ionic free metals in solution.

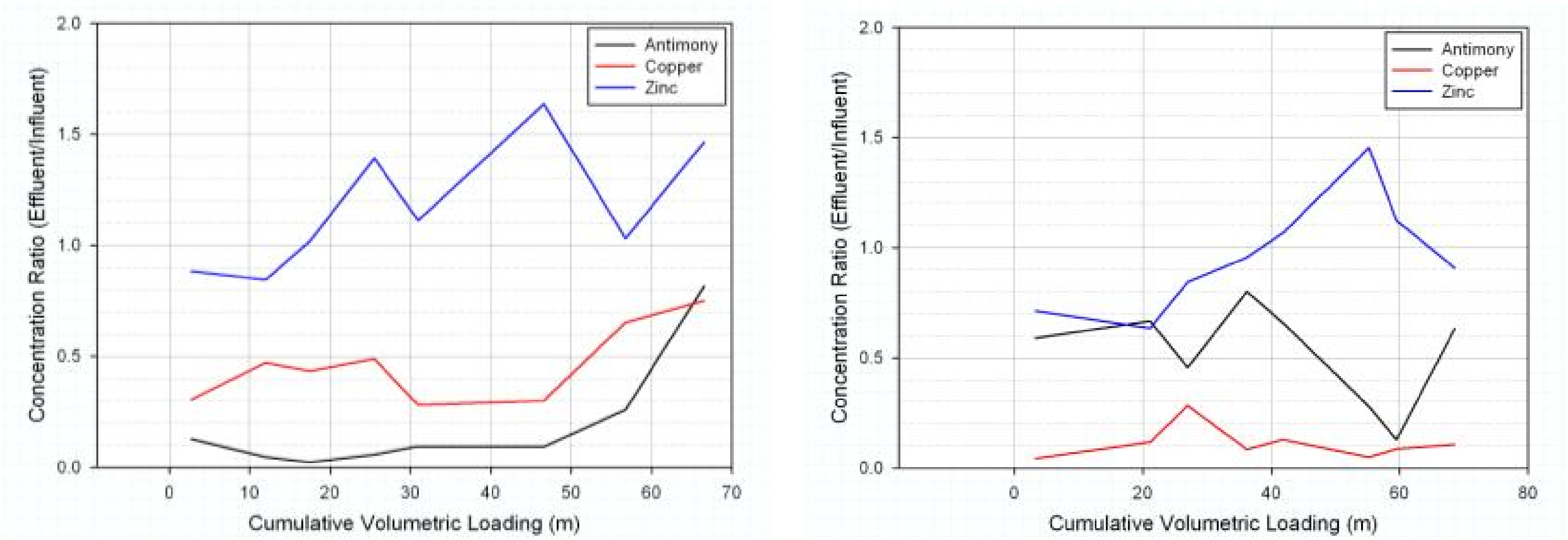


**Figure 5-3. Removal of Dissolved Antimony, Copper, and Zinc by Peat Moss-Sand (left) and GAC-Sand (right)**

## 5.3 *Effects of Soil Chemistry*

Soil chemistry can be described using several parameters, including cation exchange capacity (CEC), anion exchange (AEC), soil pH, soil organic matter content, and the concentrations of phosphorus, nitrogen, iron, aluminum, and manganese. Parameters such as CEC and AEC do not measure specific chemicals in the soil but instead measure the ability of the soil to attract certain pollutants based on their valence charge. These parameters/constituents are easily measured and often are reported from a soils' analysis performed at the state agricultural laboratory. The concentrations/values of these parameters have been linked by many researchers to improved or degraded pollutant removal performance. Many researchers are working to optimize bioretention media for the removal of specific pollutants and are reporting some of these soil chemical properties for their specific media. Based on these studies, states have tried to improve bioretention media performance by suggesting ranges of values for various chemical properties. Table 5-2 shows a comparison of media composition guidance with a focus towards those documents that specify media chemical properties. A scan of the chemical properties column shows similar recommendations for media chemical composition. In some cases, the guidance has been copied from one region to another based on success in areas with a longer history of stormwater quality management. Another interesting point to note is that the media requirements are different between infiltration and bioretention systems. However, in many cases, these devices are used for the same purpose – water quality treatment, and use the same unit removal processes for the same pollutants.

To date, no meta-analysis has been published of pollutant removal from stormwater runoff based on soil chemical properties. The research groups at Penn State Harrisburg and the University of Alabama are using several extensive (bio)filter media data sets to draw preliminary conclusions about optimal mixtures for pollutant removal in infiltration/biofiltration/bioretention/filtration systems for stormwater treatment, as noted in the above discussion. In addition, relationships between the soil parameters will be evaluated so that relationships can be developed between pollutant removal and a minimum number of soil chemistry measurements to minimize cost of analysis.

The three parameters most frequently listed in Table 5-2 by the different states guidance documents and in the studies of bioretention media are organic matter (OM) content, CEC, and soil pH. Clark and Pitt (2010) describe the impact of these parameters on median pollutant removal. This section focuses on the impact of soil parameters on pollutant retention capacity. Figure 5-4 shows the effects of OM content and CEC on pollutant capacity calculated from the long-term column tests, with a focus on five pollutants (three filtered metals, ammonia, and fluoride [an anion]), each of which have different water chemistry and, for the metals, different levels of complexation.

For the metals analyzed, it was expected that removal capacities would increase as the OM and CEC increased. However, this held true only for the dissolved cadmium and antimony. The shape of these curves, though, is somewhat different between CEC and

OM. For CEC, the capacities were very low until the CEC exceeded approximately 20 meq/100g. Then the capacities increased substantially. For these two metals, the capacities increased across the entire range of organic matter in the data set and no threshold concentration was observed. The capacity for arsenic was independent of both CEC and OM, indicating that the arsenic was in a form that was not readily removed through cation exchange processes. Arsenic in water typically is not found in the +2 charge state and it is therefore more difficult to remove through ion exchange. Interestingly, the capacity of the media for ammonia was also a function of both the CEC and OM. This indicates that the ammonia may have been present as $NH_4^+$, instead of $NH_3$. $NH_4^+$ would be expected to exchange with the cations in the media, although the +1 valence charge should indicate a low preference for exchange, especially when compared to the divalent metals. The highest capacities for fluoride were found in the media with the highest organic content and the highest cation exchange, an unexpected result since fluoride is an anion and its capacity should be independent of CEC.

The CEC reported by the soils lab was effective CEC (CECe). It is the sum of the calcium, magnesium, and potassium concentrations released from the media during testing. It is a measure of the readily-exchangeable cations. CEC may be measured by several different methods. Other methods likely would have reported different values of CEC; however, it is anticipated that the data trends would remain consistent. One question that the effective CEC raises is whether the pollutant removal is affected by the concentration of the components of the CEC in the clean media. Figure 5-5 shows the impact of magnesium and potassium concentration on the pollutant capacities. These constituents are shown because they are two of the three components of an effective CEC calculation.

Similar to the effects of CEC on capacity, the content of exchangeable potassium and magnesium had no impact on the capacity of the media for arsenic. This is likely due to the influent chemistry, with arsenic, while “dissolved”, not being in a +2 value and thus readily available for exchange. For the other pollutants, increasing potassium and magnesium contents may be related to an increase in pollutant capacity, although the data was highly variable. A review of the CEC data for this study showed that the CEC content of the media did not decrease over time, but either remained steady or increased. Figure 5-6 highlights the effluent water chemistry as it relates to the components of CEC. The effluent concentrations have been normalized by dividing the effluent quality by the influent quality. Values less than 1 indicate uptake by the medium, while values greater than 1 indicate ion release by the media, likely through exchange reactions. The results indicate that peat moss scavenges calcium, but does not remove or leach potassium and does leach some magnesium. If the increase in calcium concentration is sufficiently large compared to the losses of Mg and K, an increase in CEC would be expected. As noted in Table 5-3, this occurred for peat moss. For the site zeolite, Table 5-3 shows that the CEC decreased over time, which is supported by the leaching of calcium and potassium from the media. These results indicate that CEC can be used to provide rankings of capacity, but cannot be used to quantify exhaustion of the media, especially for media that scavenge a particular ion or where the calcium, magnesium, and/or potassium concentrations are substantially greater than the metals.

When elevated Ca, Mg, and/or K occurs, these ions can overwhelm the binding preferences of the media simply due to their high concentrations in a process similar to the regeneration of sorption media in industrial applications.

**Table 5-2. Recommended Bioretention Media Compared for Different Areas of the U.S.**

| EPA Rain Zone | City, State | Infiltration Rate | Soil Type | Chemical Properties |
|---|---|---|---|---|
| *BIORETENTION SYSTEM MEDIA* | | | | |
| 1 | PA | | 75% Loam, 25% Compost, <10% clay | pH: 5.5-6.5 Organic Matter (OM): 5-10% |
| 2 | VA | | 50% Sand, 20% Compost, 30% top soil | |
| 3 | Atlanta, GA | | Loam w/ 10-25% clay | pH: 5.5-6.5<br>OM: 1.5-3% Soluble salts: <500 ppm |
| 4 | Columbia, MO | | 10-25% clay;<br>30-55% silt;<br>35-60% Sand | pH: 5.2-7.0<br>OM: 1.5-4%<br>Mg: 35 lb/acre $P_2O_5$: 75 lb/acre<br>$K_2O$: 85 lb/acre Soluble salts: <500 ppm |
| 5 | Austin, TX | | S: 70-90%; clay: 2-10% | $n$ = 0.45 OM: 1-4% CEC: 10 meq/100g |
| 6 | CA | | L (10-25% clay) | pH: 5.5-6.5 OM: 1.5-3% Soluble salts: <500 ppm |
| 7 | WA | | 65% Loamy Sand; 35% Compost | pH: 5.5-7.0 |
| 8 | WA | | Loamy Sand | CEC: ≥ 5 meq/100g |
| 9 | Colorado Springs, CO | | Sandy Loam and sand-peat mix | |
| *INFILTRATION SYSTEM MEDIA* | | | | |
| 1 | PA | | loamy | |
| 2 | VA | 0.52-8.27 in/hr | loamy mix (<30% clay) | |
| 3 | Atlanta, GA | 3-5 in/hr | | |
| 4 | Columbia, MO | | HSG A and B | |
| 5 | Austin, TX | 3.5 ft/day | | |
| 6 | CA | 0.2-0.38 in/hr w/ ponding | HSG A-D type soils w/ low clay | |
| 7 | WA | 0.13 - 10 in/hr | loamy sands | CEC: ≥ 5 meq/100g |
| 8 | WA | 0.5-2 in/hr | loamy sands | CEC: ≥ 5 meq/100g |
| 9 | Colorado Springs, CO | > 0.5 in/hr | | |

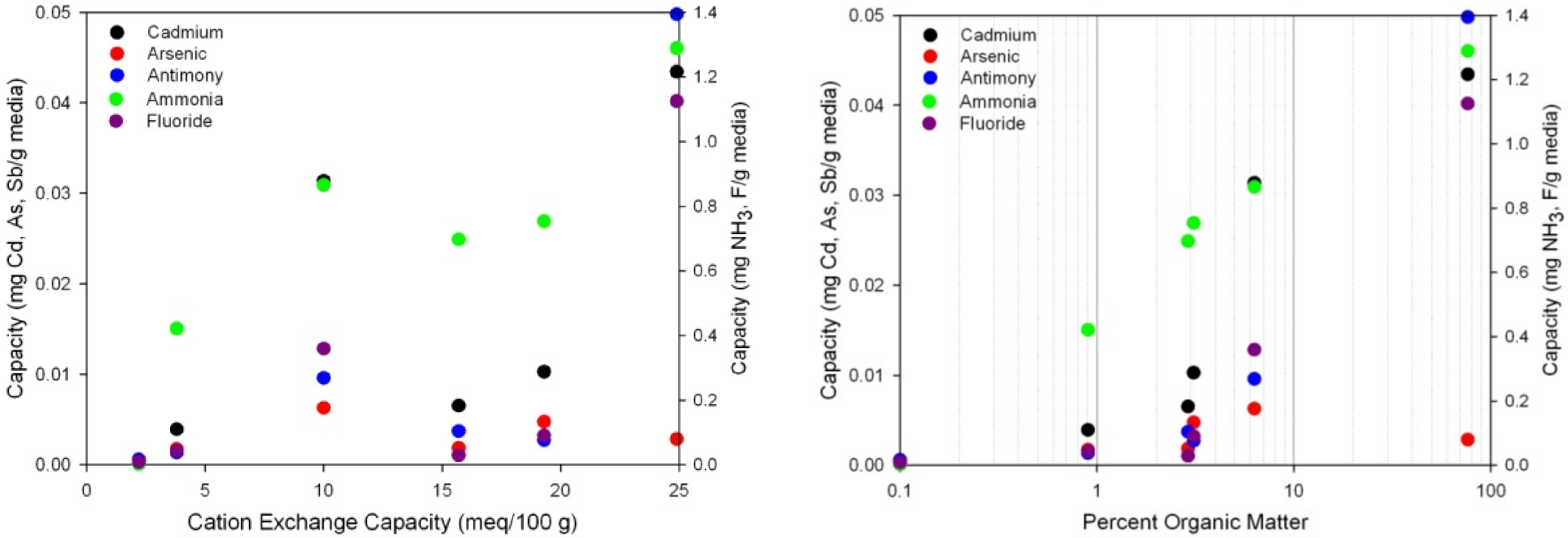


**Figure 5-4. Effects of Effective CEC and OM on Media's Capacity to Retain Cadmium (Cd), Arsenic (As), Antimony (Sb), Ammonia ($NH_3$), and Fluoride (F)**

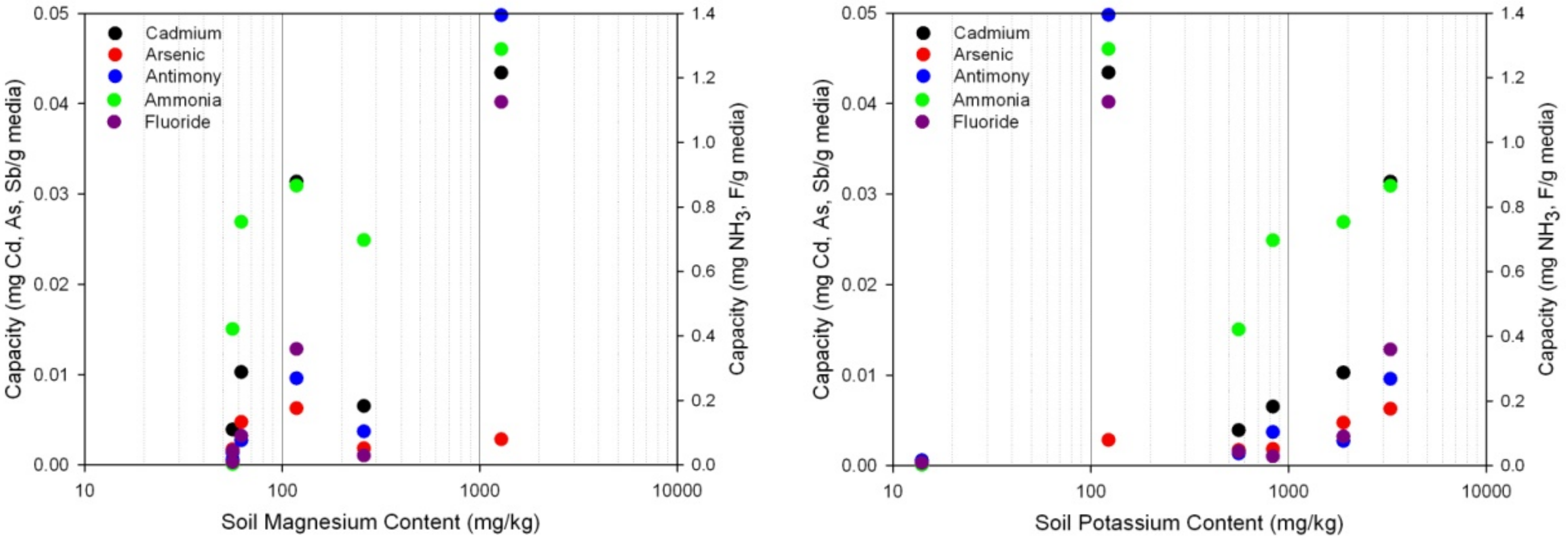


**Figure 5-5. Effect of Magnesium and Potassium Content on Media Pollutant Capacity**

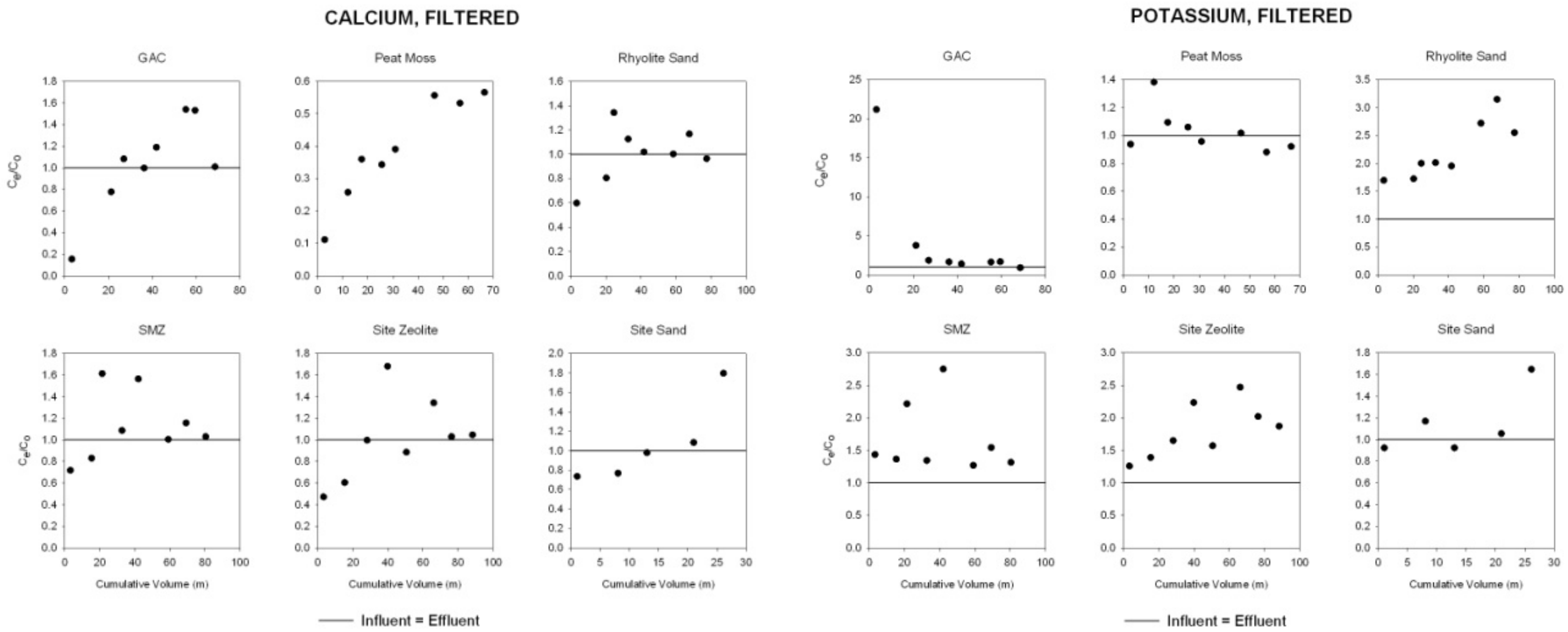


**Figure 5-6. Removal of CEC Components during Long-Term Filtration Tests (calcium left; magnesium right; potassium next page)**

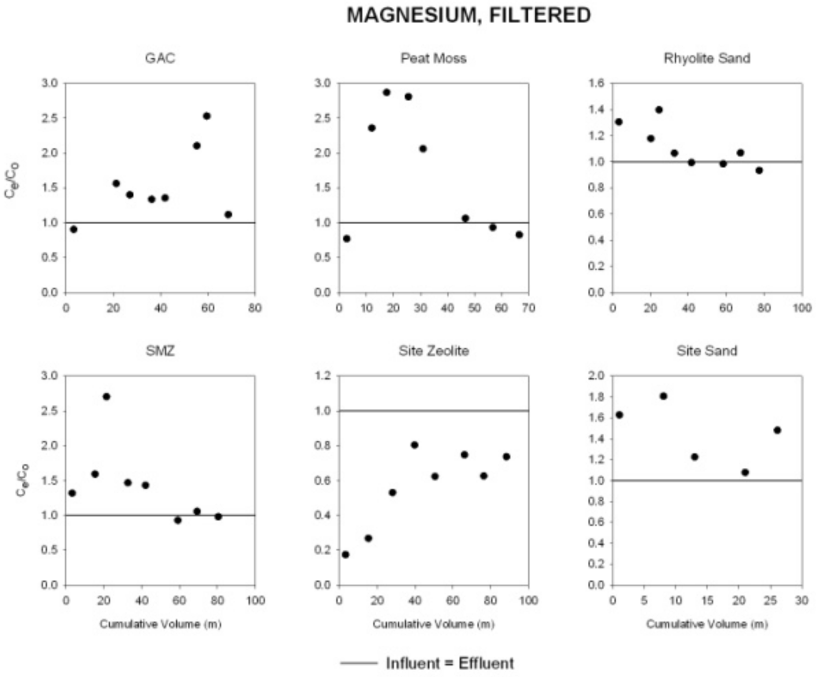


**Figure 5-6. Effect of CEC components on pollutant removal (cont.).**

**Table 5-3. Changes in CEC over Time - Comparison of "Clean" Media with "Used" Media at End of Long-Term Column Testing**

| | Initial/Clean Media (meq/100 g) | Experiment End, Top Layer of Used Media (meq/100 g) |
|---|---|---|
| Site Sand | 2.2 | 1.9 |
| Rhyolite | 3.8 | 7.4 |
| Site Zeolite | 19 | 9.4 |
| SMZ | 16 | 24 |
| GAC | 10 | 21 |
| Peat Moss | 25 | 109 |

As described in Clark and Pitt (2010), an increase in removal of filtered copper was observed as the CEC and OM increased, but copper removal was found to decrease as the pH increased. As shown in Figures 5-2 and 5-3, copper removal was similar between the zeolite and peat moss media, with excellent removals seen with the coconut-hull GAC. This carbon had the lowest soil pH, while having the highest CEC and percent carbon. The CEC and OM of the soil decreased as the soil pH increased. This was not expected since the GAC effluent typically had the highest pH. For the other metals, however, median removal of these filtered metals was not dependent on soil pH, OM, or CEC. Zinc removal was poor, nickel was generally good, and cadmium removal was generally complete at the range of values seen in this study. These results indicate that, over the range of values and media used to date, removals may not be impacted by the media chemistry for Ni, Cd, and Zn. Zinc removal may be limited by prior zinc saturation of the media.

Like filtered copper, phosphorus removal also showed trends based on soil chemistry. Phosphorus removal decreased as the organic matter content of the media increased and as soil pH decreased. Based on this set of data, carbon content in the media greater than 5 – 7% resulted in phosphorus export from the media, rather than its removal. This threshold of carbon content was the division between media based on organic matter (coconut hull carbon, peat moss) and comparatively-inorganic zeolites. This is particularly important in watersheds where phosphorus is a limiting nutrient. These preliminary results indicate that minimizing phosphorus content to the amount required for plant growth will improve phosphorus removal and retention in the media, although these results are limited because most of the media has a low organic content. Testing is ongoing with a local leaf-litter compost to add data points to that region of the graph to better isolate where phosphorus removal ends and export begins.

Studies also have related pollutant capture and retention to the concentrations of nitrogen, phosphorus, aluminum, iron and manganese in the media. Since Cd, Ni, and Zn removals were consistent in the data used in these studies across the range of soil chemistry conditions (CEC, OM, and pH), it was expected that no effect of the concentrations of Al, Fe, Mn, P and N would be seen. The two pollutants for which effects were seen were copper and phosphorus. For phosphorus, it can be seen that increasing aluminum concentration in the media will increase removals, while for phosphorus media content, concentrations above 6 ppm appear to result in reduced removals and potential transport. Copper removals were not affected by the concentrations of either nitrogen or phosphorus in the media, however, it appears that increasing the iron concentration in the media may lead to increases in copper removal. In general, the manganese data is limited in its utility because most of the media had similar manganese contents.

## *5.4 Trade-offs*

Pollutant removals in the bioretention media generally occur through ion-exchange reactions. For the design of bioretention facilities, it is important to know what ions are being exchanged during pollutant removal and to determine whether these exchanged ions are problematic in the effluent water and discharge location. An example of the trade-offs in pollutant capture versus ion export is shown in Figure 5-7 for a GAC-sand column of varying column depths. In this case, the capture of cadmium was excellent and was not a function of column depth. However, deeper columns result in greater export of potassium from the media during the initial parts of the treatment cycle, likely as a result of increased ion-exchange reactions occurring in the media due to increasing media contact (and increased media amounts as the residence time increases. These ion exchange reactions likely involve the capture of the metals as well as the capture of the hydrogen (hydronium) ion, since the pH of the effluent water was at least 1 pH unit higher than the influent water for these columns.

Based on the results in Figure 5-7, it appears that a depth of 14 inches would be sufficient for cadmium removal, since cadmium capture is not a function of depth in the ranges investigated during the supporting study, and it would minimize export of potassium from the media. However, as seen in Figure 5-8, this is not true for all pollutants. The GAC provided excellent capture of nitrate until its removal capacity was saturated. Increasing the depth increased the nitrate capture substantially. This is because the capacity for nitrate capture is small on a unit weight basis. Therefore, increasing the mass of GAC in the media, by making the media depth deeper, improved the nitrate capture and resulted in a later breakthrough on a cumulative loading basis.

These data can be re-evaluated and combined with the long-term column tests, including the media mixture columns to investigate the effectiveness of certain mixes. Figure 5-9 shows the effects of different combinations of GAC and peat moss on the removal of nitrate and phosphate. Nitrate removal increases as the percent composition of the media mixture increases in GAC; however, phosphate release is increased in direct correlation with the percent GAC. Peat moss provided no substantial removal of nitrate in the long-term column testing, but also released substantially less phosphate. In areas with problems from both phosphate and nitrate, a compromise would need to be made in the composition of GAC and peat moss. These two media components were highlighted here because during the long-term testing, both media mix components provided good removals of most metals, typically to below permit limits.

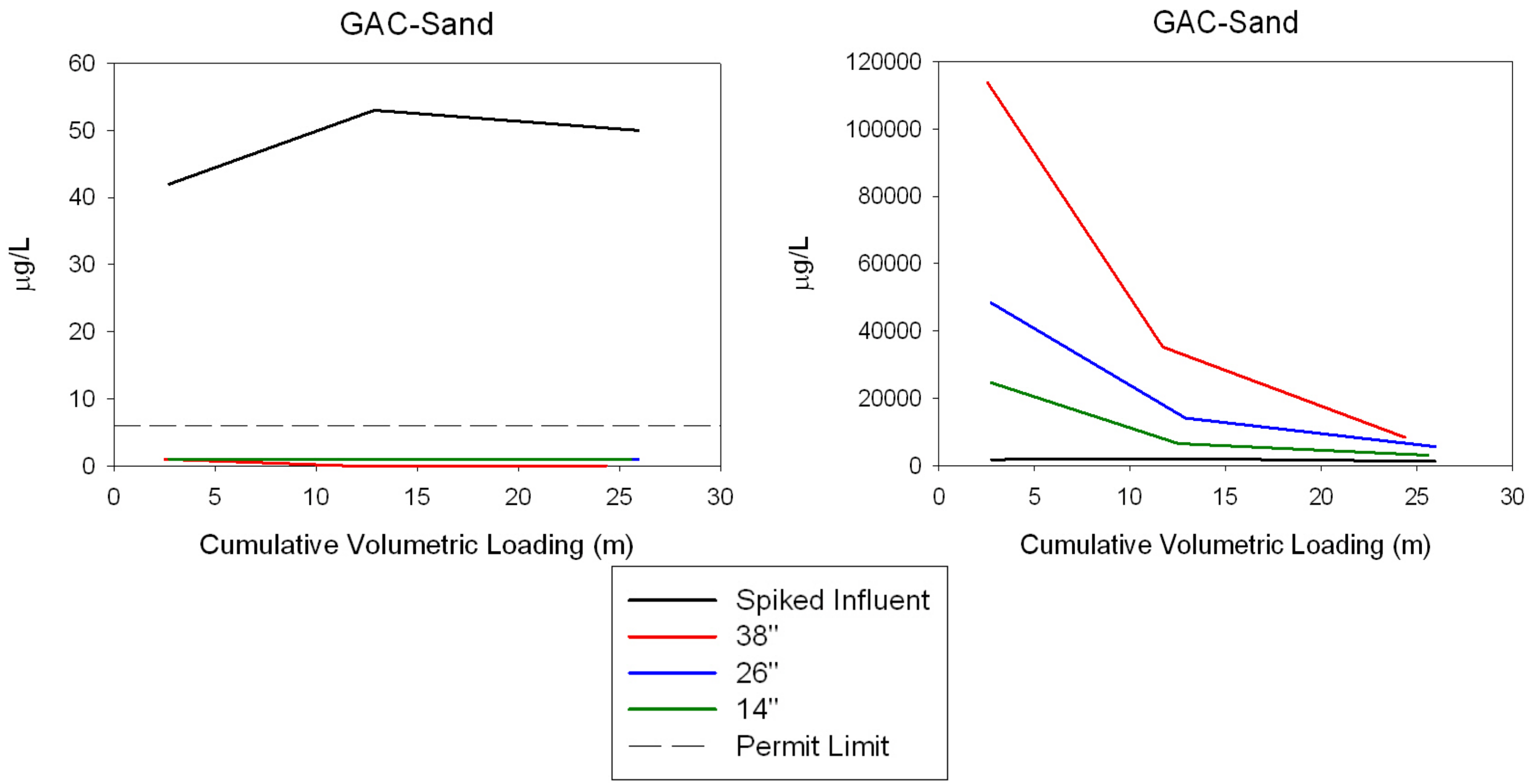


**Figure 5-7. Ion Exchange for GAC-Sand Mixture as a Function of Column Depth for Cadmium (left) and Potassium (right)**

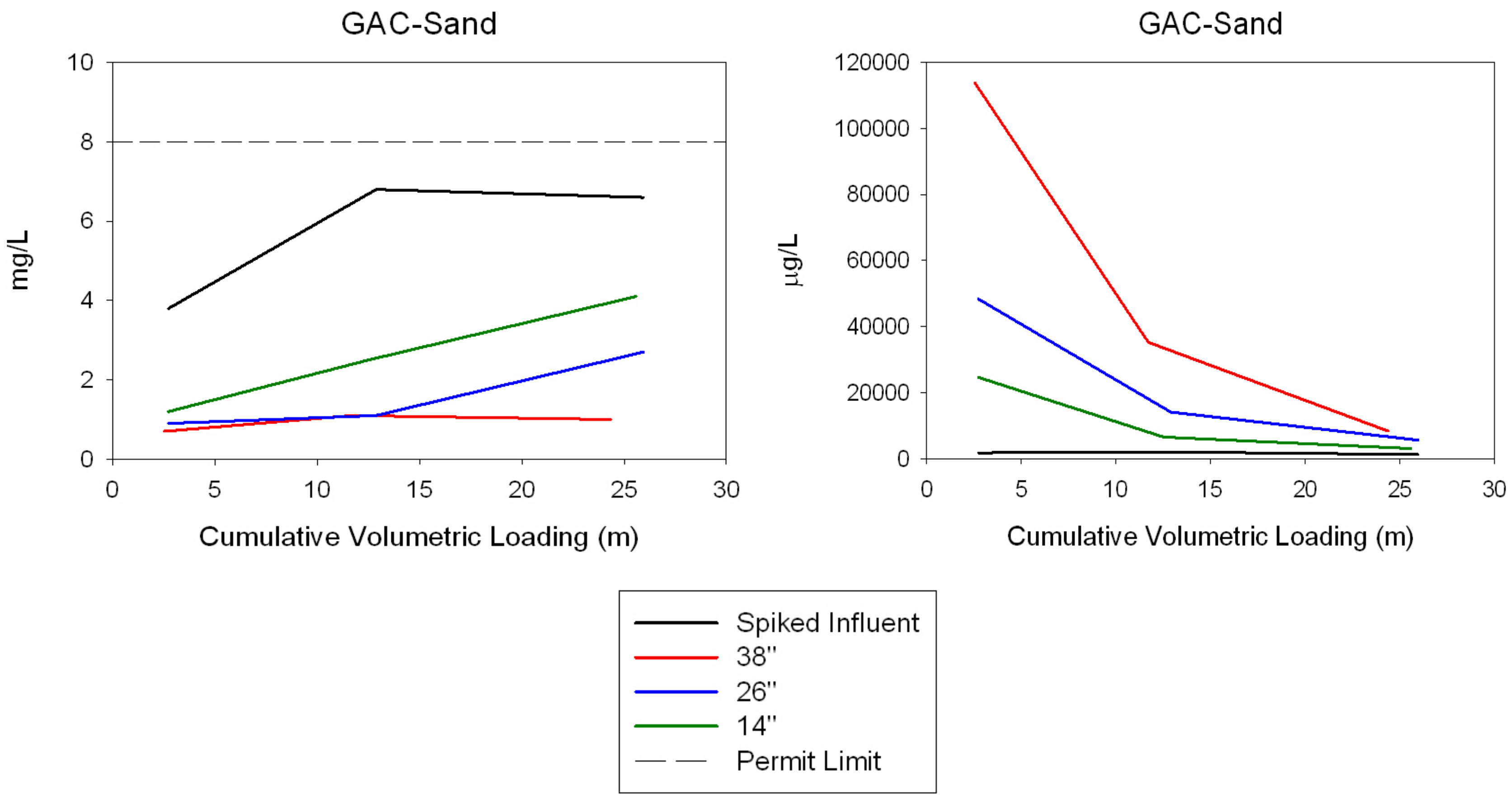


**Figure 5-8. Ion Exchanges for GAC-Sand as a Function of Column Depth for Nitrate (left) and Potassium (right)**

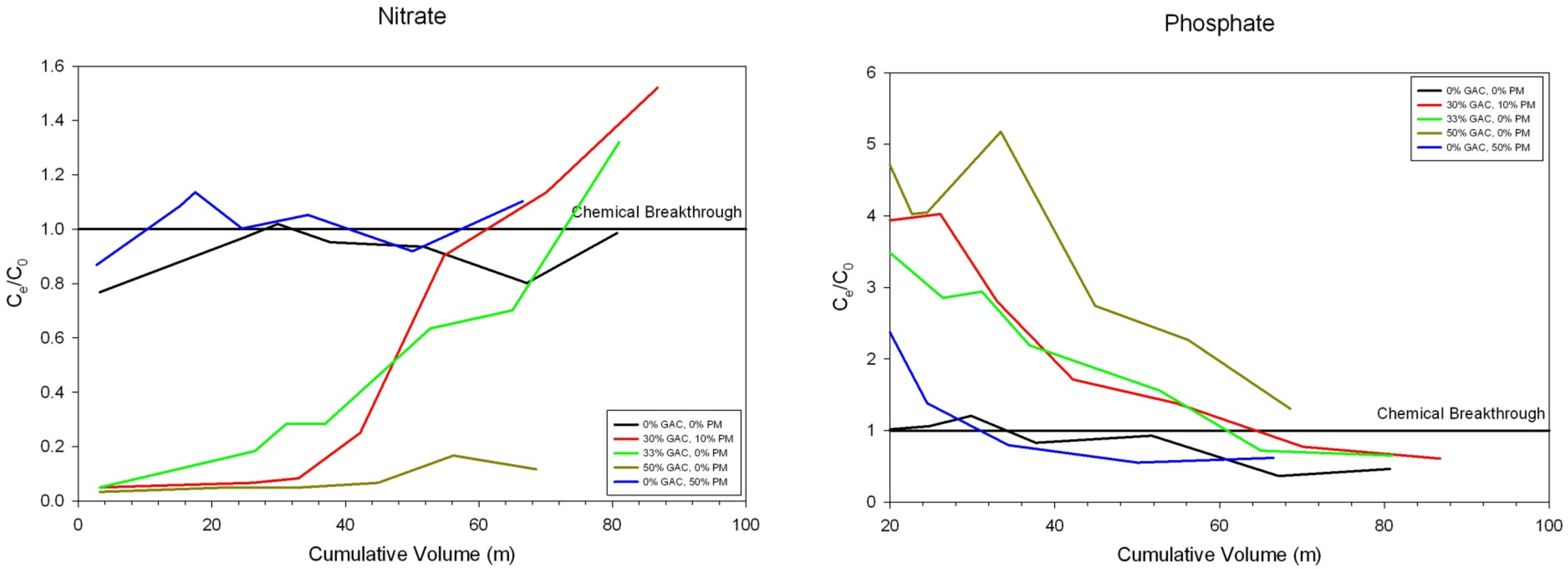


**Figure 5-9. Comparison of Percent Composition GAC and Peat Moss on Nitrate and Phosphate Removal**

## *5.5 Summary of Reactions Occurring in Stormwater Treatment Media*

These data evaluations indicate that predicting the treatment ability of bioretention/infiltration/filtration media is a function of both soil and water chemistry. They also indicate that typical assumptions that all dissolved metals are ionic and are removed rapidly by media that provide ion exchange benefits are not true. Therefore, it was imperative to run these experiments with spiked stormwater that had been given a short time to equilibrate before testing. This test sequence is more likely to replicate the field conditions where few of the pollutants are predominately in their ionic form, even those that have been filtered. One method for determining the soil factors that affect capacity is the Pearson Product Moment correlation. Table 5-4 shows the Pearson correlation coefficients for the long-term column capacity estimates, while Table 5-5 contains the Pearson coefficients for the traditional batch capacity estimates.

For the long-term column tests, very few correlations were found between estimated pollutant capacity (columns) and clean-media soil chemistry (rows) parameters, even when the p value for statistical significance was relaxed to 0.10, instead of the traditional 0.05. This is likely due to the lack of breakthrough for most of the metals and the stopping of several columns' testing due to clogging and the lack of maintenance effectiveness. At the time that these long-term tests were halted, many columns, which had different soil chemistries, had similar effluent concentrations and similar pollutant loadings (which were used as estimates of capacity without the ">" signs seen in Table 4-63). When the batch capacity estimates are correlated with the soil chemistry parameters measured through the state soils' lab, more correlations are statistically significant. The limitation of these tests is the batch nature of the tests, which do not mimic the intermittent loading of the columns with quiescent times between testing events. Therefore, these two data sets were combined with correlations between soil chemistry and the estimated capacities from the 14-inch columns (columns with less media and which were more likely to approach breakthrough, even during the short testing time of the varying column tests) to create Table 5-6. Plus signs indicate positive correlation coefficients, while minus signs indicate negative correlation coefficients. Those combinations where correlation coefficients were statistically significant (at the $p<0.1$ level) are highlighted with bold-type plus signs in the table.

## Table 5-4. Pearson Correlation Coefficients between Soil Chemistry and Long-Term Column Capacity

| | As | Al | B | Ca | Cd | Cu | Fe | Mg | Mn | Ni | Pb | Zn | K | Na | Cr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CEC | | | -0.854 | | | -0.765 | | | | | | | | | |
| OM | | | | | | | | | | | | | | | |
| Soil C | | | | | | | | | | | | | | | |
| Soil N | | | | | | | | | | | | | | | |
| Soil P | | | | | | | | 0.994 | | | | | | | |
| Soil pH | | | | | | | | 0.782 | | | | | | | |
| Soil K | | | | | | | | 0.833 | | | | | | | |
| Soil Mg | | | | | | | | | | | | | | | |
| Soil Cu | | | | | | | | | | | | | | | |
| Soil S | | | | | | | | 0.907 | | | | | | | |
| Soil Zn | | | | | | | | | | | | | | | |
| Soil Acid | | | | | | | | | | | | | | | |
| Soil Ca | | | | | | | | | | | | | | | |

| | Tl | Sb | NO2 | NO3 | NH3 | TP | COD | F | SO4 | PO4 | TN | Cl | Hard |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CEC | | | | | | | | | | | | | |
| OM | | | | | | | | | | | | | |
| Soil C | | | | | | | | | | | | | |
| Soil N | | | | | | | | | | | | | |
| Soil P | | | | | | 0.781 | | | | 1.000 | | | |
| Soil pH | | | | | | | | | | 0.759 | | | |
| Soil K | | | | | | 0.805 | | | | 0.841 | | | |
| Soil Mg | | | | | | | | | | | | | |
| Soil Cu | | | | | | | | | | | | | |
| Soil S | | | | | | 0.748 | | | | 0.939 | | | |
| Soil Zn | | | | | | | | | | | | | |
| Soil Acid | | | | | | | | | | | | | |
| Soil Ca | | | | | | | | | | | | | |

The pair(s) of variables with positive correlation coefficients and P values below 0.10 tend to increase together. For the pairs with negative correlation coefficients and P values below 0.10, one variable tends to decrease while the other increases. For pairs with P values greater than 0.10, there is no significant relationship between the two variables.

## Table 5-5. Pearson Correlation Coefficients between Soil Chemistry and Batch Testing Capacities

| | As | Al | B | Ca | Cd | Cu | Fe | Mg | Mn | Ni | Pb | Zn | K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CEC | | | | | | | | | | 0.940 | 0.783 | | 0.852 |
| OM | | | | 0.996 | 1.000 | 0.933 | | | 1.000 | 0.890 | 0.983 | 0.975 | 0.946 |
| Soil C | | | | 0.976 | 0.971 | 0.994 | | | 0.964 | 0.833 | 0.917 | 0.997 | 0.858 |
| Soil N | | | | 0.976 | 0.980 | 0.980 | | | 0.974 | 0.884 | 0.949 | 0.994 | 0.899 |
| Soil P | | 0.741 | 0.914 | | | | 0.988 | | | | | | |
| Soil pH | | | | | | | 0.774 | | | | | | -0.798 |
| Soil K | | 0.936 | | | | | 0.908 | 0.855 | | | | | |
| Soil Mg | | | | 0.986 | 0.986 | 0.905 | | | 0.987 | 0.898 | 0.975 | 0.955 | 0.961 |
| Soil Cu | | | | | | | | | | | | | |
| Soil S | | 0.785 | 0.899 | | | | 0.927 | 0.824 | | | | | |
| Soil Zn | | | | 0.982 | 0.985 | 0.889 | | | 0.987 | 0.896 | 0.979 | 0.946 | 0.964 |
| Soil Acid | | | | 0.958 | 0.959 | 0.856 | | | 0.960 | 0.898 | 0.958 | 0.917 | 0.965 |
| Soil Ca | 0.783 | | | | | | | | | | | | |

| | Na | Cr | Tl | Sb | NO3 | NH3 | TP | COD | F | SO4 | PO4 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CEC | | | 0.885 | 0.810 | 0.970 | | | | | | |
| OM | 0.775 | | 0.878 | | | | | | | | 0.730 |
| Soil C | | | 0.883 | | | | | | | | |
| Soil N | | | 0.911 | | | | | | | | |
| Soil P | | | | | | | | | | | |
| Soil pH | | | | | | | | | | | |
| Soil K | | 0.795 | | | | | | | 0.739 | | |
| Soil Mg | 0.853 | | 0.871 | | | | | | | | 0.729 |
| Soil Cu | | | | | | | | | | | |
| Soil S | | | | | | | | | | | |
| Soil Zn | 0.840 | | 0.859 | | | | | | | | 0.752 |
| Soil Acid | 0.891 | | 0.853 | | | | | | | | 0.730 |
| Soil Ca | | | | | | 0.797 | 0.779 | 0.764 | | 0.763 | |

The pair(s) of variables with positive correlation coefficients and P values below 0.10 tend to increase together. For the pairs with negative correlation coefficients and P values below 0.10, one variable tends to decrease while the other increases. For pairs with P values greater than 0.10, there is no significant relationship between the two variables.

**Table 5-6. Trend Comparison of Pearson Correlation Coefficients: Long-Term Columns, 14-inch Columns, and Batch Capacity Testing**

| | As | Al | B | Ca | Cd | Cu | Fe | Mg | Mn | Ni | Pb | Zn | K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CEC | | | - | | | - | | | | + | + | | + |
| OM | | | | ++ | + | + | | | + | + | + | + | + |
| Soil C | | | | + | ++ | ++ | | | + | ++ | + | + | + |
| Soil N | | | | + | ++ | + | | | + | ++ | + | + | + |
| Soil P | | + | ++ | | | | + | + | | | | | |
| Soil pH | | | | | | | + | + | | | | | - |
| Soil K | | + | | | | | + | ++ | | | | | |
| Soil Mg | | | | + | + | + | | | + | + | + | + | + |
| Soil Cu | | | | | | | | | | | | - | |
| Soil S | | + | + | | | | + | ++ | | | | | |
| Soil Zn | | | | + | + | + | | | + | + | + | + | + |
| Soil Acid | | | | + | + | + | | | + | + | + | + | + |
| Soil Ca | + | | | | | | - | | | | | | |

| | Na | Cr | Tl | Sb | NO2 | NO3 | NH3 | TP | COD | F | SO4 | PO4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CEC | | | + | + | | + | | | | | | |
| OM | + | | + | + | + | | - | + | | + | | ++ |
| Soil C | | | + | | | | | | | | | |
| Soil N | | | + | | | | - | | | | | |
| Soil P | | | | | | + | | + | | | | + |
| Soil pH | | | | | | | | | | | | + |
| Soil K | | + | | | | | | ++ | | + | | + |
| Soil Mg | + | | + | + | + | | | | | + | | ++ |
| Soil Cu | | | | | | | | | | | | |
| Soil S | | | | | | | | ++ | | | | + |
| Soil Zn | + | | + | + | + | | | | | | | ++ |
| Soil Acid | + | | + | | | | | | | | | + |
| Soil Ca | | | | | | | + | + | + | | +- | |

| | TN | Cl | Hard |
|---|---|---|---|
| CEC | | | |
| OM | | + | + |
| Soil C | | | |
| Soil N | | + | + |
| Soil P | + | | |
| Soil pH | + | | |
| Soil K | + | | |
| Soil Mg | | | |
| Soil Cu | | | |
| Soil S | + | | |
| Soil Zn | | | |
| Soil Acid | | | |
| Soil Ca | | | |

NOTE: "+" indicates that the coefficient for one of the soil chemistry-pollutant capacity correlation tests was positive, while "-" indicates the correlation coefficient was negative. Entries where two or more tests had correlation coefficients with the same sign are highlighted in bold type.

Media that appear to have the best removal ability for a wide range of metallic pollutants are those that have both cation exchange ability (when treatment device designs allow sufficient contact time) and comparatively high organic matter content (as seen by the multiple positive correlations between components of organic media – soil C, soil OM, soil N – and pollutant capacities. Also important is a readily available supply of exchangeable cations (Mg, Ca, Na, K) for those pollutants that are in solution in their ionic forms. Media mixtures typically work best because of the variety of removal mechanisms available and because the trade-offs can be minimized. This is true because a mixture produces the opportunity to use a second media to aid in the capture of pollutants “leached” by the first. However, these media characteristics cannot be used easily to measure media exhaustion for additional removal, especially for those media which scavenge one or more of the ionic components of CEC. For metals, this also may require a slightly acid media pH because of the generally increased solubility and resultant uptake of metals at lower pHs. Lower pHs and higher organic matter contents, however, must be evaluated further if phosphorus removal is also desired since phosphorus is removed better at higher pHs and lower organic matter contents. These results also highlight the trade-offs in pollutant capture versus cation/mineral/pollutant export when using ion-exchange media.

## 6.0 References

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## 7.0 Appendices

The following appendices are attached as separate files:

Appendix A: Clogging, Breakthrough and Removal Tests with Full-Length Columns
- A1: Flow Rates and Clogging Results from Full-Depth Column Tests
- A2: Long-Term Full-Scale Column Test Flow Rates, and Influent and Effluent Concentrations
- A3: Time Series Full Scale Column Influent and Effluent Constituent Concentration Breakthrough Plots
- A4: Probability Plots from Full-Scale Column Tests for Major Constituents and Nutrients
- A5: Probability Plots of Heavy Metals and Trace Constituents from Full-Scale Column Tests
- A6: Particle Size Removal Data from Long-Term, Full-Scale Column Tests
- A7: Constituent Removal Analyses from Full-Scale Column Tests
- A8: Heavy Metal and Trace Constituent Removals from Full-Scale Column Tests
- A9: Mercury and Radiological Data from the Full-Scale Column Tests
- A10: Breakthrough Ce/Co Plots from the Full-Depth Column Tests
- A11: Grouped probability Plots of Selected Permitted Constituent Removals during Long-Term Column Tests

Appendix B: Residence Time Tests using Varying Depth Columns

Appendix C: Media Capacity and Batch Kinetics Tests
- C1: Batch Kinetics Tests
- C2: Traditional batch capacity testing results for biofilter media components

Appendix D: Aerobic and Anaerobic Leaching Tests