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ASSESSING RISK AND POTENTIAL REUSE OF HARD ROCK MINE DRAINAGE

PASSIVE TREATMENT SOLIDS

A THESIS APPROVED FOR THE
SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE

BY THE COMMITTEE CONSISTING OF

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Abstract

Ecologically engineered mine drainage passive treatment systems rely on a series of biogeochemical reactions to decrease concentrations of ecotoxic trace metals and have proven to be an effective way to improve water quality in watersheds impacted by mining, especially in areas where access or funding is limited. Passive treatment systems require minimal regular maintenance, but occasional rehabilitative maintenance is necessary to ensure continued efficacy of the systems. These efforts include addressing residual solids by removal of iron oxyhydroxides from oxidation ponds and replacing of spent organic material from vertical flow bioreactors. In this study, iron oxyhydroxides and organic materials from two passive treatment systems located in the Tar Creek Superfund Site in the Tri-State Lead-Zinc Mining District were examined for total and leachable trace metals concentrations. The USEPA's toxicity characteristic leaching procedure (TCLP) and synthetic precipitation leaching procedure (SPLP), as well as the USGS's field leach test (FLT), were performed to evaluate the leachability of arsenic, cadmium, lead, manganese, nickel, zinc, and other trace metals from the residual solids. Biochar, municipal biosolids, and coal combustion residuals (CCR) were added to the solids to attempt to increase metals sorption and decrease leaching. The leachate produced from TCLP tests did not exceed Resource Conservation and Recovery Act limits for any of the contaminants of concern, but SPLP and FLT leachates did exceed some guidelines from the Oklahoma Water Resources Board. The addition of biochar, biosolids, and CCR did not decrease leaching of metals and in some cases increased leaching of contaminants of concern. Although it is not necessary to dispose of the mine drainage residual solids examined in this study in a hazardous waste repository, further research is necessary to determine the feasibility of reuse of the solids in subaqueous or subaerial environments.

Chapter One: Introduction

Mine drainage is a major environmental problem worldwide (e.g., Younger et al., 2002). Mine drainage is caused by the exposure of sulfide minerals to the atmosphere and water during mining and is characterized by elevated concentrations of metals and sulfate, acidic to neutral pH, and greater than average conductivity and toxicity (Moodley et al., 2018). The United States Forest Service projected that over 6000 km of streams were impacted by mine drainage as of 2010, polluting fresh water sources and impacting the ecological integrity of streams (Naidu et al., 2019). Discharges of mine drainage can be treated using continual chemical additions (active treatment) or by geochemical and biological systems with no continual energy or chemical input (passive treatment, Watzlaf et al., 2004). Active treatment includes neutralization with caustic soda, lime, and other chemicals, while passive treatment includes aerobic wetlands and ponds, limestone drains, permeable reactive barriers, and bioreactors (Naidu et al., 2019). Each treatment option forms residual solids which require further handling, though active treatment solids have much greater water content and thus require more frequent disposal (Skousen et al., 2017). These solids include iron oxyhydroxides from active treatment and some passive treatment process units, and organic matter from biologically based passive treatment process units (Kefeni et al., 2017).

Aerobic wetlands and oxidation ponds in passive treatment systems are typically designed to operate for 20-25 years, after which the buildup of iron oxyhydroxides and other metal precipitates will decrease hydraulic retention time and the efficacy of the treatment unit (Watzlaf et al., 2004). Vertical flow bioreactors (VFBRs) require more operational evaluation but can be an effective form of treatment by promoting bacterial sulfate reduction and metal sulfide precipitation. They may operate for a similar duration if organic matter is mixed and maintained

regularly (Skousen et al., 2017). Frequent monitoring of passive treatment systems helps to identify possible maintenance issues that may decrease the efficacy of the system, such as diminished residence time and flow, and increased effluent metal concentrations or undesirable pH (Skousen et al., 2017). When monitoring indicates that remediation processes within the passive treatment system may be failing, rehabilitative maintenance actions, infrequent but labor-intensive activities, must be taken to extend the life of the system. These actions can include replacement or mixing of VFBR substrates (Skousen et al., 2017; Shepherd et al., 2020) or removal of solids from the oxidation ponds (Hedin, 2006). Although removing and replacing materials can extend the life of the passive treatment system, it also creates a large volume of potentially hazardous material, especially in hard rock mine drainage treatment, which contains trace metals not seen in coal mine drainage.

Solids removed from passive treatment systems have several possible routes of disposal available depending on the results of characterization tests. If concentrations of regulated metals exceed Resource Conservation and Recovery Act (RCRA) limits, the United States Environmental Protection Agency (USEPA) requires the solids to be placed in a hazardous waste landfill. Placement of materials in these facilities requires careful planning to ensure that migration of trace metals is avoided, and the cost of disposal can elevate the cost of treatment to unsustainable levels (Kefeni et al., 2017). Additionally, hazardous substances do not become inert in this process, and any potential economic value is lost. If concentrations of regulated metals do not exceed RCRA limits, materials may be placed in nonhazardous waste landfills, which are less expensive to construct and operate, but still present the same problem of storing materials instead of recovering resources from them or putting them toward a beneficial reuse. Nonhazardous waste landfills require metal concentrations as measured by the toxicity characteristic leaching

procedure (TCLP) to be below RCRA limits (USEPA, 1984), a requirement that may be difficult to meet with hard rock mine drainage residual solids.

Several economically viable and environmentally sustainable reuse options have been identified for some mine drainage residual solids. Some uses for oxidation pond iron oxyhydroxides include pigments (Hedin, 2006), oceanic fertilizer to promote carbon sequestration (Hedin and Hedin, 2015), and phosphate sorbent to decrease eutrophication (Penn et al., 2016; Tang and Nairn, 2021). VFBR organic solids can be used as an organic-based, gradual release fertilizer or a stabilizer of contaminated soil (Rakotonimaro et al., 2017). If these passive treatment system solids are to be reused, however, it is important to ensure that potentially harmful trace metals will not leach into the environment.

The fate of trace metals is especially important when examining passive treatment residuals from hard rock mining operations like those of the Tri-State Lead-Zinc Mining District (TSMD) of northeast Oklahoma, southeast Kansas, and southwest Missouri. Underground mining began in the TSMD in the 19th century and continued through the 1960s (Nairn et al., 2010). After mining stopped, water began to accumulate in the mine workings and began to artesian flow on the ground surface in 1979 (Nairn et al., 2010), leading to the area's inclusion in the USEPA's National Priorities List in 1983 (USEPA, 2020). Oklahoma's Tar Creek Superfund Site can be seen in Figure 1.1. Artesian discharges from the mines in this area exhibit elevated concentrations of iron, lead, zinc, cadmium, and arsenic, but due to carbonate host rock also exhibit circum-neutral pH and substantial alkalinity (Nairn et al., 2010). Two multi-cell passive treatment systems, Mayer Ranch Passive Treatment System (MRPTS or Mayer Ranch) and Southeast Commerce Passive Treatment System (SECPTS or Southeast Commerce) were constructed in 2008 and 2017, respectively, to decrease metal concentrations and chemical

oxygen demand (Nairn et al., 2010; BioMost, 2018; Nairn et al., 2020). Aerial photographs of Mayer Ranch and Southeast Commerce with labeled treatment units are included as Figures 1.2 and 1.3, respectively.

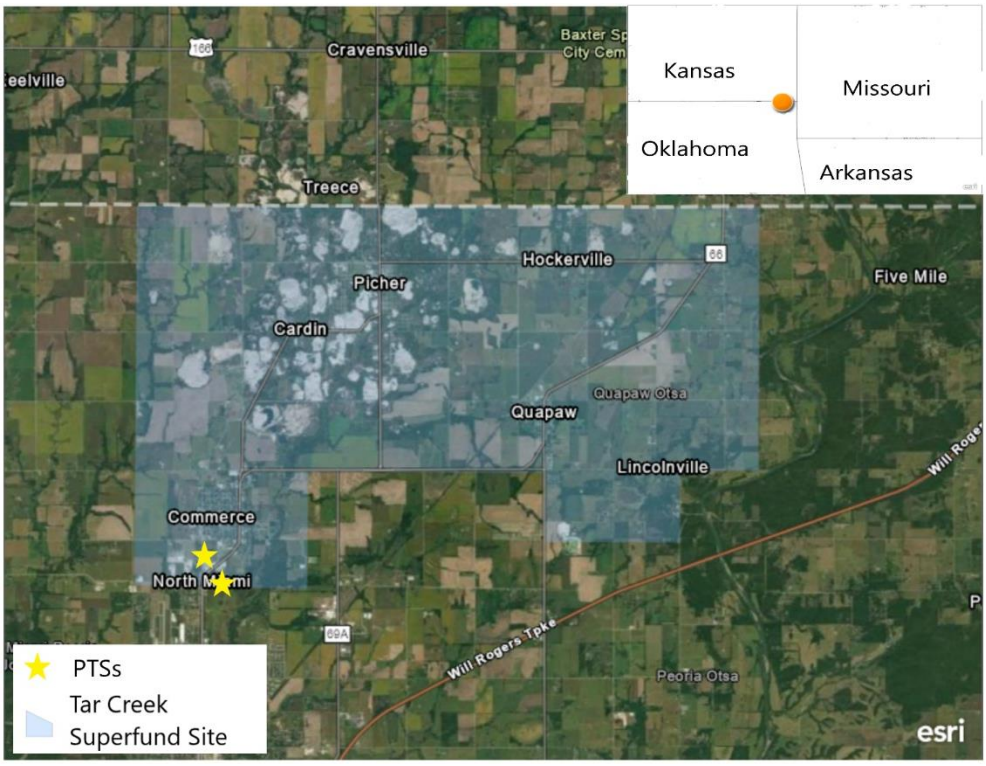

Figure 1.1: Location of the Tar Creek Superfund Site in Northeastern Oklahoma (from the Oklahoma Department of Environmental Quality, 2021)

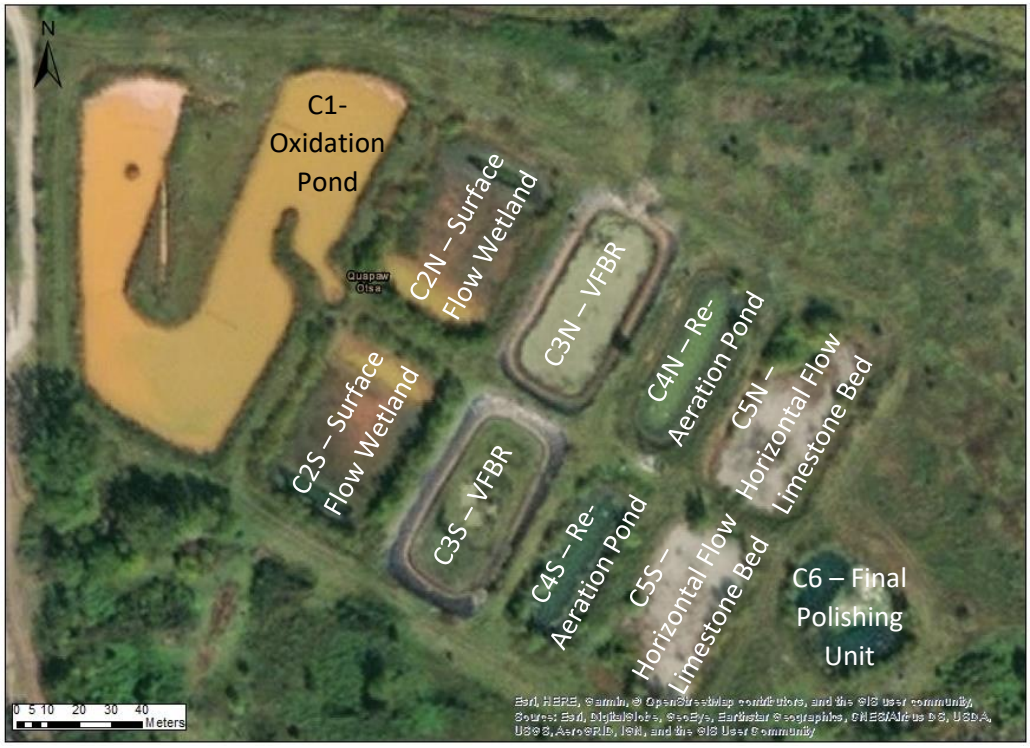

Figure 1.2: Mayer Ranch Passive Treatment System with Treatment Units Labeled

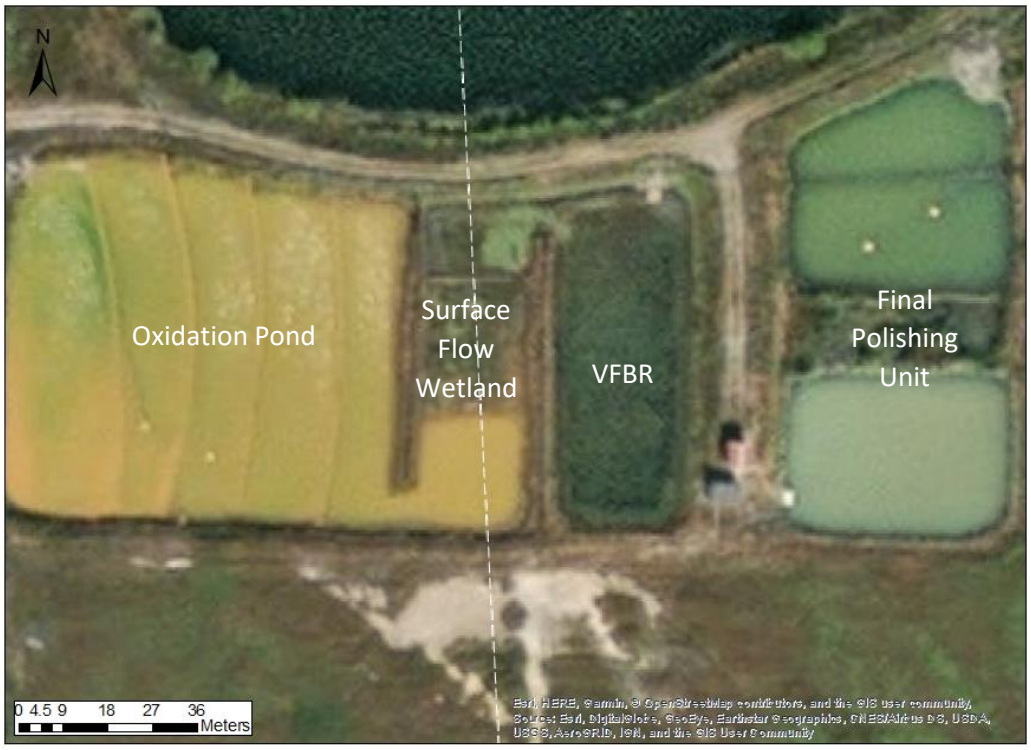

Figure 1.3: Southeast Commerce Passive Treatment System with Treatment Units Labeled

In anticipation of the eventual need to perform rehabilitative maintenance at MRPTS and SECPTS, this thesis examined accumulated solids from the oxidation ponds and VFBRs. Total recoverable metals concentrations were determined. Solids then underwent three leaching examinations representing increasingly harsh conditions: the USGS field leach test (FLT), the synthetic precipitation leaching procedure (SPLP) and TCLP. These tests were used to determine whether the solids from the MRPTS and SECPTS oxidation ponds and VFBRs contain problematic leachable fractions of trace metals. The study of trace metal leachability from the oxidation pond solids is presented in Chapter Two, and the study of trace metal leachability from the VFBR solids is presented in Chapter Three. This study also examined the ability of amendments to decrease the environmental availability of trace metals, presented as Chapter Four. Chapter Five reviews the hypotheses of the studies presented in Chapters Two through Four and offers concluding remarks on the study and suggestions for future work.

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Chapter Two: Characterization and Leachability of Trace Metals from Passive Treatment Oxidation Pond Residual Solids

Abstract

Ecologically engineered passive treatment systems have been successfully implemented to decrease acidity and concentrations of ecotoxic metals without continuous energy or material input. These systems typically have a design life of approximately 20 years, at which point rehabilitative maintenance must occur to continue water quality improvements. In the case of oxidation ponds, iron oxyhydroxide solids must be dredged to sustain effective hydraulic retention time, creating a large volume of potentially hazardous waste. In this study, iron oxyhydroxide solids from the oxidation ponds of two multi-celled passive treatment systems in the Tri-State Lead-Zinc Mining District were characterized with respect to total recoverable metals and availability of those metals as measured by the TCLP, the SPLP and the USGS FLT. TCLP results showed that the solids leached nonhazardous concentrations of metals under RCRA guidelines. SPLP and FLT resulted in concentrations of some metals exceeding Oklahoma Water Resources Board criteria for protection of public water supplies, and total metals exceeded some consensus-based toxicity benchmarks for soil and sediment. These risks should be further evaluated before implementing beneficial reuse plans for the iron oxyhydroxides.

Introduction

Oxidation ponds in passive treatment systems are typically designed to operate for 20-25 years, after which the accumulation of iron oxyhydroxide solids will decrease hydraulic retention time and thus decrease the efficacy of the treatment unit (Watzlaf et al., 2004). Regular monitoring of effluent chemistry can be used to ensure that the treatment unit is continuing to perform as

designed and indicate when maintenance may be necessary to continue treating mine drainage (Skousen et al., 2017). Maintenance can be divided into regular (quarterly to annually, minimally labor intensive), periodic (occurring every two to three years, more labor intensive), and rehabilitative (decadal, requiring substantial labor and equipment; Nairn et al., 2020). In coal mine drainage passive treatment systems, rehabilitative maintenance of oxidation ponds has consisted of the removal of iron oxyhydroxide solids, occasionally for beneficial reuse (Hedin, 2006). Although removing solids from the oxidation ponds extends the lifetime of the passive treatment system, it also creates a large volume of potentially hazardous waste, especially in settings such as the TSMD and other hard rock mining regions, where trace metal concentrations are typically greater than those seen in coal mine drainage.

Solids removed from passive treatment systems have several routes of disposal available depending on the results of characterization tests and regulations at the state and federal level. If concentrations of regulated metals in leachates exceed RCRA limits, USEPA requires the solids to be placed in a hazardous waste landfill. Placement of materials in these facilities requires careful planning to ensure that migration of trace metals is avoided, and the cost of disposal can elevate the cost of treatment to unsustainable levels (Kefeni et al., 2017). Additionally, hazardous substances do not become inert in this process, and any potential economic value is lost. If concentrations of regulated metals do not exceed RCRA limits, materials may be placed in nonhazardous waste landfills, which are less expensive to construct and operate, but still present the same problem of storing materials instead of recovering resources from them or putting them toward a beneficial reuse. Additionally, nonhazardous waste landfills require metal concentrations, as dictated by the TCLP, to be below RCRA limits (USEPA, 1984), a requirement that may be difficult to meet with hard rock mine drainage residual solids.

Several economically viable and environmentally sustainable reuse options have been identified for some mine drainage residual solids. Some potential uses for oxidation pond iron oxides include pigments (Hedin, 2006), oceanic fertilizer to promote carbon sequestration (Hedin and Hedin, 2015), and phosphate sorbent to decrease eutrophication (Penn et al., 2016; Tang and Nairn, 2021). If these iron oxyhydroxides are to be reused, however, it is important to ensure that potentially harmful trace metals will not leach into the environment where the solids are used.

Batch leaching has been used widely as a rapid evaluation for the potential environmental mobility of wastes. In the United States, TCLP is the mandated method for measuring leachability of certain compounds from a material before that material can be disposed of in a nonhazardous materials landfill (USEPA, 1984). Therefore, TCLP results are an important consideration during remedial activities such as mine drainage treatment and subsequent residual solids resolution. TCLP has been used to characterize mine wastes across the world as a regulatory requirement and as a test of the environmental availability of contaminants of potential concern in studies where soil is treated *in situ* (Jong and Parry, 2005; Sonmez and Pierzynski, 2005; Wu et al., 2013). Despite the ubiquitous and codified use of TCLP, there are several concerns regarding its use in the characterization of mine wastes (Cohen et al., 1999; Ghosh et al., 2004), such as the diversity in behavior of metals and the limited use of landfills for disposal of mine waste.

Several studies have examined whether changing distinct aspects of the TCLP test would produce different final concentrations of metals in various wastes. Studies have changed agitation manner and rate, liquid to solid ratio, extraction fluid, and amount of headspace in the container to determine whether these factors changed the results of TCLP (Cohen et al., 1999; Jong and Parry, 2005). Changes to speed or manner of agitation were found to have little effect

on the final metal concentrations produced (Cohen et al., 1999). The liquid to solid ratio of 20:1 was determined to provide conservative estimates of chromium leaching from minerals processing wastes, but differences in solubility and adsorption processes may challenge the universality of this observation (Cohen et al., 1999). Extraction fluids are also not universal in their reactivity with different metals. Cohen et al. (1999) found that acetic acid was more powerful in leaching zinc, while chromium was found in greater concentrations when deionized water was used as the extraction fluid. Furthermore, changes in headspace changed concentrations of elements susceptible to oxidation, such as iron and arsenic (Jong and Parry, 2005).

Further, many examples of mine waste disposal show that the organic-rich, slightly acidic environment of mixed solid waste landfills that TCLP is meant to simulate is not the most likely path for mining waste disposition (Hageman et al., 2005). Macias et al. (2012) found that metal rich wastes from the Iberian Pyrite Belt were misclassified using TCLP as compared to a sequential extraction. Since mine wastes are exempt from RCRA disposal guidelines (USEPA, 1980), some waste materials from derelict mining sites are stored above ground near the source instead of placed in landfills. Additionally, current best practices include prevention and immediate treatment of mine drainage and submerging mine waste material in lagoons to decrease contact with oxygen (Adiansyah et al., 2015) or otherwise isolating tailings (Engels, 2020). Thus, it may be more practical to use water as a leaching fluid when assessing mine wastes (Hageman et al., 2005).

SPLP uses the same protocol as TCLP but with an extraction fluid of dilute inorganic acids designed to mimic acidic rainwater (USEPA, 1994). This leaching test was developed by the USEPA to determine the potential for land applied wastes to release elevated concentrations of

harmful materials. Townsend et al. (2006) suggest comparing leachate concentrations directly to groundwater benchmarks as a conservative estimate of the tested material's contribution of a constituent to the groundwater. Lead and cadmium concentrations in SPLP extraction fluid from a study of coal combustion residuals (CCR) were shown to be elevated when compared to TCLP extraction fluid from the same CCR (Levasseur et al., 2006). McDonald et al. (2006) observed that SPLP does not represent environments with greater concentrations of sulfuric acid, which may be found at mine sites, but the test would be appropriate for evaluating mine drainage residuals at alternative disposal locations.

The mine waste-specific FLT was designed to accurately quantify the leachate of land-applied or stockpiled mine waste (Hageman, 2007). FLT uses deionized water and a short contact time to determine the leachable concentration of metals in open waste piles (Hageman et al., 2005). Hageman et al. (2005) compared leachate from several points in a tailings pile at the Rattler Mine in Colorado to FLT results from composites collected and analyzed by two different groups and found that the FLT concentrations correlated well to each other and to the leachate coming off the piles. Additionally, LaBar (2007) found that FLT was a good indicator of leachate composition from waster rock (chat) in the TSMD.

If the solids from passive treatment oxidation ponds are to be put to beneficial reuse, direct contact with them by flora and fauna must also be evaluated. MacDonald et al. (2000) compiled sediment quality guidelines for sediment from several different toxicity studies to determine threshold effect concentrations and probable effect concentrations for toxic effects of sediment constituents. Sediment quality guidelines specific to the TSMD were also defined in MacDonald et al. (2009). Efroymson et al. (1997) created similar guidelines to MacDonald et al. (2000) for soils that focus on microbes and invertebrates that live in close contact with the soil. These

guidelines have not been used to evaluate the risk involved in application of mine waste residuals but could provide an initial estimate of a safe application rate.

In this study, TCLP, SPLP, and FLT were used to determine the leachable concentration of metals in the oxidation pond solids from two passive treatment systems in the TSMD. The leachable fraction of metals was then used to make preliminary statements about the risk of applying these solids to the environment for beneficial reuse to develop reuse options for the solids. It was expected that the concentrations of trace metals such as lead and cadmium would exceed regulatory disposal limits set forth in USEPA Title 40 (USEPA, 1984) and/or surface water and groundwater quality standards described in Oklahoma Water Resources Board (OWRB) Title 785 (OWRB, 2017) due to the substantial decreases in concentrations of these metals in the water between the influent and effluent of the oxidation ponds.

Methods

Site Description

The TSMD, located in northeastern Oklahoma, southeastern Kansas, and southwestern Missouri, was established as a source for lead and zinc in the 19th century (Nairn et al., 2010). Mines were operated in this area until the 1960s, at which point pumping ceased and water began accumulating in the subsurface mines (Nairn et al., 2010). Artesian discharges from the mine pool began in 1979, leading the USEPA to include the area on the National Priorities List in 1983 (Nairn et al., 2010). Discharges from the mine pool are characterized by elevated concentrations of trace metals, circum-neutral pH, and elevated alkalinity due to the water's interaction with sulfide ore minerals and the carbonate host rock (Nairn et al., 2010). Some discharges near Commerce, OK have been routed into two passive treatment systems, Mayer Ranch and Southeast Commerce. These systems, constructed in 2008 and 2017 respectively, are

designed to decrease iron and trace metal concentrations in the discharges that they treat (Nairn et al., 2010; Nairn et al., 2014).

Mayer Ranch and Southeast Commerce are multi-celled passive treatment systems that use geochemical and biological processes to decrease metal concentrations (Nairn et al., 2010; Nairn et al., 2014). The first process unit in both systems is an oxidation pond, which promotes the oxidation and hydrolysis of iron and precipitation of iron oxyhydroxides and release of CO_2 gas into the atmosphere through passive, renewable-energy-powered aeration (Nairn et al., 2010; Nairn et al., 2014). Iron and trace metals accumulate in the oxidation ponds principally through precipitation of oxyhydroxides and adsorption, respectively.

Sample Collection

Water quality data for the influent and effluent of the oxidation ponds has been collected 4-12 times per year since the construction of each system. Physiochemical water quality information is generated using a YSI multiparameter sonde, and samples are collected in 250-mL HDPE bottles, acidified, returned to the Center for Restoration of Ecosystems and Watersheds (CREW) Laboratories in Norman, OK for analysis of metals and anions using USEPA methods.

Solid samples for this study were collected in a spatially distributed manner in the oxidation ponds of the Mayer Ranch and Southeast Commerce passive treatment systems. GPS coordinates were collected with a handheld Garmin unit during sample collection and used to generate Figures 2.1 and 2.2. Preliminary samples supplemented by data from previous studies were used in the formula for statistical evaluation described in Appendix IV of the Guidance for Data Usability in Risk Assessment (USEPA, 1991) to determine that at least twenty-five samples from each oxidation pond were needed to address system heterogeneity. After manually drawing down water levels, samples were collected from a catamaran and from three catwalks in the Mayer

Ranch oxidation pond by lowering a 19-L HDPE bucket into the accumulated solids. Excess water was decanted off the top of the bucket before filling labeled 7.8-L LDPE plastic bags with the mine drainage residuals. Twenty-eight samples were collected from the Mayer Ranch oxidation pond and twenty-five samples were collected from the Southeast Commerce oxidation pond. After collection, samples were transported to CREW laboratories in Norman, OK where they were stored upright in coolers at 4°C to allow additional settling of the solids.

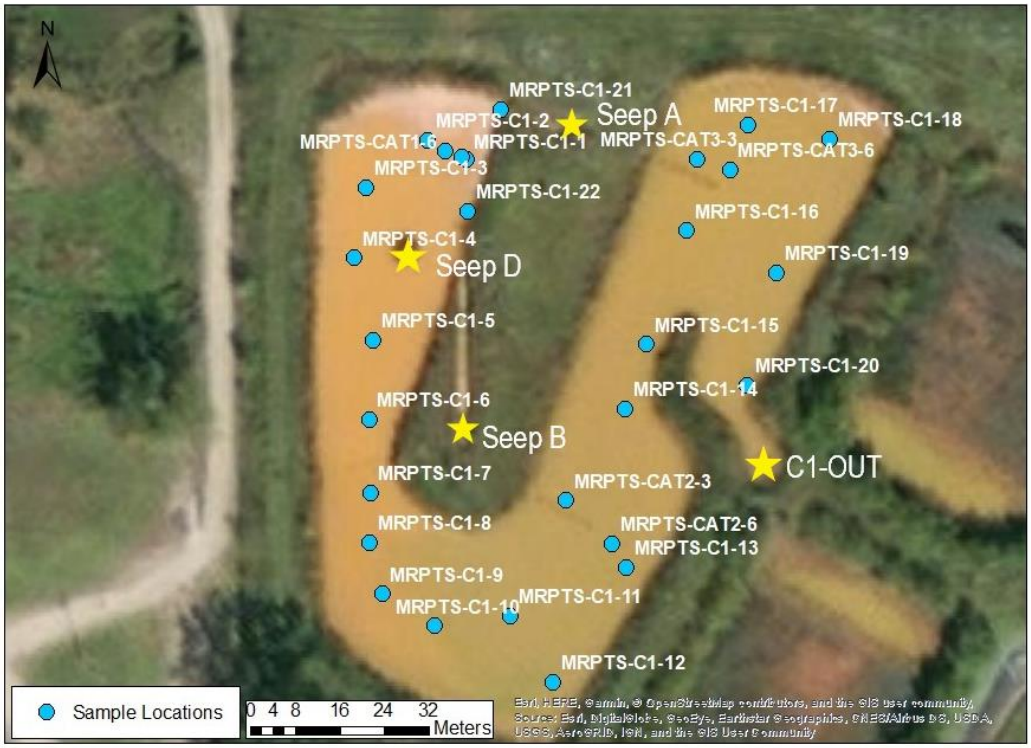

Figure 2.1: Sampling Locations within the Mayer Ranch Oxidation Pond

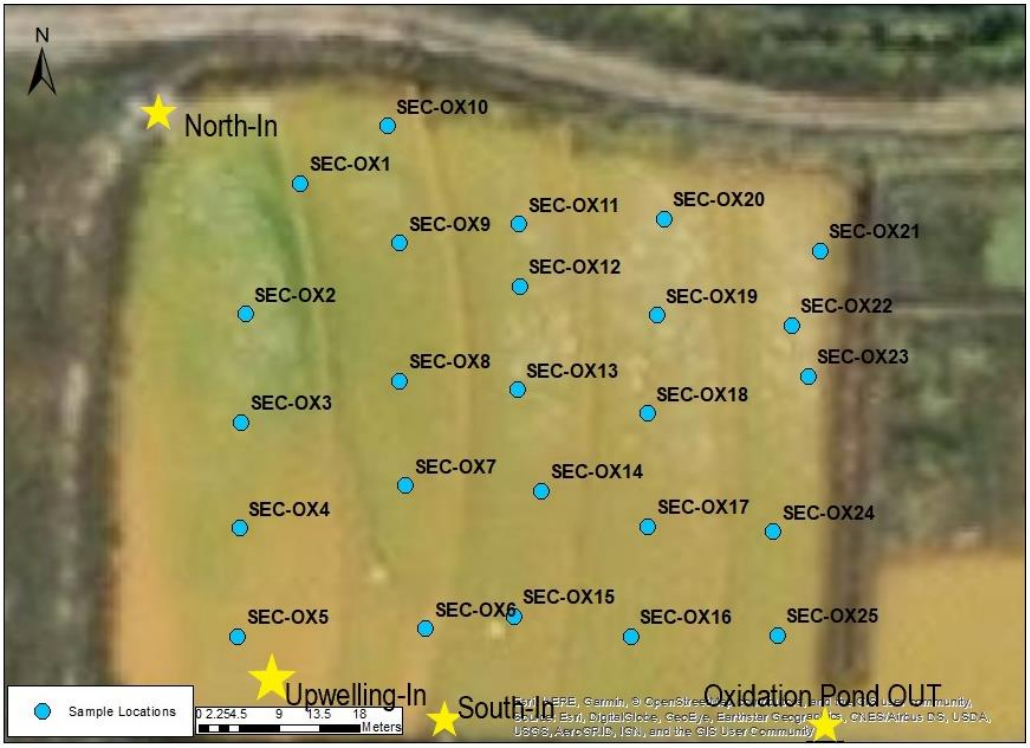

Figure 2.2: Sampling Locations within the Southeast Commerce Oxidation Pond

Physical Characterization of the Solids

Subsamples were taken from each location-specific bag for determination of moisture content, organic matter, and total metals concentrations. Approximately 25 grams of wet residuals were placed in aluminum weigh boats, tared masses were recorded, and samples were placed in an oven at 105°C and dried until constant mass was achieved (approximately 36 hours, ASTM Method D4531-86, 2008). Moisture content was determined using the difference in the mass of each sample before and after drying. Oven-dried samples were ground using a mortar and pestle to achieve a grain size that passed a 2-mm sieve. A portion of each oven-dried sample was then placed in a ceramic crucible, tared mass was recorded, and the crucible was placed in a muffle furnace heated to 375°C and left for approximately 20 hours. The difference in mass was used as an estimate of the organic matter in the solids as loss on ignition following Robertson (2011).

Another portion of the oven-dried sample was digested to prepare for the measurement of total recoverable metals using inductively coupled plasma-optical emission spectrometry (ICP-OES) following USEPA Methods 3051A and 6010C (USEPA, 2007a; USEPA, 2018). Approximately 0.25 grams of each sample was measured with mass recorded to ±0.0001 g, placed in acid-washed Teflon digestion tubes with 10 mL of trace metal grade nitric acid, and digested in a CEM Microwave Accelerated Reaction System (MARS). The MARS was used to run a pre-programmed sequence including a warm-up period, 10 minutes of temperature maintenance at 175°C, and a cool down period. The digest was then filtered through polypropylene 0.45-µm syringe filters using 10-mL syringes. Filtered digest was diluted and metals concentrations were measured using a Varian Vista-Pro ICP-OES. Concentrations measured by the ICP-OES were corrected for dilutions and initial digested masses to determine the concentration of metals in each sample in mg kg^{-1}.

Leaching Tests

Solids used in all leaching tests were air dried, as specified in the USGS FLT procedure (Hageman, 2007). FLTs were completed following a modification of the procedure set forth in Hageman (2007). Sample mass and leaching fluid volume were quartered to conserve sample mass; thus 12.5 g of air-dried and ground to less than 2-mm grain size sample was measured and placed in a 250-mL Erlenmeyer flask with 250 mL of deionized water. The flask was placed in a Burrell wrist-action shaker and agitated for 5 minutes. Flasks were then allowed to rest in the shaker for 10 minutes before the leachate was filtered through a 0.45-µm nylon syringe filter using a 10-mL syringe. Approximately 150 mL of leachate was collected from each test. Leachate was stored in 250-mL HDPE bottles until digestion.

TCLP tests were completed following USEPA Method 1311 (USEPA, 1992). To determine the appropriate extraction fluid, 5 g of each air-dried sample was used to measure the pH of the solids as described in the Preliminary Evaluations section of the procedure. Extraction fluid 1 (pH 4.93 ± 0.05) was used if the pH decreased to less than 5.0 after the addition of 3.5 mL of 1 N hydrochloric acid and heating the sample to 50°C for 10 minutes. Extraction fluid 2 (pH 2.88 ± 0.05) was used if the pH remained above 5.0 after acid addition and heating. Extraction fluid 1, which was used for most of the samples, was prepared 1 L at a time and mixed into 20-L batches, with pH adjustment after the batch had been mixed, if necessary. Extraction fluid 2, which was used for three samples from MRPTS, was prepared 2 L at a time, with pH adjustment occurring before adding the fluid to the vessels if necessary. Borosilicate TCLP vessels were prepared by adding 100 g of air-dried and ground sample and 2 L of the appropriate extraction fluid. Lids were sealed with Teflon thread seal tape to prevent leaking. The vessels were placed in an Associated Design and Manufacturing TCLP tumbler and rotated end-over-end at a rate of 30 rpm for 18 hours. Rotation was paused after approximately half an hour to vent any gas buildup due to carbonates reacting with the acid in the extraction fluid forming carbon dioxide. After 18 hours, the vessels were removed from the tumbler and the solids were left to settle for approximately half an hour before filtering through 0.7-µm glass fiber filters. After filtration, leachate was stored in 250-mL HDPE bottles until digestion.

SPLP tests followed the procedure described in USEPA Method 1312 (USEPA, 1994). SPLP extraction fluid was prepared by diluting a stock made of 1 mL of a 60:40 mixture of sulfuric and nitric acids and 20 L of deionized water. Final pH of the SPLP leaching fluid was 5.00 ± 0.05, which is the prescribed pH for materials with a planned disposal west of the Mississippi River.

Vessels were then prepared, rotated, and filtered following the same procedure as described for TCLP. SPLP leachate was also stored in 250-mL HDPE bottles until digestion.

Leachate from each test was digested following USEPA Method 3015A (USEPA, 2007b). For each sample, 45 mL of leachate was added to a Teflon digestion tube with 5 mL of concentrated trace-metal grade nitric acid and heated in a CEM MARS. Digested leachate was left in digestion tubes to cool before storing in 60-mL HDPE bottles until analysis using ICP-OES following USEPA Method 6010C (USEPA, 2018). Concentrations in leachate derived from ICP-OES analysis were corrected for dilution from the acid used in digestion and were reported as mg L^{-1}.

Three field duplicates were collected from each passive treatment system by filling two 7.8-L bags from the same 19-L bucket of solids. TCLP and SPLP blanks, digestion blanks and spikes, and digestion and ICP-OES duplicates were collected at a rate of one each per system per leaching test. Leaching test blanks were made following the TCLP and SPLP procedure described above without adding solids to the vessel. Digestion blanks and spikes were made using Nanopure deionized water. All QA/QC samples were analyzed as separate samples using ICP-OES.

Results and Discussion

Water Quality

Water quality data for the influent and effluent of the Mayer Ranch oxidation pond are provided in Table 2.1. Similar data from the Southeast Commerce oxidation pond are provided in Table 2.2. Flow is not measured at the effluent of either oxidation pond, so flow data for the effluent of the Mayer Ranch oxidation pond is estimated from the sum of the inflows and flow data for the effluent of the Southeast Commerce oxidation pond is estimated from flow measurements at the effluent of the VFBR in the system. Changes in aqueous metal concentrations between the

influents and effluents show effective iron removal via oxidation, hydrolysis, precipitation, and settling, and that arsenic, lead and zinc are also removed primarily through sorption (Nairn et al., 2010). Smaller quantities of other metals are also removed from solution in the oxidation ponds. Long term monitoring of water quality from the inflows at Mayer Ranch recorded a steady decrease in metal concentrations (Nairn et al., 2020). Metal concentrations continue to decrease between the influents and effluent of the oxidation ponds, indicating that the buildup of solids has not yet decreased the efficacy of the systems.

Table 2.1: Select Water Quality Information for Influent and Effluent of the Mayer Ranch Oxidation Pond from September 2008 to July 2020, with Influent Parameters Significantly Different from Effluent Bolded

	MRPTS Influent			MRPTS Oxidation Pond Effluent
Parameter	Seep A	Seep B	Seep D	
pH	**6.01 ± 0.11**	**5.98 ± 0.14**	**5.99 ± 0.80**	6.03 ± 0.23
Flow (L/s)	2.16 ± 0.55	4.33 ± 0.90	0.49 ± 1.05	6.91 ± 1.59
Alkalinity (mg/L $CaCO_3$)	**401 ± 34**	**376 ± 36**	**386 ± 57**	174 ± 49
Silver (µg/L)	9.72 ± 3.61	9.45 ± 3.67	10.2 ± 3.8	9.59 ± 3.69
Aluminum (µg/L)	90.1 ± 496.7	101 ± 165	95.0 ± 95.5	71.1 ± 71.6
Arsenic (µg/L)	**60.6 ± 14.3**	**60.2 ± 13.0**	**60.9 ± 14.4**	35.0 ± 12.9
Barium (µg/L)	18.6 ± 12.5	17.3 ± 15.8	17.6 ± 12.3	11.1 ± 13.1
Calcium (mg/L)	712 ± 42	713 ± 45	719 ± 105	711 ± 47
Cadmium (µg/L)	**14.3 ± 7.0**	**15.3 ± 7.3**	**15.0 ± 7.8**	3.70 ± 4.82
Cobalt (µg/L)	58.5 ± 21.9	58.8 ± 22.0	**62.9 ± 24.9**	52.8 ± 17.1
Chromium (µg/L)	4.32 ± 2.92	3.78 ± 3.11	3.47 ± 3.11	4.52 ± 3.27
Copper (µg/L)	2.73 ± 2.59	2.68 ± 1.96	2.64 ± 5.77	3.04 ± 2.19
Iron (mg/L)	**163 ± 18**	**167 ± 18**	**170 ± 30**	38.9 ± 38.4
Potassium (mg/L)	24.4 ± 1.9	24.9 ± 1.9	24.8 ± 3.8	24.6 ± 2.0
Lithium (µg/L)	301 ± 149	301 ± 147	301 ± 147	309 ± 149
Magnesium (mg/L)	183 ± 19	184 ± 25	183 ± 31	182 ± 20
Manganese (mg/L)	1.36 ± 0.13	1.40 ± 0.13	**1.49 ± 0.27**	1.33 ± 0.15
Sodium (mg/L)	97.0 ± 13.4	96.1 ± 13.5	95.6 ± 18.3	97.2 ± 13.7
Nickel (µg/L)	**872 ± 98**	**868 ± 98**	**894 ± 149**	772 ± 94
Lead (µg/L)	**71.9 ± 60.9**	**70.7 ± 64.0**	**76.3 ± 68.1**	37.9 ± 36.7
Sulfur (mg/L)	826 ± 415	826 ± 427	812 ± 413	826 ± 404
Silicon (mg/L)	**9.66 ± 4.70**	**9.23 ± 4.63**	**9.99 ± 4.81**	7.57 ± 3.75
Zinc (mg/L)	**7.51 ± 1.01**	**7.30 ± 0.98**	**8.19 ± 1.50**	5.79 ± 0.99

Table 2.2: Select Water Quality Information for Influent and Effluent of the Southeast Commerce Oxidation Pond from March 2017 to July 2020 (Upwelling-In starting June 2017), with Influent Parameters Significantly Different from Effluent Bolded

Parameter	SECPTS Influent			SECPTS Oxidation Pond Effluent
	North-In	South-In	Upwelling-In	
pH	**6.13 ± 0.12**	**6.04 ± 0.11**	**5.86 ± 0.11**	5.92 ± 0.17
Flow (L/s)	1.25 ± 0.55	0.24 ± 0.09	--	8.05 ± 4.01
Alkalinity (mg/L $CaCO_3$)	**344 ± 25**	**394 ± 22**	**322 ± 127**	108 ± 20
Silver (µg/L)	8.82 ± 4.33	**9.33 ± 4.52**	**10.0 ± 5.1**	8.00 ± 3.98
Aluminum (µg/L)	39.8 ± 180.2	51.5 ± 115.9	129 ± 277	55.1 ± 46.0
Arsenic (µg/L)	**65.5 ± 19.2**	**52.5 ± 20.2**	**83.0 ± 37.5**	<20
Barium (µg/L)	**12.7 ± 12.1**	**14.2 ± 16.6**	8.31 ± 7.62	5.94 ± 5.09
Calcium (mg/L)	**654 ± 54**	**679 ± 105**	**669 ± 196**	621 ± 57
Cadmium (µg/L)	**13.4 ± 6.1**	**14.9 ± 6.4**	**19.5 ± 9.3**	3.66 ± 1.72
Cobalt (µg/L)	**24.6 ± 12.1**	**22.6 ± 14.3**	43.3 ± 18.6	46.4 ± 7.90
Chromium (µg/L)	4.92 ± 4.06	6.53 ± 4.10	2.00 ± 3.14	5.14 ± 3.49
Copper (µg/L)	2.85 ± 1.95	3.25 ± 2.69	3.18 ± 1.84	3.55 ± 2.06
Iron (mg/L)	**129 ± 13**	**146 ± 13**	**144 ± 47**	9.32 ± 8.18
Potassium (mg/L)	**23.2 ± 1.8**	20.4 ± 1.7	**22.2 ± 6.7**	21.2 ± 1.94
Lithium (µg/L)	**244 ± 12**	**315 ± 155**	**289 ± 89**	274 ± 129
Magnesium (mg/L)	**123 ± 14**	**159 ± 13**	**150 ± 47**	139 ± 18
Manganese (mg/L)	**1.86 ± 0.14**	**1.30 ± 0.09**	**1.30 ± 0.66**	2.57 ± 0.44
Sodium (mg/L)	78.2 ± 11.3	**88.8 ± 14.1**	85.5 ± 28.5	82.3 ± 13.4
Nickel (µg/L)	**481 ± 41**	560 ± 33	**715 ± 218**	565 ± 54
Lead (µg/L)	**195 ± 77**	**224 ± 93**	**289 ± 123**	37.1 ± 15.7
Sulfur (mg/L)	688 ± 343	**770 ± 394**	**790 ± 323**	734 ± 359
Silicon (mg/L)	**18.7 ± 8.8**	**10.3 ± 5.1**	**16.7 ± 6.8**	12.9 ± 6.0
Zinc (mg/L)	**6.51 ± 0.67**	**6.50 ± 0.71**	**6.71 ± 2.09**	5.90 ± 0.84

Flow from the upwelling in the Southeast Commerce Oxidation Pond is the largest contributor of water to the system. The upwelling was uncovered during construction of the system and has significantly ($p > 0.05$) lower pH and greater arsenic, cadmium, cobalt, nickel, and lead concentrations than both the north and south inflows. Arsenic, cadmium, and lead concentrations in water decrease substantially in the oxidation pond, but the effluent pH of the Mayer Ranch oxidation pond is significantly greater ($p = 0.00036$) than the effluent of the Southeast Commerce Oxidation Pond. The increase in flow and metals loading into Southeast Commerce

has contributed to hydraulic issues within the system including higher than design water elevations and increased deposition of iron oxyhydroxide solids outside of the oxidation pond.

Physical Characterization of the Solids

The medians and standard deviations for moisture content, organic matter content, and pH of the solids from each oxidation pond are found in Table 2.3. As expected, based on the influent to the systems, the solids from the oxidation ponds have elevated moisture content, minimal organic matter content, and circum-neutral pH. Using an unpaired t-test, moisture content and pH were shown to be statistically different between the two systems ($p < 0.05$). However, organic matter content in the oxidation pond solids of the two systems is statistically similar ($p = 0.31$). Greater pH in the Mayer Ranch Oxidation Pond solids was due to greater concentrations of carbon dioxide degassing from the Mayer Ranch Oxidation Pond than the Southeast Commerce Oxidation Pond. Greater moisture content in Southeast Commerce Oxidation Pond solids was caused by differences in sampling conditions. Although water levels in both systems were lowered during sampling, water levels in the Southeast Commerce system remained higher than those at Mayer Ranch.

Table 2.3: Median Moisture Content, Organic Matter Content, and pH in Oxidation Pond Solids

	Mayer Ranch	Southeast Commerce
Moisture Content (%)	85.19 ± 3.65	89.38 ± 3.17
Organic Matter Content (% dry wt)	14.75 ± 1.61	14.27 ± 1.48
pH	6.20 ± 0.29	6.10 ± 0.32

Median concentrations of selected elements in the oxidation pond solids and their standard deviations are displayed in Table 2.4. The predominant metal in the solids was iron (46% of the total dry mass in the Mayer Ranch solids and 50% of the total dry mass in the Southeast Commerce solids). Calcium was also prevalent (1.6% of total dry mass in Mayer Ranch solids

and 1.3% of total dry mass in Southeast Commerce solids) due to the limestone bedrock in the area and resulting elevated concentrations in the source water. Other abundant elements in the solids included aluminum, magnesium, sodium, sulfur, silicon, and zinc.

Aluminum, magnesium, sodium, and silicon are all common components of the Earth's crust. Elevated sulfur and zinc were expected as principal components of the ore mined in the TSMD. Trace metals detected in the solids at a concentration of 10 mg kg^{-1} or greater included arsenic, barium, cadmium, cobalt, copper, manganese, nickel, and lead. Silver, chromium, and lithium were each detected in the oxidation pond solids at a concentration of approximately 2 mg kg^{-1}. Arsenic, cadmium, cobalt, manganese, and nickel were more abundant in the oxidation pond solids than they were in chat samples from the TSMD analyzed by LaBar (2007), copper and chromium concentrations were similar across the different materials, and lead concentrations were greater in the chat. LaBar (2007) did not measure barium, lithium, or silver concentrations in TSMD chat. Selenium is also part of the suite of analytes for the ICP-OES used in this study, but selenium concentrations were below detectable levels. Trace metals are generally not reported in studies discussing the reuse of coal mine drainage residuals (e.g., Cui et al., 2013; Hedin 2006) due to their absence in substantial concentrations (Rakotonimaro et al., 2017). Therefore, it is assumed that the concentrations of trace metals seen in the mine drainage residuals from the TSMD are elevated with respect to those seen in coal mine drainage residuals.

Table 2.4: Median Elemental Concentrations in Oxidation Pond Solids in mg kg^{-1}

Metal	Mayer Ranch	Southeast Commerce
Silver	2.27 ± 0.52	2.87 ± 0.54
Aluminum	786 ± 749	696 ± 851
Arsenic	271 ± 89	246 ± 50
Barium	35.0 ± 10.6	19.9 ± 1.7
Calcium	15756 ± 3167	12866 ± 4094
Cadmium	41.1 ± 7.7	67.0 ± 16.5
Cobalt	9.69 ± 3.20	10.8 ± 13.4
Chromium	<0.094 ± 1.08	1.96 ± 0.66
Copper	16.0 ± 10.8	10.4 ± 6.6
Iron	461575 ± 48878	504903 ± 60771
Potassium	420 ± 61	425 ± 47
Lithium	2.18 ± 1.96	2.40 ± 1.55
Magnesium	1035 ± 127	1081 ± 275
Manganese	90.1 ± 28.7	368 ± 570
Sodium	527 ± 112	1175 ± 435
Nickel	208 ± 39	91.5 ± 36.1
Lead	24.7 ± 98.6	59.1 ± 12.0
Sulfur	8952 ± 3209	8875 ± 3662
Silicon	6754 ± 2979	362 ± 76
Zinc	6005 ± 646	5712 ± 4043

Unpaired t-tests were used to compare the metal concentrations in the samples from the two oxidation ponds. The solids were statistically similar ($p > 0.05$) with respect to aluminum, cobalt, chromium, copper, potassium, lithium, magnesium, lead, sulfur, and zinc. Differences between the systems ($p < 0.05$) were seen in concentrations of silver, arsenic, barium, calcium, cadmium, iron, manganese, sodium, nickel, and silicon. Some of these differences, such as the differences in the concentrations of nickel and manganese in the solids, reflect different concentrations in the influent of the two systems. Some, such as the elevated concentrations in arsenic and barium in the Mayer Ranch solids, may be due to sorption to the iron oxyhydroxides magnified by the longer operation time of Mayer Ranch. Others may be due to relatively small differences in precipitation being magnified over time.

As indicated by the standard deviations found in Table 2.4, samples were heterogeneous with respect to metal concentrations. Field duplicates showed varying levels of agreement with their parent sample but were within the standard deviation of the samples in the treatment unit, apart from two copper concentrations. Tables of metal concentrations in each sample of the oxidation pond solids can be found in Appendix A.

Concentrations of metals in the oxidation pond solids exceeded soil or sediment benchmarks from Efroymson et al. (1997) and MacDonald et al. (2000) for aluminum, arsenic, cadmium, chromium, copper, iron, manganese, nickel, lead, and zinc in at least one sample. Concentrations of arsenic, cadmium, nickel, and zinc in the oxidation pond solids exceeded toxicity benchmarks for sediment in the TSMD in all samples, and one sample of Mayer Ranch Oxidation Pond solids exceeded the lead toxicity benchmark. Exceedances and concentration ranges are summarized in Table 2.5. The highest exceedance was iron, which showed concentrations over 2000 times the benchmark for toxicity to soil microorganisms listed in Efroymson et al. (1997). Cadmium and zinc showed the greatest exceedances of general sediment toxicity benchmarks, with concentrations between 20 and 150 times the benchmarks listed in MacDonald et al. (2000). Zinc concentrations exceeded the TSMD sediment toxicity benchmarks from MacDonald et al. (2009) by an approximate factor of 40. These benchmarks were not calculated for evaluating mine drainage residuals; however, they may help determine safe quantities for applying the residuals in a terrestrial or aquatic environment.

Table 2.5: Soil, Sediment, and TSMD-Specific Sediment Toxicity Benchmarks, Percent of Oxidation Pond Solid Samples Exceeding the Benchmarks, and the Range of Concentration for the Metal in Samples with Exceedances Bolded

Metal	Toxicity Benchmark (mg kg^{-1})	Percent of Samples Exceeding Benchmark		Concentration Range (mg kg^{-1})	
		MRPTS	SECPTS	MRPTS	SECPTS
Silver – Soil	50	0	0	1.14-3.59	1.34-3.70
Aluminum – Soil	600	93	60	488-**3972**	286-**3511**
Arsenic – Soil	60	100	100		
Arsenic – Sediment	9.79	100	100	**140-634**	**130-308**
Arsenic – TSMD	33	100	100		
Barium – Soil	3000	0	0	30.4-74.8	17.2-24.6
Cadmium – Soil	20	100	100		
Cadmium – Sediment	0.99	100	100	**28.4-63.5**	**40.0-123.7**
Cadmium – TSMD	4.98	100	100		
Cobalt – Soil	1000	0	0	5.47-20.10	4.38-79.14
Chromium – Soil	0.40	43	100		
Chromium – Sediment	43.40	0	0	<0.117-**3.38**	**1.77-4.24**
Chromium – TSMD	111	0	0		
Copper – Soil	50	4	0		
Copper – Sediment	31.6	7	0	0.88-**57.93**	4.80-24.44
Copper – TSMD	149	0	0		
Iron – Soil	200	100	100	**351779-561166**	**294163-565164**
Lithium – Soil	10	4	0	1.11-**10.02**	1.27-7.45
Manganese – Soil	100	36	88	63.1-**186.0**	88.5-**2036.5**
Nickel – Soil	90	100	52		
Nickel – Sediment	22.7	100	100	**126.6-335.4**	**52.6-162.3**
Nickel – TSMD	48.6	100	100		
Lead – Soil	500	4	0		
Lead – Sediment	35.8	7	100	21.4-**574.0**	**42.3-90.5**
Lead – TSMD	128	4	0		
Zinc – Soil	20	100	100		
Zinc – Sediment	121	100	100	**4363-7406**	**2877-18336**
Zinc – TSMD	459	100	100		

Leaching Tests

Table 2.6 shows concentrations of metals in leachate from each leaching test. TCLP leached the greatest fraction of metals in most cases, followed by SPLP, then FLT. A comparison of leaching test results for selected metals is shown in Figures 2.3 to 2.6. These observations indicate metal

concentrations in leachate depend on the pH of the extraction fluid. Sodium concentrations for TCLP and sulfur concentrations for SPLP were not representative of leaching due to their presence in the extraction fluids and thus are not included in Table 2.6.

None of the TCLP results for the RCRA metals exceeded the allowable limits (USEPA, 1984), indicating that the solids from both systems were classified as non-hazardous under RCRA. The three samples that required the use of extraction fluid 2 had more outlier concentrations than other samples. These three samples had concentrations of silver, barium, calcium, cadmium, chromium, iron, manganese, nickel, lead, silicon, and zinc that were 1.5 times the standard deviation greater than the median concentrations in the Mayer Ranch Oxidation Pond solids, though concentrations of manganese and nickel were also elevated in samples adjacent to those leached with extraction fluid 2. As extraction fluid 2 is more acidic than extraction fluid 1, these results further support the hypothesis that leaching of the examined metals is dependent on the pH of the extraction fluid. Samples leached with extraction fluid 2 have been removed from Figure 2.3 to better visualize the comparison of TCLP results with SPLP and FLT results. Results of the leaching tests for individual samples can be found in Appendix A.

Table 2.6: Median and Standard Deviation of the Concentrations of Select Elements in Leachates from Oxidation Pond Solids in mg L^{-1}

	TCLP		SPLP		FLT	
Metal	MRPTS	SECPTS	MRPTS	SECPTS	MRPTS	SECPTS
Silver	0.010 ± 0.003	0.008 ± 0.002	0.001 ± 0.0002	0.001 ± 0.0003	0.004 ± 0.003	0.005 ± 0.001
Aluminum	0.049 ± 0.211	0.058 ± 0.068	0.150 ± 0.015	0.133 ± 0.032	0.100 ± 0.055	0.103 ± 0.020
Arsenic	0.024 ± 0.015	<0.020 ± 0.008	<0.020	<0.020	<0.022	<0.020
Barium	0.161 ± 0.084	0.179 ± 0.045	0.088 ± 0.031	0.080 ± 0.023	0.004 ± 0.001	0.002 ± 0.002
Calcium	610 ± 172	487 ± 190	368 ± 64	301 ± 128	160 ± 48	161 ± 56
Cadmium	0.001 ± 0.047	0.003 ± 0.003	<0.001 ± 0.001	<0.001	<0.001	<0.001
Cobalt	0.021 ± 0.048	0.044 ± 0.246	<0.001 ± 0.001	0.002 ± 0.024	<0.002 ± 0.001	0.002 ± 0.006
Chromium	<0.001 ± 0.004	<0.001 ± 0.004	<0.001	<0.001	<0.001	<0.001
Copper	0.013 ± 0.019	0.017 ± 0.011	0.008 ± 0.002	0.008 ± 0.001	0.006 ± 0.003	0.008 ± 0.002
Iron	4.79 ± 461	3.51 ± 18.19	0.008 ± 0.012	0.008 ± 0.040	0.028 ± 1.211	0.010 ± 0.017
Potassium	12.6 ± 2.3	11.6 ± 4.6	5.45 ± 0.62	4.66 ± 3.24	4.13 ± 0.64	3.52 ± 1.92
Lithium	0.060 ± 0.020	0.055 ± 0.017	0.026 ± 0.004	0.028 ± 0.017	0.021 ± 0.008	0.013 ± 0.006
Magnesium	50.0 ± 9.6	51.6 ± 15.9	19.7 ± 3.9	26.2 ± 11.0	10.2 ± 3.2	18.3 ± 8.6
Manganese	0.772 ± 0.83	4.92 ± 10.45	0.010 ± 0.007	0.173 ± 1.882	0.005 ± 0.003	0.047 ± 0.610
Sodium	--	--	20.2 ± 3.7	52.2 ± 19.0	15.5 ± 3.5	36.9 ± 15.9
Nickel	0.440 ± 0.716	0.245 ± 0.486	0.009 ± 0.009	0.025 ± 0.072	0.004 ± 0.002	0.003 ± 0.015
Lead	0.022 ± 0.704	0.039 ± 0.042	0.023 ± 0.010	0.037 ± 0.026	0.023 ± 0.003	<0.002 ± 0.007
Sulfur	298 ± 59	278 ± 85	--	--	141 ± 37	178 ± 38
Silicon	12.5 ± 4.6	22.5 ± 4.4	1.49 ± 0.52	3.55 ± 1.61	0.466 ± 0.183	0.749 ± 0.304
Zinc	4.04 ± 19.12	9.06 ± 15.62	0.117 ± 0.245	0.225 ± 0.576	0.014 ± 0.018	0.035 ± 0.168

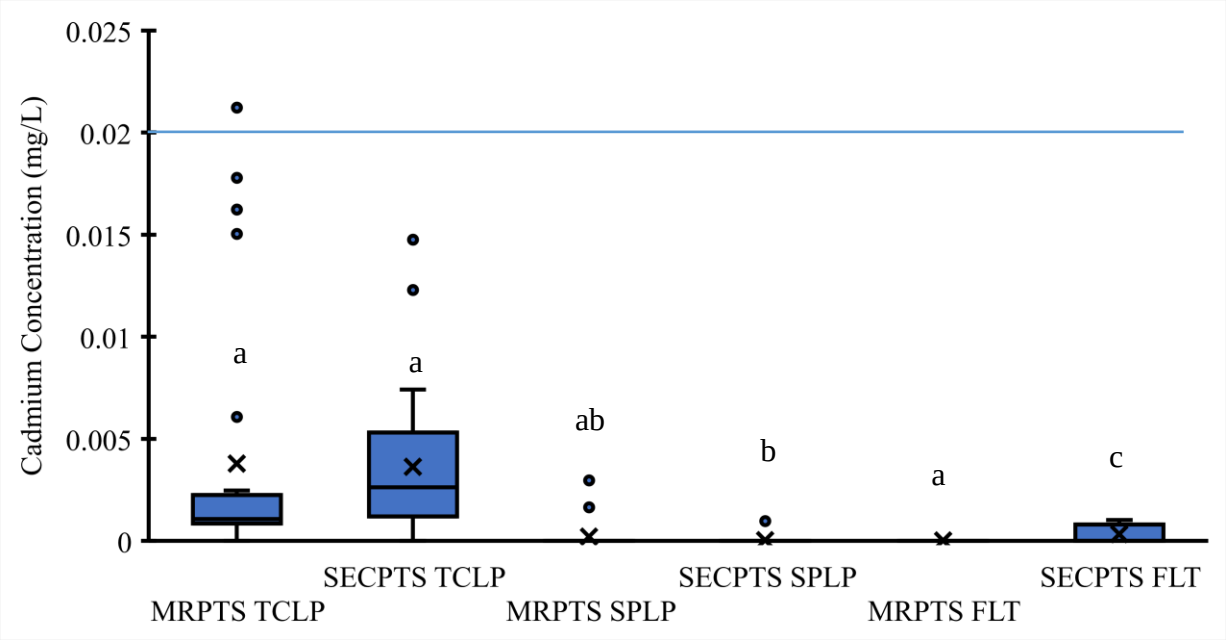

Figure 2.3: Box and Whisker Plots Showing Cadmium Concentrations in Leachates from Oxidation Pond Solids in mg L^{-1}, with a Blue Line to Indicate the OWRB Guideline and Letters to Indicate Statistically Similar Datasets

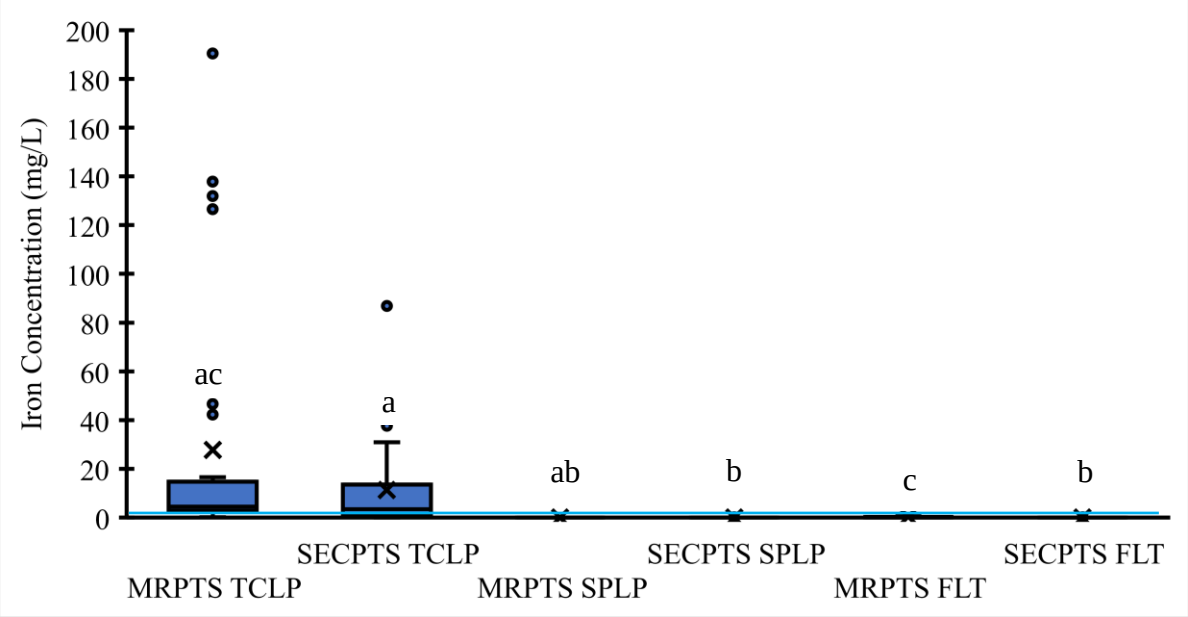

Figure 2.4: Box and Whisker Plots Showing Iron Concentrations in Leachates from Oxidation Pond Solids in mg L^{-1}, with a Blue Line to Indicate the OWRB Guideline and Letters to Indicate Statistically Similar Datasets

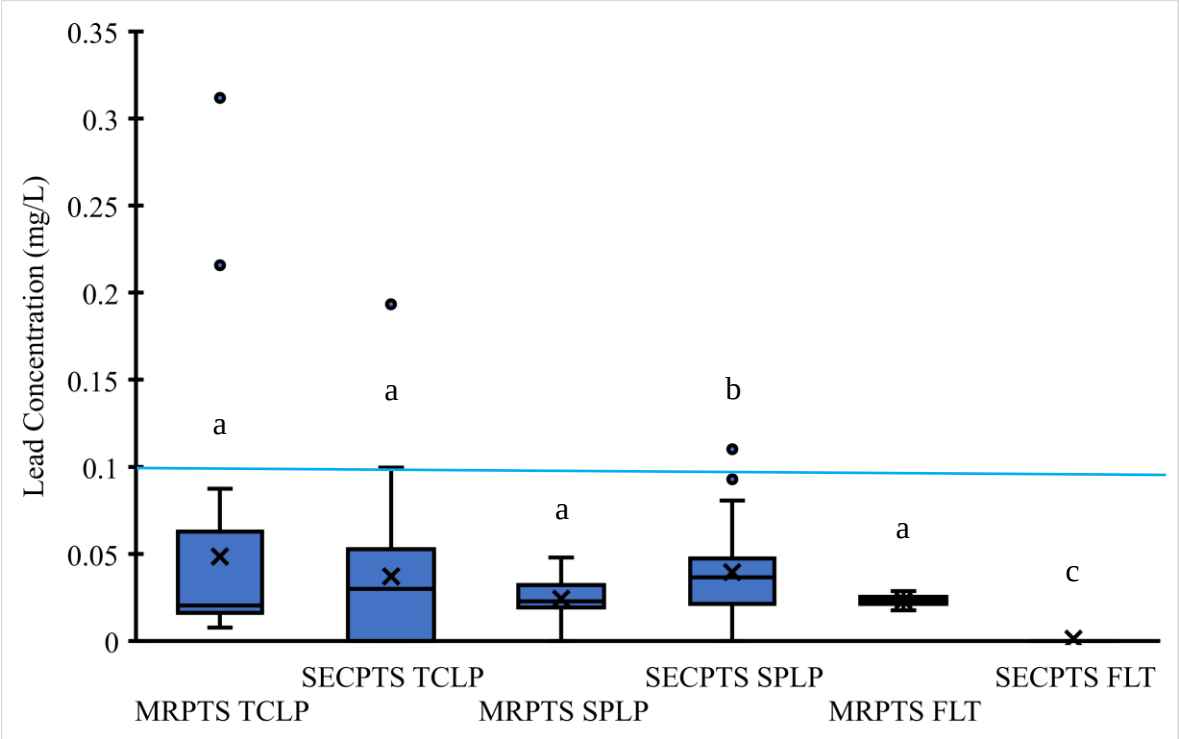

Figure 2.5: Box and Whisker Plots Showing Lead Concentrations in Leachates from Oxidation Pond Solids in mg L^{-1}, with a Blue Line to Indicate the OWRB Guideline and Letters to Indicate Statistically Similar Datasets

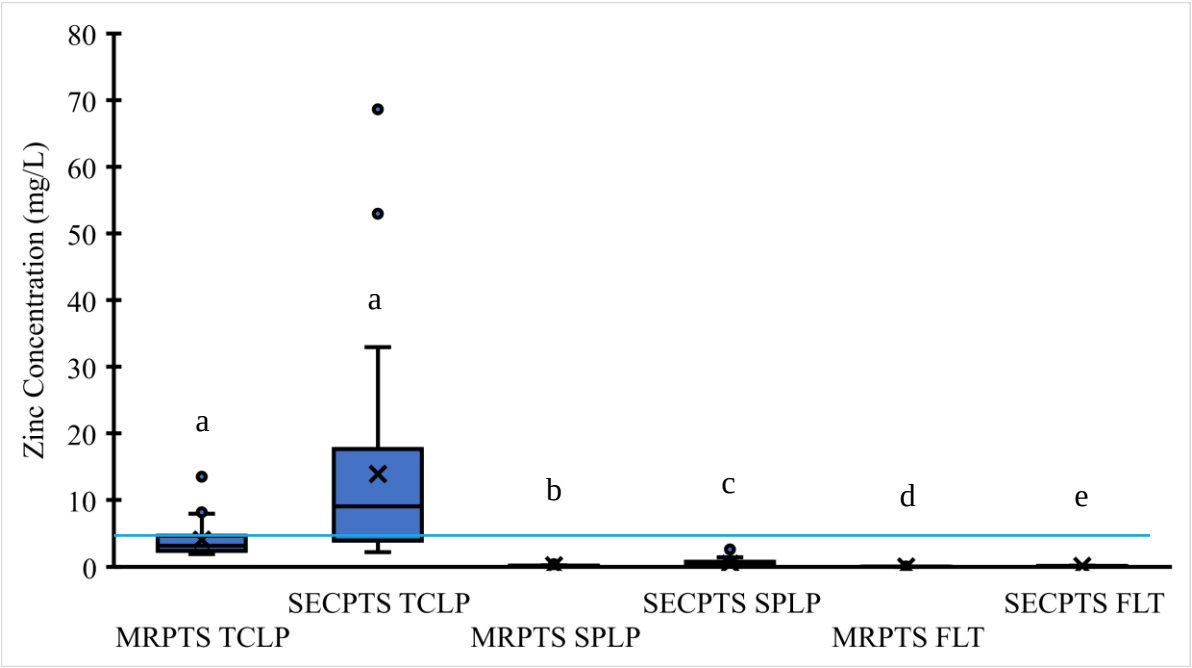

Figure 2.6: Box and Whisker Plots Showing Zinc Concentrations in Leachates from Oxidation Pond Solids in mg L^{-1}, with a Blue Line to Indicate the OWRB Guideline and Letters to Indicate Statistically Similar Datasets

SPLP and FLT leachates showed nickel concentrations below the "criterion to protect the Public Water Supply" found in Appendices G and I of OWRB Title 785 (OWRB, 2017), with the exception of one sample from Southeast Commerce, which had a nickel concentration of 309 µg L^{-1}, over twice the limit of 140 µg L^{-1}. Both systems exceeded the aluminum secondary criterion of 0.05 mg L^{-1} in both SPLP and FLT leachates. One sample, an outlier, exceeded the surface water criterion for lead of 0.1 mg L^{-1} in SPLP leachate, but the lead concentration in the same sample was below the practical quantitation limit (PQL) in FLT leachate. The manganese criterion of 0.05 mg L^{-1} was exceeded in both SPLP and FLT leachates from the Southeast Commerce system, specifically in samples from the portion of the oxidation pond furthest from the inflows. Manganese concentrations also increased in the solid samples at this point, possibly because manganese removal via sorption is not favored until the concentration of other metals has decreased and sorption sites become available (Neculita and Rosa, 2019). Iron concentrations exceeded the secondary criterion of 0.3 mg L^{-1} in some of the FLT leachates from Mayer Ranch samples. The same samples did not produce the highest iron concentrations in other leach tests, however, so the reason for increased iron in these leachates is unclear.

Although batch leaching tests are quick and easy methods for determining the concentration of metals easily mobilized by certain solutions, they are far from comprehensive analogs for how materials may behave in natural systems. Jong and Parry (2005) cite the short duration of these tests limiting the ability of the leachate to reach equilibrium and agitation leading to the breakdown of organic compounds as components of TCLP that may change the concentration of a constituent of concern in the final TCLP leachate. Additionally, larger particle sizes may be available to biota in certain field applications, which would allow greater concentrations of metals to become available. Redox states for elements such as arsenic and chromium can further

change the risk of exposure. Possible locations for beneficial reuse should be characterized and the behavior of the solids in those conditions should be studied before application of these mine waste residuals.

Conclusions

The mine drainage residuals precipitated in the oxidation ponds at the Mayer Ranch and Southeast Commerce Passive Treatment Systems are iron oxyhydroxides that, unlike coal mine drainage residuals, carry elevated concentrations of sorbed trace metals. These solids are heterogeneous, with large ranges of concentration for many of the trace metals found in the untreated mine drainage. Half of the metals analyzed showed statistically similar concentrations between the two systems. Differences between the two systems may be due to the difference in age and the accumulative effects of small differences in influent composition over time.

Of the three leaching tests performed, TCLP, the test with the most acidic extraction fluid, produced the leachate with the greatest concentrations of most metals. RCRA limits were not exceeded with TCLP leachate, however, some exceedances of groundwater quality criteria were encountered in SPLP and FLT results. It is not necessary to dispose of the solids in a hazardous waste landfill, but further evaluations such as long-term leaching tests are needed before they are put to beneficial reuse.

Future studies of the potential risk of the reuse of these solids should consider the environment where the reuse is planned. Column studies could be used to evaluate long-term leaching in soil, and fluvial analogs could simulate aquatic deployment. Toxicity studies designed for examining the metal uptake mechanisms of location-specific species should be conducted prior to placing the mine drainage residual solids. Preliminary tests show that the solids from hard rock mine

drainage in passive treatment oxidation ponds are nonhazardous but may pose some risk to organisms and water supplies.

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Chapter Three: Trace Metals Leachability from Vertical Flow Bioreactor Substrates in Two Hard Rock Mine Drainage Passive Treatment Systems

Abstract

VFBRs are an important form of biological passive treatment of mine drainage. The organic substrate in VFBRs provides an anaerobic environment for sulfate reducing bacteria, which facilitate the precipitation of metal sulfides from mine impacted waters. However, these treatment units can become clogged and require rehabilitative maintenance, such as the stirring or replacement of the organic substrate. Spent substrate from VFBRs may carry a large metal load and must be characterized before disposal. In this study, VFBR substrate from two hard rock mine drainage passive treatment systems in the Tri-State Lead-Zinc Mining District were evaluated for environmental availability of metals through three leaching tests. Concentrations of metals in leachates did not exceed RCRA limits but did exceed some OWRB guidelines. Additionally, total metals concentrations exceeded consensus-based toxicity benchmarks for soil and sediment.

Introduction

VFBRs, also sometimes known as vertical flow wetlands or ponds, sequential alkalinity-producing systems (SAPS), or biochemical reactors (BCRs), are an essential tool in mine drainage passive treatment (Watzlaf et al., 2004). These process units were originally designed to combine wetlands to decrease dissolved oxygen in mine drainage and anoxic limestone drains to increase alkalinity (Watzlaf et al., 2004), but they can also be designed to be sinks for trace metals and sulfate (Nairn et al., 2010). The organic substrate in a VFBR supports the creation of an anoxic environment and provides a source of organic matter for sulfate reducing bacteria (Skousen et al., 2017). The anoxic environment in VFBR substrates encourages biological

sulfate reduction with resulting precipitation of metal sulfides, beginning with less soluble trace metal sulfides such as copper, lead, zinc, and cadmium (Watzlaf et al., 2004).

The lifetime of a VFBR is limited by the organic substrate's reactivity and hydraulic conductivity (Skousen et al., 2017). Expected mass loading and the organic matter content of the selected substrate can be used to determine necessary substrate volumes and expected lifespan of the process unit, which is typically designed for 20 years; however, problems with hydraulic conductivity usually shorten design life (Shepherd et al., 2020). Hydraulic conductivity problems can be caused by substrate clogging due to metal precipitates, drain clogging due to roots or precipitates, and channelization and preferential flow disrupting the designed geochemistry of the process unit (Rose, 2004). These issues can typically be resolved by removal of clogs and flushing the system (Rose, 2004) or by stirring the substrate to disrupt channels and impermeable layers (Shepherd et al., 2020). Removal of spent substrate and addition of new organic matter should be considered if these techniques do not improve hydraulic conductivity but spent substrate may be hazardous and must be handled accordingly. Measurement of the fraction of metals in the solids that will become mobile within the environment is critical (Shepherd et al., 2020).

TCLP is a batch leaching test designed by the USEPA to determine the mobility of contaminants of concern in waste (USEPA, 1992). To be disposed of in a nonhazardous waste landfill, post-extraction leachate concentrations of the contaminants of concern must be below the limits set forth in RCRA (USEPA, 1984). Because of these regulations, TCLP is regularly used around the world as a preliminary examination of the toxicity of waste materials (Jong and Parry, 2005; Sonmez and Pierzynski, 2005; Wu et al., 2013). However, this test may not be the best choice if evaluation is to determine the potential for a waste to be beneficially reused (Cohen et al., 1999).

Cohen et al. (1999) found that different leaching fluids (e.g., organic or inorganic acids) had different effects depending on the metal of concern in the waste examined. They also found that greater liquid-to-solid ratios led to greater chromium leaching (Cohen et al., 1999). Jong and Parry (2005) found that iron and arsenic concentrations in leachate decreased when exposure to oxygen increased during the leaching test. Jong and Parry (2005) also found that in-situ disposal was better modeled through long-term column leaching than with TCLP.

TCLP models the conditions of a mixed solid waste landfill, which is not the likely destination for mine drainage treatment residuals (Hageman et al., 2005). Beneficial reuse, or even typical mine waste disposal, would likely not create an organic-rich, slightly acidic environment like the one that TCLP is meant to simulate (Hageman et al., 2005). The SPLP is a similar test to TCLP that was developed to simulate an environment that is open to leaching by slightly acidic rainwater (USEPA, 1994). SPLP shares a similar procedure with TCLP but uses a dilute mixture of sulfuric and nitric acids as an extraction fluid instead of the TCLP's acetic acid (USEPA, 1994). SPLP has been used to determine the feasibility of beneficial reuse of wastes with elevated metal concentrations (Cao and Dermatas, 2008; McDonald et al., 2006; Levasseur et al., 2006). These studies have found that, despite a higher pH, SPLP extraction fluid can result in greater concentrations of some metals in leachate (Levasseur et al., 2006), and that it may be an appropriate evaluation of the leaching potential of mine wastes in an environment without strong acids (McDonald et al., 2006).

The United States Geological Survey has developed a field leach test designed to simulate leachate from land-applied or stockpiled mine waste quickly and accurately (Hageman, 2007). The FLT uses deionized water as an extraction fluid and has been shown to be an appropriate analog for leachate from tailings piles and waste rock (chat, Hageman et al., 2005; LaBar, 2007).

It has also been used to evaluate the impacts of land application of biosolids (Yager et al., 2004). In this study, three tests (TCLP, SPLP, and FLT) were used in the evaluation of VFBR substrate from two mine drainage passive treatment systems in the TSMD.

This study investigated disposal and reuse options for VFBR substrates from two hard rock mine drainage passive treatment systems in northeastern Oklahoma by using TCLP, SPLP, and FLT to evaluate the risk associated with these organic materials. Due to improvements in water quality between regularly collected influent and effluent water samples from the VFBRs, it was expected that metal concentrations in leachates would exceed RCRA limits and/or OWRB guidelines. Risk associated with direct exposure of organisms to the VFBR substrates was evaluated using consensus-based screening levels. These guidelines were based on several toxicity studies of a wide range of constituents for soil organisms (Efroymson et al., 1997) and aquatic organisms in contact with sediment (MacDonald et al., 2000). Toxicity benchmarks for sediment developed for the TSMD by MacDonald et al. (2009) were also used as a comparison in order to evaluate local reuse options. Metal concentrations in the VFBR solids are expected to be above the guidelines set forth in these studies, but they are used here to make preliminary statements about maximum allowable application rate to minimize harm to flora and fauna.

Methods

Site Description

The TSMD of northeast Oklahoma, southeast Kansas, and southwest Missouri was extensively mined for lead and zinc from the 19th century to the 1960s (Nairn et al., 2010). Underground mines filled with water after shutting down, eventually leading to artesian flows at the ground surface by 1979 (Nairn et al., 2010). These discharges are net-alkaline due to the carbonate rock that hosts the mine workings and exhibit elevated concentrations of iron and trace metals such as

cadmium, lead, zinc, and arsenic (Nairn et al., 2010). Two multi-celled passive treatment systems, Mayer Ranch and Southeast Commerce, began operation in 2008 and 2017, respectively, to treat discharges from the mine pool, using a series of biogeochemical processes to decrease metal concentrations (Nairn et al., 2010; BioMost, 2018; Nairn et al., 2020).

There are three VFBRs between these two passive treatment systems, two operating in parallel with one another at Mayer Ranch and one in series with other treatment units at Southeast Commerce, as shown in Figures 1.2 and 1.3 (Nairn et al., 2010; Nairn et al., 2014). Each VFBR is preceded by an oxidation pond that receives mine drainage and promotes iron oxide formation and a surface flow wetland that continues solid settling (Nairn et al., 2010; Nairn et al., 2014). At Mayer Ranch, the process units are connected via buried pipes, but the first three treatment units at Southeast Commerce share a water surface. The substrate of the Mayer Ranch VFBRs contains 45% spent mushroom compost, 45% hardwood chips, and 10% limestone sand by volume underlain by a limestone gravel drain (LaBar and Nairn, 2018). The substrate of the Southeast Commerce VFBR contains an 80:20 by volume mixture of woodchips and spent mushroom compost and is underlain by silicate rocks to prevent clogging of the drains (BioMost, Inc., 2018). Hydraulic conductivity has been an issue in the VFBRs of both systems. The substrate of the Mayer Ranch VFBRs was stirred in early 2017 to increase hydraulic conductivity, and the Southeast Commerce VFBR has been flushed to remove possible clogs. It is hypothesized that higher-than-design water levels at Southeast Commerce due to an upwelling in the oxidation pond that was uncovered during construction of the system may be a contributor to the hydraulic conductivity problems in that system (Nairn, 2019). Water volumes have been consistently greater than system design for, causing diminished functioning of the surface flow

wetland due to high water levels and deposition of iron oxyhydroxides on the substrate of the VFBR that would be precipitated before the VFBR under design flow conditions (Nairn, 2019).

Sample Collection

Water quality and aqueous metal concentration data have been collected 4-12 times annually at the influent and effluent of each treatment unit since the construction of each system. Water quality information is generated using a YSI multiparameter sonde, and samples are collected in 250-mL HDPE bottles, acidified, returned to the CREW Laboratories in Norman, OK for analysis of metals using the ICP-OES.

Substrate samples were collected while water levels in the systems were artificially lowered, allowing access. Preliminary data from a previous study of the substrates of the Mayer Ranch VFBR (LaBar and Nairn, 2018) was used to determine the number of samples necessary to adequately characterize the metal concentrations in the substrate. Using the Guidance for Data Usability in Risk Assessment from the USEPA (1991), it was determined that 30 samples were needed from each system's VFBR substrates. Samples were collected using a stainless-steel trowel to transfer material into 7.8-L LDPE plastic bags. GPS points were recorded during sample collection using a handheld Garmin unit and were used to plot points on Figures 3.1 and 3.2. Bags were labeled and placed in coolers to return to the CREW Laboratories in Norman, OK, where they were kept at 4°C until analysis. Aerial Photographs of sample locations in the Mayer Ranch and Southeast Commerce VFBRs are presented as Figures 3.1 and 3.2, respectively.



Figure 3.1: Sampling Locations within the Mayer Ranch VFBRs



Figure 3.2: Sampling Locations within the Southeast Commerce VFBR

Physical Characterization of the Solids

A portion of each substrate sample was dried at 105°C until mass was constant (approximately 40 hours) to determine moisture content via ASTM Method D4531-86 (2008). These dried samples were then ground and sieved. Solids passing the 2 mm (Number 10) sieve were used to determine organic matter content via loss on ignition (Robertson, 2011) and total recoverable metals via USEPA Method 6010C (USEPA, 2018) after hot acid digestion. The samples being analyzed for organic matter were placed in a muffle furnace, heated to 375°C, and held at that temperature for 23 hours. The mass of the samples was recorded before and after heating and the organic matter content was calculated as the difference between the initial and final mass.

Solids analyzed for total metals were first digested using USEPA Method 3051A (USEPA, 2007a). A portion of each sample with a mass of approximately 0.5 g was placed in a Teflon digestion tube with 10 mL of trace metal grade nitric acid. Microwave digestion was then completed using a CEM MARS programmed to heat the samples to 175°C for 10 minutes. Digested samples were filtered using polypropylene Leur-lock syringe filters with a pore diameter of 0.45 µm and stored in 60-mL HDPE bottles until analysis using a Varian Vista-Pro ICP-OES following USEPA method 6010C (USEPA, 2018). Concentrations measured in the digest and the mass of the solids digested were used to determine the concentration of elements in the substrate in mg kg^{-1}.

Leaching Tests

Additional portions of the samples were air dried for leaching tests. After drying, a motorized grinder was used to decrease particle size and large rock fragments were discarded. pH was determined as described in the Preliminary Evaluations section of the TCLP document (USEPA, 1992). Twelve of the samples from the Mayer Ranch VFBRs met the criteria for using extraction

fluid 2 for TCLP. This fluid was prepared in a 2-L volumetric flask for each sample being analyzed with extraction fluid 2, while extraction fluid 1 was prepared one liter at a time and combined in a 20-L carboy to homogenize the fluid. TCLP analysis proceeded following USEPA Method 1311 (USEPA, 1992). Tumble blanks, made with TCLP extraction fluid in a tumbler with no sample, were collected at a rate of one per passive treatment system and processed with other samples. After filtration, leachate was stored in 250-mL HDPE bottles until digestion following USEPA Method 3015A (USEPA, 2007b). Digested leachate was stored in 60-mL HDPE bottles until analysis using a Varian Vista-Pro ICP-OES following USEPA Method 6010C (USEPA, 2018).

SPLP leaching fluid was prepared by diluting a stock solution of 1 mL of 60/40 weight percent sulfuric and nitric acids in 20 L of deionized water to the desired pH of 5.00 ± 0.05. The solution was prepared in a 20-L carboy. SPLP analysis proceeded following USEPA Method 1312 (USEPA, 1994). Tumble blanks prepared with SPLP leaching fluid in a tumbler without a sample were included at a rate of one per passive treatment system. Samples followed the same post-filtration steps as the TCLP leachate described above.

The FLT procedure described in Hageman (2007) was modified by decreasing the amount of sample and leaching fluid used to 12.5 g and 250 mL, respectively, to conserve sample volume. The sample was placed in a 250-mL volumetric flask with 250 mL of deionized water and shaken using a Burrell wrist-action shaker for 5 minutes and allowed to sit in the shaker for an additional 10 minutes. Leachate was filtered using a 10-mL syringe and Leur-lock 0.45-µm nylon filter and stored in 250-mL HDPE bottles until digested and analyzed according to USEPA Methods 3015A and 6010C, respectively (USEPA, 2007b; USEPA, 2018).

Results and Discussion

Water Quality

Metal concentrations and other select parameters of the influent and effluent of the Mayer Ranch VFBRs are shown in Table 3.1. The same parameters for the influent and effluent of the Southeast Commerce VFBR are shown in Table 3.2. Both VFBRs at Mayer Ranch decrease cadmium, cobalt, iron, nickel, and zinc in the effluent water. The Southeast Commerce VFBR decreases cadmium, cobalt, iron, nickel, lead, and zinc in the effluent water. Effluent from the Southeast Commerce VFBR is sampled from four outflows, with Pipe 1 being the section of the VFBR closest to the inflow from the surface flow wetland. Effluent from Pipe 1 is statistically similar ($p > 0.05$) to the influent with respect to iron and lead concentrations, indicating that metal sequestration may be inhibited in this region, possibly due to impacts from the oxidation pond. Flow from Pipe 1 has also decreased at a faster rate than the flow from the other sections of the VFBR, indicating that hydraulic conductivity problems are most acute in the section of the VFBR closest to the inflow.

Table 3.1: Median Elemental Concentrations, pH, Alkalinity, and Flow with Standard Deviations in Mayer Ranch VFBR Influents and Effluents from September 2008 to July 2020, with Influent Parameters Significantly Different from Effluent Bolded

	North VFBR		South VFBR	
Parameter	Influent	Effluent	Influent	Effluent
pH	**6.47 ± 0.42**	6.79 ± 0.22	**6.44 ± 0.42**	6.80 ± 0.18
Flow (L/s)	2.94 ± 5.02	--	3.06 ± 2.06	--
Alkalinity (mg/L $CaCO_3$)	**152 ± 43**	197 ± 91	**150 ± 29**	199 ± 68
Silver (µg/L)	9.37 ± 3.50	8.30 ± 3.09	9.91 ± 1.16	8.44 ± 3.27
Aluminum (µg/L)	**71.9 ± 261.6**	192 ± 1872	**56.5 ± 154.8**	295 ± 1177
Arsenic (µg/L)	<20	<20	<20	<20
Barium (µg/L)	9.69 ± 7.00	11.8 ± 15.9	9.97 ± 24.02	11.8 ± 7.2
Calcium (mg/L)	712 ± 71	720 ± 112	710 ± 66	716 ± 101
Cadmium (µg/L)	**1.35 ± 1.93**	1.22 ± 0.66	**1.24 ± 2.04**	1.25 ± 0.71
Cobalt (µg/L)	**50.1 ± 22.1**	8.25 ± 13.4	**46.8 ± 22.0**	7.35 ± 14.1
Chromium (µg/L)	3.68 ± 2.97	3.86 ± 2.88	4.16 ± 2.32	3.45 ± 3.70
Copper (µg/L)	3.10 ± 3.16	3.11 ± 2.47	3.02 ± 3.22	3.50 ± 3.05
Iron (mg/L)	**3.46 ± 13.7**	1.40 ± 7.97	**3.55 ± 17.2**	0.96 ± 3.08
Potassium (mg/L)	24.5 ± 3.1	24.3 ± 5.9	24.5 ± 3.0	23.8 ± 4.2
Lithium (µg/L)	302 ± 147	252 ± 128	303 ± 22	279 ± 136
Magnesium (mg/L)	179 ± 27	178 ± 30	181 ± 25	182 ± 40
Manganese (mg/L)	1.37 ± 0.56	881 ± 861	1.42 ± 0.69	1.05 ± 0.89
Sodium (mg/L)	98.6 ± 16.2	96.2 ± 17.1	96.7 ± 15.5	94.6 ± 17.4
Nickel (µg/L)	**728 ± 185**	138 ± 357	**733 ± 182**	126 ± 257
Lead (µg/L)	31.2 ± 28.4	30.0 ± 18.6	31.1 ± 22.4	30.2 ± 16.3
Sulfur (mg/L)	814 ± 402	671 ± 365	809 ± 88	710 ± 372
Silicon (mg/L)	7.24 ± 3.44	4.68 ± 3.29	7.16 ± 0.95	6.17 ± 3.39
Zinc (mg/L)	**4.48 ± 1.86**	0.52 ± 1.07	**4.66 ± 2.03**	0.42 ± 1.06

Table 3.2: Median Elemental Concentrations, pH, Alkalinity, and Flow with Standard Deviations in Southeast Commerce VFBR Influent and Effluent from March 2017 to July 2020, with Effluent Parameters Significantly Different from Influent Bolded

	VFBR	VFBR Effluent			
Parameter	Influent	Pipe 1	Pipe 2	Pipe 3	Pipe 4
pH	6.19 ± 0.27	**6.20 ± 0.11**	**6.18 ± 0.07**	6.21 ± 0.12	6.24 ± 0.29
Flow (L/s)	--	1.66 ± 0.43	2.00 ± 0.42	2.28 ± 0.45	2.36 ± 0.43
Alkalinity (mg/L $CaCO_3$)	103 ± 13	**128 ± 58**	**119 ± 39**	**130 ± 42**	**130 ± 68**
Silver (µg/L)	7.88 ± 4.00	8.04 ± 2.28	8.25 ± 0.96	7.98 ± 2.37	8.31 ± 4.06
Aluminum (µg/L)	57.4 ± 76.9	46.9 ± 5.36	49.5 ± 48.4	41.5 ± 67.0	49.9 ± 56.9
Arsenic (µg/L)	<20	<20	<20	<20	<20
Barium (µg/L)	6.55 ± 6.73	8.23 ± 7.99	8.99 ± 3.61	8.08 ± 3.23	**11.2 ± 12.3**
Calcium (mg/L)	620 ± 62	**591 ± 43**	**588 ± 47**	**594 ± 51**	621 ± 61
Cadmium (µg/L)	2.69 ± 1.43	**1.14 ± 0.64**	**1.26 ± 0.60**	**0.882±0.464**	**1.05 ± 0.48**
Cobalt (µg/L)	39.6 ± 12.3	**6.23 ± 10.0**	**17.8 ± 9.8**	30.9 ± 18.2	**11.8 ± 10.9**
Chromium (µg/L)	5.15 ± 3.74	5.51 ± 2.49	<0.587	7.77 ± 2.75	5.06 ± 3.47
Copper (µg/L)	3.64 ± 1.82	3.37 ± 1.37	3.26 ± 1.60	3.19 ± 1.20	3.40 ± 1.69
Iron (mg/L)	4.06 ± 3.22	3.59 ± 3.38	**1.12 ± 1.22**	**0.46 ± 0.64**	**0.95 ± 0.84**
Potassium (mg/L)	20.6 ± 2.4	20.3 ± 1.6	20.2 ± 1.6	20.2 ± 1.7	20.5 ± 2.5
Lithium (µg/L)	268 ± 124	255 ± 88	250 ± 30	253 ± 70	268 ± 118
Magnesium (mg/L)	137 ± 19	**127 ± 14**	**126 ± 11**	**126 ± 12**	138 ± 18
Manganese (mg/L)	2.41 ± 0.59	1.92 ± 1.22	1.70 ± 2.06	1.66 ± 1.90	2.17 ± 1.28
Sodium (mg/L)	81.3 ± 13.0	85.3 ± 9.2	85.1 ± 8.9	83.8 ± 9.1	84.4 ± 13.0
Nickel (µg/L)	529 ± 63	**66.0 ± 117.4**	**151 ± 225**	**74.1 ± 31.6**	**47.4 ± 264.2**
Lead (µg/L)	28.0 ± 10.1	32.6 ± 12.9	22.9 ± 8.3	23.8 ± 10.6	**23.6 ± 8.0**
Sulfur (mg/L)	711 ± 346	**664 ± 227**	**677 ± 46**	**661 ± 177**	702 ± 321
Silicon (mg/L)	11.9 ± 5.39	11.9 ± 3.7	11.5 ± 1.5	11.3 ± 3.3	12.4 ± 5.3
Zinc (mg/L)	5.43 ± 1.13	**0.04 ± 0.46**	**0.56 ± 2.06**	**0.37 ± 2.09**	**0.05 ± 0.68**

Physical Characterization of the Solids

The median moisture content, organic matter content, and pH from the 30 samples from each system's VFBR substrates and their standard deviations are listed in Table 3.3. Moisture content was statistically similar between the two systems ($p = 0.29$). However, organic matter content and pH were statistically different between the two systems ($p < 0.05$). Remaining organic matter content can be used as an analog for the remaining biogeochemical lifespan of a VFBR (Shepherd et al., 2020), which is consistent with the younger of the two systems having a higher

percentage of organic matter content in the substrate. The pH of the VFBRs was influenced by the addition of limestone sand to the organic matter at Mayer Ranch. This alkalinity augmentation was not added to the Southeast Commerce Passive Treatment System, which has an organic-only VFBR substrate (BioMost, 2018). The lack of carbonate buffering in the Southeast Commerce VFBR appears to allow the organic acids and metal acidity present in the substrate to exhibit more influence over the pH of the substrate.

Table 3.3: Median Moisture Content, Organic Matter Content, and pH in VFBR Substrates

	Mayer Ranch	Southeast Commerce
Moisture Content (%)	76.99 ± 6.93	76.26 ± 7.55
Organic Matter Content (% dry mass)	23.58 ± 5.26	35.09 ± 10.76
pH	6.37 ± 0.42	3.91 ± 0.74

Median metal and sulfur concentrations and their standard deviations can be found in Table 3.4. Major constituents (>10,000 mg kg^{-1}) included calcium, iron, sulfur, and zinc. Aluminum (approximately 8,000 mg kg^{-1} in Mayer Ranch solids and approximately 5,500 mg kg^{-1} in Southeast Commerce solids), nickel (approximately 3,000 mg kg^{-1}), magnesium (approximately 2,000 mg kg^{-1}), potassium, and manganese (approximately 1,000 mg kg^{-1} each) are also notable constituents. Lead is present at median concentrations of 55 mg kg^{-1} in the Mayer Ranch substrate and 93 mg kg^{-1} in the Southeast Commerce substrate. Cadmium is present at concentrations of 10 mg kg^{-1} and 55 mg kg^{-1} in the Mayer Ranch and Southeast Commerce VFBRs, respectively.

Comparing iron concentrations in the solids overlying Pipe 1 (samples 9-10, 19-20, and 29-30) and Pipe 4 (samples 1-2, 11-12, and 21-22) in the Southeast Commerce VFBR showed that iron concentrations were elevated in the solids overlying Pipe 4 ($p = 0.0498$), while lead concentrations in the same substrates were found to be statistically similar ($p = 0.5136$). These

iron concentrations provide additional support to the hypothesis that the portion of the VFBR further from the inflow has been more effective at retaining iron. Concentrations of metals in individual samples can be found in Appendix B.

Table 3.4: Median Elemental Concentration in VFBR Substrates in mg kg^{-1}

	Mayer Ranch	Southeast Commerce
Silver	0.381 ± 0.345	0.547 ± 0.563
Aluminum	7540 ± 1505	5440 ± 1328
Arsenic	18.4 ± 6.6	36.7 ± 15.6
Barium	36.3 ± 13.9	16.6 ± 23.3
Calcium	23785 ± 18567	12818 ± 3069
Cadmium	9.17 ± 5.74	54.7 ± 27.1
Cobalt	360 ± 220	516 ± 272
Chromium	13.5 ± 3.3	6.12 ± 1.49
Copper	72.5 ± 25.5	82.1 ± 44.6
Iron	65852 ± 41306	66134 ± 63503
Potassium	1331 ± 223	866 ± 138
Lithium	19.5 ± 2.6	10.5 ± 2.7
Magnesium	2208 ± 248	1740 ± 384
Manganese	1648 ± 3265	1024 ± 9248
Sodium	473 ± 101	592 ± 145
Nickel	3192 ± 1838	2619 ± 2355
Lead	15.7 ± 4.3	92.6 ± 28.2
Sulfur	21196 ± 13397	67190 ± 30315
Selenium	<4.43	<4.43 ± 1.93
Silicon	46.1 ± 14.6	56.2 ± 31.2
Zinc	43224 ± 19369	62472 ± 28732

A comparison of the northern and southern treatment units in the Mayer Ranch Passive Treatment System shows that approximately half of the metals concentrations are statistically similar ($p > 0.05$) in the two VFBRs. Concentrations are different ($p < 0.05$) in silver, aluminum, barium, cadmium, chromium, iron, potassium, manganese, and zinc. Aluminum, chromium, potassium, and zinc concentrations are elevated in the northern VFBR (C3N), and silver, barium, cadmium, iron, and manganese are elevated in the southern VFBR (C3S).

Comparing the VFBRs in the two systems shows additional differences in metal concentrations. Concentrations of silver, arsenic, cadmium, cobalt, sodium, lead, and sulfur were elevated ($p < 0.05$) in the Southeast Commerce VFBR solids compared to the concentrations in the combined Mayer Ranch VFBRs. Some of these differences can be attributed to the increased amount of iron oxides deposited on the top of the SECPTS VFBR due to its shared water surface with the oxidation pond and surface flow wetland in the system, which is exacerbated by greater-than-design volumetric discharge rates due to contributions from the upwelling in the oxidation pond that was uncovered during construction. Elevated concentrations of aluminum, barium, chromium, potassium, and lithium in the Mayer Ranch VFBR solids compared to the Southeast Commerce VFBR solids may be due to the age difference in the systems. Elevated calcium and magnesium in the Mayer Ranch VFBR solids can be attributed to the difference in inorganic material (limestone sand in Mayer Ranch as opposed to organic-only substrate in Southeast Commerce).

The substrates from the VFBRs examined in this study do not meet the consensus-based sediment and soil guidelines defined in MacDonald et al. (2000) and Efroymson et al. (1997), respectively. A summary of these guidelines and the exceedances observed in the VFBR substrates is included as Table 3.5. LaBar and Nairn (2018) report iron, zinc, and manganese concentrations exceeding sediment guidelines from MacDonald et al. (2000) and cadmium concentrations exceeding soil guidelines from Efroymson et al. (1997) in samples of the Mayer Ranch substrate taken before system operation began. Aluminum, iron, manganese, nickel, and zinc are the primary concerns when compared to the sediment guidelines from MacDonald et al. (2000). Median arsenic, cadmium, copper, nickel, lead, and zinc are all above the soil guidelines from Efroymson et al. (1997). Arsenic, cadmium, copper, nickel, lead, and zinc also exceeded

the site-specific benchmarks from MacDonald et al. (2009) in at least one sample. Additions of the VFBR substrates to soil and sediments would be limited by zinc according to these guidelines and would be on the order of 0.001% of the soil mass and 0.1% of sediment mass to remain in compliance with these guidelines. Zinc would also limit the application of these materials within the TSMD, but the rate of application could be increased to 0.7% of the mass.

Table 3.5: Soil and Sediment Toxicity Benchmarks, Percent of VFBR Substrate Samples Exceeding the Benchmarks, and the Range of Concentration for the Metal in Samples with Exceedances Bolded

Metal	Toxicity Benchmark (mg kg^{-1})	Percent of Samples Exceeding Benchmark		Concentration Range (mg kg^{-1})	
		MRPTS	SECPTS	MRPTS	SECPTS
Silver – Soil	50	0	0	<0.282-1.12	<0.282-3.01
Aluminum – Soil	600	100	100	**4816-10280**	**3080-8710**
Arsenic – Soil	60	0	6.7		
Arsenic – Sediment	9.79	90	97	8.02-**33.46**	7.62-**70.72**
Arsenic – TSMD	33	3.3	57		
Barium – Soil	3000	0	0	12.33-71.56	7.48-96.09
Cadmium – Soil	20	13	100		
Cadmium – Sediment	0.99	100	100	**3.81-23.26**	**26.9-116.4**
Cadmium – TSMD	4.98	83	100		
Cobalt - Soil	1000	0	10	57.03-840.76	80.8-1064.3
Chromium – Soil	0.40	100	100		
Chromium – Sediment	43.40	0	0	**5.74-19.59**	**1.52-9.16**
Chromium – TSMD	111	0	0		
Copper – Soil	50	77	70		
Copper – Sediment	31.6	97	83	30.11-**155.50**	4.40-**177.75**
Copper – TSMD	149	3.3	10		
Iron – Soil	200	100	100	**26350-173908**	**22696-280648**
Lithium – Soil	10	100	57	**15.25-30.16**	5.17-**15.13**
Manganese – Soil	100	100	100	**365.6-736.7**	**221-44321**
Nickel – Soil	90	100	100		
Nickel – Sediment	22.7	100	100	**1041-8411**	**590-10466**
Nickel – TSMD	48.6	100	100		
Lead – Soil	500	0	0		
Lead – Sediment	35.8	0	100	9.27-24.84	**37.69-187.13**
Lead – TSMD	128	0	13		
Zinc – Soil	20	100	100		
Zinc – Sediment	121	100	100	**7951-92370**	**7587-101064**
Zinc – TSMD	459	100	100		

Leaching Tests

The median concentrations resulting from each of the leaching tests are detailed in Table 3.6. TCLP resulted in the greatest concentration for most the elements analyzed when leachates were statistically different. However, Southeast Commerce TCLP concentrations of aluminum,

cadmium, and iron were less than Southeast Commerce SPLP and FLT concentrations, which were statistically similar ($p > 0.05$). Cadmium and iron concentrations in Mayer Ranch leachates were statistically similar between the three tests. Lead concentrations were greatest in FLT leachates from both systems. Silicon concentrations were greatest in the SPLP leachate from the Southeast Commerce substrates but were greatest in the TCLP leachate from the Mayer Ranch substrates. These results show that there may be factors other than pH to consider when performing leaching tests, especially when the pH of the solids is more acidic, as is seen in the Southeast Commerce VFBR. Additionally, iron mobility may change between the systems due to iron oxide deposition within the Southeast Commerce VFBR. These factors seem to especially affect the chief contaminants of concern at the Tar Creek Superfund Site: cadmium, lead, and zinc. Sodium is present in the TCLP extraction fluid and sulfur is present in the SPLP extraction fluid, so these concentrations are not representative of leaching and thus are not included in Table 3.6.

Samples from both systems produced TCLP leachates well below RCRA limits, indicating that the substrate of the VFBRs are classified as nonhazardous. However, nickel concentrations in SPLP and FLT leachate from both systems were well above the 140 $\mu g\ L^{-1}$ set in the "criteria to protect the Public Water Supply" found in Appendices G and I of OWRB Title 785 (OWRB, 2017). Additionally, aluminum, cadmium, chromium, iron, manganese, lead, selenium, and zinc concentrations in SPLP and FLT leachates from both systems exceeded secondary criteria for protection of public water supply (OWRB, 2017). These results indicate that further research is necessary to ensure that surface water and groundwater are protected if these solids are put to beneficial reuse. Column leach tests with soil or sediment from a proposed reuse site could help determine concentrations expected to be available to the environment over time.

Leachates from the two different VFBRs at Mayer Ranch were statistically similar for all elements tested except copper in the SPLP leachates, which was slightly elevated in the C3S leachates. These elevated concentrations reflect slight differences in median concentrations of copper in the solids.

As seen with the total concentrations, leachable metals and sulfur varied between the systems. These differences may be principally due to differences in connectivity with the preceding treatment units in the respective system and the age of the systems, which both relate to the mineralogy of the inorganic precipitates within the VFBR. A comparison of sequential extractions between the two systems may provide insight into the differences and could be compared to results of the same analysis completed on Mayer Ranch VFBR substrates in 2010 and 2014 (LaBar and Nairn, 2018).

Table 3.6: Median and Standard Deviation of the Concentrations of Select Elements in Leachates from VFBR Solids in mg L^{-1}

	TCLP		SPLP		FLT	
Metal	MRPTS	SECPTS	MRPTS	SECPTS	MRPTS	SECPTS
Silver	0.020 ± 0.010	0.008 ± 0.002	0.009 ± 0.002	0.008 ± 0.004	0.004 ± 0.003	0.009 ± 0.004
Aluminum	0.362 ± 0.707	1.00 ± 0.74	<0.004 ± 0.006	2.09 ± 2.60	0.113 ± 0.095	2.36 ± 2.18
Arsenic	0.011 ± 0.015	<0.020	<0.020	<0.020 ± 0.010	<0.022	<0.020 ± 0.007
Barium	0.136 ± 0.075	0.127 ± 0.027	0.082 ± 0.014	0.095 ± 0.017	0.009 ± 0.005	0.008 ± 0.005
Calcium	16400 ± 1095	255 ± 68	515 ± 196	304 ± 77	164 ± 71	214 ± 65
Cadmium	<0.001 ± 0.004	0.001 ± 0.004	<0.001	0.003 ± 0.015	<0.001 ± 0.001	0.004 ± 0.038
Cobalt	5.00 ± 4.15	6.59 ± 4.00	0.872 ± 2.334	8.43 ± 4.98	0.556 ± 1.956	8.11 ± 5.42
Chromium	0.002 ± 0.004	0.002 ± 0.001	<0.001 ± 0.0004	0.002 ± 0.002	<0.001 ± 0.026	0.003 ± 0.002
Copper	0.013 ± 0.006	0.017 ± 0.002	0.008 ± 0.001	0.007 ±0.003	0.006 ± 0.001	0.009 ± 0.009
Iron	0.206 ± 12.000	1.68 ± 3.81	0.005 ± 0.003	14.9 ± 87.2	0.009 ± 0.282	13.8 ± 61.6
Potassium	23.6 ± 6.3	19.2 ± 4.6	10.2 ± 3.40	7.64 ± 2.54	7.51 ± 2.20	7.93 ± 2.63
Lithium	0.105 ± 0.018	0.068 ± 0.010	0.062 ± 0.019	0.048 ± 0.007	0.045 ± 0.015	0.041 ± 0.010
Magnesium	58.1 ± 7.1	48.3 ± 8.2	46.5 ± 12.1	39.3 ± 6.8	31.3 ± 11.0	44.8 ± 11.1
Manganese	17.5 ± 23.4	15.1 ± 18.3	1.80 ± 5.11	18.8 ± 23.6	0.733 ± 4.305	13.6 ± 17.0
Sodium	--	--	18.7 ± 4.7	16.6 ± 2.8	13.8 ± 3.6	15.9 ± 3.8
Nickel	60.7 ± 33.1	52.8 ± 32.9	9.58 ± 18.26	67.7 ± 48.7	8.28 ± 16.4	67.7 ± 49.9
Lead	0.204 ± 0.130	0.009 ± 0.016	<0.008	0.018 ± 0.109	0.049 ± 0.034	0.044 ± 0.117
Sulfur	395 ± 209	498 ± 251	--	--	184 ± 85	563 ± 378
Selenium	0.035 ± 0.014	0.026 ± 0.017	<0.022	<0.022 ± 0.012	<0.022	<0.022 ± 0.009
Silicon	8.00 ± 7.75	6.73 ± 8.25	3.40 ± 0.85	7.20 ± 4.08	0.759 ± 0.241	1.22 ± 0.57
Zinc	63.0 ± 44.3	272 ± 285	5.05 ± 10.24	498 ± 316	7.76 ± 20.69	407 ± 442

When pH was evaluated in the solids, 12 out of the 30 samples from the Mayer Ranch VFBRs (5 from C3N, 7 from C3S) had enough acid neutralization capacity to mandate the use of TCLP extraction fluid 2. Out of the 20 elements reported for TCLP, nine showed statistical differences between the extraction fluids ($p < 0.05$), six of which had greater median concentrations in leachates that used extraction fluid 2. These results are consistent with the hypothesis that lower pH in the extraction fluid will lead to greater metal concentrations in the leachate. Copper, potassium, and sulfur did not follow this trend, possibly due to differences in the behavior of these elements in response to changes in pH, such as the insolubility of copper sulfide (Watzlaf et al., 2004), the formation of volatile hydrogen sulfide at low pH, and potassium's status as an alkali metal.

As can be seen in the standard deviations reported in Tables 3.4 and 3.6, the VFBR substrates from both passive treatment systems are heterogeneous. Box and whisker plots of select metal concentrations in leachates are presented as Figure 3.3 to 3.7 to demonstrate the heterogeneity of the concentrations. Concentrations from individual samples can be found in Appendix B.

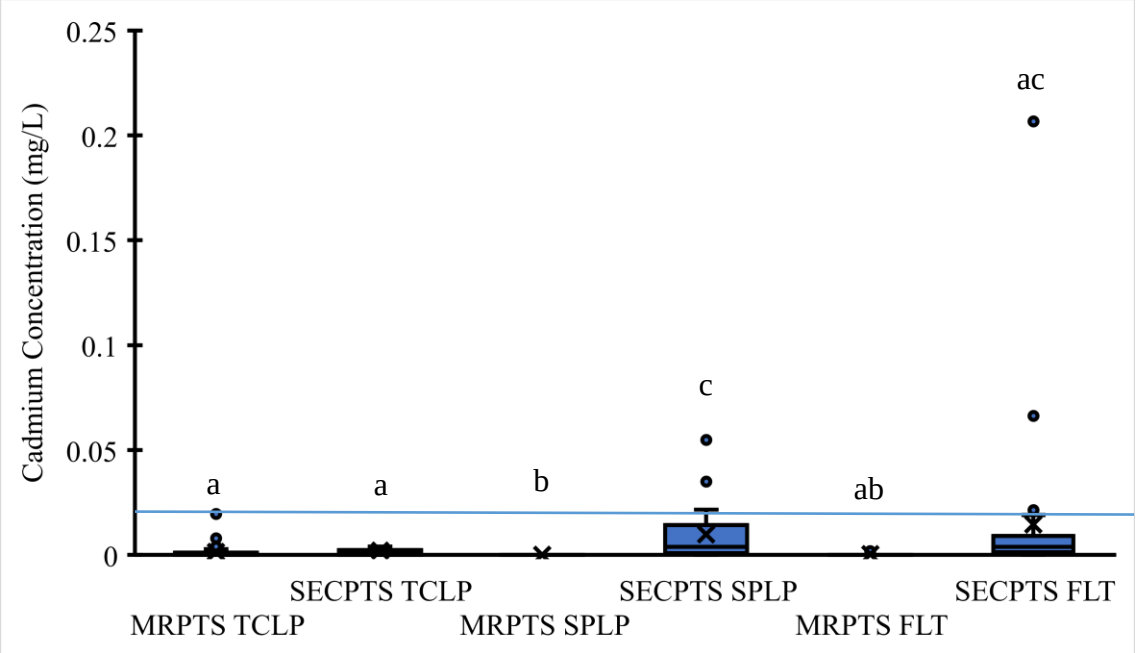

Figure 3.3: Cadmium Concentrations in Leachates from VFBR Substrates in mg L^{-1}, with a Blue Line to Indicate the OWRB Guideline and Letters to Indicate Statistically Similar Datasets

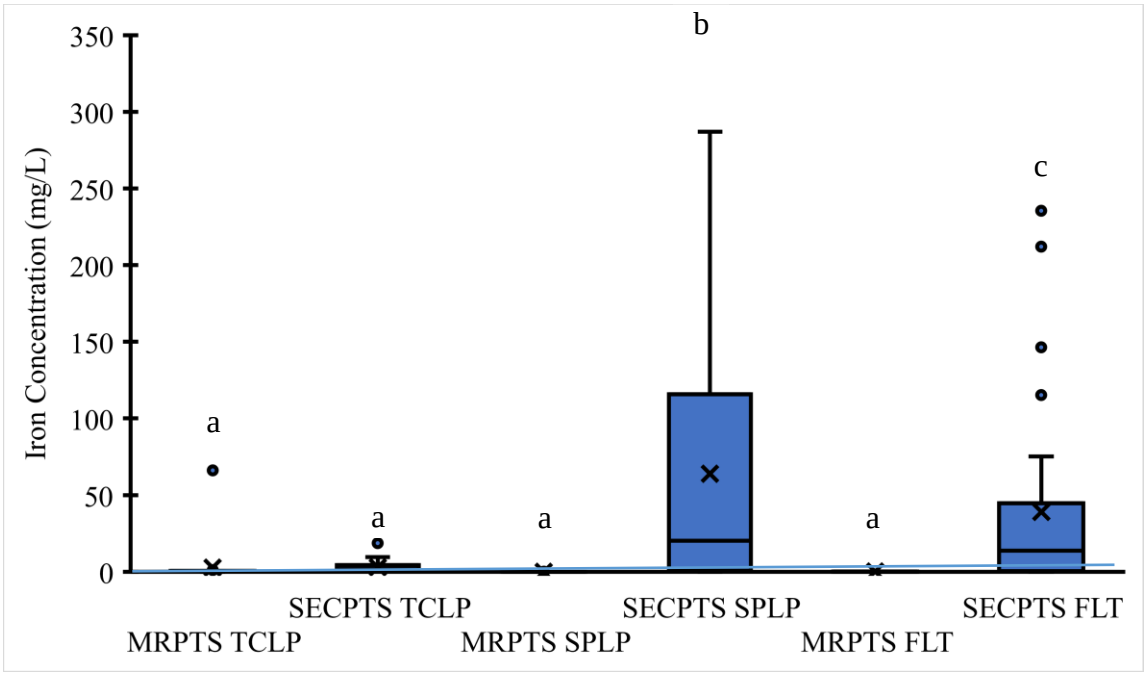

Figure 3.4: Iron Concentrations in Leachates from VFBR Substrates in mg L^{-1}, with a Blue Line to Indicate the OWRB Guideline and Letters to Indicate Statistically Similar Datasets

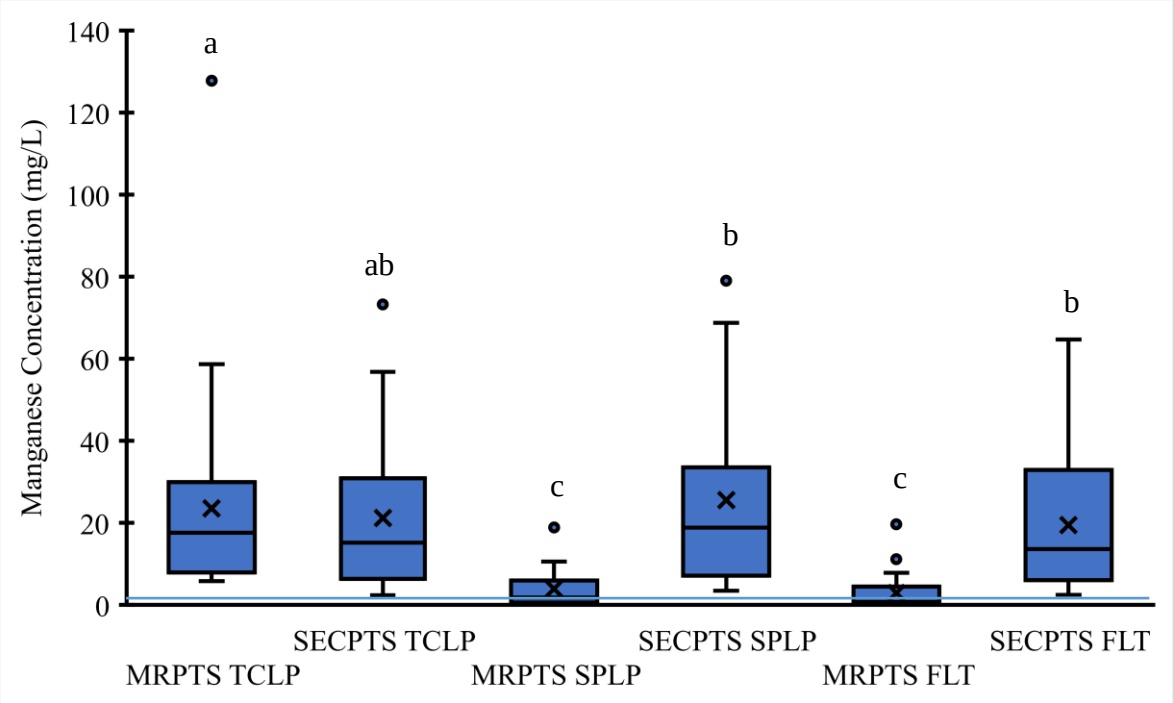

Figure 3.5: Manganese Concentrations in Leachates from VFBR Substrates in mg L^{-1}, with a Blue Line to Indicate the OWRB Guideline and Letters to Indicate Statistically Similar Datasets

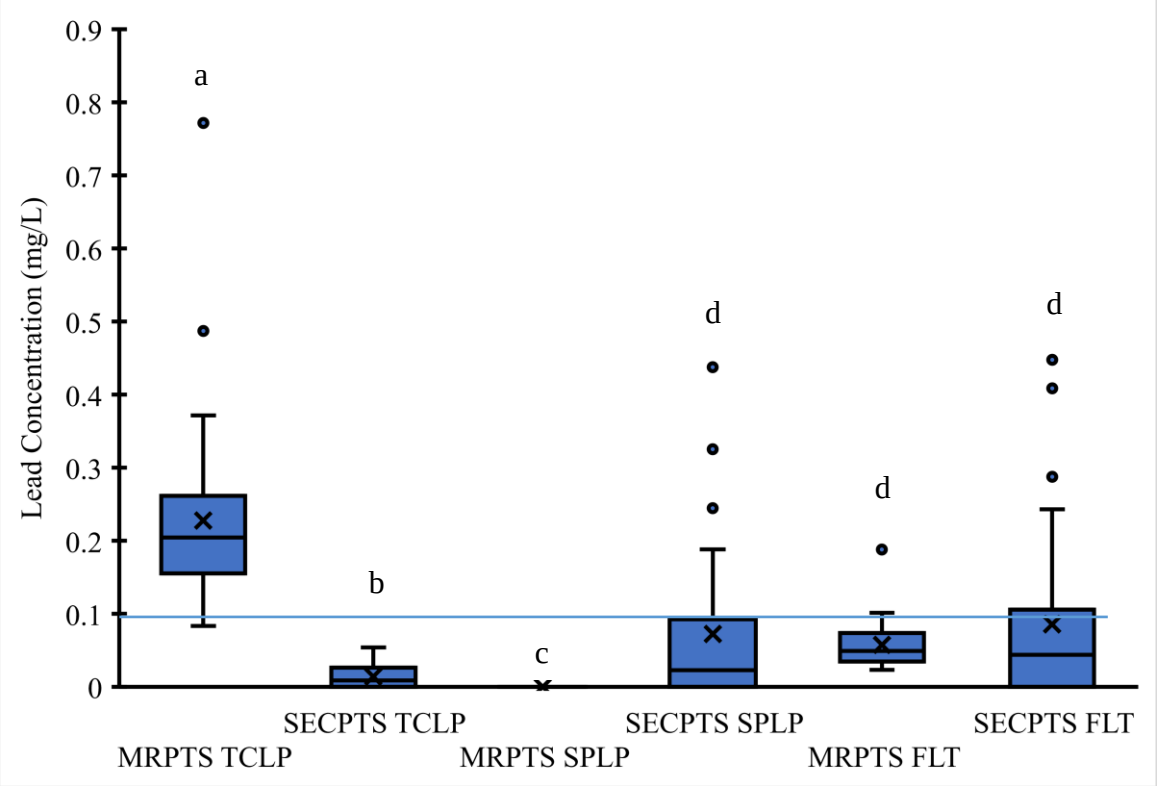

Figure 3.6: Lead Concentrations in Leachates from VFBR Substrates in mg L^{-1}, with a Blue Line to Indicate the OWRB Guideline and Letters to Indicate Statistically Similar Datasets

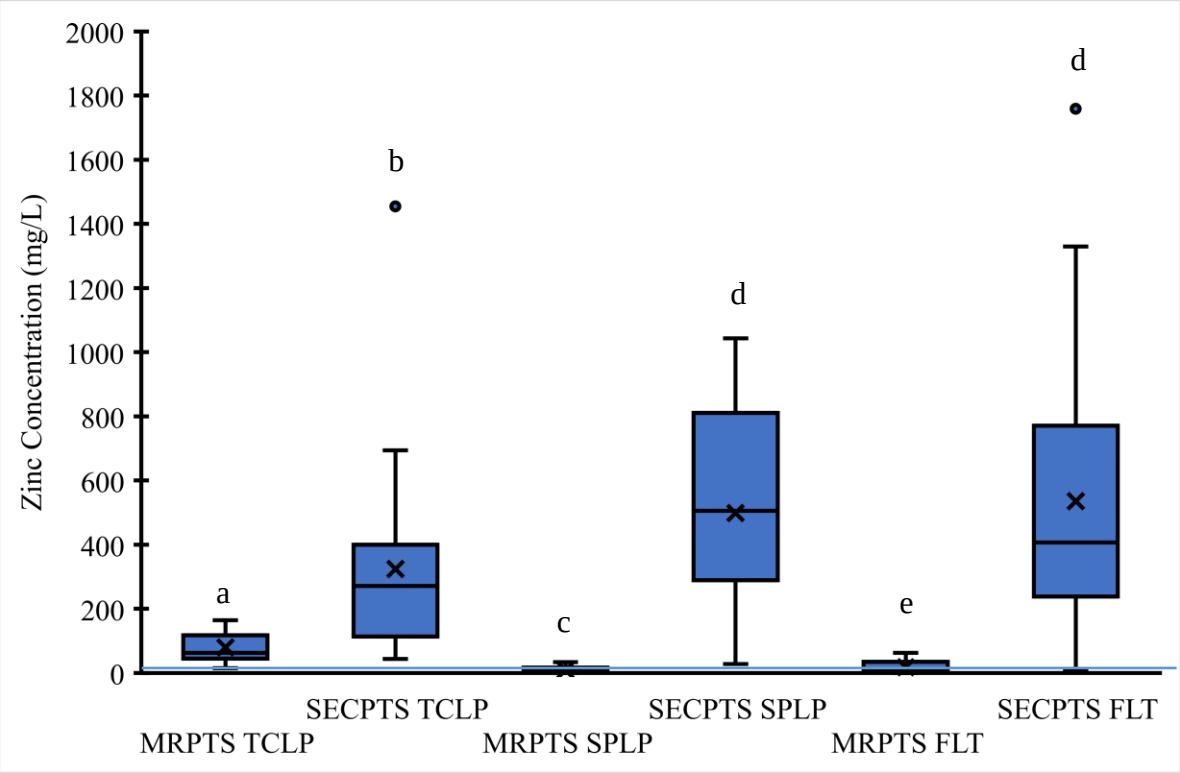

Figure 3.7: Zinc Concentrations in Leachates from VFBR Substrates in mg L^{-1}, with a Blue Line to Indicate the OWRB Guideline and Letters to Indicate Statistically Similar Datasets

The greatest concentrations of metals in SPLP and FLT leachate from the Southeast Commerce VFBR were observed in the samples taken from the northern end of the VFBR, closest to the inflow. Outliers (concentrations more than 1.5 times the interquartile range greater than the median) seen in Figures 3.3 to 3.7 on plots of the Southeast Commerce SPLP and FLT leachates were all from samples 8, 9, 10, 18, 19, or 20, with the exception of an outlier in manganese concentration seen at sample point 15. As can be seen on the aerial photograph in Figure 3.2, all of these samples were taken from the portion of the VFBR closest to the inflow from the surface flow wetland. Outliers in TLCP concentrations were found at sample points 4 (manganese) and 25 (iron and zinc). The presence of these outliers and greater interquartile ranges for the Southeast Commerce leachates relative to those from Mayer Ranch indicates that metals are not

retained as well in the Southeast Commerce substrate, especially at the influent end of the VFBR. Because the effect is concentrated at the influent end of the VFBR, this more exchangeable fraction of metals may be due in part to the influence of the shared water surface of the oxidation pond and surface flow wetland preceding the VFBR at Southeast Commerce.

More closely grouped concentrations in the Mayer Ranch leachates indicate more consistent metal sequestration across these two VFBRs. However, the greatest concentration of iron, manganese, and lead in the Mayer Ranch VFBR TCLP leachates were observed at sampling point C3S-2, which was the sample taken closest to the inflow point at the southern VFBR. However, C3S-2 was also one of the samples for which TCLP extraction fluid 2 was used, along with C3S-10, the other outlier for lead concentrations in TCLP leachate. The additional acidity of extraction fluid 2 seems to have had more impact on leaching, especially since most metal concentrations from the C3S-2 sample were less than the median in SPLP and FLT leachates as well as in the total recoverable concentrations measured from the solids.

Increased leaching from Southeast Commerce VFBR solids may be due to differences in how metals are stored within the solids. Because Southeast Commerce is a younger system, the metals are more likely to be in the exchangeable fraction, and thus are more readily leached. Two sets of sequential extraction tests on Mayer Ranch VFBR solids in 2010 and 2014 showed that as the system aged, a greater percentage of metals measured in the solids were associated with refractory organics and sulfides (LaBar and Nairn, 2011; LaBar and Nairn, 2018). This result is due to increasing availability of sulfide as sulfate reducing bacteria metabolize available sulfate over time. So, although metal concentrations may be similar in the solids, more of the metals are susceptible to leaching in the younger Southeast Commerce solids.

The pH of the solids may play a role in the increased leaching seen from SPLP and FLT in the Southeast Commerce solids. As seen in Table 3.3, the median pH of the Southeast Commerce solids was below the pK_a of acetic acid (pK_a = 4.75), which, along with the NaOH in TCLP extraction fluid 1, introduces a buffering effect in the TCLP leachate of the Southeast Commerce VFBR solids. Because of this buffering, the final pH of the TCLP leachate (median = 4.90) is greater than the final pH of the SPLP and FLT leachates (medians = 3.60 and 3.33, respectively), leading to increased leaching in the solutions with more acidic pH. The importance of the final pH of the leachate is discussed in McDonald et al. (2006), who suggest using a leaching test based on final pH of the leachate to determine the potential of a waste exposed to highly acidic environments to release metals. Due to the net-alkaline nature of the waters in the TSMD, the VFBR solids in this study are unlikely to encounter highly acidic environments, however, since the Southeast Commerce VFBR solids themselves generate acidity, the use of neutralizing reagents may be an important part of disposal or reuse even in neutral environments.

Conclusions

VFBR substrate removal and replacement are a vital part of rehabilitative maintenance in passive treatment systems, but removing the substrate has the potential to generate hazardous waste. To evaluate the potential for reuse of VFBR substrate from two passive treatment systems in the TSMD, total recoverable metals in the substrates were measured and three leaching tests were performed on spatially distributed samples of the substrate. Consensus-based benchmarks for terrestrial and aquatic toxicity and state regulations for surface water and groundwater quality were used as screening levels for evaluating risk associated with environmental exposure to the substrates and their leachates, respectively.

Total metals analysis of the substrate from the VFBRs in this study showed concentrations of trace metals that have the potential to pose risks to aquatic and terrestrial life. Zinc concentrations were the greatest relative to the soil and sediment consensus-based toxicity benchmarks, with concentrations on the order of 1000 times greater than the benchmarks of 20 mg kg^{-1} for soil and 121 mg kg^{-1} for sediment and on the order of 200 times greater than the benchmark of 459 mg kg^{-1} for sediment in the TSMD. More directed toxicity studies using location-specific species outside of the TSMD are recommended to more accurately determine the threat that these substrates may pose before a disposal location is chosen.

The substrate of the VFBRs in this study produced TCLP leachates with metals concentrations below RCRA limits, but some trace metal concentrations in SPLP and FLT leachates exceeded state guidelines for the protection of public water supplies. TCLP produced the greatest concentrations of some trace metals, but not of cadmium, lead, and zinc, which are of primary concern in the TSMD. SPLP and FLT were more likely to cause greater leaching of metals in the Southeast Commerce solids due to greater exchangeable fractions of metals and lower pH. Concentrations of cadmium, iron, lead, manganese, and zinc were elevated in the leachates from samples taken from the area around the inflow of the Southeast Commerce VFBR, indicating a more exchangeable deposition of trace metals in this area, possibly due to the influence of the surface flow wetland and oxidation pond. More equitable distribution of the inflow waters and increased control of the water level in the system would be beneficial in managing the preceding units' effect on the VFBR, but both of these solutions may require interventions outside the current scope of feasibility for the system.

Disposal for these substrates and options for their beneficial reuse are undetermined. A nonhazardous waste landfill can be used to dispose of the VFBR substrate from Mayer Ranch

and Southeast Commerce, but further studies, such as toxicity testing or column leaching tests with mixtures of disposal site soil or sediment and VFBR substrate, are needed before beneficial reuse is allowed.

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Chapter Four: Sorptive Amendments to Address Leachability of Trace Metals from Hard Rock Mine Drainage Passive Treatment Residual Solids

Abstract

Passive treatment of mine drainage effectively decreases the concentration of ecotoxic metals in impacted water and sequesters the metals in residual solids, the composition of which vary depending on the biogeochemical process in use. Mine drainage passive treatment systems must undergo rehabilitative maintenance to continue functioning over decadal time scales. This maintenance includes removing residuals from the system, creating large amounts of potentially hazardous waste. In this study, the use of three amendments, biochar, biosolids, and CCR, to increase retention of ecotoxic metals in hard rock mine drainage treatment residual solids was examined. Three leaching tests were used to determine whether the retention of metals was increased by the addition of these amendments. Although the amendments had neutral to basic pH, large surface areas, and cation exchange capacities that were hypothesized to increase sorption of trace metals, the concentrations of most metals were statistically similar or elevated compared to the control. Further research may show that an application rate greater than 5% by mass or a mixture of amendments may decrease the concentration of metals available to the environment.

Introduction

Two passive treatment systems were constructed to improve water quality of net-alkaline mine drainage from the former TSMD in northeastern Oklahoma, southeastern Kansas, and southwestern Missouri. The Mayer Ranch, which started operation in 2008, and the Southeast Commerce, which started operation in 2017, both use a series of biogeochemical process units to decrease the concentration of iron and trace metals in the drainage from the lead-zinc mine

workings (Nairn et al., 2010; BioMost, 2018). Both systems begin with an oxidation pond, which receives the artesian discharges to be treated by each system, promoting iron oxidation and precipitation and concurrent trace metal retention through sorption to iron oxides (Nairn et al., 2010; BioMost, 2018). The systems also include VFBRs, which create an environment conducive to bacterial sulfate reduction and the subsequent formation of metal sulfides (Nairn et al., 2010; BioMost, 2018). These process units are expected to be the focus of rehabilitative maintenance as the systems age.

Process units in passive treatment systems are designed based on water quantity and quality data from the sources of water they will be treating, usually assuming a 20-year lifespan (Watzlaf et al., 2004; Shepherd et al., 2020). VFBRs have been documented to develop hydraulic conductivity issues that shorten their lifetime, including clogging due to metal precipitates and roots and development of preferential flow pathways (Rose, 2004). The efficacy of oxidation ponds similarly decreases near the end of the lifespan due to decreasing residence time caused by the buildup of iron oxyhydroxide solids (Watzlaf et al., 2004). Some hydraulic conductivity issues in VFBRs can be addressed by stirring the substrate or removing the material causing clogs (Shepherd et al., 2020; Rose, 2004), but continued issues may call for the removal and replacement of the organic substrate (Shepherd et al., 2020). Rehabilitative maintenance in oxidation ponds also involves removal of material (Hedin, 2006). Materials removed from passive treatment systems may be hazardous and must be characterized and handled according to the results (Shepherd et al., 2020).

The options for disposal or reuse of the mine drainage residual solids removed from oxidation ponds and VFBRs depend on the concentration and availability of potentially toxic trace metals in these solids. The USEPA requires placement of wastes with leachable concentrations of

certain trace metals above RCRA limits in hazardous waste repositories (USEPA, 1984). However, the use of these facilities can elevate the cost of passive treatment to unsustainable levels (Kefeni et al., 2017). Previous studies have shown that oxidation pond solids can be reused as pigments (Hedin, 2006), as oceanic fertilizer to promote microbial carbon sequestration (Hedin and Hedin, 2015), and as a sorbent for phosphate to decrease eutrophication (Penn et al., 2016; Tang and Nairn, 2021). The organic substrates of VFBRs have been used to stabilize contaminated soil and as gradual release fertilizer (Rakotonimaro et al., 2017). Before the solids can be reused, however, they must be evaluated to ensure that the presence of trace metals in the solids will not negatively impact the receiving environment.

Soil remediation practices are increasingly moving toward in situ stabilization of potentially harmful elements using amendments that promote sorption and precipitation of the contaminants of concern (Vareda et al., 2016; Paulose et al., 2006). This study examined the possibility of using this method to decrease the leachability of trace metals in mine drainage residual solids. Sorptive amendments include a wide range of materials, such as synthetic compounds designed to promote sorption and precipitation, as well as composts of agricultural and human wastes, phosphate-rich materials, biochar (pyrolized organic matter), “raw” organic matter (unaltered plant cuttings and other agricultural byproducts), and industrial byproducts such as CCR, red mud, and bauxite (Navarro, 2012; Hernandez et al., 2015; Beauchemin et al., 2015; Fellet et al., 2011; Phillips et al., 2016; Lomaglio et al., 2018; Dang et al., 2015; Ijagbemi et al., 2009; Lee et al., 2019; Cui et al., 2014; Ding et al., 2017; Feigl et al., 2012; Whitbread-Abrutat, 1997). Large surface area to volume or mass ratios (specific surface area or SSA) lead to a greater number of available sorption sites, which in turn lead to more metals adsorbed to the sorbent (Jang et al., 2005). Polar functional groups are also important to increase cation exchange capacity (CEC)

(Ho and McKay, 2000). Some metals may be preferentially adsorbed by certain materials, and pH is a factor in the order in which metal ions tend to be adsorbed if the pH range is wide (Jang et al., 2005).

Biochar has been the focus of many recent in situ stabilization studies due to its slow rate of decomposition and large SSA (Novak et al., 2016). Biochar is produced by high-temperature heating of organic material in hypoxic conditions (Beesley et al., 2011). Differing temperatures and feedstocks can lead to differences in pH, porosity, and CEC in biochar (Novak et al., 2016). Hardwood biochar has been shown to increase cadmium and zinc retention, while manure-based biochar increases lead retention due to the formation of insoluble lead-phosphorus compounds (Beesley et al., 2011). When pyrolysis temperature is increased, organic matter is volatilized and the remaining material is less available to organisms (Novak et al., 2016). In manure-based biochar, as with other manure-based materials, phosphorus leaching can become a problem, but an addition of 5% by weight biochar to contaminated soil has been beneficial for metal retention (Lomaglio et al., 2018; Fellet et al., 2011; Phillips et al., 2016).

Biosolids are a byproduct of treating municipal wastewater and can be found in water reclamation facilities around the world. Mixing biosolids with soil contaminated with smelting slag retained cadmium, lead, and antimony at rates of >90%, 50%, and 33% respectively (Navarro, 2012). Hernandez et al. (2015) found that plant communities were richer in contaminated soil with thermally dried biosolids retaining trace metals than they were in contaminated soils with trace metals removed by ethylenediaminetetraacetic acid (EDTA). However, biosolids may contribute to nutrient leaching if applied in excess (van Herwijnen et al., 2007).

CCR, also known as fly ash, is a byproduct of power generation via coal combustion that retains metals and nutrients in soils (Lee et al., 2019). CCR increases pH and retains metals, including cadmium, lead, and zinc, through precipitation and sorption over multi-year studies (Shaheen et al., 2014). CCR also tends to improve the efficacy of other amendments (Moodley et al., 2018), which may be an advantage in beneficial reuse of mine drainage residuals.

Although many materials have been shown to be effective sorptive amendments for metals in general, little is known about using sorptive amendments to stabilize trace metals in mine drainage treatment residuals. Due to the possibility that the eventual fate of the mine drainage residual solids may be disposal in a landfill and that the objective of removing the residual solids will be to extend the life of the system at minimal cost, biosolids and CCR, two locally available materials that have been well documented as soil stabilizers, were used as amendments in this study. Additionally, biochar, which can also be produced from local materials and can be made to fit the remediation goals by using different feedstocks or pyrolysis temperatures (Novak et al., 2016), was also used as an amendment in this study. These amendments have been effective in stabilizing the principal contaminants of concern (cadmium, lead, and zinc) in previous studies (Navarro, 2012; Beesley et al., 2011; Shaheen et al., 2014). As Navarro (2012), Beesley et al., (2011), and Shaheen et al. (2014) state that surface area and ion exchange capacity are essential factors for effective sorption, these properties were measured in this study. The pH of the amendments and the mixtures was also measured, as pH is a factor in the leachability of metals from solid materials (Beesley et al., 2011). It was expected that metals leachability would decrease when compared to a control composite for all amended composites, and that the amendments' power to decrease leachability would increase with SSA, CEC, and pH of the amendment.

Methods

The three amendments used in this study were black walnut shell biochar from ReACCT, LLC of Stockton, Missouri, municipal biochar from the City of Norman, Oklahoma Water Reclamation Facility, and CCR from the Grand River Dam Authority's Grand River Energy Center in Chouteau, Oklahoma. These amendments were evaluated in terms of moisture content, organic matter content, pH, SSA, CEC and anion exchange capacity (AEC), point of zero net charge (PZNC), and total metal content. Moisture content was determined via ASTM Method D4531-86 (2008) by drying three replicates of each amendment of known mass to a constant dry mass at 105°C, over approximately 20 hours. Organic matter was determined by loss on ignition (Robertson, 2011) using the average of five replicates for each amendment. Oven-dried samples of known mass in ceramic crucibles were heated to 375°C and maintained at that temperature for 15 hours. The difference in mass before and after heating were used to calculate the percent organic matter in the sample. The pH of each amendment was determined by placing 5 g of the material in a beaker with 96.5 mL of water, mixing for five minutes, and recording the pH measured by an Accumet pH meter to the nearest 0.01 standard unit. The procedure was repeated five times for each amendment.

SSA was measured using the method described by Carter et al. (1986), with some modifications following the comments in the method. This method has been developed for determination of surface area of soils and clays using the theoretical SSA of 810 m^2 g^{-1} for montmorillonite. Three portions of each amendment were dried for 24 hours at 110°C. The mass of each replicate (W_s) was then measured in a pre-tared aluminum weigh boat with parafilm cover. Each weigh boat then received 3 mL of ethylene glycol monoethyl ether (EGME), was gently swirled to cover the sample in the solvent and placed into a desiccator attached to a vacuum pump. The pump was

then used to evacuate the desiccator for 45 minutes, after which the valve to the desiccator was closed and the samples were allowed to sit overnight. The next day, the mass of the samples was measured, the samples were placed back in the desiccator, and the desiccator was evacuated for 45 minutes. After an additional hour and fifteen minutes (two hours total), the mass of the samples was recorded again. This cycle repeated until the samples reached constant mass. The mass of the EGME retained (W_a) was calculated as the difference between the initial mass of the sample and weigh boat and the final, and the surface area was calculated using the following equation:

$A = \frac{W_a}{W_s \times 0.000286}$ where A is the surface area in $m^2\ g^{-1}$.

CEC, AEC, and PZNC were measured using the methods described in Zelanzy et al. (1996). The amount of sample and solution was halved to accommodate 50-mL centrifuge tubes, and concentrations of salt solutions were doubled to measure greater CEC and AEC. Shaking was accomplished using a Burrell wrist-action shaker. The final KCl solution was diluted to 50 mL after decanting and analyzed to determine initial K^+ and Cl^- concentrations. After each exchange rinse with 1 M $NaNO_3$, the supernatant was retained in the same flask. The exchange rinses were diluted to 50 mL and analyzed to determine final K^+ and Cl^- concentrations. Chloride concentrations were determined using a Seal Analytical AQ300 Discrete Analyzer following USEPA Method 105-A (Seal, 2009). Potassium concentrations were measured using a Varian Vista-Pro ICP-OES using USEPA Method 3015A (USEPA, 2007a) for digestion of the samples and USEPA Method 6010C (USEPA, 2018) for analyses. Microsoft Excel was used to plot the AEC and CEC at the final pH of the washing solution and create trendlines to calculate the PZNC.

To determine total metals in the amendments, five replicates of 0.5 grams of oven-dried amendments were digested following USEPA Method 3051A (USEPA, 2007b). Digested samples were filtered and analyzed following USEPA Method 6010C (USEPA, 2018) using a Varian Vista-Pro ICP-OES. Concentrations in the diluted acid and the initial mass of the digested sample were used to calculate the concentration of metals in the solids in mg kg^{-1}.

Samples of oxidation pond mine drainage residuals and VFBR substrates were collected from Mayer Ranch and Southeast Commerce while water levels in the system were artificially lowered in July 2020. Iron oxide samples were collected from the oxidation ponds using a 19-L plastic bucket and a catamaran to move around the surface of the ponds. VFBR substrate samples were collected using a stainless-steel trowel. All samples were stored in 7.8-L LDPE plastic bags and refrigerated at 4°C until analysis. Sampling locations at Mayer Ranch and Southeast Commerce are displayed in Figures 4.1 and 4.2, respectively.



Figure 4.1: Mayer Ranch Passive Treatment System with Sampling Locations

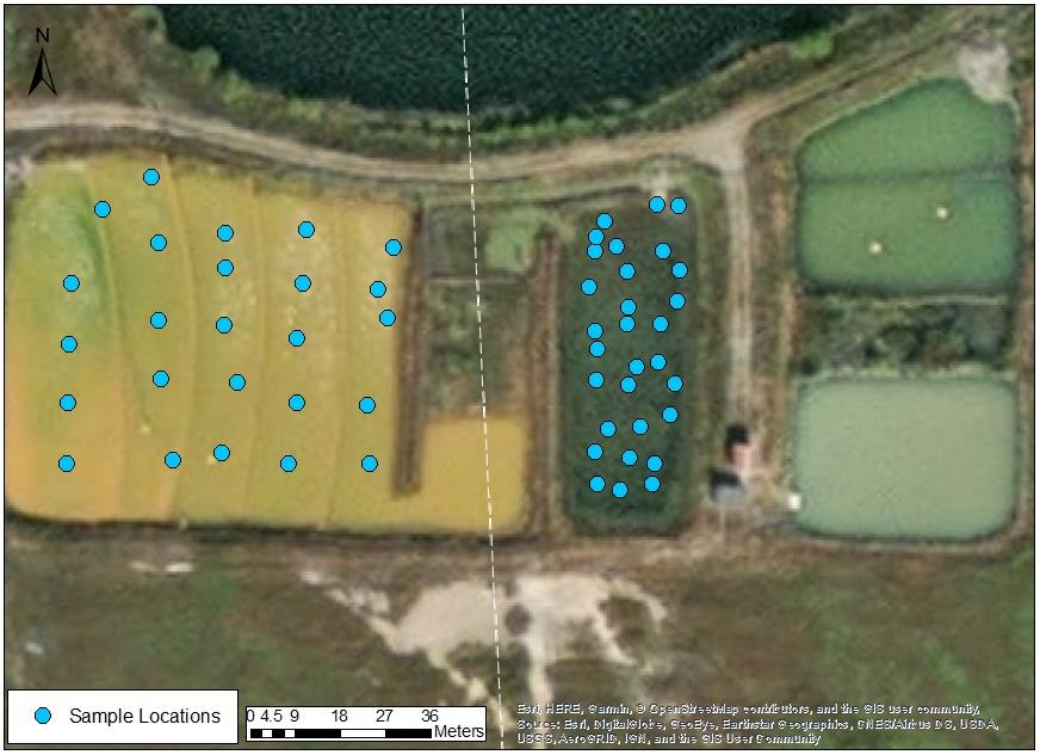

Figure 4.2: Southeast Commerce Passive Treatment System with Sampling Locations

After total recoverable and leachable metals were measured in each of the spatially distributed samples, remaining sample mass from each process unit was placed in a clean 208-L LDPE bag held within a cooler for structure. The two VFBRs at Mayer Ranch were treated as one process unit during this study. Samples were mixed using stainless-steel spoons and by agitating the bags. Moisture content of the composited samples was measured to accurately mix amendments on a 5% dry mass basis. Samples of each composite were portioned into a stainless-steel bowl on a wet-mass basis to dry to 700 g, including the 5% of the amendment. Amendments were added and homogenized using a stainless-steel mixing paddle for 5 minutes. The sides of the bowl were scraped using a silicone spatula and the paddle was turned for 30 more seconds. Control samples of each composite were homogenized in the same way with no amendment added. Amended composites and controls were then air dried for one week in parchment paper-lined aluminum pans. Before leaching studies, each composite was placed in a drying oven set to 50°C overnight to ensure that the composites were completely dry.

Dried composites were ground using a mortar and pestle to prepare for the leaching tests. TCLP, SPLP, and FLT were completed in triplicate for each composite. TCLP and SPLP followed USPA Methods 1311 and 1312, respectively (USEPA, 1992a; USEPA, 1994). Using the pH results from the Preliminary Evaluations section of the TCLP document, it was determined that all composites should be analyzed using TCLP extraction fluid 1. The TCLP extraction fluid was prepared one liter at a time and homogenized using a 20-L carboy. The SPLP extraction fluid was prepared using a stock of diluted H_2SO_4/HNO_3 added to a 20-L carboy with deionized water. Both extraction fluids were adjusted, as necessary, to obtain pH 4.93 ± 0.05 for TCLP and 5.00 ± 0.05 for SPLP. FLT followed Hageman (2007), but with the mass of sample and volume of leaching fluid quartered to conserve sample volume. Samples and deionized water were

combined in a 250-mL Erlenmeyer flask and shaken for 5 minutes using a Burrell wrist-action shaker. The contents of the flasks settled for 10 minutes in the shaker before being filtered. Filtered leachates from all tests were digested using USEPA Method 3015A (USEPA, 2007a) and analyzed following USEPA Method 6010C using a Perkin-Elmer Optima ICP-OES.

Results and Discussion

Amendments Characterization

The organic matter content, SSA, and pH, of the amendments are displayed in Table 4.1. Organic matter content and pH were statistically different ($p < 0.05$) between the three amendments. The biochar and biosolids were circum-neutral, and the CCR was alkaline, which is cited as one of its advantageous properties in remediation (Shaheen et al., 2014). Organic matter content was highest in the biochar, followed by biosolids, then CCR, as expected. SSA follows the same pattern, although both biochar and CCR were statistically similar ($p > 0.05$) to biosolids in regard to SSA. This result may be due to the heterogeneous nature of a waste product such as biosolids. It may also be due to the need to remove a replicate for both biochar and biosolids SSA measurement due to sample loss.

Table 4.1: Organic Matter Content, SSA, and pH of Amendments Used in Treatment of Mine Drainage Residuals

	Biochar	Biosolids	CCR
Organic Matter (%)	97.02 ± 0.18	73.16 ± 0.68	0.16 ± 0.02
SSA (m^2 g^{-1})	653.52 ± 59.17	459.88 ± 101.87	126.77 ± 12.99
pH	7.86 ± 0.16	8.60 ± 0.04	11.46 ± 0.07

AEC and CEC at pH 7 and at the PZNC, along with the pH value of the PZNC for each amendment are presented in Table 4.2. CEC and AEC increased with pH for each amendment. Measured CECs for each material were consistent with values found in the literature (e.g., Trakal et al., 2017; Garrido et al., 2005; Pathan et al., 2003). Low to negative AECs and PZNCs for

biochar and biosolids were also found in the literature (Mukherjee et al., 2011; Bakatula et al., 2018). Mukherjee et al. (2011) suggests that biochar has a negative absolute surface charge, leading to what Zelanzy et al. (1996) refers to as "negative sorption," or expulsion, of anions. Near-zero correlation of calculated AEC with pH may also be an indicator of low to no AEC in biochar and biosolids. More negative calculated AEC at pH 7 for CCR may indicate that the linear relationship between AEC and pH may not extend to pH 7.

Table 4.2: Ion Exchange Capacity and PZNC for Hardwood Biochar, Municipal Biosolids, and CCR

Material	AEC at pH 7 (cmol/kg)	CEC at pH 7 (cmol/kg)	PZNC (pH units)	Ion Exchange Capacity at PZNC (cmol/kg)
Biochar	-0.60	28.69	4.29	-0.70
Biosolids	-2.43	54.45	3.23	-2.65
CCR	-43.00	1.87	11.64	7.13

The mean metal and sulfur concentrations in the amendments are presented in Table 4.3. Concentrations measured in each replicate can be found in Appendix C. Biochar had the least concentration of all elements measured except potassium, which had the greatest concentration in biochar. Biosolids had the greatest concentrations of chromium, copper, manganese, lead, selenium, and zinc. CCR had the greatest concentrations of aluminum, arsenic, calcium, iron, lithium, magnesium, sodium, and nickel. CCR and biosolids had statistically similar ($p > 0.05$) concentrations of silver and barium. Metal concentrations were expected to be elevated in CCR. Biosolids metal concentrations were consistent with the findings of the National Sewage Sludge Survey (USEPA, 1992b). These concentrations were compared to the median concentrations of metals and sulfur in the mine drainage residuals, shown in Table 4.4, to determine if the amendments contributed substantial concentrations of any metals of concern. Although there are many instances where metal concentrations in the amendments were a substantial portion of the

concentrations of those metals in the mine drainage passive treatment residuals, fewer metals in the amendments were measured at concentrations great enough to substantially impact the concentrations in the residuals at an application rate of 5% by mass. Selenium, for example, was measured in the three amendments but was below detection limits in the samples of the oxidation pond solids and most of the samples of the VFBR solids. Additionally, concentrations of potassium in biochar, of barium, chromium, and copper in biosolids, and of aluminum, barium, calcium, chromium, lithium, magnesium, and sodium in CCR were great enough to substantially increase concentrations of these metals in the composited residuals amended with these materials at a rate of 5% by mass.

Table 4.3: Mean Metal and Sulfur Concentrations and Their Standard Deviations in Amendments used in Treatment of Mine Drainage Passive Treatment Residual Solids

	Biochar	Biosolids	CCR
Silver	0.100 ± 0.093	1.71 ± 0.22	1.53 ± 0.30
Aluminum	16.5 ± 2.2	6,347 ± 661	72,001 ± 917
Arsenic	<0.020	6.69 ± 0.41	27.4 ± 0.7
Barium	17.7 ± 1.1	592 ± 16	1,240 ± 676
Calcium	3,411 ± 245	19,485 ± 323	187,354 ± 1523
Cadmium	<0.001	1.01 ± 0.02	1.44 ± 0.05
Cobalt	<0.001	2.80 ± 0.11	19.4 ± 0.8
Chromium	0.028 ± 0.038	115 ± 2	52.9 ± 0.3
Copper	15.4 ± 1.7	526 ± 14	130 ± 1
Iron	78.8 ± 10.6	8,863 ± 403	35,273 ± 484
Potassium	8,236 ± 587	3,017 ± 225	4,111 ± 48
Lithium	0.047 ± 0.043	8.28 ± 0.82	60.4 ± 0.5
Magnesium	941 ± 78	7,044 ± 547	30,069 ± 256
Manganese	22.9 ± 1.5	551 ± 21	275 ± 2
Sodium	22.3 ± 0.8	1,044 ± 33	9,311 ± 71
Nickel	0.775 ± 0.072	17.3 ± 0.7	42.6 ± 0.3
Lead	<0.008	18.6 ± 0.6	14.0 ± 2.1
Selenium	0.740 ± 1.031	18.6 ± 0.5	10.8 ± 1.1
Zinc	19.5 ± 0.7	668 ± 23	135 ± 2

Table 4.4: Median Metal Concentrations Measured in Mine Drainage Passive Treatment Residual Solids Taken from the Oxidation Ponds and VFBRs of Mayer Ranch and Southeast Commerce Passive Treatment Systems in mg kg^{-1}

	MRPTS Oxidation Pond	SECPTS Oxidation Pond	MRPTS VFBR	SECPTS VFBR
Silver	2.27 ± 0.52	2.87 ± 0.54	0.381 ± 0.345	0.547 ± 0.563
Aluminum	786 ± 749	696 ± 851	7540 ± 1505	5440 ± 1328
Arsenic	271 ± 89	246 ± 50	18.4 ± 6.6	36.7 ± 15.6
Barium	35.0 ± 10.6	19.9 ± 1.7	36.3 ± 13.9	16.6 ± 23.3
Calcium	15756 ± 3167	12866 ± 4094	23785 ± 18567	12818 ± 3069
Cadmium	41.1 ± 7.7	67.0 ± 16.5	9.17 ± 5.74	54.7 ± 27.1
Cobalt	9.69 ± 3.20	10.8 ± 13.4	360 ± 220	516 ± 272
Chromium	<0.094 ± 1.08	1.96 ± 0.66	13.5 ± 3.3	6.12 ± 1.49
Copper	16.0 ± 10.8	10.4 ± 6.6	72.5 ± 25.5	82.1 ± 44.6
Iron	461575 ± 48878	504903 ± 60771	65852 ± 41306	66134 ± 63503
Potassium	420 ± 61	425 ± 47	1331 ± 223	866 ± 138
Lithium	2.18 ± 1.96	2.40 ± 1.55	19.5 ± 2.6	10.5 ± 2.7
Magnesium	1035 ± 127	1081 ± 275	2208 ± 248	1740 ± 384
Manganese	90.1 ± 28.7	368 ± 570	1648 ± 3265	1024 ± 9248
Sodium	527 ± 112	1175 ± 435	473 ± 101	592 ± 145
Nickel	208 ± 39	91.5 ± 36.1	3192 ± 1838	2619 ± 2355
Lead	24.7 ± 98.6	59.1 ± 12.0	15.7 ± 4.3	92.6 ± 28.2
Selenium	<4.43	<4.43	<4.43	<4.43 ± 1.93
Zinc	6005 ± 646	5712 ± 4043	43224 ± 19369	62472 ± 28732

The passive treatment residuals in this study were compared to toxicity benchmarks for soil and sediment defined by Efroymson et al. (1997) and MacDonald et al. (2000), respectively, to estimate an application rate of the residuals that would not adversely impact terrestrial and aquatic organisms. Additional sediment benchmarks were defined by MacDonald et al. (2009) to reflect different toxicity thresholds seen in the TSMD. The hardwood biochar used as an amendment in this study did not exceed any of these benchmarks, but biosolids and CCR both exceeded multiple benchmarks, as seen in Table 4.5. The chromium concentration in both biosolids and CCR exceeds the soil benchmark by the largest factor, requiring an application rate of 0.3% biosolids by mass and 0.7% CCR by mass to maintain compliance with the guidelines from Efroymson et al. (1997). However, if the passive treatment residual solids were amended

with the biosolids and CCR at a rate of 5% by mass and applied at a rate that maintains compliance with the guidelines from Efroymson et al. (1997) and MacDonald et al. (2000), application rates of the amendments would be one tenth of the maximum application rate of the amendments alone. Chromium, copper, and zinc benchmarks for the TSMD were exceeded by the biosolids, but at a much smaller rate than the not site-specific benchmarks were exceeded.

Table 4.5: Soil, Sediment, and TSMD-Specific Toxicity Benchmarks, Percent of Biosolids and CCR Samples Exceeding the Benchmarks, and the Range of Concentration for the Metal in Samples, with Exceedances Bolded

Metal	Toxicity Benchmark (mg kg^{-1})	Percent of Replicates Exceeding Benchmark		Concentration Range (mg kg^{-1})	
		Biosolids	CCR	Biosolids	CCR
Aluminum – Soil	600	100	100	**5390-7128**	**70887-73062**
Arsenic – Sediment	9.79	0	100	6.24-7.20	**26.54-28.50**
Cadmium – Sediment	0.99	80	100	0.98-**1.03**	**1.35-1.48**
Chromium – Soil	0.40	100	100		
Chromium – Sediment	43.40	100	100	**111.1-117.4**	**52.6-53.5**
Chromium – TSMD	111	100	0		
Copper – Soil	50	100	100		
Copper – Sediment	31.6	100	100	**513.6-549.4**	**128.4-131.3**
Copper – TSMD	149	100	0		
Iron – Soil	200	100	100	**8165-9127**	**34645-36003**
Lithium – Soil	10	0	100	7.30-9.29	**59.81-61.05**
Manganese – Soil	100	100	100	**519.2-577.5**	**271.7-277.9**
Nickel – Sediment	22.7	0	100	16.30-18.04	**42.24-43.11**
Zinc – Soil	20	100	100		
Zinc – Sediment	121	100	100	**638.5-696.5**	**132.4-137.3**
Zinc – TSMD	459	100	0		

Leaching Tests

Tables 4.6-4.11 show the leaching concentrations from the control composite and the percent difference from the control for each amended composite. A summary of the increases and decreases in metal concentrations caused by different amendments in different leaching tests is provided as Table 4.12. If the control concentration was below the PQL, but the concentration

was above the PQL in the amended composites, the concentration in mg L^{-1} is shown in the tables and italicized. Concentrations measured in each replicate for each treatment can be found in Appendix C. As can be seen in the tables, most metals concentrations were not changed significantly by the addition of the amendments. Significant changes ($p < 0.05$) were slightly more likely to be increases rather than decreases in metal concentrations (101 increases across all metals vs. 95 decreases). CCR was the only amendment that decreased the leaching of more metals than it increased. However, CCR amended composites still saw more increases in metal concentrations than composites amended with biosolids, which caused fewer significant changes to metal concentrations. TCLP leachates changed the most from control to amended, both in increases and decreases. SPLP and FLT were nearly equal in the number of metals with significant changes between the control and amended composites, but with different metals changing for each test.

Table 4.6: Concentrations of Metals in the Oxidation Ponds Control Composite TCLP Leachate in mg L^{-1} and the Percent Difference of the Amended Composite Leachates, with Bolded Values Indicating a Significant Change and Increases from Below the Detection Limit Indicated with Italics and Reported in mg L^{-1}

	MRPTS Oxidation Pond				SECPTS Oxidation Pond			
	Control (mg L^{-1})	Biochar % diff	Biosolids % diff	CCR % diff	Control (mg L^{-1})	Biochar % diff	Biosolids % diff	CCR % diff
Silver	0.002	20.0	20.0	-40.0	0.004	0	-25.0	-16.7
Aluminum	0.084	32.7	34.1	**124.8**	0.027	**161.6**	**402.7**	**504.1**
Arsenic	<0.020	0	0	0	<0.020	0	0	0
Barium	0.145	-24.5	-2.04	-2.30	0.133	6.70	10.1	14.8
Calcium	958	-7.48	**-11.7**	**26.2**	386	-9.18	-3.39	**42.2**
Cadmium	0.001	-100	-100	66.7	<0.001	0	0	0
Cobalt	0.033	-11.1	**-24.4**	**-35.6**	0.151	**33.2**	**17.2**	**-25.6**
Chromium	<0.001	0	0	0	<0.001	0	0	0
Copper	<0.001	0	0	0	<0.001	0	0	0
Iron	21.9	**-41.6**	**-41.7**	**-81.5**	14.6	**65.2**	**68.8**	**-65.6**
Potassium	9.56	**255.7**	**41.4**	17.2	7.79	**317.2**	**73.6**	**19.0**
Lithium	0.047	-3.97	**-11.9**	**23.8**	0.040	**25.2**	**16.8**	**31.8**
Magnesium	27.2	15.9	**28.6**	**98.9**	36.8	3.08	**29.5**	**84.5**
Manganese	0.725	**-24.4**	-9.04	**-56.0**	8.98	**25.5**	-3.09	**-54.7**
Nickel	0.551	-25.9	**-33.0**	**-40.2**	0.394	17.7	17.7	-1.12
Lead	<0.008	0	0	0	0.047	**39.4**	-18.9	**-100**
Selenium	<0.022	*0.012*	*0.015*	***0.078***	0.272	-16.9	-19.6	27.2
Zinc	4.60	-7.01	**-18.3**	**-60.7**	7.291	**34.7**	13.5	**-52.7**

Table 4.7: Concentrations of Metals in the VFBRs Control Composite TCLP Leachate in mg L^{-1} and the Percent Difference of the Amended Composite Leachates, with Bolded Values Indicating a Significant Change

	MRPTS VFBR				SECPTS VFBR			
	Control (mg L^{-1})	Biochar % diff	Biosolids % diff	CCR % diff	Control (mg L^{-1})	Biochar % diff	Biosolids % diff	CCR % diff
Silver	0.006	20	-6.67	-20	0.004	-25.0	**-25.0**	16.7
Aluminum	0.044	37.0	-21.0	27.7	1.01	32.4	**31.9**	**264.4**
Arsenic	<0.020	0	0	0	<0.020	0	0	0
Barium	0.134	**28.3**	**31.9**	**69.0**	0.055	-10.7	10.7	**52.3**
Calcium	1136	**21.2**	**24.1**	0.505	617	-4.59	-5.76	**87.4**
Cadmium	0.003	25.0	-25.0	0	0.004	0.0	**80.0**	30.0
Cobalt	2.30	**4.35**	**-38.2**	**-40.6**	4.63	2.52	-0.48	**-34.4**
Chromium	0.001	100	50	-100	0.013	11.4	20.0	**-34.3**
Copper	<0.001	0	0	0	<0.001	0	0	0
Iron	0.026	773.9	956.5	54.3	2.28	281.9	-15.1	**-60.6**
Potassium	19.4	**142.6**	**39.9**	5.13	10.4	100.1	0.828	**18.8**
Lithium	0.067	-7.73	-3.31	**28.7**	0.042	-9.65	-3.51	**27.2**
Magnesium	53.0	**7.54**	**25.2**	**21.6**	37.55	**-11.3**	8.78	**65.8**
Manganese	12.5	**28.4**	**-26.3**	**-25.0**	15.0	-9.68	-5.18	**-24.3**
Nickel	24.0	**5.73**	**11.6**	**-47.1**	38.2	3.01	-2.85	**-31.8**
Lead	0.009	**248.1**	-100	-100	<0.008	0	0	0
Selenium	0.196	34.2	**27.5**	12.1	0.074	-24.0	-2.00	-19.0
Zinc	15.0	11.1	**-34.9**	**-35.2**	125	**44.6**	**64.5**	**-76.0**

Table 4.8: Concentrations of Metals in the Oxidation Ponds Control Composite SPLP Leachate in mg L^{-1} and the Percent Difference of the Amended Composite Leachates, with Bold Values Indicating a Significant Change and Increases from Below the Detection Limit Indicated with Italics and Reported in mg L^{-1}

	MRPTS Oxidation Pond				SECPTS Oxidation Pond			
	Control (mg L^{-1})	Biochar % diff	Biosolids % diff	CCR % diff	Control (mg L^{-1})	Biochar % diff	Biosolids % diff	CCR % diff
Silver	0.001	0.0	-100	50	0.001	0.0	0.0	0.0
Aluminum	0.016	**195.5**	70.5	104.5	0.059	0.0	-8.81	-3.14
Arsenic	<0.020	0	0	0	<0.020	0	*0.009*	0
Barium	0.078	-27.6	**-50.5**	-8.10	0.081	-4.55	21.8	-6.36
Calcium	557	-0.898	**-7.02**	**10.3**	309	**-24.6**	**-27.1**	0.287
Cadmium	<0.001	0	0	0	<0.001	0	0	0
Cobalt	0.007	47.4	5.26	5.26	0.007	**-20.0**	-15.0	**-45.0**
Chromium	<0.001	0	0	0	<0.001	0	0	0
Copper	<0.001	0	0	0	<0.001	*0.001*	*0.001*	0
Iron	0.096	-87.1	-100	-76.2	0.105	7.95	-35.2	-54.4
Potassium	3.88	**276.7**	**49.1**	-5.05	3.49	**326.0**	**66.9**	0.0
Lithium	0.027	-2.78	-5.56	**-23.6**	0.031	1.19	**-9.52**	**-26.2**
Magnesium	12.2	**14.7**	**46.3**	**20.0**	28.8	**-13.7**	4.88	6.13
Manganese	0.009	72.0	0	-100	0.824	-0.45	**-42.7**	**-96.3**
Sodium	14.5	-1.17	-4.84	-14.0	52.7	**-15.4**	**-18.9**	16.5
Nickel	0.069	3.21	12.3	-3.74	0.030	8.75	5.00	**-63.8**
Lead	<0.008	0	0	0	<0.008	0	0	0
Selenium	0.056	15.2	31.1	29.8	0.357	20.8	-1.04	-1.56
Zinc	0.094	196.4	-65.2	-83.0	0.019	531.4	237.3	121.6

Table 4.9: Concentrations of Metals in the VFBRs Control Composite SPLP Leachate in mg L^{-1} and the Percent Difference of the Amended Composite Leachates, with Bold Values Indicating a Significant Change and Increases from Below the Detection Limit Indicated with Italics and Reported in mg L^{-1}

	MRPTS VFBR				SECPTS VFBR			
	Control (mg L^{-1})	Biochar % diff	Biosolids % diff	CCR % diff	Control (mg L^{-1})	Biochar % diff	Biosolids % diff	CCR % diff
Silver	0.001	100	100	33.3	0.004	-9.09	-27.3	-27.3
Aluminum	0.031	43.4	15.7	-9.64	2.58	-20.9	**38.4**	**-96.6**
Arsenic	<0.020	0	0	0	<0.020	0	0	*0.011*
Barium	0.071	**29.5**	16.6	**60.6**	0.060	3.70	0.0	21.0
Calcium	266	**16.9**	7.67	-7.54	317	-12.9	-3.02	**34.4**
Cadmium	<0.001	0	0	0	0.010	-25.0	**35.7**	**-100**
Cobalt	0.219	**-20.5**	**-65.4**	**-86.3**	6.75	-8.69	0.466	**-77.1**
Chromium	<0.001	0	0	0	0.014	18.4	-34.2	**-100**
Copper	<0.001	0	0	0	0.001	333.3	233.3	-100
Iron	0.016	825.8	70.8	14.6	49.0	-50.0	-10.3	**-100**
Potassium	7.03	**171.6**	**60.7**	-9.07	8.55	219.7	2.00	6.82
Lithium	0.052	-5.00	-4.29	**-23.6**	0.053	-3.50	-6.29	-4.90
Magnesium	34.1	**13.2**	**22.8**	**-13.4**	43.5	-4.52	13.9	*63.9*
Manganese	1.92	-38.0	-78.3	-87.3	16.0	-11.3	1.21	**-81.7**
Sodium	15.0	7.31	**16.4**	8.50	16.7	-8.67	-5.98	23.3
Nickel	2.26	10.4	4.37	**-82.7**	64.6	-9.42	-2.33	**-76.0**
Lead	<0.008	0	0	0	0.052	-14.2	-7.80	**-100**
Selenium	0.159	2.56	**6.29**	0.932	0.114	62.0	-18.2	**225.3**
Zinc	0.332	-42.5	**-77.9**	-65.7	302.2	3.50	**29.3**	**-95.9**

Table 4.10: Concentrations of Metals in the Oxidation Ponds Control Composite FLT Leachate in mg L^{-1} and the Percent Difference of the Amended Composite Leachates, with Bolded Values Indicating a Significant Change and Increases from Below the Detection Limit Indicated with Italics and Reported in mg L^{-1}

	MRPTS Oxidation Pond				SECPTS Oxidation Pond			
	Control (mg L^{-1})	Biochar % diff	Biosolids % diff	CCR % diff	Control (mg L^{-1})	Biochar % diff	Biosolids % diff	CCR % diff
Silver	<0.0005	0	0	0	0.001	0.0	-33.3	0.0
Aluminum	0.007	221.1	-100	-100	0.047	-9.45	-19.7	19.7
Arsenic	<0.020	0	0	0	<0.020	0	0	0
Barium	0.003	*33.3*	77.8	**733.3**	0.003	0.0	71.4	**1143**
Calcium	126	18.2	66.2	81.0	135	-9.64	-45.4	-29.5
Cadmium	<0.001	0	0	0	<0.001	0	0	0
Cobalt	0.006	6.25	12.5	18.8	0.005	7.14	-14.3	**-35.8**
Chromium	<0.001	0	0	0	<0.001	0	0	0
Copper	<0.001	0	0	0	0.001	0.0	100	150
Iron	0.031	-66.5	25.1	143.1	0.080	-70.6	45.1	242.6
Potassium	1.91	**345.4**	119.1	43.7	2.37	**365.9**	36.3	-34.2
Lithium	0.011	13.3	26.7	3.33	0.018	6.25	-16.7	**-37.5**
Magnesium	1.11	**89.9**	547.1	291.2	16.0	-15.1	-15.7	-49.2
Manganese	0.001	0.0	0.0	-100	0.359	13.7	**-51.5**	**-97.9**
Sodium	6.51	**21.1**	55.5	55.2	44.5	**-30.2**	-28.2	-44.4
Nickel	0.007	33.3	177.8	177.8	0.007	22.2	-50	**-100**
Lead	<0.008	0	0	0	<0.008	0	0	0
Selenium	0.027	19.2	39.7	89.0	0.307	-4.70	-19.0	-6.14
Zinc	<0.003	0	*0.001*	0	0.082	**-41.5**	**-50.9**	**-75.0**

Table 4.11: Concentrations of Metals in the VFBRs Control Composite FLT Leachate in mg L^{-1} and the Percent Difference of the Amended Composite Leachates, with Bolded Values Indicating a Significant Change and Increases from Below the Detection Limit Indicated with Italics and Reported in mg L^{-1}

	MRPTS VFBR				SECPTS VFBR			
	Control (mg L^{-1})	Biochar % diff	Biosolids % diff	CCR % diff	Control (mg L^{-1})	Biochar % diff	Biosolids % diff	CCR % diff
Silver	<0.0005	0	*0.004*	0	0.004	**-25.0**	**-41.7**	**-75.0**
Aluminum	0.032	-8.05	27.6	**132.2**	1.58	**28.2**	**73.8**	**-93.4**
Arsenic	0.022	-100	-100	-100	<0.020	0	0	0
Barium	<0.001	***0.003***	0.005	***0.104***	<0.001	0	0	***0.056***
Calcium	63.0	13.4	73.1	85.7	187.4	5.20	-20.7	-12.0
Cadmium	<0.001	0	0	0	0.009	-8.00	**144**	**-100**
Cobalt	0.066	5.03	**-57.5**	**-88.8**	6.56	**8.47**	3.26	**-91.1**
Chromium	<0.001	0	0	0	0.014	**51.4**	24.3	**-100**
Copper	<0.001	0	0	0	0.002	33.3	300.0	16.7
Iron	0.005	692.3	276.9	426.9	26.2	-14.7	3.58	**-99.8**
Potassium	3.45	155.0	123.2	44.9	8.85	**140.9**	-13.9	**-26.3**
Lithium	0.022	-1.69	33.9	3.39	0.041	**17.0**	7.14	**-23.2**
Magnesium	11.6	12.8	110.9	44.4	47.7	-3.19	3.40	**9.70**
Manganese	0.395	**-48.5**	**-78.0**	**-81.9**	16.9	-3.22	-1.23	**-94.1**
Sodium	7.22	4.04	66.6	**60.1**	16.8	-12.3	**-18.1**	**-15.9**
Nickel	0.781	14.5	28.9	**-84.1**	61.7	**8.53**	2.05	**-90.0**
Lead	<0.008	0	0	0	0.084	**-26.5**	-9.73	**-100**
Selenium	0.099	0.373	32.8	27.2	0.220	-5.89	-12.6	**39.4**
Zinc	0.090	60.5	-15.2	-47.3	225	**42.5**	**58.8**	**-97.7**

Table 4.12: Summary of Increases and Decreases in Metal Concentrations Relative to Control in TCLP (T), SPLP (S), and FLT (F) Leachates from Mayer Ranch (MR) and Southeast Commerce (SEC), Oxidation Ponds (Ox Ponds) and VFBR Solids when Amended with Biochar, Biosolids, and CCR. Increases Noted by the Presence of a Letter and Decreases by the Presence of a Letter in Parentheses

	Biochar				Biosolids				CCR			
	Ox Ponds		VFBRs		Ox Ponds		VFBRs		Ox Ponds		VFBRs	
Metal	MR	SEC	MR	SEC	MR	SEC	MR	SEC	MR	SEC	MR	SEC
Ag				(F)				(T,F)				
Al	S,F	T		F		T		S,F	T,F	F	T	T(S,F)
Ba			T,S,F			(S)	T				T,S,F	T,F
Ca		(S)	T,S		(T,S)	(S)	T	S	T,S	T		T,S
Cd								T,S,F				(S,F)
Co		T(S)	T(S)	F	(T)	T	(T,S,F)		(T)	(T,S,F)	(T,S,F)	(T,S,F)
Cr				F								(T,S,F)
Fe	(T)	T			(T)	T			(T)	(T)		(T,S,F)
K	T,S,F	T,S,F	T,S		T,S	T,S	T,S		F	T		T(F)
Li		T			T		T(S)		(T,S)F	T(S,F)	T(S)	T(F)
Mg	S,F	(S)	T,S	(T)	T,S	T	T,S		T,S	T	T(S)	T,S,F
Mn	(T)	T	T(F)			(S,F)	(T,F)		(T)	(T,S,F)	(T,F)	(T,S,F)
Na	F	(S,F)				(S)	S	(F)		(S)	(S)F	(S,F)
Ni			T	F	(T)		T		(T)	(S,F)	(T,S,F)	(T,S,F)
Pb		T	T	(F)						(T)		(S,F)
Se							T			T		S,F
Zn		T(F)		T,F	(T)	(F)	(T,S)	T,S,F	(T)	(T,F)	(T)	(T,S,F)

Concentrations of specific metals in specific treatment units responded differently to the various amendments and leaching tests (Tables 4.6-4.12). Similar changes in response to amendments have been documented in previous studies (Shaheen et al., 2017; Li et al., 2017; Cho et al., 2005). Changes in the efficacy of amendments have been attributed to competition for sorption sites from other metals (Shaheen et al., 2017) and changes in pH, which in turn change the surface chemistry of the amendment (Cho et al., 2005). The pH of the composites is shown in Table 4.13. The more acidic pH of the Southeast Commerce VFBR composites indicates more competition for sorption sites and decreased availability of those sites due to increased concentration of hydrogen ions. Conversely, the increase in pH seen in the CCR amended composites and all the amended composites of Mayer Ranch VFBR substrate indicates more sorption sites are available and there is less competition with hydrogen ions.

Table 4.13: pH of Composites of Treatment Unit Solids and Amendments

Amendment	MRPTS Ox Pond	SECPTS Ox Pond	MRPTS VFBR	SECPTS VFBR
Biochar	6.44	6.27	6.91	4.06
Biosolids	6.34	6.03	7.25	3.98
CCR	6.79	6.94	7.05	5.90
None (Control)	6.82	6.55	6.54	4.50

Li et al. (2017) list five mechanisms for metal retention seen when biochar is added to an aqueous solution: complexation, cation exchange, precipitation, electrostatic attraction, and reduction. Of these five, reduction of sorbates is the only factor not linked to pH, which controls changes in surface charge of the sorbent (CEC and electrostatic attraction) and the speciation of the sorbate (complexation and precipitation with hydroxide ions, Cho et al., 2005). CECs of the amendments at the measured pH values in Table 4.13 are shown in Table 4.14.

Table 4.14: CECs of Amendments at pH Measured Before Leachate was Added in cmol kg^{-1}

Amendment	MRPTS Ox Pond	SECPTS Ox Pond	MRPTS VFBR	SECPTS VFBR
Biochar	22.61	20.77	27.71	-3.19
Biosolids	44.45	39.75	58.24	8.67
CCR	1.64	1.81	1.93	0.63

Cadmium concentrations increased with the addition of biosolids to the Southeast Commerce VFBR substrate and decreased when CCR was added to the same substrate. These changes are inversely related to changes in pH with the addition of biosolids and CCR to the Southeast Commerce VFBR substrate. The increase in cadmium mobility is thus associated with a change in speciation rather than the unavailability of sorption sites.

Oxidation pond solids from the two different systems have different pH thresholds for iron leaching. An overall more acidic pH in the Southeast Commerce oxidation pond solids combined with a decrease in pH in biochar- and biosolids-amended composites increased iron leaching. The beneficial effect of the CCR amendment suggests that iron retention depended on the speciation of iron as a hydroxide rather than the sorption of iron ions.

Increases in lead concentrations in Mayer Ranch VFBR and Southeast Commerce oxidation pond composites amended with biochar are a result of lead forming complexes with dissolved organic matter from the biochar, a hindrance to metal retention discussed in Beesley et al. (2010). The decrease in lead in the CCR-amended composites may be attributed to the increase in pH relative to the control, along with an increase in retention of lead with increasing concentrations of other metals observed by Cho et al. (2005). Increased retention with greater concentration of other metals may also contribute to the decrease in lead concentration in the Southeast Commerce VFBR-biochar composite, as the negative CEC indicates expulsion of ions

from biochar, though this interaction may not occur with organic materials such as the VFBR substrate.

Despite other studies finding that zinc is frequently outcompeted for sorption sites (Cho et al., 2005; Kumpiene et al., 2008), zinc concentrations decreased in at least one test for each amendment used in this study. Both cation exchange and increasing pH have been shown to increase zinc retention (Kumpiene et al., 2008). Increases in zinc leaching can be attributed to low pH in the biosolids-amended Southeast Commerce VFBR composite, negative CEC in the biochar-amended Southeast Commerce VFBR composite and increased ionic strength in the biochar-amended Southeast Commerce oxidation pond TCLP extraction fluid relative to FLT extraction fluid for the same composite, where a decrease in zinc concentration was observed.

Although the response of individual elements to the addition of amendments was varied, the estimated positive charge of ions in the leaching solution, shown in Table 4.15, went unchanged in most residual-amendment-leaching test combinations. When the concentrations of metals were normalized using molar mass and typical charge, the addition of biochar increased metal concentrations in the TCLP and SPLP leachates from the MRPTS VFBR and the FLT solution from the SECPTS VFBR but decreased metal concentrations in the SPLP leachate from the SECPTS oxidation pond. Biosolids addition followed a similar pattern but had no effect on the SECPTS VFBR leachates. CCR increased metal activity in TCLP leachates from each treatment unit except the MRPTS VFBR and decreased metal activity in the SPLP and FLT leachates from the SECPTS VFBR.

Table 4.15: Mean Estimated Positive Charge in Leachates in meq L^{-1} and Standard Deviations, with Bold Values Indicating Significant Change from the Control

		TCLP	SPLP	FLT
MRPTS Oxidation Pond	Biochar	48.58 ± 1.67	29.72 ± 0.83	8.18 ± 0.80
	Biosolids	46.32 ± 1.60	28.07 ± 0.86	11.61 ± 4.27
	CCR	**65.42 ± 1.43**	**32.52 ± 0.38**	12.27 ± 4.23
	Control	51.69 ± 2.66	29.55 ± 0.69	6.74 ± 0.50
SECPTS Oxidation Pond	Biochar	23.94 ± 0.25	**16.10 ± 0.28**	8.87 ± 0.62
	Biosolids	25.17 ± 0.64	**15.81 ± 0.64**	6.27 ± 1.65
	CCR	**34.00 ± 0.36**	20.03 ± 1.46	6.56 ± 3.40
	Control	24.22 ± 1.15	20.28 ± 0.64	10.08 ± 2.10
MRPTS VFBR	Biochar	**77.70 ± 2.72**	**20.14 ± 0.86**	5.28 ± 0.92
	Biosolids	**78.90 ± 0.76**	**18.97 ± 0.76**	8.26 ± 2.48
	CCR	64.49 ± 0.74	15.64 ± 0.83	7.88 ± 2.35
	Control	64.23 ± 1.36	17.21 ± 0.44	4.59 ± 0.82
SECPTS VFBR	Biochar	41.89 ± 3.86	33.48 ± 3.33	**30.94 ± 0.69**
	Biosolids	42.28 ± 0.75	39.29 ± 1.39	29.40 ± 2.54
	CCR	**66.83 ± 3.08**	**29.74 ± 1.34**	**13.91 ± 0.77**
	Control	41.41 ± 3.02	36.78 ± 3.16	27.08 ± 1.38

As discussed above, changes in concentrations of individual metals were caused by different reactions to changes in pH and CEC, but the overall sorption of metal ions either remained unchanged by the addition of amendments or was decreased. These results suggest that increases in exchangeable ions from the addition of amendments (primarily in biosolids and CCR) and/or increased mobility of ions due to increased dissolved organic matter (in biochar and biosolids) counteracted the amendments' metal retention capacity (Beesley et al., 2010). The increased release of metals after the addition of biochar was also observed by Fellet et al. (2011), who reported that concentrations of some metals increased in soil treated with their lowest application rate of biochar, while higher application rates decreased metal concentrations, suggesting that the application rate of 5% by weight used in this study was not sufficient to retain excess metal ions, and that a greater application rate may produce the desired metal retention. Other studies using a 5% by mass amendment of biochar (Beauchemin et al., 2015; Fellet et al., 2011; Lomaglio et al., 2018), biosolids (Hernandez et al., 2015), or CCR (Lee et al., 2019) include only the impacts of

the amendment on the contaminants of concern, making a comparison of the ionic strength of the leachate difficult. However, it can be assumed that the presence of elevated concentrations of base metals as well as trace metals impact the efficacy of cation retention using amendments. A greater application rate of the amendments may be more effective for trace metal retention, but it would also increase the exchangeable ions and soluble organic matter, which would further confound the desired effect.

Conclusions

The treatment of contaminated soils and sediments, as well as mine wastes, has increasingly been accomplished in situ using sorptive amendments. Biochar, biosolids, and CCR have been used to retain metals in contaminated soils and sediments, including those impacted by mining, but have not previously been examined as a treatment for decreasing metal availability in residuals from the passive treatment of hard rock mine drainage. The addition of 5% by dry weight of biochar, biosolids, and CCR had mixed effects on the concentrations of metals of concern in the leachates produced from mine drainage residual solids and did not change the overall concentration of metal ions in these leachates.

Future work could confirm the causes of the inefficacy of the amendments in this study, which may include the introduction of leachable metals from the amendments and the binding of previously adsorbed metals to soluble organic matter. Future studies should also examine whether increased application rates or a combination of amendments would produce decreased concentrations of metals in leachate, or if the undesired effects of additional ions and soluble organic matter would continue to counteract the sorption capacity of the materials.

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Chapter Five: Conclusions

The Mayer Ranch and Southeast Commerce Passive Treatment Systems have shown that substantially improving water quality of mine drainage discharges from the TSMD mine pool is possible. These systems, however, will need rehabilitative maintenance in the long term to continue removal of metals from the water that they treat. Rehabilitative maintenance will include removal of iron oxyhydroxide solids from the oxidation ponds and replacing the organic substrate of the VFBRs. These materials need to be characterized before disposal so that all possible options for disposal or possible reuse can be explored.

The solids from both the Mayer Ranch and Southeast Commerce oxidation ponds produced TCLP leachates that did not contain concentrations of regulated metals that exceeded RCRA limits. However, when metals concentrations in SPLP and FLT leachates were compared to OWRB criteria for surface water and groundwater, exceedances of aluminum, iron, lead, manganese, and nickel guidelines were seen in the leachates from at least one system. Additionally, total recoverable metals concentrations in the solids far exceeded soil and sediment benchmarks based on risk to terrestrial and aquatic organisms. These potential risks to organisms and water supplies should be examined for specific reuse scenarios before the iron oxyhydroxides are dredged and a plan for reuse is implemented.

The solids from the VFBRs in both systems followed a similar pattern to the solids from the oxidation ponds. RCRA limits were not exceeded in the TCLP leachates, but SPLP and FLT leachates showed aluminum, cadmium, chromium, iron, manganese, nickel, lead, selenium, and zinc concentrations that exceeded OWRB guidelines for surface water and groundwater and concentrations of total recoverable metals far exceeded soil and sediment guidelines. Leaching of some metals in SPLP and FLT leachates from the VFBR substrates were greater than the TCLP

leachates, which indicates different sorption processes occurring in the VFBRs than the more pH dependent leaching seen in the oxidation pond solids. The processes by which these solids retain potentially leachable metals should be further examined as part of the continuing evaluation for reuse of the VFBR solids.

When biochar, biosolids, and CCR amendments were mixed into the oxidation pond and VFBR solids at a rate of 5% by mass, changes in retention of metals varied by test, type of residual solid, amendment, and metal. Although CCR retained cadmium and zinc more often than biochar and biosolids, most of the amended composites did not differ significantly from the control composites when total positive charge in leachate solutions was considered. Previous studies have seen improvements in metals retention when the application rate of the amendments is increased (Fellet et al., 2011), and that combinations of amendments can improve performance (Moodley et al., 2018). Varying the amount of amendments added to mine drainage residuals could be the subject of future studies, but further examination of the mechanisms of metal retention in these materials may suggest a different direction.

Given the data presented in this study, the hypotheses that the concentration of metals in the TCLP leachate from the mine drainage residuals would exceed RCRA guidelines and that the sorptive amendments would decrease the concentration of metals in the leachates must be rejected. The hypothesis that metal concentrations in leachates would exceed guidelines was accepted because concentrations of metals in SPLP and FLT leachates exceeded OWRB guidelines.

Continued characterization of the solids will be important as a disposal or reuse plans develop. Moving the solids to any environment other than a landfill would require characterization of the planned disposal or reuse site to determine whether the elevated concentrations of trace metals

found in the solids would harm the local ecosystem. If beneficial reuse such as the use of iron oxyhydroxides as a phosphate sorbent is planned, the amount of the solids needed to decrease nutrients to desired concentrations must be weighed against the amount of trace metals that mass of solids would leach. If the solids will be mixed with soil or sediment and left in the environment permanently, long term leaching studies using columns or similar analogs should be completed. There are many options for the disposal or reuse of residual solids from mine drainage passive treatment, but care must be taken to ensure no harm is done to the environment.

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Appendix A: Data from Oxidation Pond Solids Characterization

Table A-1: Elemental Concentrations in the Solids of the Mayer Ranch Oxidation Pond Solids in mg kg^{-1}, with Bolded Values Exceeding Soil Benchmarks, Italicized Values Exceeding Sediment Benchmarks, and Highlighted Values Exceeding TSMD-Specific Benchmarks

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	S	Se	Si	Zn
Soil Guidelines	50	600	60	3000		20	1000	0.4	50	200		10		100		90	500		70		20
Sediment			9.79			0.99		43.4	31.6							22.7	35.8				121
TSMD Guidelines			33			4.98		111	149							48.6	128				459
PQL	1.12	7.16	7.86	0.618	26.0	0.306	0.436	0.928	0.433	0.395	11.3	0.257	0.425	0.217	4.83	0.609	3.11	21.0	8.76	3.45	1.29
C1-1	2.08	**968**	***308***	40.2	16956	***40.3***	9.03	<PQL	21.6	**442715**	455	2.32	1216	80.1	717	***198***	25.1	9161	<PQL	10601	***5768***
C1-2	2.27	**786**	***340***	41.4	15460	***40.6***	8.81	<PQL	22.9	**470353**	432	1.80	1182	63.2	624	***199***	25.0	8830	<PQL	10932	***6535***
C1-3	2.24	**762**	***272***	33.8	17459	***39.3***	9.48	<PQL	10.1	**420504**	410	1.99	987	89.2	516	***202***	24.3	9120	<PQL	9563	***5374***
C1-4	3.34	**601**	***292***	35.9	19710	***60.1***	9.69	**1.85**	27.2	**510110**	405	2.39	1055	**122**	555	***245***	35.0	9209	<PQL	465	***6784***
C1-5	2.44	**691**	***302***	37.1	15543	***42.6***	8.82	**1.70**	10.5	**484994**	408	1.72	1045	77.2	567	***193***	25.9	7613	<PQL	10266	***6005***
C1-6	2.03	**732**	***280***	34.2	16549	***41.1***	8.61	<PQL	25.2	**480787**	402	1.95	964	90.1	498	***198***	24.9	7929	<PQL	9751	***5820***
C1-6 FD	2.23	**696**	***257***	32.3	15098	***38.1***	7.92	<PQL	16.0	**434261**	397	1.70	944	76.8	527	***179***	21.4	7721	<PQL	8931	***4964***
C1-7	2.10	**869**	***249***	33.7	13275	***38.6***	8.98	**3.38**	6.68	**434966**	379	1.88	746	73.0	435	***195***	23.4	6200	<PQL	8517	***5444***
C1-8	2.00	**792**	***278***	34.2	14767	***41.9***	9.56	<PQL	20.8	**440704**	413	1.87	1004	76.9	642	***209***	24.7	9191	<PQL	8358	***5911***
C1-9	2.61	**872**	***294***	36.6	15052	***44.4***	9.51	<PQL	13.7	**467587**	424	1.96	1148	78.2	742	***203***	26.6	9617	<PQL	8507	***5471***
C1-10	2.32	**722**	***273***	33.3	15605	***42.2***	10.0	**2.59**	20.9	**496061**	430	2.04	1120	91.3	699	***217***	26.7	9290	<PQL	8786	***5997***
C1-11	2.40	**748**	***271***	33.1	14681	***42.3***	10.0	**1.67**	12.9	**483409**	400	1.91	943	85.6	462	***206***	25.9	8832	<PQL	8248	***6253***
C1-11 FD	2.88	**690**	***272***	33.2	15756	***43.1***	10.7	<PQL	15.7	**500313**	403	2.01	965	97.3	492	***225***	25.1	8833	<PQL	8416	***6760***
C1-12	2.25	**710**	***266***	33.8	16499	***42.4***	9.99	<PQL	24.6	**463790**	407	2.32	944	**100**	485	***193***	23.7	7899	<PQL	7563	***5470***
C1-13	2.70	**816**	***266***	35.0	12971	***44.8***	8.70	**1.40**	18.5	**493167**	426	1.98	1070	71.8	680	***181***	24.3	8952	<PQL	7850	***5377***
C1-14	2.05	**1171**	***240***	35.8	13963	***40.2***	8.82	**1.38**	21.2	**380119**	410	3.01	854	81.5	399	***179***	22.7	8361	<PQL	5871	***4363***
C1-15	2.15	**1176**	***235***	38.0	12521	***40.5***	11.1	<PQL	10.3	**463090**	420	2.83	890	86.1	467	***217***	24.9	9484	<PQL	7357	***6008***
C1-16	2.21	**921**	***210***	32.3	16762	***39.5***	10.9	<PQL	3.84	**440720**	420	2.86	1045	**101**	520	***213***	26.0	12852	<PQL	6713	***6095***
C1-17	1.85	**1432**	***188***	37.0	20334	***38.0***	15.9	**2.93**	10.1	**363757**	492	4.89	1175	**146**	639	***255***	***574***	13631	<PQL	5163	***6348***
C1-18	2.68	**1279**	***196***	35.1	21301	***39.9***	13.5	<PQL	11.9	**448502**	464	4.14	1106	**130**	804	***249***	23.0	16758	<PQL	6487	***6237***
C1-19	2.15	**1146**	***198***	31.4	23728	***39.3***	12.6	<PQL	19.3	**438777**	464	4.36	1232	**136**	590	***232***	22.9	17206	<PQL	6233	***6286***
C1-20	1.14	**3972**	***141***	61.6	18049	***28.4***	19.8	<PQL	21.0	**351779**	633	**10.0**	1237	**186**	526	***286***	23.5	15917	<PQL	4090	***6953***
C1-20 FD	1.84	**3412**	***155***	56.0	15789	***30.5***	20.1	<PQL	***57.9***	**362466**	582	8.25	1138	**166**	482	***335***	23.2	15747	<PQL	3830	***7406***
C1-21	2.42	**653**	***634***	63.4	24273	***38.8***	5.47	<PQL	0.875	**438930**	507	<PQL	981	73.5	350	***127***	24.5	4205	<PQL	5761	***5741***
C1-22	2.01	**969**	***462***	74.8	24103	***37.2***	6.79	<PQL	3.96	**416787**	579	1.11	956	82.6	508	***152***	21.9	6675	<PQL	6333	***6405***
CAT1-3	3.59	**631**	***285***	33.7	19215	***59.9***	11.9	**1.92**	18.2	**553286**	396	2.31	933	**110**	479	***249***	32.7	8517	<PQL	500	***7234***
CAT1-6	3.39	488	***316***	37.7	17536	***56.7***	12.5	**1.77**	12.6	**471626**	407	2.45	1035	95.9	547	***208***	33.1	7504	<PQL	428	***5735***
CAT2-3	2.39	**688**	***261***	30.4	13295	***42.1***	9.65	<PQL	21.2	**461575**	417	1.57	952	73.7	569	***210***	23.2	8906	<PQL	6067	***5956***
CAT2-6	2.37	**732**	***303***	37.4	15424	***44.2***	9.15	<PQL	5.36	**494080**	393	1.78	860	92.7	383	***204***	24.7	7887	<PQL	6754	***5959***
CAT3-3	2.33	**931**	***220***	30.9	15613	***42.0***	12.4	**2.18**	*33.1*	**452333**	472	2.97	1217	**101**	690	***248***	22.5	13750	<PQL	5763	***6137***
CAT3-6	3.43	560	***236***	31.1	14923	***63.5***	13.1	**1.84**	6.93	**561166**	471	3.57	1211	**106**	711	***264***	*36.4*	11932	<PQL	425	***6750***

Table A-2: Elemental Concentrations in the Solids of the Southeast Commerce Oxidation Pond Solids in mg kg^{-1}, with Bolded Values Exceeding Soil Benchmarks, Italicized Values Exceeding Sediment Benchmarks, and Highlighted Values Exceeding TSMD-Specific Benchmarks

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	S	Se	Si	Zn
Soil Guidelines	50	600	60	3000		20	1000	0.4	50	200		10		100		90	500		70		20
Sediment Guidelines			9.79			0.99		43.4	31.6							22.7	35.8				121
TSMD Guidelines			33			4.98		111	149							48.6	128				459
PQL	1.12	1.52	7.84	0.665	25.5	0.305	0.026	0.232	0.431	0.394	20.0	5.46	0.424	0.332	4.81	0.608	3.10	20.9	8.76	1.04	1.79
Ox 1	2.85	411	***228***	18.9	15755	***58.8***	12.4	**1.80**	14.9	**471366**	424	1.27	1042	94.1	1028	*70.3*	*54.8*	8858	<PQL	406	***3203***
Ox 2	3.05	545	***246***	19.5	16006	***67.5***	11.1	**1.79**	10.2	**536354**	416	1.80	1174	**180**	1280	*52.6*	*56.8*	8883	<PQL	430	***3346***
Ox 3	3.16	480	***253***	18.6	12810	***65.1***	7.42	**1.96**	10.5	**505508**	457	2.16	1161	**137**	728	*71.2*	*59.2*	7368	<PQL	353	***3935***
Ox 4	3.15	577	***246***	19.4	16289	***59.7***	9.99	**2.02**	16.1	**484717**	572	3.02	1763	93.9	1068	*68.2*	*88.0*	12001	<PQL	428	***2878***
Ox 5	3.25	480	***289***	22.5	18286	***65.1***	10.7	**1.91**	9.46	**504298**	464	1.68	1271	**107**	851	*65.9*	*80.0*	8441	<PQL	576	***4398***
Ox 5 FD	2.76	582	***308***	23.8	19664	***65.5***	8.56	**1.96**	18.5	**470749**	500	1.86	1348	**114**	988	*63.3*	*78.8*	8866	<PQL	428	***4671***
Ox 6	2.69	**626**	***278***	21.2	18752	***61.0***	5.86	**2.02**	6.21	**503965**	510	2.05	1473	**114**	987	*62.9*	*82.9*	10850	<PQL	387	***3975***
Ox 7	3.53	402	***253***	18.9	17398	***60.7***	9.43	**1.85**	10.7	**518841**	483	1.83	1444	88.5	1216	*60.0*	*55.8*	11629	<PQL	313	***3078***
Ox 8	3.17	545	***269***	19.8	18732	***65.0***	9.96	**1.90**	10.0	**523812**	410	1.52	799	**105**	2001	*56.1*	*53.8*	8988	<PQL	414	***4506***
Ox 9	3.18	286	***273***	19.9	15598	***67.9***	5.03	**1.96**	4.80	**529156**	427	1.89	1360	**133**	723	*62.9*	*55.5*	8582	<PQL	435	***4085***
Ox 9 FD	3.70	380	***302***	20.2	14820	***72.6***	8.90	**2.02**	5.52	**540081**	390	2.24	1228	**224**	643	*68.5*	*57.9*	7846	<PQL	404	***6035***
Ox 10	3.07	470	***261***	17.2	15953	***65.0***	6.58	**1.77**	8.11	**506878**	468	1.72	1348	**136**	1208	***95.9***	*47.2*	11827	<PQL	365	***5332***
Ox 11	1.34	**3511**	***130***	19.4	5905	***39.9***	8.58	**4.17**	15.9	**294163**	466	6.26	715	**962**	498	*87.1*	*42.3*	3586	<PQL	241	***4914***
Ox 12	2.90	**1717**	***228***	23.6	8682	***75.0***	12.8	**2.38**	8.78	**490892**	426	3.96	1144	**1547**	1503	***126***	*90.5*	8305	<PQL	282	***11700***
Ox 13	2.80	**931**	***283***	19.4	8922	***71.5***	10.8	**1.93**	23.9	**565164**	399	2.57	775	**346**	1032	***134***	*58.9*	5902	<PQL	264	***6760***
Ox 14	2.72	440	***276***	20.0	8643	***67.5***	4.39	**1.80**	8.11	**534642**	357	1.61	584	**315**	848	*87.0*	*55.4*	4941	<PQL	340	***5789***
Ox 14 FD	3.19	472	***274***	18.8	5405	***69.7***	11.1	**1.80**	24.1	**555399**	360	1.49	553	**597**	1213	***103***	*58.3*	4425	<PQL	399	***4999***
Ox 15	3.12	**815**	***293***	21.6	14726	***66.6***	14.7	**3.44**	5.73	**564173**	444	1.81	985	**447**	1762	*74.9*	*63.8*	8687	<PQL	461	***5636***
Ox 16	1.94	**1201**	***199***	19.9	9279	***81.0***	11.1	**1.94**	7.13	**538195**	400	2.80	737	**555**	594	***135***	*68.0*	10630	<PQL	409	***16379***
Ox 17	2.65	**1393**	***204***	20.0	9925	***66.1***	15.1	**2.19**	17.1	**507314**	434	3.30	1033	**670**	1679	***130***	*67.1*	8487	<PQL	346	***5988***
Ox 18	2.79	**1449**	***199***	21.5	9442	***82.7***	10.5	**2.23**	20.6	**473881**	421	3.65	990	**953**	1624	***131***	*71.6*	10282	<PQL	360	***9567***
Ox 19	2.59	**1741**	***186***	19.3	8317	***117***	10.9	**2.22**	19.4	**492580**	414	3.73	1104	**1716**	1860	***143***	*74.8*	11048	<PQL	239	***18336***
Ox 20	2.39	**1340**	***213***	22.1	8953	***70.3***	15.7	**2.08**	5.16	**495637**	416	3.15	1032	**1138**	1143	***162***	*66.8*	8194	<PQL	322	***8556***
Ox 21	3.12	**1043**	***182***	19.0	15025	***71.2***	20.3	**1.89**	8.72	**469726**	415	3.80	1072	**2036**	1824	***162***	*55.7*	22315	<PQL	388	***12363***
Ox 22	2.26	**1211**	***194***	20.1	10827	***124***	17.9	**1.89**	23.2	**477577**	412	3.90	1156	**1628**	2055	***144***	*63.3*	15119	<PQL	308	***13063***
Ox 23	1.80	**2364**	***163***	20.7	12492	***66.1***	79.1	**2.62**	9.13	**414034**	466	5.98	1031	**820**	1270	***128***	*57.7*	13499	<PQL	289	***9215***
Ox 24	2.96	**766**	***197***	19.4	12534	***69.2***	8.94	**1.88**	24.4	**539909**	414	2.92	951	**390**	1354	***140***	*52.1*	13172	<PQL	290	***7478***
Ox 25	1.90	**3417**	***135***	24.6	12921	***49.4***	11.8	**4.24**	20.8	**338547**	513	7.45	1089	**561**	1016	***128***	*64.3*	12204	<PQL	289	***6017***

Table A-3: Elemental Concentrations in Mayer Ranch Oxidation Pond Solids TCLP Leachate in mg L^{-1}, with Samples Leached with Extraction Fluid 2 Highlighted

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Ni	Pb	S	Se	Si	Zn
RCRA Limits	5		5	100		1		5								5		1		
PQL	0.003	0.018	0.020	0.002	0.066	0.001	0.001	0.002	0.001	0.001	0.029	0.001	0.001	0.001	0.002	0.017	0.053	0.022	0.005	0.003
C1-1	0.011	0.046	0.029	0.167	618	0.001	0.021	<PQL	0.017	4.27	12.6	0.061	56.6	0.676	0.466	0.016	334	<PQL	17.1	4.67
C1-2	0.011	0.332	0.030	0.154	649	0.001	0.025	<PQL	0.048	1.55	14.1	0.068	66.5	0.601	0.399	0.020	376	<PQL	17.9	7.98
C1-3	0.012	0.974	0.024	0.188	737	0.001	0.024	<PQL	0.112	3.14	12.5	0.062	57.1	0.811	0.440	0.021	414	<PQL	15.2	5.12
C1-4	0.011	0.035	0.029	0.127	700	0.001	0.018	<PQL	0.013	2.72	10.7	0.051	54.6	0.778	0.379	0.012	379	<PQL	15.8	4.57
C1-5	0.010	0.052	0.026	0.126	602	0.001	0.016	<PQL	0.016	2.69	11.9	0.059	57.2	0.663	0.315	0.019	318	<PQL	15.1	5.26
C1-6	0.011	0.072	0.033	0.121	648	0.001	0.016	<PQL	0.018	3.23	11.8	0.055	55.7	0.783	0.318	0.008	342	<PQL	14.2	4.41
C1-6 FD	0.011	0.028	0.025	0.120	634	0.001	0.015	<PQL	0.013	2.92	11.5	0.052	54.5	0.739	0.283	0.016	337	<PQL	14.3	4.29
C1-7	0.010	0.047	<PQL	0.167	573	0.001	0.016	<PQL	0.014	3.70	10.0	0.048	47.5	0.769	0.290	0.011	292	<PQL	13.5	4.60
C1-8	0.011	0.041	0.029	0.135	627	0.001	0.012	<PQL	0.015	1.78	12.6	0.055	55.4	0.630	0.283	0.012	346	<PQL	13.1	2.41
C1-9	0.010	0.035	<PQL	0.155	586	0.001	0.012	<PQL	0.014	2.64	12.5	0.057	55.7	0.668	0.319	0.012	308	<PQL	12.5	2.39
C1-10	0.010	0.033	0.024	0.153	580	0.001	0.014	<PQL	0.014	4.67	11.6	0.060	54.4	0.762	0.373	0.017	298	<PQL	12.8	2.15
C1-11	0.011	0.027	0.030	0.160	579	0.001	0.017	<PQL	0.012	4.05	11.6	0.051	48.9	0.654	0.363	0.017	295	<PQL	11.5	2.47
C1-11 FD	0.010	0.027	0.023	0.162	580	0.001	0.017	<PQL	0.013	5.98	11.5	0.055	50.0	0.760	0.449	0.016	288	<PQL	12.1	2.64
C1-12	0.011	0.020	0.022	0.183	619	0.002	0.016	<PQL	0.013	9.31	12.0	0.064	49.0	0.828	0.329	0.022	282	<PQL	9.98	1.90
C1-13	0.011	0.033	0.024	0.265	618	0.001	0.193	<PQL	0.014	7.81	12.9	0.059	49.9	0.993	1.73	0.022	257	<PQL	9.47	3.05
C1-14	0.009	0.520	<PQL	0.197	507	0.002	0.018	<PQL	0.011	16.6	13.7	0.072	35.2	0.755	0.378	0.065	263	<PQL	9.40	2.23
C1-15	0.008	0.325	<PQL	0.135	474	0.001	0.024	<PQL	0.012	7.74	13.0	0.066	30.4	0.813	0.641	0.070	232	0.024	10.6	3.25
C1-16	0.009	0.254	<PQL	0.122	554	0.016	0.043	<PQL	0.009	127	14.7	0.101	39.0	1.24	0.864	0.038	254	<PQL	9.09	2.33
C1-17	0.012	0.260	<PQL	0.113	846	0.018	0.066	<PQL	0.010	138	15.7	0.113	34.8	2.00	1.15	0.031	395	0.024	9.92	2.80
C1-18	0.020	0.167	0.036	0.501	1060	0.159	0.123	0.004	0.009	1543	10.2	0.100	49.7	3.35	2.29	2.36	303	<PQL	25.3	35.9
C1-19	0.024	0.046	0.038	0.434	1120	0.218	0.135	<PQL	0.010	2135	8.69	0.124	49.5	3.75	2.49	3.28	274	<PQL	20.6	29.2
C1-20	0.010	0.049	<PQL	0.218	589	0.021	0.106	<PQL	0.015	190	15.3	0.066	52.3	2.23	1.81	0.312	249	<PQL	11.4	8.19
C1-20 FD	0.010	0.020	0.022	0.210	585	0.015	0.117	<PQL	0.017	132	14.5	0.059	50.8	2.32	1.84	0.216	234	<PQL	12.0	13.5
C1-21	0.013	0.574	0.048	0.187	1211	0.002	0.121	0.021	0.011	10.9	13.7	0.033	60.8	2.42	2.69	0.028	112	<PQL	28.2	104
C1-22	0.010	0.233	<PQL	0.142	610	<PQL	0.091	<PQL	0.010	0.180	21.0	0.047	34.6	0.649	0.893	0.082	245	<PQL	11.2	5.77
CAT1-3	0.011	0.025	0.024	0.175	707	0.001	0.019	<PQL	0.014	4.99	10.6	0.049	50.3	0.716	0.366	0.017	380	<PQL	15.5	4.04
CAT1-6	0.010	0.030	0.034	0.142	640	0.001	0.021	<PQL	0.015	4.79	11.2	0.060	54.3	0.687	0.433	0.018	309	<PQL	17.2	4.24
CAT2-3	0.009	0.213	<PQL	0.151	517	0.001	0.012	<PQL	0.011	3.71	12.6	0.061	31.6	0.596	0.281	0.070	281	0.029	9.87	2.07
CAT2-6	0.008	0.243	<PQL	0.161	575	0.001	0.037	<PQL	0.014	2.03	14.9	0.072	39.0	0.772	0.756	0.087	322	0.027	11.5	2.54
CAT3-3	0.009	0.235	0.017	0.192	576	0.006	0.029	<PQL	0.012	42.3	15.4	0.089	35.1	1.13	0.687	0.057	295	<PQL	9.25	2.50
CAT3-6	0.010	0.233	<PQL	0.177	583	0.006	0.026	<PQL	0.010	46.6	14.0	0.085	34.3	1.09	0.544	0.056	322	0.025	9.09	2.33

Table A-4: Elemental Concentrations in Southeast Commerce Oxidation Pond Solids TCLP Leachate in mg L^{-1}

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Ni	Pb	S	Se	Si	Zn
RCRA Limits	5		5	100		1		5								5		1		
PQL	0.003	0.018	0.020	0.002	0.066	0.001	0.002	0.001	0.001	0.001	0.029	0.001	0.001	0.001	0.002	0.017	0.053	0.022	0.005	0.018
Ox 1	0.012	0.025	0.023	0.072	746	0.002	0.016	<PQL	0.018	0.678	16.7	0.052	66.1	1.02	0.167	<PQL	349	<PQL	21.1	3.90
Ox 2	0.011	0.021	<PQL	0.211	656	0.002	0.014	<PQL	0.016	0.582	12.2	0.053	57.2	1.86	0.125	<PQL	275	<PQL	20.6	3.54
Ox 3	0.011	0.024	0.022	0.202	627	0.003	0.023	<PQL	0.016	1.62	16.8	0.075	65.0	2.03	0.190	<PQL	302	<PQL	22.3	7.46
Ox 4	0.010	0.019	<PQL	0.107	598	0.003	0.013	<PQL	0.018	0.076	19.3	0.086	77.6	0.670	0.151	0.018	317	<PQL	17.4	2.70
Ox 5	0.011	0.054	<PQL	0.201	717	0.007	0.018	<PQL	0.022	0.773	18.2	0.058	63.3	0.952	0.143	<PQL	309	<PQL	16.8	5.46
Ox 5 FD	0.013	0.038	<PQL	0.085	765	0.007	0.019	<PQL	0.025	0.620	23.7	0.091	87.1	1.18	0.152	<PQL	376	<PQL	15.9	5.89
Ox 6	0.013	<PQL	0.024	0.170	815	0.001	0.015	<PQL	0.016	0.203	22.8	0.094	84.3	1.11	0.152	<PQL	437	<PQL	17.2	3.93
Ox 7	0.011	0.020	<PQL	0.175	701	<PQL	0.010	<PQL	0.017	0.239	17.3	0.062	66.5	0.671	0.110	0.019	370	<PQL	17.6	2.29
Ox 8	0.010	0.022	<PQL	0.184	668	<PQL	0.010	<PQL	0.018	0.824	11.7	0.043	34.9	0.573	0.089	0.023	277	<PQL	16.2	2.90
Ox 9	0.011	0.019	0.020	0.150	724	<PQL	0.011	<PQL	0.019	0.816	12.7	0.081	78.9	1.03	0.107	<PQL	390	<PQL	16.6	2.17
Ox 9 FD	0.010	0.023	<PQL	0.224	555	0.001	0.016	<PQL	0.016	2.44	9.16	0.072	60.7	1.89	0.140	0.018	255	<PQL	17.4	4.32
Ox 10	0.012	0.016	<PQL	0.087	659	<PQL	0.017	<PQL	0.016	0.266	18.3	0.067	66.0	1.06	0.177	<PQL	357	<PQL	18.7	2.22
Ox 11	0.006	0.108	<PQL	0.153	244	0.001	0.269	0.002	0.017	3.44	8.60	0.034	40.2	17.92	0.357	0.020	154	<PQL	23.1	15.0
Ox 12	0.005	0.080	<PQL	0.164	257	0.006	0.458	0.004	0.016	7.87	6.91	0.039	42.7	31.0	0.558	0.032	173	<PQL	26.8	68.6
Ox 13	0.008	0.041	<PQL	0.183	276	0.001	0.057	<PQL	0.017	3.31	8.32	0.046	36.5	4.77	0.285	0.060	147	<PQL	27.3	12.4
Ox 14	0.009	0.228	<PQL	0.260	339	0.006	0.032	0.002	0.046	8.46	8.87	0.051	28.3	3.63	0.245	0.042	155	<PQL	25.2	8.79
Ox 14 FD	0.005	0.246	<PQL	0.228	204	0.015	0.072	0.002	0.043	3.59	7.02	0.041	25.5	9.17	0.212	0.028	129	<PQL	26.2	10.6
Ox 15	0.010	0.198	<PQL	0.222	522	0.002	0.031	0.001	0.035	7.20	12.3	0.050	47.6	5.06	0.244	0.033	253	<PQL	25.5	10.5
Ox 16	0.007	0.090	<PQL	0.195	399	0.003	0.268	0.001	0.016	13.4	11.8	0.057	48.3	8.24	0.765	0.044	296	0.024	27.4	28.7
Ox 17	0.007	0.127	0.021	0.221	316	0.002	0.184	<PQL	0.016	13.6	9.99	0.043	42.8	8.96	0.518	0.043	209	<PQL	26.2	6.83
Ox 18	0.007	0.111	<PQL	0.166	328	0.003	0.272	0.001	0.016	10.9	9.73	0.050	49.3	14.9	0.627	0.042	273	<PQL	27.6	15.2
Ox 19	0.006	0.122	<PQL	0.180	295	0.003	0.524	0.003	0.017	14.4	8.62	0.060	58.4	31.1	0.982	0.056	279	0.029	29.4	53.0
Ox 20	0.007	0.171	<PQL	0.179	293	0.002	0.295	0.002	0.014	10.1	10.2	0.038	51.5	17.1	0.604	0.042	215	0.033	26.9	11.0
Ox 21	0.008	0.061	<PQL	0.163	560	0.012	1.07	0.003	0.017	86.9	9.84	0.079	51.8	33.4	1.74	0.193	434	<PQL	21.9	33.0
Ox 22	0.007	0.076	<PQL	0.192	382	0.005	0.587	0.003	0.015	30.0	9.31	0.070	54.0	28.2	1.28	0.084	327	0.027	28.9	22.3
Ox 23	0.007	0.120	<PQL	0.170	354	0.005	0.348	0.019	0.016	30.9	10.4	0.051	42.4	12.5	1.05	0.082	233	<PQL	22.7	19.1
Ox 24	0.008	0.055	<PQL	0.217	451	0.004	0.111	<PQL	0.059	25.8	11.7	0.066	46.3	5.07	1.06	0.064	306	<PQL	22.8	9.33
Ox 25	0.008	0.137	<PQL	0.163	376	0.005	0.296	<PQL	0.014	37.7	11.6	0.050	46.8	7.72	1.70	0.099	232	<PQL	22.2	18.5

Table A-5: Elemental Concentrations in Mayer Ranch Oxidation Pond Solids SPLP Leachate in mg L^{-1}, with Bolded Values Exceeding the OWRB WQGs

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	Se	Si	Zn
OWRB WQGs	0.05	0.05	0.04	1		0.02		0.05	1	0.3				0.05		0.14	0.1	0.01		5
PQL	0.0005	0.004	0.020	0.002	0.066	0.001	0.001	0.001	0.001	0.002	0.029	0.001	0.001	0.001	0.012	0.003	0.011	0.022	0.003	0.005
C1-1	0.001	**0.156**	<PQL	0.038	383	0.003	<PQL	<PQL	0.008	0.007	5.10	0.029	27.4	0.023	21.2	0.026	0.034	<PQL	3.22	0.687
C1-2	0.001	**0.164**	<PQL	0.041	417	<PQL	<PQL	<PQL	0.007	0.013	5.35	0.029	29.6	0.021	24.7	0.015	0.034	<PQL	2.68	0.237
C1-3	0.001	**0.170**	<PQL	0.082	450	<PQL	<PQL	<PQL	0.008	0.019	5.05	0.027	24.4	0.015	19.7	0.012	0.029	<PQL	2.35	0.099
C1-4	0.001	**0.170**	<PQL	0.090	485	<PQL	<PQL	<PQL	0.007	0.016	5.75	0.028	27.7	0.009	32.4	0.005	0.037	<PQL	1.43	0.077
C1-5	0.001	**0.155**	<PQL	0.084	389	<PQL	<PQL	<PQL	0.008	0.009	5.33	0.026	25.6	0.013	22.1	0.010	0.033	<PQL	2.08	0.094
C1-6	0.001	**0.156**	<PQL	0.088	403	<PQL	<PQL	<PQL	0.008	0.007	5.35	0.027	25.9	0.014	22.1	0.010	0.032	<PQL	2.23	0.092
C1-6 FD	0.001	**0.149**	<PQL	0.100	365	<PQL	<PQL	<PQL	0.007	0.004	4.90	0.023	22.4	0.008	19.9	0.010	0.029	<PQL	2.08	0.110
C1-7	0.001	**0.151**	<PQL	0.088	385	<PQL	<PQL	<PQL	0.010	0.011	4.42	0.017	18.0	0.008	23.3	0.005	0.019	<PQL	1.61	0.076
C1-8	0.001	**0.161**	<PQL	0.116	408	0.002	0.002	<PQL	0.010	0.024	5.83	0.028	24.7	0.016	26.7	0.018	0.035	<PQL	1.94	0.634
C1-9	0.001	**0.150**	<PQL	0.053	345	<PQL	0.001	<PQL	0.008	0.008	5.19	0.024	20.5	0.026	29.6	0.019	0.048	<PQL	1.80	0.377
C1-10	0.001	**0.157**	<PQL	0.062	337	<PQL	0.005	<PQL	0.016	0.044	5.00	0.025	20.6	0.025	21.0	0.045	0.022	<PQL	2.04	1.14
C1-11	0.001	**0.149**	<PQL	0.064	368	<PQL	<PQL	<PQL	0.007	0.005	5.23	0.024	19.0	0.008	19.9	0.006	0.018	<PQL	1.47	0.118
C1-11 FD	0.001	**0.148**	<PQL	0.113	365	<PQL	<PQL	<PQL	0.009	0.021	5.01	0.023	19.3	0.009	19.9	0.007	0.020	<PQL	1.55	0.097
C1-12	0.001	**0.147**	<PQL	0.090	364	<PQL	<PQL	<PQL	0.007	0.031	5.14	0.024	16.7	0.004	19.5	<PQL	0.020	<PQL	1.27	0.117
C1-13	0.001	**0.140**	<PQL	0.135	330	<PQL	<PQL	<PQL	0.009	0.020	5.38	0.024	17.5	0.004	23.8	<PQL	0.018	<PQL	1.17	0.132
C1-14	0.001	**0.135**	<PQL	0.139	313	<PQL	<PQL	<PQL	0.007	0.041	5.46	0.023	17.3	0.006	20.1	<PQL	0.020	<PQL	1.20	0.127
C1-15	0.001	**0.144**	<PQL	0.103	334	<PQL	<PQL	<PQL	0.007	0.022	5.45	0.024	21.1	0.009	23.7	0.008	0.022	<PQL	1.49	0.129
C1-16	0.001	**0.146**	<PQL	0.119	356	<PQL	<PQL	<PQL	0.007	0.008	6.02	0.029	21.4	0.007	21.0	0.007	0.026	<PQL	1.19	0.141
C1-17	0.002	**0.179**	<PQL	0.083	515	<PQL	<PQL	<PQL	0.010	0.039	6.77	0.037	19.6	0.011	18.7	0.009	0.022	<PQL	1.33	0.081
C1-18	0.001	**0.157**	<PQL	0.122	403	<PQL	<PQL	<PQL	0.009	0.026	5.69	0.027	17.6	0.008	18.7	0.007	0.023	<PQL	1.16	0.156
C1-19	0.001	**0.151**	<PQL	0.166	379	0.002	0.003	<PQL	0.013	0.005	5.53	0.031	20.6	0.015	16.2	0.024	0.028	<PQL	1.40	0.681
C1-20	0.001	**0.137**	<PQL	0.111	313	<PQL	<PQL	<PQL	0.008	0.003	6.53	0.028	24.1	0.027	17.7	0.022	0.028	<PQL	1.78	0.126
C1-20 FD	0.001	**0.121**	<PQL	0.109	265	<PQL	<PQL	<PQL	0.008	<PQL	6.10	0.022	19.7	0.017	16.9	0.017	0.024	<PQL	1.43	0.231
C1-21	0.001	**0.103**	<PQL	0.083	189	<PQL	<PQL	<PQL	0.006	0.021	6.60	0.026	14.8	0.019	15.7	0.014	<PQL	<PQL	1.06	0.076
C1-22	0.001	**0.121**	<PQL	0.048	270	<PQL	<PQL	<PQL	0.015	0.008	6.77	0.022	17.3	0.010	16.8	0.021	0.016	<PQL	1.54	0.088
CAT1-3	0.001	**0.174**	<PQL	0.043	470	<PQL	<PQL	<PQL	0.008	0.004	4.28	0.020	18.7	0.011	18.0	0.009	0.023	<PQL	2.03	0.078
CAT1-6	0.001	**0.156**	<PQL	0.052	387	<PQL	<PQL	<PQL	0.008	0.005	5.17	0.031	25.5	0.016	20.7	0.013	0.032	<PQL	2.28	0.086
CAT2-3	0.001	**0.148**	<PQL	0.075	372	<PQL	<PQL	<PQL	0.007	0.005	5.64	0.019	15.2	0.005	22.7	<PQL	<PQL	<PQL	0.937	0.094
CAT2-6	0.001	**0.148**	<PQL	0.073	351	<PQL	<PQL	<PQL	0.006	<PQL	5.65	0.025	19.3	0.008	20.2	0.008	0.019	<PQL	1.44	0.076
CAT3-3	0.001	**0.148**	<PQL	0.091	368	<PQL	<PQL	<PQL	0.006	0.008	6.43	0.030	18.6	0.005	20.5	0.006	0.021	<PQL	1.21	0.133
CAT3-6	0.001	**0.152**	<PQL	0.095	381	<PQL	<PQL	<PQL	0.008	0.006	5.58	0.029	16.9	0.007	18.8	0.005	0.018	<PQL	1.17	0.094

Table A-6: Elemental Concentrations in Southeast Commerce Oxidation Pond Solids SPLP Leachate in mg L^{-1}, with Bolded Values Exceeding the OWRB WQGs

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	Se	Si	Zn
OWRB WQGs	0.05	0.05	0.04	1		0.02		0.05	1	0.3				0.05		0.14	0.1	0.01		5
PQL	0.0005	0.004	0.020	0.002	0.066	0.001	0.001	0.001	0.001	0.002	0.029	0.001	0.001	0.001	0.012	0.003	0.011	0.022	0.003	0.005
Ox 1	0.001	**0.174**	<PQL	0.084	434	<PQL	0.034	<PQL	0.010	0.199	9.25	0.050	33.3	**0.053**	58.7	**0.309**	0.044	<PQL	1.23	2.59
Ox 2	0.001	**0.173**	<PQL	0.086	414	<PQL	0.013	<PQL	0.008	0.063	6.05	0.032	20.2	0.021	60.7	0.135	0.020	<PQL	1.21	1.19
Ox 3	0.001	**0.156**	<PQL	0.079	397	<PQL	<PQL	<PQL	0.007	0.006	7.56	0.041	26.0	0.017	43.1	0.007	0.029	<PQL	1.32	0.081
Ox 5	0.001	**0.147**	<PQL	0.087	368	<PQL	<PQL	<PQL	0.007	0.003	7.60	0.035	26.1	0.016	44.3	0.006	0.033	<PQL	1.42	0.082
Ox 5 FD	0.001	**0.163**	<PQL	0.099	436	<PQL	<PQL	<PQL	0.008	0.004	9.68	0.056	34.7	0.022	53.2	0.008	0.049	<PQL	1.40	0.068
Ox 7	0.001	**0.174**	<PQL	0.074	496	<PQL	<PQL	<PQL	0.009	0.045	9.45	0.044	30.8	0.012	69.0	0.006	0.043	<PQL	1.47	0.096
Ox 8	0.001	**0.140**	<PQL	0.048	334	<PQL	<PQL	<PQL	0.006	0.004	5.16	0.018	9.76	0.003	78.3	<PQL	0.021	<PQL	1.35	0.073
Ox 9	0.001	**0.173**	<PQL	0.076	473	<PQL	<PQL	<PQL	0.008	0.007	6.16	0.051	34.9	0.016	45.4	0.005	0.051	<PQL	1.53	0.096
Ox 9 FD	0.001	**0.142**	<PQL	0.050	334	<PQL	<PQL	<PQL	0.007	0.005	3.41	0.030	22.3	0.017	26.2	0.005	0.027	<PQL	1.84	0.074
Ox 10	0.001	**0.207**	<PQL	0.080	679	<PQL	0.002	<PQL	0.010	0.011	18.2	0.097	67.2	0.039	101	0.024	0.110	<PQL	1.60	0.606
Ox 11	0.001	**0.094**	<PQL	0.059	160	<PQL	0.004	<PQL	0.006	0.012	3.14	0.018	21.3	**0.920**	27.8	0.017	0.027	<PQL	3.53	0.134
Ox 12	0.001	**0.104**	<PQL	0.083	204	<PQL	0.012	<PQL	0.009	0.010	2.89	0.025	27.8	**2.16**	50.0	0.047	0.047	<PQL	3.58	0.795
Ox 13	0.001	**0.100**	<PQL	0.080	182	<PQL	<PQL	<PQL	0.006	0.007	3.15	0.023	16.3	**0.106**	35.5	0.016	0.020	<PQL	3.57	0.115
Ox 14	0.001	**0.099**	<PQL	0.077	181	<PQL	0.002	<PQL	0.008	0.004	3.41	0.024	13.0	**0.072**	40.5	0.024	<PQL	<PQL	3.12	0.267
Ox 14 FD	0.001	**0.082**	<PQL	0.078	141	<PQL	<PQL	<PQL	0.008	0.004	3.23	0.025	16.0	**0.398**	59.2	0.015	<PQL	<PQL	3.75	0.183
Ox 15	0.001	**0.125**	<PQL	0.054	282	<PQL	<PQL	<PQL	0.008	0.010	4.65	0.021	16.7	**0.062**	61.3	0.008	0.016	<PQL	2.10	0.095
Ox 16	0.001	**0.136**	<PQL	0.100	310	<PQL	0.013	<PQL	0.008	0.032	4.86	0.032	29.0	**0.950**	30.8	0.064	0.041	<PQL	5.40	0.756
Ox 17	0.001	**0.108**	<PQL	0.081	210	<PQL	0.003	<PQL	0.007	0.006	4.05	0.021	22.4	**0.383**	56.1	0.025	0.021	<PQL	4.54	0.169
Ox 18	0.001	**0.113**	<PQL	0.090	222	0.001	0.009	<PQL	0.008	0.008	4.12	0.026	26.8	**1.53**	64.3	0.044	0.040	<PQL	5.10	0.383
Ox 19	0.002	**0.105**	<PQL	0.063	205	<PQL	0.024	<PQL	0.006	0.013	3.72	0.031	33.6	**3.93**	79.6	0.066	0.068	<PQL	5.23	1.02
Ox 20	0.001	**0.106**	<PQL	0.055	195	<PQL	0.006	<PQL	0.008	0.010	3.91	0.019	26.9	**1.11**	45.5	0.029	0.036	<PQL	4.54	0.181
Ox 21	0.002	**0.170**	<PQL	0.038	445	<PQL	0.117	<PQL	0.008	0.058	4.73	0.047	36.0	**8.02**	74.6	**0.214**	0.093	<PQL	4.48	1.42
Ox 22	0.002	**0.149**	<PQL	0.118	336	<PQL	0.037	<PQL	0.008	0.033	4.75	0.047	38.4	**4.91**	89.3	0.125	0.081	<PQL	6.57	0.783
Ox 23	0.001	**0.125**	<PQL	0.098	275	<PQL	0.014	<PQL	0.009	0.007	4.60	0.026	25.9	**1.44**	40.6	0.070	0.043	<PQL	4.35	0.447
Ox 24	0.001	**0.130**	<PQL	0.138	293	<PQL	0.002	<PQL	0.008	0.008	4.66	0.027	23.9	**0.240**	51.2	0.035	0.029	<PQL	4.29	0.284
Ox 25	0.001	**0.125**	<PQL	0.120	255	<PQL	0.007	<PQL	0.008	0.008	4.66	0.022	26.2	**0.665**	35.6	0.061	0.037	<PQL	3.73	0.448

Table A-7: Elemental Concentrations in Mayer Ranch Oxidation Pond Solids FLT Leachate in mg L^{-1}, with Bolded Values Exceeding the OWRB WQGs

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	S	Se	Si	Zn
OWRB WQGs	0.05	0.05	0.04	1		0.02		0.05	1	0.3				0.05		0.14	0.1		0.01		5
PQL	0.003	0.004	0.022	0.002	0.066	0.001	0.001	0.001	0.001	0.001	0.029	0.001	0.001	0.001	0.012	0.002	0.011	0.053	0.022	0.003	0.003
C1-1	0.006	**0.299**	<PQL	0.005	179	<PQL	0.002	<PQL	0.011	0.205	4.30	0.023	14.7	0.007	16.9	0.006	0.027	161	<PQL	0.764	0.014
C1-2	0.019	**0.261**	<PQL	0.006	171	<PQL	0.002	<PQL	0.005	0.186	4.75	0.027	15.2	0.007	17.7	0.005	0.025	156	<PQL	0.842	0.022
C1-3	0.003	**0.094**	<PQL	0.003	113	<PQL	0.002	<PQL	0.004	**0.728**	3.19	0.020	10.2	0.005	11.9	0.004	0.022	97.9	<PQL	0.438	0.015
C1-4	<PQL	**0.082**	<PQL	0.003	109	<PQL	<PQL	<PQL	0.006	<PQL	3.04	0.017	9.74	0.004	12.3	0.004	0.024	116	<PQL	0.433	0.006
C1-5	0.005	**0.094**	<PQL	0.006	149	<PQL	0.002	<PQL	0.006	0.008	3.98	0.022	14.2	0.006	16.0	0.005	0.025	137	<PQL	0.610	0.026
C1-6	0.004	**0.100**	<PQL	0.005	163	<PQL	<PQL	<PQL	0.005	**0.338**	4.00	0.023	13.4	0.005	15.6	0.004	0.021	147	<PQL	0.547	0.016
C1-6 FD	0.004	**0.117**	<PQL	0.006	206	<PQL	0.002	<PQL	0.005	0.212	4.03	0.026	14.1	0.006	15.7	0.004	0.026	179	<PQL	0.800	0.016
C1-7	0.003	**0.094**	<PQL	0.004	160	<PQL	<PQL	<PQL	0.005	0.032	3.44	0.018	9.64	0.004	16.9	0.004	0.021	140	<PQL	0.488	0.014
C1-8	0.005	**0.103**	<PQL	0.006	174	<PQL	<PQL	<PQL	0.005	0.132	5.14	0.029	15.8	0.005	20.9	0.003	0.026	162	<PQL	0.542	0.008
C1-9	0.006	**0.110**	<PQL	0.006	196	<PQL	<PQL	<PQL	0.007	**0.483**	5.06	0.029	15.1	0.005	21.7	0.005	0.026	179	<PQL	0.574	0.009
C1-10	0.004	**0.126**	<PQL	0.005	199	0.001	0.002	<PQL	0.007	**6.11**	4.73	0.046	15.6	0.013	18.0	0.006	0.022	179	<PQL	0.804	0.092
C1-11	0.005	**0.123**	<PQL	0.006	217	<PQL	<PQL	<PQL	0.008	**0.331**	4.60	0.025	14.3	0.005	16.2	0.006	0.025	190	<PQL	0.622	0.014
C1-11 FD	<PQL	**0.102**	<PQL	0.004	156	<PQL	0.002	<PQL	0.006	**1.96**	4.23	0.023	12.5	0.007	14.6	0.004	0.020	142	<PQL	0.466	0.038
C1-12	0.004	**0.125**	<PQL	0.005	205	<PQL	<PQL	<PQL	0.006	**2.80**	5.00	0.036	10.9	0.007	17.1	0.005	0.025	175	<PQL	0.494	0.043
C1-13	0.004	**0.109**	<PQL	0.005	190	<PQL	<PQL	<PQL	0.013	**1.10**	4.70	0.025	9.27	0.003	17.7	<PQL	0.022	164	<PQL	0.412	0.030
C1-14	0.002	**0.071**	<PQL	0.003	96	<PQL	<PQL	<PQL	0.007	<PQL	3.49	0.010	6.74	0.001	11.4	0.004	0.023	98.2	<PQL	0.225	<PQL
C1-15	0.003	**0.105**	<PQL	0.005	147	<PQL	0.002	<PQL	0.006	0.010	4.57	0.021	12.5	0.004	17.5	0.003	0.020	139	<PQL	0.491	0.021
C1-16	0.002	**0.058**	<PQL	0.003	66	<PQL	<PQL	<PQL	0.009	<PQL	3.29	0.012	6.63	<PQL	10.2	0.004	0.024	71.1	<PQL	0.169	0.009
C1-17	<PQL	**0.062**	<PQL	0.003	71	<PQL	<PQL	<PQL	0.008	0.012	3.48	0.007	5.72	0.001	9.08	0.004	0.019	71.8	<PQL	0.186	0.015
C1-18	0.003	**0.073**	<PQL	0.003	91	<PQL	<PQL	<PQL	0.007	0.012	3.57	0.015	6.58	0.002	10.0	<PQL	0.026	94.2	<PQL	0.203	0.009
C1-19	0.005	**0.122**	<PQL	0.004	194	<PQL	<PQL	<PQL	0.008	**0.373**	5.25	0.026	10.7	0.002	13.9	0.005	0.021	170	<PQL	0.309	0.013
C1-20	0.004	**0.076**	<PQL	0.004	90	<PQL	<PQL	<PQL	0.007	0.032	4.54	0.007	10.1	0.005	12.2	0.006	0.019	110	<PQL	0.328	0.016
C1-20 FD	0.002	**0.065**	<PQL	0.004	78	<PQL	<PQL	<PQL	0.007	0.026	4.03	0.013	9.13	0.004	11.3	0.004	0.018	91.6	<PQL	0.326	0.009
C1-21	0.002	**0.063**	<PQL	<PQL	69	<PQL	<PQL	<PQL	0.008	0.023	3.68	0.014	5.98	0.011	7.62	0.007	0.019	67.3	<PQL	0.355	0.015
C1-22	<PQL	**0.065**	<PQL	<PQL	78	<PQL	0.002	<PQL	0.002	<PQL	3.60	0.016	6.31	0.010	8.01	0.006	0.022	75.7	<PQL	0.530	0.015
CAT1-3	0.004	**0.222**	<PQL	0.003	211	<PQL	<PQL	<PQL	0.002	0.011	4.09	0.023	10.8	0.004	16.4	<PQL	0.026	177	<PQL	0.650	<PQL
CAT1-6	0.004	**0.108**	<PQL	0.003	166	<PQL	<PQL	<PQL	0.002	0.003	3.99	0.021	13.7	0.006	15.5	0.003	0.025	149	<PQL	0.547	<PQL
CAT2-3	0.004	**0.100**	<PQL	0.004	168	<PQL	<PQL	<PQL	0.002	<PQL	4.41	0.018	7.37	<PQL	15.8	<PQL	0.024	141	<PQL	0.340	<PQL
CAT2-6	0.004	**0.091**	<PQL	0.004	144	<PQL	0.002	<PQL	0.002	<PQL	4.13	0.019	9.64	0.003	14.0	0.003	0.029	127	<PQL	0.351	<PQL
CAT3-3	0.004	**0.096**	<PQL	0.005	153	<PQL	<PQL	<PQL	0.002	0.020	5.14	0.018	7.54	<PQL	14.5	<PQL	0.021	131	<PQL	0.316	<PQL
CAT3-6	0.004	**0.123**	<PQL	0.005	191	<PQL	<PQL	<PQL	0.005	0.028	4.94	0.024	10.2	0.002	15.5	<PQL	0.023	166	<PQL	0.401	<PQL

Table A-8: Elemental Concentrations in Southeast Commerce Oxidation Pond Solids FLT Leachate in mg L^{-1}, with Bolded Values Exceeding the OWRB WQGs

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	S	Se	Si	Zn
OWRB WQGs	0.05	0.05	0.04	1		0.02		0.05	1	0.3				0.05		0.14	0.1		0.01		5
PQL	0.003	0.004	0.020	0.002	0.066	0.001	0.002	0.001	0.001	0.001	0.029	0.001	0.001	0.001	0.012	0.002	0.017	0.053	0.022	0.003	0.003
Ox 1	0.007	**0.139**	<PQL	<PQL	245	<PQL	0.002	<PQL	0.007	0.009	6.33	0.012	16.1	<PQL	54.6	<PQL	<PQL	231	<PQL	0.578	0.034
Ox 2	0.006	**0.113**	<PQL	0.002	169	0.001	<PQL	<PQL	0.009	0.013	3.40	0.008	7.06	0.004	34.6	<PQL	<PQL	153	<PQL	0.476	0.036
Ox 3	0.005	**0.106**	<PQL	0.002	204	0.001	<PQL	<PQL	0.007	0.007	5.18	0.015	15.2	0.008	22.3	<PQL	<PQL	179	<PQL	0.585	0.029
Ox 4	0.005	**0.104**	<PQL	<PQL	177	0.001	0.002	<PQL	0.010	0.013	6.55	0.025	23.7	0.006	28.4	0.003	<PQL	173	<PQL	0.505	0.028
Ox 5	0.006	**0.111**	<PQL	<PQL	218	<PQL	0.002	<PQL	0.008	0.003	6.54	0.014	18.6	0.006	36.2	0.003	0.036	200	<PQL	0.624	0.027
Ox 5 FD	0.006	**0.104**	<PQL	<PQL	209	<PQL	0.002	<PQL	0.007	0.006	7.49	0.024	23.9	0.010	40.4	0.003	<PQL	202	<PQL	0.605	0.025
Ox 6	0.007	**0.135**	<PQL	<PQL	286	0.001	0.002	<PQL	0.008	0.005	10.1	0.028	35.9	0.008	51.4	0.003	<PQL	280	<PQL	0.703	0.026
Ox 7	0.005	**0.089**	<PQL	<PQL	146	<PQL	0.002	<PQL	0.006	0.006	4.98	0.011	12.7	<PQL	32.3	<PQL	<PQL	226	<PQL	0.374	0.018
Ox 8	0.006	**0.107**	<PQL	<PQL	191	<PQL	<PQL	<PQL	0.008	0.006	4.32	0.009	4.15	<PQL	68.4	<PQL	<PQL	190	<PQL	0.618	0.019
Ox 9	0.006	**0.121**	<PQL	0.003	244	0.001	0.002	<PQL	0.006	0.005	5.70	0.023	26.0	0.004	41.9	<PQL	<PQL	232	<PQL	0.623	0.017
Ox 9 FD	0.004	**0.096**	<PQL	0.002	161	<PQL	<PQL	<PQL	0.010	0.010	2.34	0.011	12.3	0.005	19.4	<PQL	<PQL	228	<PQL	0.510	0.019
Ox 10	0.005	**0.101**	<PQL	<PQL	181	<PQL	0.002	<PQL	0.005	0.008	5.24	0.012	13.1	0.004	32.3	<PQL	<PQL	168	<PQL	0.467	0.016
Ox 11	0.005	**0.071**	<PQL	0.003	95.2	0.001	0.004	<PQL	0.006	0.010	2.73	0.012	19.3	**0.620**	29.3	0.006	<PQL	169	<PQL	0.920	0.079
Ox 12	0.004	**0.062**	<PQL	0.003	82.6	0.001	0.006	<PQL	0.005	0.008	1.70	0.010	15.3	**0.942**	32.2	0.008	<PQL	148	<PQL	0.789	0.311
Ox 13	0.005	**0.075**	<PQL	0.002	111	<PQL	0.002	<PQL	0.006	0.003	2.37	0.013	9.99	**0.065**	28.9	0.005	<PQL	168	<PQL	1.17	0.046
Ox 14	0.003	**0.064**	<PQL	0.002	83.4	<PQL	<PQL	<PQL	0.005	0.009	1.91	0.007	3.59	0.028	24.0	<PQL	<PQL	104	<PQL	0.708	0.024
Ox 14 FD	0.004	**0.099**	<PQL	0.004	94.3	<PQL	0.002	<PQL	0.009	0.084	2.38	0.015	10.2	**0.286**	47.0	0.003	<PQL	173	<PQL	1.06	0.074
Ox 15	0.005	**0.081**	<PQL	<PQL	121	<PQL	<PQL	<PQL	0.009	0.033	2.97	0.009	7.47	0.025	43.4	<PQL	<PQL	202	<PQL	0.451	0.024
Ox 16	0.007	**0.120**	<PQL	0.007	208	<PQL	0.009	<PQL	0.008	0.014	4.42	0.023	29.7	**0.586**	31.1	0.028	<PQL	210	<PQL	1.33	0.568
Ox 17	0.006	**0.088**	<PQL	0.003	122	<PQL	0.003	<PQL	0.006	0.047	3.26	0.013	19.0	**0.194**	51.9	0.011	<PQL	154	<PQL	1.07	0.033
Ox 18	0.005	**0.119**	<PQL	0.006	142	<PQL	0.007	<PQL	0.009	0.020	3.52	0.017	25.4	**0.841**	62.6	0.017	<PQL	180	<PQL	1.31	0.186
Ox 19	0.005	**0.076**	<PQL	0.004	96.0	<PQL	0.010	<PQL	0.011	0.037	2.72	0.016	25.4	**1.62**	66.8	0.022	<PQL	154	<PQL	1.11	0.478
Ox 20	0.003	**0.091**	<PQL	0.003	91.4	0.001	0.004	<PQL	0.012	0.022	3.00	0.008	18.3	**0.453**	35.6	0.013	<PQL	174	<PQL	1.01	0.049
Ox 21	0.005	**0.108**	<PQL	0.005	195	0.001	0.030	<PQL	0.006	0.018	3.53	0.021	26.7	**1.99**	58.5	0.061	<PQL	232	<PQL	1.14	0.482
Ox 22	0.006	**0.123**	<PQL	0.006	201	0.001	0.015	<PQL	0.008	0.034	3.80	0.027	36.0	**2.13**	84.1	0.050	<PQL	261	<PQL	1.41	0.437
Ox 23	0.004	**0.092**	<PQL	0.003	131	<PQL	0.005	<PQL	0.008	0.017	3.48	0.011	20.4	**0.423**	37.6	0.014	<PQL	149	<PQL	0.832	0.153
Ox 24	0.005	**0.114**	<PQL	0.005	161	0.001	0.003	<PQL	0.011	0.013	3.97	0.016	18.4	**0.106**	46.3	0.013	<PQL	178	<PQL	1.12	0.079
Ox 25	0.003	**0.076**	<PQL	0.003	99.8	<PQL	0.004	<PQL	0.009	0.011	2.94	0.008	14.7	**0.166**	22.9	0.018	<PQL	164	<PQL	0.911	0.059

Appendix B: Data from VFBR Solids Characterization

Table B-1: Elemental Concentrations in the Solids of the Mayer Ranch VFBR Solids in mg kg^{-1}, with Bolded Values Exceeding Soil Benchmarks, Italicized Values Exceeding Sediment Benchmarks, and Highlighted Values Exceeding TSMD-Specific Benchmarks

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	S	Se	Si	Zn
Soil Guidelines	50	600	60	3000		20	1000	0.4	50	200		10		100		90	500		70		20
Sediment Guidelines			9.79			0.99		43.4	31.6							22.7	35.8				121
TSMD Guidelines			33			4.98		111	149							48.6	128				459
PQL	0.567	1.36	3.96	0.312	12.2	0.154	0.199	0.220	0.231	0.197	5.70	0.130	0.214	0.168	2.44	0.419	1.57	10.6	4.42	1.74	0.652
C3N-1	<PQL	**9213**	*19.4*	28.6	9643	*9.24*	466	**14.2**	***55.8***	**68563**	1410	**22.7**	2270	**1081**	472	***4575***	18.9	43018	<PQL	57.9	***65003***
C3N-2	0.415	**8688**	*33.5*	25.5	19678	*16.6*	100	**12.5**	***60.8***	**126528**	1301	**21.2**	2320	**1833**	561	***1549***	19.5	33949	<PQL	61.3	***75987***
C3N-3	<PQL	**9973**	*20.0*	28.6	19729	*8.66*	260	**17.0**	***72.6***	**62887**	1582	**23.2**	2293	**1892**	488	***2310***	15.0	42975	<PQL	33.1	***82427***
C3N-4	0.444	**7231**	*18.3*	28.7	22632	*8.99*	587	**12.7**	***59.6***	**67352**	1267	**18.2**	2245	**1966**	432	***4573***	13.3	19445	<PQL	21.0	***43628***
C3N-5	0.506	**7805**	*28.2*	29.8	24937	*14.8*	363	**10.7**	*49.3*	**115734**	1040	**24.4**	1921	**1197**	396	***3331***	18.0	29389	<PQL	41.6	***55512***
C3N-6	<PQL	**7611**	*9.91*	34.1	41802	*4.39*	150	**17.0**	***108***	**29460**	1695	**18.1**	2422	**1782**	475	***1854***	9.40	15588	<PQL	33.1	***49084***
C3N-7	<PQL	**8450**	9.09	36.6	49008	*3.81*	163	**18.2**	***72.9***	**26350**	1819	**21.4**	2238	**366**	435	***2491***	11.8	7103	<PQL	49.8	***40819***
C3N-8	<PQL	**7696**	*22.8*	39.6	19937	*14.8*	125	**14.3**	***90.7***	**102735**	1402	**20.1**	2401	**4470**	581	***1340***	19.6	29216	<PQL	41.5	***46292***
C3N-9	<PQL	**8394**	*15.0*	44.4	36464	*4.79*	316	**16.5**	***90.8***	**33656**	1539	**22.8**	2432	**764**	468	***3958***	14.7	13679	<PQL	50.7	***42820***
C3N-10	0.322	**7469**	*13.3*	34.3	27604	*5.73*	335	**13.9**	***72.9***	**40610**	1283	**19.8**	1995	**787**	354	***4071***	12.1	15466	<PQL	47.7	***37674***
C3N-11	<PQL	**8185**	*12.5*	23.6	11728	*5.07*	410	**15.3**	***82.4***	**37109**	1445	**19.5**	2372	**783**	407	***5873***	12.1	34949	<PQL	24.8	***55245***
C3N-12	<PQL	**7250**	*11.2*	52.9	54585	*5.02*	71.6	**19.6**	***81.4***	**35304**	1607	**19.5**	2111	**787**	423	***1041***	18.4	9649	<PQL	20.0	***26294***
C3N-13	0.272	**7890**	*28.6*	23.4	13316	*10.9*	794	**13.5**	***96.0***	**80604**	1365	**20.6**	2951	**895**	737	***8411***	19.1	61621	<PQL	51.7	***75742***
C3N-14	<PQL	**7112**	*14.2*	31.1	20098	*4.47*	285	**14.5**	***62.5***	**30970**	1280	**19.5**	2221	**919**	473	***2898***	12.7	17073	<PQL	45.6	***57802***
C3N-15	<PQL	**8184**	*15.4*	41.4	14744	*8.13*	324	**13.4**	***65.8***	**58743**	1315	**18.8**	1923	**1022**	337	***3543***	12.9	19541	<PQL	41.9	***37348***
C3S-1	1.01	**5106**	*23.9*	41.1	31005	***23.3***	699	**5.74**	*32.3*	**173908**	888	**18.1**	1868	**6781**	516	***4133***	24.1	36773	<PQL	65.9	***40149***
C3S-2	1.11	**4951**	*22.0*	53.4	33646	***21.9***	474	**6.84**	*33.9*	**149376**	855	**16.9**	1801	**4948**	684	***3047***	24.8	21051	<PQL	33.6	***23867***
C3S-3	0.532	**5769**	*15.3*	39.7	38407	*9.09*	361	**16.7**	***65.0***	**63558**	1147	**18.0**	2166	**1201**	437	***4733***	13.0	12612	<PQL	16.5	***34195***
C3S-4	0.421	**5864**	*18.6*	36.1	17177	*9.62*	683	**10.0**	***61.8***	**71288**	1242	**17.5**	2156	**3580**	470	***6500***	15.2	28555	<PQL	18.7	***47613***
C3S-5	0.373	**6164**	*24.3*	22.1	10139	*12.5*	740	**8.28**	*44.0*	**82245**	1167	**16.6**	1996	**4872**	597	***5496***	18.5	33468	<PQL	51.9	***53799***
C3S-6	1.12	**5226**	8.02	57.3	102651	*4.65*	81.2	**11.4**	***74.9***	**31670**	1356	**19.2**	1935	**764**	376	***1210***	9.27	4463	<PQL	12.1	***7951***
C3S-7	0.474	**5371**	*10.7*	51.8	40663	*7.42*	229	**17.4**	***80.8***	**51073**	1129	**18.4**	2040	**1851**	379	***2656***	13.5	12673	<PQL	46.6	***18300***
C3S-8	0.460	**6371**	*11.6*	34.2	29212	*8.56*	57.0	**14.5**	***95.2***	**59862**	1292	**17.9**	2089	**2370**	465	***1310***	13.5	21341	<PQL	54.0	***33306***
C3S-9	0.554	**6406**	*21.7*	71.6	30086	***21.7***	363	**12.9**	***76.1***	**151188**	1347	**16.1**	2310	**13776**	589	***2197***	20.4	19919	<PQL	50.2	***28016***
C3S-10	0.622	**6719**	*24.4*	60.1	26673	***21.3***	313	**12.0**	***92.2***	**145040**	1241	**18.2**	2430	**12249**	541	***2445***	21.6	22072	<PQL	30.7	***34142***
C3S-11	<PQL	**9614**	*27.0*	12.4	12648	*10.7*	841	**11.4**	*36.3*	**72035**	1456	**23.6**	2196	**748**	569	***6678***	22.2	40306	<PQL	53.4	***92370***
C3S-12	0.491	**9638**	*15.9*	65.4	21148	*11.5*	422	**12.1**	*41.0*	**77645**	1469	**26.2**	2151	**3943**	475	***2648***	20.6	19816	<PQL	33.6	***28459***
C3S-13	0.471	**4816**	*14.2*	31.9	38822	*7.01*	363	**11.9**	***72.4***	**45891**	1145	**15.3**	1929	**756**	436	***3053***	11.5	11574	<PQL	51.2	***44143***
C3S-14	<PQL	**8919**	*22.6*	39.2	12773	*10.9*	360	**16.3**	***155***	**64351**	1664	**21.0**	2632	**1515**	693	***5028***	16.1	44458	<PQL	57.9	***56190***
C3S-15	0.390	**10280**	*19.5*	46.4	17746	*11.4*	600	**13.2**	30.1	**77596**	1428	**30.2**	2292	**3054**	473	***4089***	21.9	24280	<PQL	59.0	***42206***

Table B-2: Elemental Concentrations in the Solids of the Southeast Commerce VFBR Solids in mg kg^{-1}, with Bolded Values Exceeding Soil Benchmarks, Italicized Values Exceeding Sediment Benchmarks, and Highlighted Values Exceeding TSMD-Specific Benchmarks

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	S	Se	Si	Zn
Soil Guidelines	50	600	60	3000		20	1000	0.4	50	200		10		100		90	500		70		20
Sediment Guidelines			9.79			0.99		43.4	31.6							22.7	35.8				121
TSMD Guidelines			33			4.98		111	149							48.6	128				459
PQL	0.568	0.772	3.97	0.313	13.1	0.133	0.220	0.117	0.232	0.197	5.71	0.130	0.215	0.218	2.44	0.308	1.57	10.6	4.43	1.08	0.653
SEC VFBR1	0.136	**6778**	7.62	38.5	4995	***26.9***	80.8	*8.66*	30.6	**22696**	686	**13.9**	909	**729**	205	***810***	*182*	12458	<PQL	57.6	***13883***
SEC VFBR2	1.46	**5411**	*38.3*	50.5	11062	***95.7***	723	*5.19*	*49.3*	**95297**	1062	**11.3**	1454	**18430**	461	***922***	*95.0*	35971	4.17	90.4	***12587***
SEC VFBR3	0.492	**6486**	*13.8*	28.5	6895	***29.5***	352	*6.68*	*41.4*	**52504**	802	**14.5**	1117	**4675**	305	***1987***	*142*	34097	<PQL	86.1	***7587***
SEC VFBR4	0.690	**5582**	*22.3*	31.7	16030	***46.0***	401	*7.09*	***89.8***	**67576**	933	**10.4**	1546	**6331**	477	***2822***	*79.0*	67871	1.81	113	***15269***
SEC VFBR5	3.01	**3102**	*57.3*	96.1	11161	***49.5***	**1042**	*1.52*	4.40	**280648**	784	5.17	938	**44321**	391	***2038***	*37.7*	12711	9.77	157	***20072***
SEC VFBR6	0.152	**5528**	*25.4*	17.2	13414	***53.7***	333	*5.89*	***103***	**57697**	787	**10.4**	1702	**1061**	462	***2141***	*84.5*	63712	<PQL	118	***12752***
SEC VFBR7	0.472	**8711**	*47.1*	21.1	14587	***110***	340	*9.16*	***98.9***	**62665**	1171	**15.0**	2095	**399**	578	***2226***	*105*	72297	<PQL	21.5	***73021***
SEC VFBR8	0.561	**5019**	***64.1***	11.1	11348	***112***	529	*5.42*	***52.6***	**78311**	805	9.66	1563	**775**	538	***4044***	*107*	#####	<PQL	31.5	***81606***
SEC VFBR9	0.533	**4953**	*36.8*	10.2	11655	***30.3***	917	*5.52*	***105***	**64885**	831	9.37	1913	**287**	616	***10466***	*85.9*	#####	<PQL	18.5	***79712***
SEC VFBR10	0.515	**7626**	*54.8*	9.92	10062	***49.4***	**1039**	*7.78*	***68.7***	**63201**	1011	**14.2**	1622	**240**	527	***9557***	*120*	#####	<PQL	76.2	***101063***
SEC VFBR11	1.13	**7331**	*46.8*	56.2	11539	***61.5***	381	*7.04*	18.2	**202210**	990	**15.1**	1554	**9040**	614	***902***	*99.9*	15322	<PQL	54.7	***22087***
SEC VFBR12	1.09	**7162**	*56.7*	89.6	12027	***60.2***	548	*7.94*	16.8	**214228**	1073	**14.0**	1547	**20350**	606	***1273***	*93.7*	18236	<PQL	47.1	***22915***
SEC VFBR13	1.37	**5139**	*50.6*	26.7	11835	***88.7***	207	*5.08*	25.9	**217607**	801	9.70	1511	**3981**	574	***935***	*124*	28447	<PQL	59.6	***36682***
SEC VFBR14	0.700	**6206**	*26.1*	33.7	17719	***36.9***	447	*7.21*	***112***	**90817**	1016	**11.6**	2214	**6269**	675	***3811***	*157*	65410	<PQL	79.3	***56481***
SEC VFBR15	0.619	**7160**	*39.9*	30.4	18322	***72.4***	317	*8.43*	***168***	**68130**	1214	**11.2**	2303	**4446**	669	***1568***	*65.4*	77901	<PQL	23.4	***71180***
SEC VFBR16	0.651	**4613**	*23.1*	14.7	15667	***37.1***	435	*5.35*	***100***	**79887**	831	8.74	1864	**1048**	507	***3499***	*86.0*	80154	<PQL	53.1	***72095***
SEC VFBR17	0.703	**5136**	*29.3*	14.7	18820	***50.3***	504	*6.26*	***178***	**62105**	989	9.40	2550	**979**	881	***4345***	*80.3*	#####	<PQL	62.9	***71742***
SEC VFBR18	0.529	**5398**	*23.0*	15.2	16266	***29.5***	350	*7.15*	***159***	**45780**	957	9.60	2205	**221**	642	***4491***	*103*	78646	<PQL	26.1	***42225***
SEC VFBR19	0.508	**3839**	*29.7*	10.3	12375	***29.4***	560	*4.70*	***108***	**37224**	735	6.89	1931	**355**	706	***6926***	*96.0*	75599	<PQL	19.6	***58518***
SEC VFBR20	0.331	**5529**	*51.4*	14.5	13534	***82.1***	831	*6.66*	***100***	**36072**	890	**10.7**	1887	**354**	675	***2509***	*91.6*	66510	<PQL	65.5	***69517***
SEC VFBR21	<PQL	**7685**	*28.7*	26.8	8952	***34.5***	112	*7.08*	*31.9*	**67384**	854	**15.1**	1288	**1303**	352	***590***	*84.9*	19709	<PQL	59.3	***26847***
SEC VFBR22	1.01	**4831**	***70.7***	71.8	13643	***52.8***	918	*5.80*	*39.4*	**159868**	894	8.88	1545	**16963**	550	***917***	*73.4*	19199	<PQL	50.3	***19919***
SEC VFBR23	0.762	**5468**	*36.7*	16.1	12624	***55.8***	**1064**	*5.28*	***59.6***	**102128**	833	**10.6**	1770	**1941**	652	***4268***	*88.2*	60564	<PQL	48.2	***61196***
SEC VFBR24	0.796	**6642**	*48.4*	21.4	15547	***83.1***	632	*6.40*	***64.5***	**105842**	1194	**12.0**	1956	**4359**	730	***2686***	*78.1*	60369	<PQL	60.0	***65352***
SEC VFBR25	0.756	**5067**	*49.5*	11.9	13595	***59.5***	553	*5.06*	***76.0***	**127698**	760	9.21	1709	**874**	549	***3556***	*90.6*	78465	<PQL	41.2	***63747***
SEC VFBR26	<PQL	**4964**	*16.3*	11.6	13925	***57.8***	675	*5.97*	***118***	**48271**	879	9.26	2070	**358**	723	***2627***	*91.3*	87941	<PQL	69.3	***93717***
SEC VFBR27	0.316	**5126**	*35.5*	13.6	10382	***116***	543	*5.97*	***76.6***	**50320**	850	**10.6**	1542	**543**	537	***2052***	*131*	73403	<PQL	42.4	***71625***
SEC VFBR28	0.412	**4458**	*26.5*	11.6	13816	***70.2***	434	*5.08*	***119***	**51243**	851	8.01	2051	**1001**	789	***3095***	*108*	81408	<PQL	69.9	***81395***
SEC VFBR29	0.410	**3080**	*42.1*	7.48	13012	***102***	802	*5.03*	***87.5***	**37466**	747	5.97	2008	**402**	730	***4165***	*69.7*	88467	<PQL	29.6	***89308***
SEC VFBR30	0.414	**6592**	*22.3*	14.1	12381	***35.2***	257	*7.19*	***91.6***	**37496**	952	**12.5**	1793	**577**	621	***2610***	*94.7*	63500	<PQL	54.4	***75292***

Table B-3: Elemental Concentrations in Mayer Ranch VFBR Solids TCLP Leachate in mg L^{-1}, with Samples Leached with Extraction Fluid 2 Highlighted

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Ni	Pb	S	Se	Si	Zn
RCRA Limits	5		5	100		1		5								5		1		
PQL	0.003	0.004	0.020	0.002	0.066	0.001	0.002	0.001	0.001	0.001	0.029	0.001	0.001	0.001	0.002	0.011	0.053	0.022	0.003	0.003
C3N-1	0.018	0.343	0.022	0.057	1434	0.004	6.72	0.002	0.030	0.276	31.9	0.118	53.9	17.2	55.8	0.184	688	0.031	6.26	118
C3N-2	0.010	0.261	<PQL	0.097	809	0.003	0.355	0.001	0.015	0.103	24.7	0.098	58.2	9.85	8.61	0.176	213	0.035	19.3	39.4
C3N-3	0.012	0.306	<PQL	0.106	949	0.020	1.76	0.001	0.021	0.372	20.9	0.090	51.4	7.38	32.7	0.139	278	0.037	7.53	38.3
C3N-4	0.019	0.344	<PQL	0.128	1664	<PQL	8.87	0.003	0.014	0.147	23.8	0.106	59.8	34.0	64.2	0.261	723	0.033	8.25	120
C3N-5	0.017	0.301	<PQL	0.149	1211	<PQL	7.76	0.002	0.013	0.123	26.1	0.128	59.8	27.1	60.8	0.227	465	0.023	12.0	112
C3N-6	0.014	0.299	<PQL	0.142	1230	<PQL	0.187	<PQL	0.013	0.166	27.3	0.090	55.4	7.76	4.28	0.168	171	0.030	9.92	15.4
C3N-7	0.035	0.773	0.030	0.261	3526	<PQL	2.68	0.001	0.007	0.150	16.3	0.094	52.7	5.73	55.8	0.135	258	0.032	5.46	36.8
C3N-8	0.013	0.290	0.022	0.133	1050	<PQL	0.158	0.001	0.013	0.321	31.7	0.094	64.2	16.2	4.99	0.219	222	0.033	17.3	33.0
C3N-9	0.020	0.393	<PQL	0.118	1723	<PQL	4.81	0.001	0.015	0.119	23.1	0.105	60.9	7.88	75.9	0.132	719	0.022	3.99	120
C3N-10	0.033	1.42	0.033	0.194	3478	<PQL	8.96	0.003	0.009	2.41	17.5	0.119	61.2	24.0	101.7	0.182	435	0.039	5.68	135
C3N-11	0.019	0.369	<PQL	0.131	1662	0.001	6.05	0.001	0.021	0.115	23.4	0.119	59.0	7.44	85.6	0.136	704	0.038	5.03	105
C3N-12	0.031	0.766	0.033	0.253	3158	<PQL	1.16	0.002	0.007	0.148	19.9	0.089	57.0	14.4	18.6	0.208	155	0.033	10.5	46.4
C3N-13	0.020	0.348	<PQL	0.116	1619	<PQL	5.60	<PQL	0.013	0.136	23.8	0.112	58.0	5.81	70.3	0.124	647	0.026	5.36	58.4
C3N-14	0.033	1.25	0.030	0.221	3218	<PQL	4.83	0.004	0.012	2.11	18.9	0.116	54.1	30.1	69.7	0.261	355	0.034	9.66	97.1
C3N-15	0.030	1.31	<PQL	0.281	3082	<PQL	7.13	0.004	0.009	0.649	21.0	0.137	61.2	25.2	74.1	0.226	391	0.031	16.9	116
C3S-1	0.016	0.343	<PQL	0.085	1420	<PQL	5.16	0.002	0.013	0.227	22.5	0.096	46.3	30.4	36.5	0.261	636	0.042	10.6	48.3
C3S-2	0.035	3.59	0.033	0.354	3853	0.008	12.4	0.024	0.010	66.1	18.3	0.092	71.7	128	68.5	0.771	399	0.089	23.2	152
C3S-3	0.041	0.785	0.038	0.264	3920	<PQL	4.19	0.002	0.010	0.537	15.6	0.071	39.4	16.8	60.5	0.160	347	0.042	6.40	48.7
C3S-4	0.017	0.332	<PQL	0.110	1454	0.002	6.37	0.002	0.021	0.215	32.3	0.107	51.6	23.5	67.5	0.210	670	0.036	6.65	80.7
C3S-5	0.017	0.352	<PQL	0.123	1403	0.001	9.51	0.004	0.022	0.316	33.9	0.127	64.8	45.0	85.3	0.371	714	0.046	7.63	67.0
C3S-6	0.040	0.793	0.027	0.270	3669	<PQL	0.740	0.003	0.007	0.197	20.3	0.090	52.8	9.76	11.3	0.179	253	0.040	6.98	25.6
C3S-7	0.048	1.11	0.033	0.306	4216	<PQL	3.94	0.004	0.005	3.30	21.6	0.087	51.5	23.4	39.1	0.240	330	0.052	8.99	55.8
C3S-8	0.012	0.284	<PQL	0.130	995	<PQL	0.130	0.001	0.011	0.510	26.1	0.066	46.6	5.93	4.75	0.136	143	0.030	9.94	16.4
C3S-9	0.022	0.939	0.026	0.147	2142	<PQL	0.181	0.003	0.009	0.123	16.5	0.074	62.4	29.8	13.7	0.303	137	0.043	35.8	165
C3S-10	0.021	2.15	0.028	0.192	2290	<PQL	0.974	0.006	0.007	0.328	18.8	0.093	66.9	58.6	34.1	0.487	209	0.060	32.5	163
C3S-11	0.020	0.308	0.023	0.138	1171	<PQL	17.7	<PQL	0.017	0.071	30.2	0.134	58.2	7.29	133	0.083	592	0.027	7.58	117
C3S-12	0.017	0.358	<PQL	0.107	1534	0.005	4.78	0.003	0.016	0.046	36.1	0.105	47.7	22.5	41.0	0.213	637	0.040	7.29	59.1
C3S-13	0.037	1.03	0.036	0.225	3752	<PQL	7.81	0.003	0.018	1.15	28.5	0.111	63.2	17.9	69.9	0.201	343	0.044	14.1	58.5
C3S-14	0.020	0.367	<PQL	0.134	1435	<PQL	7.42	0.001	0.017	0.077	34.8	0.119	63.3	11.4	112	0.160	687	<PQL	5.74	100
C3S-15	0.018	0.341	0.022	0.103	1419	<PQL	9.61	0.003	0.018	0.030	37.1	0.114	47.0	33.8	65.4	0.271	577	0.042	7.74	48.0

Table B-4: Elemental Concentrations in Southeast Commerce VFBR Solids TCLP Leachate in mg L^{-1}

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Ni	Pb	S	Se	Si	Zn
RCRA Limits	5		5	100		1		5								5		1		
PQL	0.003	0.018	0.020	0.002	0.066	0.001	0.002	0.001	0.001	0.001	0.029	0.001	0.001	0.001	0.002	0.017	0.053	0.022	0.005	0.018
VFBR 1	0.005	0.805	<PQL	0.168	155	0.002	1.51	0.002	0.018	0.258	17.5	0.063	33.0	16.2	20.8	0.029	167	0.028	5.77	71.1
VFBR 2	0.006	0.297	<PQL	0.146	317	0.002	0.428	0.004	0.017	0.111	29.2	0.059	52.7	35.3	11.6	<PQL	242	0.042	30.2	83.4
VFBR 3	0.007	0.556	<PQL	0.157	306	<PQL	4.92	0.006	0.016	0.414	23.2	0.069	49.3	54.9	43.0	<PQL	367	0.038	18.3	130
VFBR 4	0.008	0.877	<PQL	0.138	272	<PQL	4.39	0.007	0.017	0.574	20.9	0.062	48.2	73.2	38.2	0.021	374	0.047	8.10	122
VFBR 5	0.007	1.16	<PQL	0.142	276	0.001	3.10	0.002	0.017	1.36	19.2	0.083	46.7	12.2	34.5	<PQL	431	<PQL	6.64	239
VFBR 6	0.007	2.05	<PQL	0.123	350	0.003	7.71	0.004	0.018	2.27	17.5	0.082	55.7	37.0	46.0	0.024	782	0.025	5.23	588
VFBR 7	0.007	1.07	<PQL	0.129	301	<PQL	5.50	0.001	0.016	1.39	21.3	0.074	55.3	7.78	34.3	<PQL	423	<PQL	9.17	178
VFBR 8	0.008	0.987	<PQL	0.121	257	0.003	6.18	0.002	0.016	6.93	14.8	0.057	41.5	6.32	55.1	0.022	531	<PQL	2.16	312
VFBR 9	0.012	1.84	<PQL	0.101	251	0.001	12.9	0.001	0.017	9.51	14.7	0.064	45.0	3.94	131	0.028	812	<PQL	2.52	644
VFBR 10	0.013	1.09	<PQL	0.097	203	<PQL	15.1	<PQL	0.021	4.09	18.3	0.056	42.1	2.28	130	<PQL	499	<PQL	3.41	289
VFBR 11	0.006	0.298	<PQL	0.124	250	0.002	0.728	0.002	0.016	0.222	21.0	0.066	49.2	13.4	15.3	<PQL	185	0.027	27.4	64.4
VFBR 12	0.005	0.330	<PQL	0.148	224	0.003	0.314	0.002	0.015	0.111	19.8	0.061	45.0	21.2	13.7	<PQL	189	0.029	19.9	57.5
VFBR 13	0.009	0.535	<PQL	0.153	287	<PQL	5.44	0.003	0.016	0.754	21.6	0.067	49.5	29.3	50.4	<PQL	394	0.031	11.1	127
VFBR 14	0.009	1.48	<PQL	0.124	366	<PQL	7.57	0.005	0.015	0.970	21.4	0.079	61.6	47.0	69.8	<PQL	576	0.042	7.99	246
VFBR 15	0.007	1.34	<PQL	0.156	441	0.002	4.59	0.005	0.020	1.03	25.6	0.085	68.0	45.3	21.9	0.029	653	0.034	9.69	302
VFBR 16	0.012	0.988	<PQL	0.101	427	0.002	9.68	0.002	0.019	1.99	20.8	0.074	56.6	21.8	70.0	0.030	885	<PQL	11.2	694
VFBR 17	0.009	1.93	<PQL	0.125	254	<PQL	9.17	0.002	0.016	4.30	16.8	0.068	53.8	14.1	67.8	0.019	566	<PQL	3.17	357
VFBR 18	0.011	2.76	<PQL	0.119	302	0.001	8.14	0.001	0.015	4.88	16.1	0.071	58.6	4.86	80.9	0.025	645	<PQL	2.06	390
VFBR 19	0.008	1.72	<PQL	0.144	204	0.002	5.50	0.002	0.015	2.29	17.3	0.076	31.5	5.00	58.1	0.045	358	0.026	3.56	254
VFBR 20	0.009	1.30	<PQL	0.125	219	0.001	7.39	0.001	0.019	4.53	18.9	0.071	43.9	6.20	70.9	0.018	549	<PQL	4.49	385
VFBR 21	0.005	0.463	<PQL	0.222	197	0.001	0.852	0.002	0.015	0.103	25.2	0.100	42.8	9.78	8.44	<PQL	140	0.029	17.8	44.0
VFBR 22	0.007	0.288	<PQL	0.145	333	0.004	0.340	0.002	0.019	0.080	22.8	0.063	60.0	19.70	8.90	<PQL	273	0.033	29.9	75.8
VFBR 23	0.009	0.663	<PQL	0.176	236	0.002	8.94	0.006	0.022	0.910	20.7	0.071	46.4	56.7	76.0	<PQL	483	0.037	7.96	242
VFBR 24	0.008	0.385	<PQL	0.151	239	<PQL	6.22	0.002	0.016	0.504	22.0	0.072	50.2	14.0	43.5	<PQL	299	0.029	15.0	88.9
VFBR 25	0.011	3.50	<PQL	0.092	357	0.023	13.6	0.004	0.022	18.6	4.82	0.077	57.0	17.4	115	0.054	1346	<PQL	3.04	1454
VFBR 26	0.008	0.956	<PQL	0.122	241	<PQL	9.69	0.001	0.016	2.99	17.1	0.067	47.8	6.06	57.8	0.025	542	0.026	6.83	358
VFBR 27	0.007	0.827	<PQL	0.127	213	0.001	6.97	0.002	0.018	1.97	19.2	0.069	44.8	19.2	42.8	<PQL	504	0.028	6.30	378
VFBR 28	0.009	1.51	<PQL	0.112	243	0.002	9.71	0.003	0.016	5.93	14.7	0.064	48.3	18.8	72.4	0.030	717	<PQL	3.68	587
VFBR 29	0.008	1.24	<PQL	0.104	183	0.002	10.6	0.002	0.017	5.93	13.7	0.061	43.5	11.0	76.7	0.020	610	<PQL	3.54	547
VFBR 30	0.010	1.02	<PQL	0.126	263	<PQL	7.55	0.001	0.018	3.53	12.7	0.050	36.0	4.37	70.8	<PQL	496	<PQL	2.61	428

Table B-5: Elemental Concentrations in Mayer Ranch VFBR Solids SPLP Leachate in mg L^{-1}, with Bolded Values Exceeding the OWRB WQGs

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	Se	Si	Zn
OWRB WQGs	0.05	0.05	0.04	1		0.02		0.05	1	0.3				0.05		0.14	0.1	0.01		5
PQL	0.003	0.004	0.020	0.002	0.066	0.001	0.001	0.001	0.001	0.001	0.029	0.001	0.001	0.001	0.012	0.002	0.008	0.022	0.005	0.003
C3N-1	0.010	<PQL	<PQL	0.095	681	0.002	3.21	<PQL	0.010	0.005	14.2	0.082	59.7	**8.73**	21.8	**21.2**	<PQL	<PQL	3.37	**25.5**
C3N-2	0.007	<PQL	<PQL	0.094	246	<PQL	0.021	<PQL	0.007	0.007	7.97	0.049	40.0	**0.516**	18.4	**0.525**	<PQL	<PQL	4.79	0.548
C3N-3	0.008	<PQL	<PQL	0.089	374	<PQL	0.610	<PQL	0.007	0.005	8.72	0.057	50.3	**1.80**	18.8	**9.57**	<PQL	<PQL	3.98	**9.82**
C3N-4	0.010	<PQL	<PQL	0.086	686	0.001	3.41	<PQL	0.008	<PQL	10.7	0.069	55.3	**10.6**	19.1	**20.3**	<PQL	<PQL	3.70	**20.9**
C3N-5	0.010	<PQL	<PQL	0.084	550	0.003	4.34	<PQL	0.011	0.008	11.3	0.077	58.1	**8.27**	20.7	**34.2**	<PQL	<PQL	5.10	**30.4**
C3N-6	0.006	<PQL	<PQL	0.087	181	<PQL	0.014	<PQL	0.006	0.006	7.20	0.042	30.1	**0.192**	14.3	**0.253**	<PQL	<PQL	3.51	0.312
C3N-7	0.007	<PQL	<PQL	0.090	370	<PQL	0.300	<PQL	0.007	0.003	7.51	0.055	37.3	**0.501**	15.7	**4.38**	<PQL	<PQL	2.33	1.61
C3N-8	0.006	<PQL	<PQL	0.084	226	<PQL	0.047	<PQL	0.006	0.006	11.2	0.051	42.5	**0.905**	23.1	**0.487**	<PQL	<PQL	4.66	0.932
C3N-9	0.010	<PQL	<PQL	0.082	524	<PQL	1.87	<PQL	0.007	<PQL	10.2	0.074	49.1	**2.06**	16.1	**22.6**	<PQL	<PQL	2.24	**18.1**
C3N-10	0.011	<PQL	<PQL	0.077	632	<PQL	2.63	<PQL	0.008	0.005	8.99	0.067	46.2	**2.96**	14.2	**23.4**	<PQL	<PQL	1.97	**20.9**
C3N-11	0.010	<PQL	<PQL	0.048	616	0.002	2.43	<PQL	0.007	0.003	10.3	0.072	52.7	**1.92**	18.0	**30.5**	<PQL	<PQL	2.60	**10.0**
C3N-12	0.005	<PQL	<PQL	0.094	150	<PQL	0.034	<PQL	0.006	0.010	6.49	0.033	24.2	**0.273**	11.7	**0.551**	<PQL	<PQL	2.62	0.527
C3N-13	0.010	<PQL	<PQL	0.088	709	0.002	2.59	<PQL	0.007	0.004	11.1	0.075	56.7	**1.51**	20.3	**30.2**	<PQL	<PQL	3.16	**11.7**
C3N-14	0.007	0.027	<PQL	0.081	398	<PQL	0.459	<PQL	0.007	0.003	10.1	0.065	44.9	**1.52**	18.2	**7.02**	<PQL	<PQL	3.17	2.48
C3N-15	0.010	<PQL	<PQL	0.082	529	<PQL	1.27	<PQL	0.008	0.006	11.2	0.081	50.3	**1.80**	18.4	**10.9**	<PQL	<PQL	3.75	**6.30**
C3S-1	0.011	<PQL	<PQL	0.065	658	<PQL	0.872	<PQL	0.008	0.006	10.7	0.059	46.5	**5.34**	19.0	**5.41**	<PQL	<PQL	3.74	2.98
C3S-2	0.008	<PQL	<PQL	0.076	556	<PQL	0.235	<PQL	0.010	0.010	9.18	0.040	43.2	**1.57**	25.8	**2.95**	<PQL	<PQL	3.05	0.951
C3S-3	0.009	<PQL	<PQL	0.068	465	<PQL	0.879	<PQL	0.008	0.003	8.81	0.047	33.9	**1.99**	12.2	**10.0**	<PQL	<PQL	2.51	**5.05**
C3S-4	0.012	<PQL	<PQL	0.076	639	0.003	3.43	<PQL	0.008	<PQL	14.6	0.073	50.9	**9.76**	18.9	**36.0**	<PQL	<PQL	3.40	**25.0**
C3S-5	0.010	<PQL	<PQL	0.065	619	0.003	4.14	0.002	0.009	<PQL	14.6	0.084	63.6	**18.9**	24.6	**37.2**	<PQL	<PQL	3.57	**12.0**
C3S-6	0.007	<PQL	<PQL	0.115	177	<PQL	0.067	<PQL	0.007	0.006	6.06	0.032	23.2	**0.358**	8.21	**0.880**	<PQL	<PQL	1.80	0.409
C3S-7	0.006	<PQL	<PQL	0.121	194	<PQL	0.093	<PQL	0.007	0.005	7.49	0.031	23.7	**0.160**	8.55	**1.25**	<PQL	<PQL	1.97	0.241
C3S-8	0.005	<PQL	<PQL	0.080	160	<PQL	0.014	<PQL	0.011	0.012	6.68	0.032	27.2	**0.347**	12.5	**0.327**	<PQL	<PQL	3.43	0.634
C3S-9	0.005	<PQL	<PQL	0.069	176	0.002	0.003	<PQL	0.008	0.007	6.78	0.031	30.6	0.050	18.0	0.114	<PQL	<PQL	3.16	0.328
C3S-10	0.006	<PQL	<PQL	0.072	235	<PQL	0.012	<PQL	0.007	0.004	7.55	0.043	39.4	**0.465**	18.7	**0.434**	<PQL	<PQL	3.87	0.438
C3S-11	0.012	<PQL	<PQL	0.083	607	0.010	10.5	<PQL	0.012	0.013	14.5	0.096	65.1	**3.50**	27.2	**74.5**	<PQL	<PQL	4.08	**34.4**
C3S-12	0.011	<PQL	<PQL	0.073	645	<PQL	1.55	<PQL	0.008	0.007	18.8	0.069	47.3	**7.71**	19.9	**11.4**	<PQL	<PQL	3.85	**6.25**
C3S-13	0.008	<PQL	<PQL	0.074	425	<PQL	0.530	<PQL	0.009	0.005	12.2	0.062	47.8	**0.826**	19.7	**5.25**	<PQL	<PQL	4.42	1.31
C3S-14	0.012	<PQL	<PQL	0.077	515	0.006	3.16	<PQL	0.008	0.011	16.5	0.080	58.8	**3.90**	24.8	**46.6**	<PQL	<PQL	3.20	**13.2**
C3S-15	0.012	0.024	<PQL	0.075	682	0.004	6.21	0.002	0.009	0.006	17.1	0.087	57.2	**18.9**	20.7	**42.3**	<PQL	<PQL	4.08	**17.2**

Table B-6: Elemental Concentrations in Southeast Commerce VFBR Solids SPLP Leachate in mg L^{-1}, with Bolded Values Exceeding the OWRB WQGs

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	Se	Si	Zn
OWRB WQGs	0.05	0.05	0.04	1		0.02		0.05	1	0.3				0.05		0.14	0.1	0.01		5
PQL	0.003	0.004	0.020	0.002	0.066	0.001	0.001	0.001	0.001	0.001	0.029	0.001	0.001	0.001	0.012	0.002	0.008	0.022	0.005	0.003
SEC VFBR1	0.004	**0.237**	<PQL	0.095	196	0.001	1.30	<PQL	0.007	0.044	7.59	0.042	27.5	**18.8**	10.3	**20.8**	<PQL	<PQL	6.12	**58.1**
SEC VFBR2	0.003	**0.142**	<PQL	0.079	234	0.001	0.354	<PQL	0.006	0.017	11.2	0.038	33.9	**24.4**	16.9	**6.40**	<PQL	<PQL	11.8	**50.7**
SEC VFBR3	0.006	**0.820**	<PQL	0.115	226	0.001	7.23	0.002	0.004	0.171	8.97	0.052	37.4	**68.2**	16.7	**53.6**	0.011	**0.025**	9.52	**283**
SEC VFBR4	0.007	**2.09**	<PQL	0.116	349	0.001	6.95	0.002	0.004	**7.32**	10.2	0.051	42.5	**79.3**	18.6	**60.0**	<PQL	**0.037**	5.58	**375**
SEC VFBR5	0.005	**0.487**	<PQL	0.069	342	0.005	1.52	<PQL	0.007	0.014	8.28	0.061	38.4	**35.4**	15.5	**25.7**	<PQL	**0.031**	17.0	**401**
SEC VFBR6	0.006	**2.19**	<PQL	0.108	351	0.002	7.01	0.002	0.005	**12.3**	10.1	0.052	38.8	**32.3**	18.1	**41.6**	<PQL	<PQL	9.04	**355**
SEC VFBR7	0.005	**2.67**	<PQL	0.099	284	0.005	7.39	0.001	0.005	**32.0**	8.03	0.054	41.1	**7.61**	17.1	**47.9**	0.013	<PQL	7.20	**531**
SEC VFBR8	0.008	**4.68**	0.024	0.088	279	**0.055**	8.43	0.005	0.002	**257**	3.03	0.043	33.5	**7.14**	13.2	**78.7**	0.028	<PQL	2.27	**822**
SEC VFBR9	0.013	**7.19**	0.021	0.065	305	**0.035**	16.0	0.008	0.002	**287**	2.41	0.046	33.8	**3.85**	12.5	**166**	0.032	<PQL	2.66	**1043**
SEC VFBR10	0.014	**4.63**	<PQL	0.075	286	0.016	20.4	0.008	0.002	**182**	4.45	0.043	34.2	**3.42**	13.7	**187**	0.029	<PQL	3.41	**761**
SEC VFBR11	0.006	**0.154**	<PQL	0.075	281	0.000	0.422	<PQL	0.004	0.219	8.91	0.043	39.2	**8.51**	18.3	**10.5**	<PQL	<PQL	11.9	**33.3**
SEC VFBR12	0.004	**0.165**	<PQL	0.065	179	0.001	0.170	<PQL	0.006	**1.84**	7.21	0.037	27.0	**8.43**	13.3	**6.04**	<PQL	<PQL	8.39	**29.5**
SEC VFBR13	0.006	**1.47**	<PQL	0.106	214	0.001	5.32	0.002	0.006	**8.73**	8.01	0.043	33.4	**38.2**	15.7	**49.7**	0.015	<PQL	4.79	**297**
SEC VFBR14	0.007	**1.83**	<PQL	0.113	345	0.001	7.32	0.003	0.004	**1.81**	9.46	0.056	45.0	**68.7**	19.3	**67.7**	0.018	**0.032**	8.90	**378**
SEC VFBR15	0.005	**1.31**	<PQL	0.096	380	0.002	4.28	<PQL	0.004	0.225	12.1	0.057	49.8	**79.0**	20.7	**27.1**	0.013	**0.033**	10.1	**391**
SEC VFBR16	0.011	**3.05**	<PQL	0.079	416	0.006	11.1	0.003	0.012	**26.5**	7.83	0.056	51.6	**32.9**	19.2	**97.0**	0.073	<PQL	13.4	**898**
SEC VFBR17	0.014	**5.50**	0.025	0.111	392	0.013	12.0	0.002	0.012	**112**	7.64	0.054	50.6	**16.1**	19.6	**118**	0.069	<PQL	3.20	**729**
SEC VFBR18	0.017	**11.6**	0.032	0.098	536	**0.057**	11.6	0.003	0.012	**246**	2.97	0.060	53.0	**4.22**	16.5	**130**	**0.184**	<PQL	1.60	**1015**
SEC VFBR19	0.013	**5.88**	<PQL	0.121	221	**0.022**	10.3	0.003	0.010	**181**	4.13	0.042	33.7	**6.09**	11.9	**118**	**0.437**	<PQL	2.41	**571**
SEC VFBR20	0.012	**5.35**	0.035	0.102	304	0.019	10.4	0.002	0.008	**136**	3.78	0.048	39.3	**6.22**	13.2	**123**	**0.325**	<PQL	2.31	**923**
SEC VFBR21	0.006	**0.155**	0.024	0.105	182	<PQL	1.46	0.001	0.008	**0.654**	8.59	0.053	32.6	**12.9**	12.2	**12.6**	**0.245**	<PQL	9.46	**87.8**
SEC VFBR22	0.006	**0.060**	<PQL	0.067	292	<PQL	0.115	0.001	0.015	**0.811**	8.27	0.039	48.1	**7.21**	21.1	**3.40**	<PQL	<PQL	11.7	**30.4**
SEC VFBR23	0.011	**1.90**	<PQL	0.108	232	0.001	11.3	0.005	0.011	**14.9**	6.64	0.046	38.2	**65.0**	16.6	**113**	<PQL	<PQL	3.43	**498**
SEC VFBR24	0.010	**0.860**	0.034	0.089	324	<PQL	9.40	0.002	0.009	**4.19**	10.8	0.055	46.8	**22.8**	20.3	**79.6**	0.044	<PQL	12.3	**291**
SEC VFBR25	0.013	**4.64**	<PQL	0.081	363	0.014	11.3	0.002	0.009	**115**	5.20	0.050	43.8	**23.4**	15.7	**118**	<PQL	<PQL	5.43	**814**
SEC VFBR26	0.010	**2.15**	0.002	0.085	323	0.004	11.9	0.001	0.010	**43.6**	6.71	0.048	44.4	**6.98**	17.3	**86.0**	**0.180**	<PQL	7.10	**514**
SEC VFBR27	0.010	**3.86**	<PQL	0.086	355	0.013	9.71	0.003	0.009	**57.9**	5.83	0.058	42.2	**30.2**	15.9	**66.4**	0.083	<PQL	8.13	**882**
SEC VFBR28	0.011	**3.97**	<PQL	0.073	306	0.014	11.4	0.002	0.008	**119**	4.89	0.046	40.7	**18.8**	15.7	**103**	**0.109**	<PQL	3.55	**810**
SEC VFBR29	0.011	**1.60**	<PQL	0.115	293	0.004	10.4	0.002	0.010	**25.4**	7.59	0.047	41.3	**24.8**	17.3	**90.4**	**0.188**	<PQL	11.6	**540**
SEC VFBR30	0.011	**2.42**	<PQL	0.099	275	0.004	8.17	0.001	0.008	**44.2**	6.44	0.040	35.9	**5.58**	14.6	**94.5**	0.059	<PQL	2.84	**550**

Table B-7: Elemental Concentrations in Mayer Ranch VFBR Solids FLT Leachate in mg L^{-1}, with Bolded Values Exceeding the OWRB WQGs

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	S	Se	Si	Zn
OWRB WQGs	0.05	0.05	0.04	1		0.02		0.05	1	0.3				0.05		0.14	0.1		0.01		5
PQL	0.003	0.004	0.022	0.002	0.066	0.001	0.001	0.001	0.001	0.001	0.029	0.001	0.001	0.001	0.012	0.003	0.011	0.053	0.022	0.003	0.003
C3N-1	0.006	**0.509**	<PQL	0.013	366	0.006	3.50	**0.071**	0.007	0.026	11.8	0.072	45.6	**7.34**	17.0	**27.5**	0.094	393	<PQL	0.917	**42.3**
C3N-2	<PQL	**0.206**	<PQL	0.004	116	<PQL	0.010	<PQL	0.008	0.206	6.59	0.039	25.5	**0.106**	15.2	**0.237**	0.039	123	<PQL	1.58	0.564
C3N-3	0.005	**0.245**	<PQL	0.008	225	<PQL	0.481	<PQL	0.007	0.013	7.60	0.055	35.6	**0.811**	15.0	**9.74**	0.065	234	<PQL	1.09	**12.4**
C3N-4	0.005	**0.123**	<PQL	0.009	210	0.002	1.99	<PQL	0.006	<PQL	6.80	0.046	32.7	**4.42**	11.3	**12.3**	0.068	226	<PQL	0.665	**20.5**
C3N-5	0.004	**0.112**	<PQL	0.011	194	0.002	4.63	**0.071**	0.003	0.037	8.38	0.056	43.5	**5.73**	16.5	**34.6**	0.077	269	<PQL	1.10	**57.7**
C3N-6	<PQL	**0.070**	<PQL	0.002	66.1	<PQL	0.005	<PQL	0.006	<PQL	5.27	0.024	14.3	**0.070**	9.86	0.122	0.025	77.9	<PQL	0.632	0.080
C3N-7	0.003	**0.092**	<PQL	0.007	127	<PQL	0.123	<PQL	0.006	<PQL	5.29	0.037	22.3	**0.153**	10.7	**2.14**	0.038	128	<PQL	0.477	0.800
C3N-8	0.003	**0.088**	<PQL	0.002	96.4	0.002	0.010	<PQL	0.006	<PQL	8.71	0.033	24.3	**0.174**	17.1	**0.237**	0.036	112	<PQL	1.09	0.516
C3N-9	0.005	**0.264**	<PQL	0.011	269	<PQL	2.29	**0.068**	0.005	0.086	8.94	0.059	45.6	**2.14**	13.8	**30.2**	0.072	311	<PQL	0.685	**42.5**
C3N-10	0.005	**0.129**	<PQL	0.013	224	<PQL	2.22	<PQL	0.006	0.140	7.38	0.055	37.2	**1.68**	11.0	**20.8**	0.054	250	<PQL	0.616	**33.8**
C3N-11	0.005	**0.233**	<PQL	0.012	258	<PQL	2.88	**0.069**	0.006	0.229	9.29	0.067	45.4	**2.52**	15.7	**35.0**	0.073	302	<PQL	0.732	**36.9**
C3N-12	<PQL	**0.082**	<PQL	0.003	90.4	<PQL	0.023	<PQL	0.006	0.005	6.21	0.027	16.5	**0.064**	10.4	**0.422**	0.027	106	<PQL	0.639	0.206
C3N-13	0.004	**0.113**	<PQL	0.009	158	<PQL	1.33	<PQL	0.006	0.014	8.04	0.054	33.3	**0.611**	14.9	**14.9**	0.057	183	<PQL	0.702	**11.0**
C3N-14	0.004	**0.121**	<PQL	0.011	193	<PQL	0.400	<PQL	0.006	0.014	7.19	0.044	26.7	**0.654**	11.3	**6.99**	0.046	186	<PQL	0.759	**5.32**
C3N-15	0.003	**0.107**	<PQL	0.011	167	<PQL	0.494	<PQL	0.005	0.005	7.94	0.050	30.9	**0.514**	13.8	**5.94**	0.051	177	<PQL	0.955	**5.18**
C3S-1	0.004	**0.106**	<PQL	0.007	168	<PQL	1.13	<PQL	0.005	<PQL	7.43	0.042	32.2	**3.27**	14.8	**8.51**	0.064	189	<PQL	1.10	**7.58**
C3S-2	0.004	**0.127**	<PQL	0.012	142	<PQL	0.118	<PQL	0.006	<PQL	5.20	0.027	25.4	**0.584**	19.4	**1.50**	0.044	152	<PQL	0.772	0.944
C3S-3	0.003	**0.106**	<PQL	0.007	168	<PQL	0.619	<PQL	0.005	<PQL	5.36	0.037	22.4	**0.888**	7.97	**8.06**	0.036	162	<PQL	0.481	**7.94**
C3S-4	0.006	**0.317**	<PQL	0.014	321	<PQL	3.40	<PQL	0.007	0.013	11.3	0.067	45.4	**7.76**	16.0	**35.6**	**0.101**	363	<PQL	0.894	**45.0**
C3S-5	0.004	**0.116**	<PQL	0.009	200	<PQL	4.29	<PQL	0.007	<PQL	11.7	0.062	52.5	**19.6**	21.7	**33.9**	**0.188**	299	<PQL	0.945	**34.3**
C3S-6	0.004	**0.125**	<PQL	0.023	187	<PQL	0.018	<PQL	0.009	<PQL	7.80	0.036	23.1	**0.188**	8.41	**0.397**	0.039	169	<PQL	0.502	0.181
C3S-7	0.003	**0.094**	<PQL	0.014	113	<PQL	0.074	<PQL	0.006	0.051	5.47	0.027	17.5	**0.153**	6.50	**1.12**	0.028	109	<PQL	0.364	0.673
C3S-8	0.018	**0.084**	<PQL	0.002	85.6	<PQL	0.004	<PQL	0.006	0.090	5.10	0.021	16.9	**0.065**	9.35	**0.254**	0.023	98.2	<PQL	0.828	0.161
C3S-9	0.002	**0.073**	<PQL	<PQL	72.1	<PQL	<PQL	<PQL	0.007	<PQL	4.50	0.021	17.1	0.014	13.3	0.051	0.025	89.8	<PQL	0.722	0.052
C3S-10	<PQL	**0.084**	<PQL	<PQL	91.2	<PQL	0.005	<PQL	0.002	<PQL	4.68	0.021	17.9	**0.053**	11.3	**0.226**	0.027	110	<PQL	0.753	0.092
C3S-11	0.006	**0.101**	<PQL	0.008	161	<PQL	7.86	<PQL	0.007	0.296	8.39	0.055	42.8	**2.42**	17.4	**53.3**	0.041	267	<PQL	0.760	**59.1**
C3S-12	0.005	**0.113**	<PQL	0.012	156	<PQL	1.95	**0.059**	0.005	0.082	10.4	0.047	31.6	**7.16**	14.1	**14.4**	0.079	191	<PQL	0.845	**24.2**
C3S-13	0.004	**0.090**	<PQL	0.007	128	<PQL	0.365	<PQL	0.005	<PQL	6.81	0.035	21.8	**0.219**	12.2	**3.7**	0.032	123	<PQL	0.768	2.06
C3S-14	0.005	**0.271**	<PQL	0.012	181	<PQL	3.62	<PQL	0.008	**1.53**	12.0	0.061	44.6	**4.39**	18.4	**53.4**	0.076	282	<PQL	0.688	**62.4**
C3S-15	0.004	**0.107**	<PQL	0.009	158	<PQL	4.42	<PQL	0.004	0.005	9.56	0.052	36.4	**11.1**	13.7	**27.3**	0.099	214	<PQL	0.763	**26.0**

Table B-8: Elemental Concentrations in Southeast Commerce VFBR Solids FLT Leachate in mg L^{-1}, with Bolded Values Exceeding the OWRB WQGs

Samples	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	S	Se	Si	Zn
OWRB WQGs	0.05	0.05	0.04	1		0.02		0.05	1	0.3				0.05		0.14	0.1		0.01		5
PQL	0.003	0.004	0.020	0.002	0.066	0.001	0.002	0.001	0.001	0.001	0.029	0.001	0.001	0.001	0.012	0.002	0.017	0.053	0.022	0.003	0.003
SEC VFBR1	0.004	**0.526**	<PQL	0.012	119	0.001	0.910	0.001	0.006	0.132	5.60	0.021	23.2	**10.4**	7.15	**15.7**	<PQL	148	<PQL	0.651	**42.6**
SEC VFBR2	0.004	**0.313**	<PQL	0.005	129	0.001	0.479	0.002	0.006	0.022	7.98	0.028	40.1	**15.2**	15.9	**5.64**	<PQL	195	<PQL	1.62	**60.6**
SEC VFBR3	0.006	**1.64**	<PQL	0.016	151	0.002	6.65	0.006	0.010	**3.55**	7.18	0.037	38.2	**55.2**	11.9	**57.3**	0.029	433	**0.024**	1.03	**337**
SEC VFBR4	0.008	**2.18**	<PQL	0.012	193	0.002	6.85	0.007	0.008	**9.20**	9.19	0.040	47.7	**64.7**	16.3	**65.4**	0.042	564	**0.027**	0.919	**432**
SEC VFBR5	0.005	**0.758**	<PQL	0.004	214	0.008	1.45	0.002	0.008	0.079	7.26	0.047	43.1	**13.8**	13.6	**19.5**	<PQL	381	<PQL	3.16	**262**
SEC VFBR6	0.007	**2.65**	<PQL	0.008	197	0.004	7.85	0.005	0.010	**12.2**	9.04	0.049	56.2	**40.7**	17.2	**48.6**	0.040	591	**0.024**	1.04	**506**
SEC VFBR7	0.009	**2.55**	<PQL	0.005	253	0.007	8.37	0.001	0.011	**18.1**	7.93	0.049	56.8	**7.17**	17.3	**54.5**	0.049	719	<PQL	0.942	**654**
SEC VFBR8	0.010	**4.96**	0.022	0.004	203	**0.207**	8.39	0.007	0.039	**212**	2.07	0.036	38.3	**6.62**	9.30	**76.2**	**0.408**	1094	<PQL	1.08	**1105**
SEC VFBR9	0.018	**7.93**	<PQL	0.004	236	**0.066**	16.4	0.007	0.044	**236**	1.73	0.039	40.8	**3.54**	8.82	**176**	**0.447**	1597	<PQL	1.17	**1759**
SEC VFBR10	0.019	**5.14**	0.021	0.002	220	**0.022**	21.8	0.011	0.016	**146**	1.45	0.037	41.5	**3.01**	10.4	**208**	**0.287**	1193	<PQL	0.955	**1117**
SEC VFBR11	0.004	**0.089**	<PQL	0.003	128	0.001	0.265	<PQL	0.006	0.030	6.91	0.022	35.3	**2.76**	16.7	**5.30**	<PQL	157	<PQL	2.26	**15.2**
SEC VFBR12	0.004	**0.065**	<PQL	0.003	79	0.001	0.044	<PQL	0.005	0.010	3.59	0.014	18.0	**2.41**	7.48	**2.16**	<PQL	122	<PQL	1.17	**8.82**
SEC VFBR13	0.006	**1.12**	<PQL	0.013	138	0.001	4.52	0.003	0.008	**3.44**	7.40	0.028	36.5	**32.9**	11.9	**46.1**	0.018	350	<PQL	0.949	**254**
SEC VFBR14	0.008	**1.38**	<PQL	0.015	207	0.001	5.76	0.004	0.011	**1.17**	9.73	0.044	56.1	**38.7**	18.4	**56.1**	0.021	453	**0.023**	1.39	**280**
SEC VFBR15	0.005	**1.39**	<PQL	0.015	204	0.003	3.45	0.004	0.009	**0.422**	10.8	0.041	57.1	**41.1**	18.2	**25.1**	<PQL	485	<PQL	1.31	**359**
SEC VFBR16	0.009	**2.55**	<PQL	0.013	221	0.007	9.28	0.003	0.009	**19.2**	7.93	0.043	52.5	**23.3**	16.0	**71.2**	0.057	772	<PQL	1.46	**831**
SEC VFBR17	0.015	**7.62**	<PQL	0.005	346	0.011	15.5	0.003	0.012	**65.6**	9.46	0.057	65.7	**18.2**	19.2	**131**	**0.145**	1332	<PQL	1.15	**1218**
SEC VFBR18	0.012	**6.24**	<PQL	0.009	363	0.007	11.2	0.002	0.009	**39.2**	8.97	0.051	61.7	**6.16**	17.3	**120**	**0.102**	948	<PQL	1.01	**672**
SEC VFBR19	0.012	**5.11**	<PQL	0.015	240	**0.021**	9.18	0.005	0.016	**115**	6.85	0.034	34.2	**5.61**	8.76	**107**	**0.243**	700	<PQL	0.987	**488**
SEC VFBR20	0.009	**2.56**	0.021	0.009	215	0.004	7.71	0.002	0.009	**20.8**	10.7	0.042	42.8	**5.57**	13.0	**78.1**	0.056	516	<PQL	0.986	**382**
SEC VFBR21	0.003	**0.175**	<PQL	0.012	117	0.001	0.725	0.001	0.004	0.164	7.04	0.025	27.3	**6.56**	9.68	**8.70**	<PQL	161	<PQL	1.23	**52.1**
SEC VFBR22	0.005	**0.111**	<PQL	0.002	163	0.001	0.095	<PQL	0.007	0.008	7.07	0.025	43.1	**2.93**	19.8	**1.82**	<PQL	194	<PQL	2.00	**15.0**
SEC VFBR23	0.009	**0.860**	<PQL	0.017	179	<PQL	7.66	0.004	0.008	**3.05**	9.12	0.038	44.0	**39.6**	15.4	**72.3**	0.023	384	<PQL	1.65	**192**
SEC VFBR24	0.010	**1.08**	<PQL	0.015	235	0.001	9.06	0.002	0.009	**7.25**	12.2	0.042	54.7	**20.2**	18.8	**70.1**	0.026	508	<PQL	1.46	**305**
SEC VFBR25	0.009	**2.04**	<PQL	0.017	233	0.002	9.49	0.003	0.007	**15.3**	10.6	0.045	51.0	**32.9**	17.0	**81.8**	0.045	562	<PQL	2.90	**370**
SEC VFBR26	0.011	**3.12**	<PQL	0.005	258	0.005	14.0	0.001	0.010	**41.9**	8.63	0.049	53.5	**7.49**	17.7	**87.3**	0.095	763	<PQL	1.56	**662**
SEC VFBR27	0.008	**2.99**	<PQL	0.006	251	0.016	9.26	0.003	0.009	**33.4**	8.24	0.046	45.6	**29.2**	13.0	**54.4**	0.078	851	<PQL	2.02	**935**
SEC VFBR28	0.012	**3.41**	<PQL	0.008	294	0.009	12.7	0.004	0.010	**52.8**	7.67	0.046	53.5	**26.0**	16.7	**95.9**	**0.116**	897	<PQL	1.38	**751**
SEC VFBR29	0.012	**4.13**	<PQL	0.003	256	0.019	13.2	0.003	0.012	**75.3**	7.03	0.043	47.8	**13.3**	14.6	**106**	**0.148**	1124	<PQL	1.28	**1329**
SEC VFBR30	0.013	**2.82**	<PQL	0.005	274	0.005	10.4	0.002	0.007	**36.7**	10.2	0.043	49.7	**7.00**	15.9	**102**	0.088	764	<PQL	1.20	**665**

Appendix C: Data from Characterization of Amendments and Leaching of Amended Mine Drainage Treatment Residuals

Table C-1: Concentrations of Select Elements Present in Biochar, Biosolids, and CCR Used as Sorptive Amendments

Sample	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	S	Se	Si	Zn
PQL	0.003	0.004	0.02	0.002	0.1	0.001	0.001	0.001	0.001	0.001	0.03	0.001	0.001	0.001	0.01	0.002	0.01	0.1	0.02	0.01	0.003
Biochar 1	0.178	13.9	<PQL	16.4	3075	<PQL	<PQL	<PQL	18.0	65.5	7471	<PQL	834	20.8	21.7	0.695	<PQL	237	<PQL	19.9	19.0
Biochar 2	<PQL	19.0	<PQL	17.2	3392	<PQL	<PQL	<PQL	15.5	77.4	8176	0.080	929	22.7	22.4	0.790	<PQL	262	<PQL	25.1	19.1
Biochar 3	0.183	18.8	<PQL	19.5	3761	<PQL	<PQL	0.065	15.8	80.2	9118	0.076	1053	25.2	23.8	0.874	<PQL	256	1.58	25.6	20.6
Biochar 4	0.141	15.6	<PQL	18.0	3462	<PQL	<PQL	<PQL	14.0	75.7	8270	<PQL	950	23.1	22.1	0.714	<PQL	255	2.12	18.8	19.7
Biochar 5	<PQL	15.4	<PQL	17.5	3367	<PQL	<PQL	0.073	13.7	95.0	8145	0.077	939	22.7	21.7	0.803	<PQL	248	<PQL	18.7	18.9
Biochar Average	**0.167**	**16.5**	**<PQL**	**17.7**	**3411**	**<PQL**	**<PQL**	**0.069**	**15.4**	**78.8**	**8236**	**0.078**	**941**	**22.9**	**22.3**	**0.775**	**<PQL**	**251**	**1.85**	**21.6**	**19.5**
Biosolids 1	1.97	6043	6.51	583	19983	1.03	2.78	115	519	8866	2820	7.69	6859	548	1010	17.1	18.5	15764	19	357	657
Biosolids 2	1.58	6662	7.04	615	19369	1.03	2.96	117	549	9106	3206	8.88	6381	519	1085	18.0	19.6	15398	19	365	696
Biosolids 3	1.94	5390	6.24	574	19094	0.984	2.64	111	514	8165	2770	7.30	6798	560	1017	16.3	18.6	14607	18	379	638
Biosolids 4	1.55	6517	7.20	590	19526	1.00	2.81	116	522	9051	3014	8.22	7773	552	1037	17.5	18.2	14895	18	351	684
Biosolids 5	1.53	7128	6.48	599	19451	1.02	2.81	115	528	9128	3275	9.29	7407	578	1072	17.7	18.3	14055	19	280	666
Biosolids Average	**1.71**	**6348**	**6.69**	**592**	**19485**	**1.01**	**2.80**	**115**	**526**	**8863**	**3017**	**8.28**	**7044**	**551**	**1044**	**17.3**	**18.6**	**14944**	**18.6**	**346**	**668**
CCR 1	1.73	71312	28.5	1863	185893	1.35	19.1	53.5	131	35220	4181	61.0	29845	274	9414	43.1	14.8	2577	11.1	52.6	137
CCR 2	1.58	72722	27.6	573	188988	1.48	19.8	52.6	128	35204	4056	59.8	30219	276	9228	42.2	11.5	3596	8.99	83.6	133
CCR 3	1.01	70887	26.5	1009	186023	1.45	19.8	52.8	129	34645	4081	60.0	29825	272	9267	42.5	12.7	2734	10.5	88.3	137
CCR 4	1.77	72022	27.0	2050	186926	1.42	18.2	52.7	130	35292	4105	60.4	30030	274	9304	42.5	17.1	2547	11.5	52.7	132
CCR 5	1.56	73062	27.5	706	188942	1.48	20.3	52.8	131	36003	4133	60.8	30428	278	9341	42.7	13.7	2602	11.6	63.3	134
CCR Average	**1.53**	**72001**	**27.4**	**1240**	**187354**	**1.44**	**19.4**	**52.9**	**130**	**35273**	**4111**	**60.4**	**30069**	**275**	**9311**	**42.6**	**14.0**	**2811**	**10.8**	**68.1**	**135**

Table C-2: Elemental Concentrations in TCLP Leachate in mg L^{-1} from Mayer Ranch Oxidation Pond Solids Amended with Biochar (BC), Biosolids (BS), CCR, and the Unamended Control (C)

Sample	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Ni	Li	Se	Zn
PQL	*0.0005*	*0.018*	*0.022*	*0.002*	*0.066*	*0.001*	*0.002*	*0.001*	*0.001*	*0.002*	*0.029*	*0.014*	*0.001*	*0.001*	*0.002*	*0.017*	*0.022*	*0.003*
C1 BC TCLP 1	0.002	0.140	<PQL	0.147	889	<PQL	0.044	<PQL	<PQL	13.0	34.8	0.049	33.4	0.609	0.536	<PQL	<PQL	5.01
C1 BC TCLP 2	0.003	0.112	<PQL	0.090	914	<PQL	0.023	<PQL	<PQL	13.1	35.3	0.044	32.1	0.533	0.352	<PQL	0.036	3.99
C1 BC TCLP 3	0.001	0.081	<PQL	0.092	856	<PQL	0.021	<PQL	<PQL	12.3	31.9	0.041	29.1	0.502	0.339	<PQL	<PQL	3.83
C1 BC TCLP Avg	**0.002**	**0.111**	**<PQL**	**0.110**	**886**	**<PQL**	**0.030**	**<PQL**	**<PQL**	**12.8**	**34.0**	**0.045**	**31.5**	**0.548**	**0.409**	**<PQL**	**0.036**	**4.28**
C1 BS TCLP 1	0.002	0.140	<PQL	0.153	812	<PQL	0.028	<PQL	<PQL	12.8	13.5	0.040	35.0	0.666	0.391	<PQL	<PQL	3.97
C1 BS TCLP 2	0.002	0.091	<PQL	0.148	850	<PQL	0.023	<PQL	<PQL	12.8	13.3	0.041	34.5	0.651	0.351	<PQL	0.046	3.61
C1 BS TCLP 3	0.002	0.106	<PQL	0.126	875	<PQL	0.024	<PQL	<PQL	12.8	13.8	0.042	35.5	0.662	0.367	<PQL	<PQL	3.69
C1 BS TCLP Avg	**0.002**	**0.112**	**<PQL**	**0.142**	**846**	**<PQL**	**0.025**	**<PQL**	**<PQL**	**12.8**	**13.5**	**0.041**	**35.0**	**0.660**	**0.370**	**<PQL**	**0.046**	**3.76**
C1 CCR TCLP 1	0.001	0.191	<PQL	0.094	1232	0.002	0.023	<PQL	<PQL	4.11	12.2	0.059	56.4	0.326	0.339	<PQL	0.077	2.02
C1 CCR TCLP 2	0.001	0.199	<PQL	0.171	1183	0.002	0.020	<PQL	<PQL	4.15	10.3	0.058	52.0	0.319	0.331	<PQL	0.077	1.72
C1 CCR TCLP 3	0.001	0.174	<PQL	0.160	1211	0.001	0.021	<PQL	<PQL	3.92	11.1	0.057	54.0	0.312	0.320	<PQL	0.080	1.68
C1 CCR TCLP Avg	**0.001**	**0.188**	**<PQL**	**0.142**	**1209**	**0.002**	**0.021**	**<PQL**	**<PQL**	**4.06**	**11.2**	**0.058**	**54.1**	**0.319**	**0.330**	**<PQL**	**0.078**	**1.81**
C1 C TCLP 1	0.001	0.092	<PQL	0.130	908	0.001	0.033	<PQL	<PQL	22.1	8.99	0.044	25.3	0.687	0.554	<PQL	<PQL	4.48
C1 C TCLP 2	0.002	0.078	<PQL	0.160	956	0.001	0.033	<PQL	<PQL	22.8	9.70	0.047	27.3	0.732	0.532	<PQL	<PQL	4.69
C1 C TCLP 3	0.002	0.081	<PQL	0.146	1009	0.001	0.033	<PQL	<PQL	21.0	10.00	0.049	29.1	0.757	0.568	<PQL	<PQL	4.63
C1 C TCLP Avg	**0.002**	**0.084**	**<PQL**	**0.145**	**958**	**0.001**	**0.033**	**<PQL**	**<PQL**	**21.9**	**9.56**	**0.047**	**27.2**	**0.725**	**0.551**	**<PQL**	**<PQL**	**4.60**

Table C-3: Elemental Concentrations in SPLP Leachate in mg L^{-1} from Mayer Ranch Oxidation Pond Solids Amended with Biochar (BC), Biosolids (BS), CCR, and the Unamended Control (C)

Sample	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	Se	Zn
PQL	*0.0005*	*0.018*	*0.022*	*0.002*	*0.066*	*0.001*	*0.002*	*0.001*	*0.001*	*0.002*	*0.029*	*0.014*	*0.001*	*0.001*	*0.012*	*0.002*	*0.017*	*0.022*	*0.003*
C1 BC SPLP 1	<PQL	0.053	<PQL	0.063	541	<PQL	0.017	<PQL	<PQL	0.013	14.3	0.024	13.3	0.034	14.0	0.079	<PQL	0.039	0.718
C1 BC SPLP 2	0.001	0.047	<PQL	0.056	545	<PQL	0.006	<PQL	<PQL	<PQL	14.5	0.027	14.1	0.007	14.6	0.070	<PQL	0.073	0.062
C1 BC SPLP 3	0.001	0.044	<PQL	0.050	570	<PQL	0.009	<PQL	<PQL	0.024	15.1	0.027	14.5	0.007	14.4	0.066	<PQL	0.081	0.053
C1 BC SPLP Avg	**0.001**	**0.048**	**<PQL**	**0.056**	**552**	**<PQL**	**0.010**	**<PQL**	**<PQL**	**0.019**	**14.6**	**0.026**	**13.9**	**0.016**	**14.4**	**0.071**	**<PQL**	**0.064**	**0.278**
C1 BS SPLP 1	<PQL	0.033	<PQL	0.037	528	<PQL	0.006	<PQL	<PQL	<PQL	5.97	0.026	18.2	0.009	14.1	0.078	<PQL	0.079	0.029
C1 BS SPLP 2	<PQL	0.019	<PQL	0.027	501	<PQL	0.008	<PQL	<PQL	<PQL	5.44	0.023	16.6	0.009	12.9	0.074	<PQL	0.066	0.021
C1 BS SPLP 3	<PQL	0.031	<PQL	0.052	524	<PQL	0.009	<PQL	<PQL	<PQL	5.97	0.027	18.5	0.010	14.4	0.081	<PQL	0.076	0.048
C1 BS SPLP Avg	**<PQL**	**0.028**	**<PQL**	**0.039**	**518**	**<PQL**	**0.007**	**<PQL**	**<PQL**	**<PQL**	**5.79**	**0.025**	**17.8**	**0.009**	**13.8**	**0.078**	**<PQL**	**0.073**	**0.033**
C1 CCR SPLP 1	0.001	0.034	<PQL	0.071	611	<PQL	0.009	<PQL	<PQL	0.033	3.63	0.020	14.1	<PQL	11.8	0.067	<PQL	0.080	0.018
C1 CCR SPLP 2	0.001	0.030	<PQL	0.060	612	<PQL	0.008	<PQL	<PQL	0.029	3.59	0.020	14.3	<PQL	12.1	0.066	<PQL	0.059	0.014
C1 CCR SPLP 3	0.001	0.036	<PQL	0.083	621	<PQL	0.006	<PQL	<PQL	0.007	3.84	0.021	15.3	<PQL	13.6	0.068	<PQL	0.079	0.016
C1 CCR SPLP Avg	**0.001**	**0.033**	**<PQL**	**0.071**	**614**	**<PQL**	**0.007**	**<PQL**	**<PQL**	**0.023**	**3.69**	**0.020**	**14.6**	**<PQL**	**12.5**	**0.067**	**<PQL**	**0.073**	**0.016**
C1 C SPLP 1	0.001	0.024	<PQL	0.057	547	<PQL	0.009	<PQL	<PQL	0.159	3.95	0.027	11.3	0.014	17.7	0.082	<PQL	0.041	0.264
C1 C SPLP 2	<PQL	<PQL	<PQL	0.084	551	<PQL	0.006	<PQL	<PQL	0.063	3.81	0.027	12.3	0.007	12.8	0.063	<PQL	0.064	0.006
C1 C SPLP 3	0.001	0.024	<PQL	0.092	573	<PQL	0.007	<PQL	<PQL	0.067	3.89	0.027	12.9	0.007	13.1	0.062	<PQL	0.062	0.011
C1 C SPLP Avg	**0.001**	**0.024**	**<PQL**	**0.078**	**557**	**<PQL**	**0.007**	**<PQL**	**<PQL**	**0.096**	**3.88**	**0.027**	**12.2**	**0.009**	**14.5**	**0.069**	**<PQL**	**0.056**	**0.094**

Table C-4: Elemental Concentrations in FLT Leachate in mg L^{-1} from Mayer Ranch Oxidation Pond Solids Amended with Biochar (BC), Biosolids (BS), CCR, and the Unamended Control (C)

Sample	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	Se	Zn
PQL	*0.0005*	*0.018*	*0.022*	*0.002*	*0.066*	*0.001*	*0.002*	*0.001*	*0.001*	*0.002*	*0.029*	*0.014*	*0.001*	*0.001*	*0.012*	*0.002*	*0.017*	*0.022*	*0.003*
C1 BC FLT 1	<PQL	0.021	<PQL	0.004	140	<PQL	0.007	<PQL	<PQL	0.007	8.34	0.012	1.82	0.001	7.78	0.008	<PQL	<PQL	<PQL
C1 BC FLT 2	<PQL	0.028	<PQL	0.004	141	<PQL	0.006	<PQL	<PQL	0.004	8.20	0.012	1.91	0.001	7.67	0.008	<PQL	0.043	<PQL
C1 BC FLT 3	<PQL	0.019	<PQL	0.004	166	<PQL	0.007	<PQL	<PQL	0.020	8.93	0.013	2.61	0.001	8.19	0.011	<PQL	0.053	<PQL
C1 BC FLT Avg	**<PQL**	**0.023**	**<PQL**	**0.004**	**149**	**<PQL**	**0.006**	**<PQL**	**<PQL**	**0.010**	**8.49**	**0.013**	**2.12**	**0.001**	**7.88**	**0.009**	**<PQL**	**0.048**	**<PQL**
C1 BS FLT 1	<PQL	<PQL	<PQL	0.004	124	<PQL	0.006	<PQL	<PQL	0.001	3.07	0.011	2.75	0.001	7.36	0.011	<PQL	0.038	<PQL
C1 BS FLT 2	<PQL	<PQL	<PQL	0.007	234	<PQL	0.007	<PQL	<PQL	0.107	4.64	0.016	8.85	0.001	11.3	0.020	<PQL	0.032	0.003
C1 BS FLT 3	<PQL	<PQL	<PQL	0.007	271	<PQL	0.008	<PQL	<PQL	0.008	4.82	0.016	10.0	0.001	11.7	0.024	<PQL	0.043	<PQL
C1 BS FLT Avg	**<PQL**	**<PQL**	**<PQL**	**0.006**	**210**	**<PQL**	**0.007**	**<PQL**	**<PQL**	**0.039**	**4.18**	**0.014**	**7.21**	**0.001**	**10.1**	**0.019**	**<PQL**	**0.038**	**0.003**
C1 CCR FLT 1	<PQL	<PQL	<PQL	0.032	288	<PQL	0.006	<PQL	<PQL	0.184	3.23	0.012	6.05	<PQL	11.6	0.024	<PQL	0.054	<PQL
C1 CCR FLT 2	<PQL	<PQL	<PQL	0.029	257	<PQL	0.008	<PQL	<PQL	0.013	3.01	0.012	5.70	<PQL	11.5	0.019	<PQL	0.051	<PQL
C1 CCR FLT 3	<PQL	<PQL	<PQL	0.022	140	<PQL	0.008	<PQL	<PQL	0.028	1.98	0.010	1.32	<PQL	7.20	0.012	<PQL	0.048	<PQL
C1 CCR FLT Avg	**<PQL**	**<PQL**	**<PQL**	**0.028**	**228**	**<PQL**	**0.007**	**<PQL**	**<PQL**	**0.075**	**2.74**	**0.011**	**4.36**	**<PQL**	**10.1**	**0.019**	**<PQL**	**0.051**	**<PQL**
C1 C FLT 1	<PQL	0.021	<PQL	0.003	116	<PQL	0.006	<PQL	<PQL	0.049	1.82	0.011	0.741	0.001	6.37	0.006	<PQL	0.038	<PQL
C1 C FLT 2	<PQL	<PQL	<PQL	0.003	129	<PQL	0.006	<PQL	<PQL	0.002	1.94	0.011	1.15	0.001	6.61	0.006	<PQL	<PQL	<PQL
C1 C FLT 3	<PQL	<PQL	<PQL	0.003	134	<PQL	0.007	<PQL	<PQL	0.042	1.96	0.011	1.45	0.001	6.55	0.009	<PQL	0.043	<PQL
C1 C FLT Avg	**<PQL**	**0.021**	**<PQL**	**0.003**	**126**	**<PQL**	**0.006**	**<PQL**	**<PQL**	**0.031**	**1.91**	**0.011**	**1.11**	**0.001**	**6.51**	**0.007**	**<PQL**	**0.041**	**<PQL**

Table C-5: Elemental Concentrations in TCLP Leachate in mg L^{-1} from Southeast Commerce Oxidation Pond Solids Amended with Biochar (BC), Biosolids (BS), CCR, and the Unamended Control (C)

Sample	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Ni	Pb	Se	Zn
PQL	*0.0005*	*0.018*	*0.022*	*0.002*	*0.052*	*0.001*	*0.002*	*0.001*	*0.001*	*0.002*	*0.029*	*0.014*	*0.001*	*0.001*	*0.002*	*0.017*	*0.022*	*0.003*
Ox BC TCLP 1	0.004	0.068	<PQL	0.131	356	<PQL	0.204	<PQL	<PQL	24.1	32.6	0.049	38.1	11.3	0.484	0.073	0.232	10.1
Ox BC TCLP 2	0.004	0.064	<PQL	0.144	345	<PQL	0.203	<PQL	<PQL	24.3	33.3	0.051	38.5	11.5	0.460	0.063	0.223	9.71
Ox BC TCLP 3	0.004	0.080	<PQL	0.149	352	<PQL	0.194	<PQL	<PQL	23.9	31.5	0.049	37.3	10.9	0.448	0.060	0.223	9.65
Ox Bc TCLP Avg	**0.004**	**0.071**	**<PQL**	**0.141**	**351**	**<PQL**	**0.201**	**<PQL**	**<PQL**	**24.1**	**32.5**	**0.050**	**37.9**	**11.3**	**0.464**	**0.066**	**0.226**	**9.82**
Ox BS TCLP 1	0.003	0.124	<PQL	0.119	361	<PQL	0.178	<PQL	<PQL	24.0	13.4	0.046	47.3	8.75	0.476	0.048	0.209	8.53
Ox BS TCLP 2	0.003	0.141	<PQL	0.168	384	<PQL	0.179	<PQL	<PQL	25.0	13.6	0.047	47.7	8.78	0.471	0.039	0.194	8.26
Ox BS TCLP 3	0.003	0.142	<PQL	0.151	375	<PQL	0.173	<PQL	<PQL	24.9	13.5	0.047	47.9	8.57	0.446	0.028	0.253	8.04
Ox Bs TCLP Avg	**0.003**	**0.136**	**<PQL**	**0.146**	**373**	**<PQL**	**0.177**	**<PQL**	**<PQL**	**24.6**	**13.5**	**0.046**	**47.6**	**8.70**	**0.464**	**0.038**	**0.219**	**8.28**
Ox CCR TCLP 1	0.003	0.208	<PQL	0.119	556	<PQL	0.112	<PQL	<PQL	4.76	9.89	0.053	68.4	4.05	0.402	<PQL	0.358	4.40
Ox CCR TCLP 2	0.004	0.121	<PQL	0.172	545	<PQL	0.110	<PQL	<PQL	5.05	9.03	0.052	68.3	4.08	0.383	<PQL	0.323	2.92
Ox CCR TCLP 3	0.003	0.161	<PQL	0.166	548	<PQL	0.114	<PQL	<PQL	5.27	8.88	0.051	66.9	4.06	0.384	<PQL	0.358	3.01
Ox CCR TCLP Avg	**0.004**	**0.163**	**<PQL**	**0.152**	**550**	**<PQL**	**0.112**	**<PQL**	**<PQL**	**5.03**	**9.27**	**0.052**	**67.9**	**4.06**	**0.390**	**<PQL**	**0.346**	**3.45**
Ox C TCLP 1	0.004	0.037	<PQL	0.120	399	<PQL	0.153	<PQL	<PQL	15.9	8.28	0.039	37.8	9.12	0.408	0.051	0.200	7.63
Ox C TCLP 2	0.004	0.023	<PQL	0.130	365	<PQL	0.141	<PQL	<PQL	12.4	7.39	0.040	36.2	8.48	0.356	0.038	0.343	6.74
Ox C TCLP 3	0.004	0.021	<PQL	0.148	396	<PQL	0.158	<PQL	<PQL	15.5	7.70	0.040	36.4	9.33	0.420	0.052	0.273	7.50
Ox C TCLP Avg	**0.004**	**0.027**	**<PQL**	**0.133**	**386**	**<PQL**	**0.151**	**<PQL**	**<PQL**	**14.6**	**7.79**	**0.040**	**36.8**	**8.98**	**0.394**	**0.047**	**0.272**	**7.29**

Table C-6: Elemental Concentrations in SPLP Leachate in mg L^{-1} from Southeast Commerce Oxidation Pond Solids Amended with Biochar (BC), Biosolids (BS), CCR, and the Unamended Control (C)

Sample	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	Se	Zn
PQL	*0.0005*	*0.018*	*0.022*	*0.002*	*0.052*	*0.001*	*0.002*	*0.001*	*0.001*	*0.002*	*0.029*	*0.014*	*0.001*	*0.001*	*0.012*	*0.002*	*0.017*	*0.022*	*0.003*
Ox BC SPLP 1	0.001	0.063	<PQL	0.047	233	<PQL	0.006	<PQL	0.001	0.142	14.8	0.032	24.4	0.794	46.9	0.041	<PQL	0.579	0.182
Ox BC SPLP 2	0.001	0.058	<PQL	0.097	229	<PQL	0.006	<PQL	0.001	0.116	14.5	0.031	24.5	0.821	43.1	0.028	<PQL	0.331	0.089
Ox BC SPLP 3	0.001	0.056	<PQL	0.090	237	<PQL	0.007	<PQL	<PQL	0.082	15.3	0.031	25.6	0.847	43.9	0.028	<PQL	0.382	0.087
Ox Bc SPLP Avg	**0.001**	**0.059**	**<PQL**	**0.078**	**233**	**<PQL**	**0.006**	**<PQL**	**0.001**	**0.113**	**14.9**	**0.031**	**24.8**	**0.821**	**44.6**	**0.032**	**<PQL**	**0.431**	**0.119**
Ox BS SPLP 1	0.001	0.053	0.027	0.079	216	<PQL	0.006	<PQL	0.002	0.041	5.67	0.028	29.0	0.454	41.5	0.031	<PQL	0.343	0.090
Ox BS SPLP 2	0.001	0.057	<PQL	0.148	234	<PQL	0.006	<PQL	0.001	0.105	6.21	0.029	31.5	0.484	45.2	0.031	<PQL	0.380	0.004
Ox BS SPLP 3	0.001	0.051	<PQL	0.071	226	<PQL	0.008	<PQL	0.001	0.058	5.59	0.028	30.0	0.478	41.6	0.031	<PQL	0.336	0.097
Ox Bs SPLP Avg	**0.001**	**0.054**	**0.027**	**0.099**	**225**	**<PQL**	**0.006**	**<PQL**	**0.001**	**0.068**	**5.83**	**0.028**	**30.2**	**0.472**	**42.8**	**0.031**	**<PQL**	**0.353**	**0.064**
Ox CCR SPLP 1	0.001	0.057	<PQL	0.089	293	<PQL	0.004	<PQL	<PQL	0.048	3.44	0.022	29.3	0.042	41.4	0.010	<PQL	0.353	0.046
Ox CCR SPLP 2	0.001	0.057	<PQL	0.074	302	<PQL	0.003	<PQL	<PQL	0.032	3.40	0.022	29.8	0.024	41.7	0.011	<PQL	0.380	0.039
Ox CCR SPLP 3	0.001	0.058	<PQL	0.066	336	<PQL	0.004	<PQL	<PQL	0.063	3.63	0.024	32.5	0.026	49.2	0.011	<PQL	0.320	0.041
Ox CCR SPLP Avg	**0.001**	**0.057**	**<PQL**	**0.076**	**310**	**<PQL**	**0.004**	**<PQL**	**<PQL**	**0.048**	**3.49**	**0.023**	**30.5**	**0.031**	**44.1**	**0.011**	**<PQL**	**0.351**	**0.042**
Ox C SPLP 1	0.001	0.059	<PQL	0.054	320	<PQL	0.008	<PQL	<PQL	0.127	3.47	0.030	28.3	0.850	51.1	0.030	<PQL	0.393	0.029
Ox C SPLP 2	0.001	0.061	<PQL	0.098	312	<PQL	0.008	<PQL	<PQL	0.129	3.57	0.032	29.8	0.851	54.3	0.030	<PQL	0.356	0.020
Ox C SPLP 3	0.001	0.057	<PQL	0.092	296	<PQL	0.007	<PQL	<PQL	0.059	3.43	0.031	28.2	0.772	52.9	0.029	<PQL	0.321	0.008
Ox C SPLP Avg	**0.001**	**0.059**	**<PQL**	**0.081**	**309**	**<PQL**	**0.007**	**<PQL**	**<PQL**	**0.105**	**3.49**	**0.031**	**28.8**	**0.824**	**52.7**	**0.030**	**<PQL**	**0.357**	**0.019**

Table C-7: Elemental Concentrations in FLT Leachate in mg L^{-1} from Southeast Commerce Oxidation Pond Solids Amended with Biochar (BC), Biosolids (BS), CCR, and the Unamended Control (C)

Sample	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	Se	Zn
PQL	*0.0005*	*0.018*	*0.022*	*0.002*	*0.052*	*0.001*	*0.002*	*0.001*	*0.001*	*0.002*	*0.029*	*0.014*	*0.001*	*0.001*	*0.012*	*0.002*	*0.017*	*0.022*	*0.003*
Ox BC FLT 1	0.001	0.041	<PQL	0.003	120	<PQL	0.006	<PQL	<PQL	0.031	10.0	0.018	12.6	0.403	27.9	0.008	<PQL	0.283	0.048
Ox BC FLT 2	0.001	0.040	<PQL	0.002	115	<PQL	0.004	<PQL	0.001	0.007	10.7	0.019	13.2	0.392	31.1	0.008	<PQL	0.302	0.049
Ox BC FLT 3	0.001	0.047	<PQL	0.002	130	<PQL	0.007	<PQL	0.001	0.033	12.4	0.020	14.8	0.429	34.2	0.009	<PQL	0.293	0.049
Ox Bc FLT Avg	**0.001**	**0.043**	**<PQL**	**0.003**	**122**	**<PQL**	**0.006**	**<PQL**	**0.001**	**0.024**	**11.1**	**0.019**	**13.5**	**0.408**	**31.0**	**0.008**	**<PQL**	**0.293**	**0.049**
Ox BS FLT 1	<PQL	0.050	<PQL	0.006	91.3	<PQL	0.004	<PQL	0.001	0.155	4.12	0.017	18.9	0.210	40.4	0.006	<PQL	0.278	0.049
Ox BS FLT 2	0.001	0.029	<PQL	0.004	73.3	<PQL	0.003	<PQL	0.001	0.057	2.95	0.014	12.1	0.172	30.3	0.002	<PQL	0.267	0.038
Ox BS FLT 3	0.001	0.034	<PQL	0.003	55.7	<PQL	0.006	<PQL	0.002	0.136	2.62	0.013	9.29	0.140	25.1	0.002	<PQL	0.202	0.036
Ox Bs FLT Avg	**0.001**	**0.038**	**<PQL**	**0.004**	**73.4**	**<PQL**	**0.004**	**<PQL**	**0.001**	**0.116**	**3.23**	**0.015**	**13.4**	**0.174**	**31.9**	**0.003**	**<PQL**	**0.249**	**0.041**
Ox CCR FLT 1	0.001	0.037	<PQL	0.030	71.5	<PQL	0.003	<PQL	0.002	0.139	1.09	0.010	4.71	0.006	19.4	<PQL	<PQL	0.273	0.018
Ox CCR FLT 2	0.001	0.032	<PQL	0.029	63.0	<PQL	0.003	<PQL	0.002	0.090	1.14	0.010	4.02	0.006	18.8	<PQL	<PQL	0.254	0.014
Ox CCR FLT 3	0.001	0.100	<PQL	0.038	150	<PQL	0.003	<PQL	0.001	0.593	2.46	0.013	15.6	0.011	35.9	<PQL	<PQL	0.338	0.030
Ox CCR FLT Avg	**0.001**	**0.056**	**<PQL**	**0.032**	**94.9**	**<PQL**	**0.003**	**<PQL**	**0.002**	**0.274**	**1.56**	**0.011**	**8.10**	**0.007**	**24.7**	**<PQL**	**<PQL**	**0.289**	**0.021**
Ox C FLT 1	0.001	0.044	<PQL	0.002	105	<PQL	0.004	<PQL	0.001	0.122	2.04	0.017	14.0	0.322	40.9	0.006	<PQL	0.246	0.087
Ox C FLT 2	0.001	0.057	<PQL	0.003	172	<PQL	0.006	<PQL	<PQL	0.087	2.78	0.019	19.0	0.428	48.9	0.009	<PQL	0.332	0.086
Ox C FLT 3	0.001	0.040	<PQL	0.002	127	<PQL	0.006	<PQL	0.001	0.032	2.30	0.018	14.9	0.327	43.6	0.006	<PQL	0.344	0.077
Ox C FLT Avg	**0.001**	**0.047**	**<PQL**	**0.003**	**135**	**<PQL**	**0.005**	**<PQL**	**0.001**	**0.080**	**2.37**	**0.018**	**16.0**	**0.359**	**44.5**	**0.007**	**<PQL**	**0.307**	**0.083**

Table C-8: Elemental Concentrations in TCLP Leachate in mg L^{-1} from Mayer Ranch VFBR Solids Amended with Biochar (BC), Biosolids (BS), CCR, and the Unamended Control (C)

Sample	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Ni	Pb	Se	Zn
PQL	*0.0005*	*0.018*	*0.022*	*0.002*	*0.066*	*0.001*	*0.001*	*0.001*	*0.001*	*0.002*	*0.029*	*0.001*	*0.001*	*0.001*	*0.002*	*0.008*	*0.022*	*0.003*
C3 BC TCLP 1	0.007	0.073	<PQL	0.189	1317	0.002	2.35	0.002	<PQL	0.563	48.4	0.060	56.9	15.9	24.9	0.038	0.308	16.9
C3 BC TCLP 2	0.007	0.051	<PQL	0.158	1422	0.001	2.41	0.001	<PQL	0.067	47.3	0.063	57.5	16.3	25.4	0.028	0.230	17.2
C3 BC TCLP 3	0.007	0.057	<PQL	0.168	1392	0.008	2.42	0.001	<PQL	0.040	45.7	0.062	56.4	16.0	25.7	0.039	0.252	15.8
C3 Bc TCLP Avg	**0.007**	**0.060**	**<PQL**	**0.171**	**1377**	**0.004**	**2.40**	**0.001**	**<PQL**	**0.223**	**47.1**	**0.062**	**57.0**	**16.1**	**25.3**	**0.035**	**0.263**	**16.6**
C3 BS TCLP 1	0.004	0.068	<PQL	0.182	1422	0.004	1.47	0.002	<PQL	0.714	28.9	0.064	66.2	9.30	27.0	<PQL	0.224	10.7
C3 BS TCLP 2	0.006	0.020	<PQL	0.166	1392	0.001	1.48	0.001	<PQL	0.051	27.0	0.067	66.9	9.47	27.3	<PQL	0.266	9.92
C3 BS TCLP 3	0.006	0.017	<PQL	0.181	1413	0.001	1.31	<PQL	<PQL	0.045	25.6	0.063	65.9	8.86	25.9	<PQL	0.261	8.65
C3 Bs TCLP Avg	**0.005**	**0.035**	**<PQL**	**0.176**	**1409**	**0.002**	**1.42**	**0.002**	**<PQL**	**0.270**	**27.2**	**0.065**	**66.3**	**9.21**	**26.7**	**<PQL**	**0.250**	**9.75**
C3 CCR TCLP 1	0.004	0.051	<PQL	0.237	1128	0.003	1.40	<PQL	<PQL	0.039	20.5	0.090	65.2	9.60	12.8	<PQL	0.212	10.4
C3 CCR TCLP 2	0.004	0.048	<PQL	0.210	1141	0.002	1.32	<PQL	<PQL	0.037	19.8	0.081	62.4	9.02	12.3	<PQL	0.211	9.29
C3 CCR TCLP 3	0.004	0.070	<PQL	0.231	1156	0.003	1.37	<PQL	<PQL	0.042	21.0	0.088	65.6	9.53	12.9	<PQL	0.237	9.41
C3 CCR TCLP Avg	**0.004**	**0.056**	**<PQL**	**0.226**	**1141**	**0.003**	**1.36**	**<PQL**	**<PQL**	**0.039**	**20.4**	**0.086**	**64.4**	**9.38**	**12.7**	**<PQL**	**0.220**	**9.70**
C3 C TCLP 1	0.006	0.041	<PQL	0.140	1132	0.004	2.27	<PQL	<PQL	0.036	19.7	0.066	52.0	12.6	23.8	<PQL	0.199	14.1
C3 C TCLP 2	0.006	0.039	<PQL	0.136	1166	0.003	2.30	<PQL	<PQL	0.020	19.8	0.068	53.2	12.5	23.8	0.012	0.187	14.1
C3 C TCLP 3	0.006	0.052	<PQL	0.126	1109	0.001	2.32	0.002	<PQL	0.021	18.8	0.068	53.7	12.5	24.3	0.018	0.203	16.7
C3 C TCLP Avg	**0.006**	**0.044**	**<PQL**	**0.134**	**1136**	**0.003**	**2.30**	**0.002**	**<PQL**	**0.026**	**19.4**	**0.067**	**53.0**	**12.5**	**24.0**	**0.015**	**0.196**	**15.0**

Table C-9: Elemental Concentrations in SPLP Leachate in mg L^{-1} from Mayer Ranch VFBR Solids Amended with Biochar (BC), Biosolids (BS), CCR, and the Unamended Control (C)

Sample	Ag	Al	Ar	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	Se	Zn
PQL	*0.0005*	*0.018*	*0.022*	*0.002*	*0.066*	*0.001*	*0.001*	*0.001*	*0.001*	*0.002*	*0.029*	*0.001*	*0.001*	*0.001*	*0.012*	*0.002*	*0.008*	*0.022*	*0.003*
C3 BC SPLP 1	0.002	0.062	<PQL	0.099	310	<PQL	0.191	<PQL	<PQL	0.401	18.7	0.049	38.8	1.23	16.3	2.76	<PQL	0.168	0.277
C3 BC SPLP 2	0.002	0.033	<PQL	0.093	300	<PQL	0.160	<PQL	<PQL	0.026	18.0	0.047	37.0	1.11	14.2	2.20	<PQL	0.160	0.127
C3 BC SPLP 3	0.002	0.037	<PQL	0.086	324	<PQL	0.170	<PQL	<PQL	0.031	20.6	0.052	40.0	1.23	17.6	2.53	<PQL	0.161	0.170
C3 Bc SPLP Avg	**0.002**	**0.044**	**<PQL**	**0.093**	**311**	**<PQL**	**0.174**	**<PQL**	**<PQL**	**0.153**	**19.1**	**0.049**	**38.6**	**1.19**	**16.0**	**2.50**	**<PQL**	**0.163**	**0.191**
C3 BS SPLP 1	0.002	0.040	<PQL	0.093	272	<PQL	0.071	<PQL	<PQL	0.014	11.2	0.050	40.6	0.414	17.8	2.12	<PQL	0.193	0.071
C3 BS SPLP 2	0.002	0.036	<PQL	0.077	289	<PQL	0.072	<PQL	<PQL	0.011	11.1	0.048	41.8	0.424	17.2	2.31	<PQL	0.154	0.062
C3 BS SPLP 3	0.002	0.031	<PQL	0.080	298	<PQL	0.083	<PQL	<PQL	0.059	11.6	0.051	43.2	0.408	17.2	2.66	<PQL	0.159	0.087
C3 Bs SPLP Avg	**0.002**	**0.036**	**<PQL**	**0.083**	**287**	**<PQL**	**0.076**	**<PQL**	**<PQL**	**0.028**	**11.3**	**0.050**	**41.8**	**0.416**	**17.4**	**2.36**	**<PQL**	**0.169**	**0.073**
C3 CCR SPLP 1	0.001	0.032	<PQL	0.128	234	<PQL	0.039	<PQL	<PQL	0.027	6.19	0.039	28.3	0.292	16.1	0.486	<PQL	0.152	0.150
C3 CCR SPLP 2	0.001	0.029	<PQL	0.111	239	<PQL	0.029	<PQL	<PQL	0.002	6.59	0.041	30.5	0.246	17.2	0.380	<PQL	0.153	0.108
C3 CCR SPLP 3	0.002	0.022	<PQL	0.106	265	<PQL	0.022	<PQL	<PQL	0.028	6.40	0.039	29.8	0.196	15.4	0.311	<PQL	0.176	0.084
C3 CCR SPLP Avg	**0.001**	**0.028**	**<PQL**	**0.115**	**246**	**<PQL**	**0.030**	**<PQL**	**<PQL**	**0.019**	**6.39**	**0.040**	**29.5**	**0.244**	**16.2**	**0.392**	**<PQL**	**0.160**	**0.114**
C3 C SPLP 1	0.001	0.033	<PQL	0.078	271	<PQL	0.196	<PQL	<PQL	0.009	6.61	0.050	33.2	1.75	14.5	2.10	<PQL	0.153	0.212
C3 C SPLP 2	0.001	0.026	<PQL	0.062	273	<PQL	0.231	<PQL	<PQL	0.031	7.01	0.052	34.3	2.00	15.1	2.39	<PQL	0.138	0.390
C3 C SPLP 3	0.001	0.033	<PQL	0.074	255	<PQL	0.229	<PQL	<PQL	0.010	7.47	0.053	34.8	2.01	15.3	2.30	<PQL	0.186	0.394
C3 C SPLP Avg	**0.001**	**0.031**	**<PQL**	**0.071**	**266**	**<PQL**	**0.219**	**<PQL**	**<PQL**	**0.016**	**7.03**	**0.052**	**34.1**	**1.92**	**15.0**	**2.26**	**<PQL**	**0.159**	**0.332**

Table C-10: Elemental Concentrations in FLT Leachate in mg L^{-1} from Mayer Ranch VFBR Solids Amended with Biochar (BC), Biosolids (BS), CCR, and the Unamended Control (C)

Sample	Ag	Al	Ar	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	Se	Zn
PQL	*0.0005*	*0.018*	*0.022*	*0.002*	*0.066*	*0.001*	*0.001*	*0.001*	*0.001*	*0.002*	*0.029*	*0.001*	*0.001*	*0.001*	*0.012*	*0.002*	*0.008*	*0.022*	*0.003*
C3 BC FLT 1	<PQL	0.027	<PQL	0.003	70.6	<PQL	0.086	<PQL	<PQL	0.054	9.84	0.022	13.3	0.248	8.64	1.12	<PQL	0.096	0.364
C3 BC FLT 2	<PQL	0.026	<PQL	0.002	58.4	<PQL	0.079	<PQL	<PQL	0.013	6.93	0.020	10.7	0.171	6.34	0.832	<PQL	0.096	0.068
C3 BC FLT 3	<PQL	0.037	<PQL	0.004	85.6	<PQL	0.044	<PQL	<PQL	0.047	9.66	0.022	15.2	0.191	7.55	0.730	<PQL	0.108	0.001
C3 Bc FLT Avg	**<PQL**	**0.030**	**<PQL**	**0.003**	**71.5**	**<PQL**	**0.070**	**<PQL**	**<PQL**	**0.038**	**8.81**	**0.021**	**13.1**	**0.203**	**7.51**	**0.895**	**<PQL**	**0.100**	**0.144**
C3 BS FLT 1	<PQL	0.041	<PQL	0.002	70.1	<PQL	0.021	<PQL	<PQL	0.016	5.42	0.024	17.4	0.063	8.77	0.742	<PQL	0.074	0.072
C3 BS FLT 2	0.001	0.036	<PQL	0.007	138	<PQL	0.029	<PQL	<PQL	0.033	10.1	0.032	29.3	0.103	15.3	1.22	<PQL	0.161	0.084
C3 BS FLT 3	<PQL	0.047	<PQL	0.006	119	<PQL	0.034	<PQL	<PQL	0.006	7.59	0.031	26.5	0.093	12.0	1.06	<PQL	0.160	0.072
C3 Bs FLT Avg	**0.001**	**0.041**	**<PQL**	**0.005**	**109**	**<PQL**	**0.028**	**<PQL**	**<PQL**	**0.018**	**7.71**	**0.029**	**24.4**	**0.087**	**12.0**	**1.01**	**<PQL**	**0.132**	**0.076**
C3 CCR FLT 1	<PQL	0.070	<PQL	0.103	156	<PQL	0.010	<PQL	<PQL	0.024	6.25	0.027	21.9	0.089	13.4	0.151	<PQL	0.132	0.056
C3 CCR FLT 2	<PQL	0.070	<PQL	0.108	112	<PQL	0.007	<PQL	<PQL	0.002	4.98	0.022	16.7	0.070	12.0	0.129	<PQL	0.120	0.039
C3 CCR FLT 3	<PQL	0.084	<PQL	0.102	84.0	<PQL	0.006	<PQL	<PQL	0.050	3.78	0.019	11.5	0.056	9.32	0.092	<PQL	0.127	0.048
C3 CCR FLT Avg	**<PQL**	**0.075**	**<PQL**	**0.104**	**117**	**<PQL**	**0.007**	**<PQL**	**<PQL**	**0.025**	**5.00**	**0.023**	**16.7**	**0.071**	**11.6**	**0.124**	**<PQL**	**0.126**	**0.047**
C3 C FLT 1	<PQL	0.037	<PQL	<PQL	68.9	<PQL	0.080	<PQL	<PQL	0.006	4.33	0.023	13.7	0.473	8.13	0.956	<PQL	0.108	0.172
C3 C FLT 2	<PQL	0.028	0.029	<PQL	51.3	<PQL	0.057	<PQL	<PQL	0.003	2.64	0.019	8.49	0.298	5.64	0.637	<PQL	0.082	0.031
C3 C FLT 3	<PQL	0.032	0.038	<PQL	69.0	<PQL	0.062	<PQL	<PQL	0.006	3.40	0.023	12.6	0.413	7.89	0.752	<PQL	0.108	0.067
C3 C FLT Avg	**<PQL**	**0.032**	**0.033**	**<PQL**	**63.0**	**<PQL**	**0.066**	**<PQL**	**<PQL**	**0.005**	**3.45**	**0.022**	**11.6**	**0.395**	**7.22**	**0.781**	**<PQL**	**0.099**	**0.090**

Table C-11: Elemental Concentrations in TCLP Leachate in mg L^{-1} from Southeast Commerce VFBR Solids Amended with Biochar (BC), Biosolids (BS), CCR, and the Unamended Control (C)

Sample	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Ni	Pb	Se	Zn
PQL	*0.0005*	*0.018*	*0.022*	*0.002*	*0.052*	*0.001*	*0.002*	*0.001*	*0.001*	*0.002*	*0.029*	*0.014*	*0.001*	*0.001*	*0.002*	*0.017*	*0.022*	*0.003*
VFBR BC TCLP 1	0.004	1.02	<PQL	0.061	551	0.003	4.60	0.016	<PQL	1.61	24.3	0.040	35.3	13.3	37.5	<PQL	0.093	178
VFBR BC TCLP 2	0.002	2.06	<PQL	0.034	654	0.004	5.41	0.013	<PQL	22.9	13.6	0.036	32.7	14.7	45.3	<PQL	<PQL	191
VFBR BC TCLP 3	0.003	0.950	<PQL	0.052	563	0.003	4.23	0.014	<PQL	1.52	24.6	0.039	31.8	12.6	35.1	<PQL	0.076	172
VFBR Bc TCLP Avg	**0.003**	**1.34**	**<PQL**	**0.049**	**589**	**0.004**	**4.75**	**0.014**	**<PQL**	**8.69**	**20.9**	**0.038**	**33.3**	**13.6**	**39.3**	**<PQL**	**0.084**	**180**
VFBR BS TCLP 1	0.003	1.38	<PQL	0.066	552	0.008	4.82	0.018	<PQL	1.86	10.8	0.042	44.2	15.1	39.0	<PQL	0.071	219
VFBR BS TCLP 2	0.003	1.30	<PQL	0.059	604	0.007	4.52	0.014	<PQL	1.96	10.1	0.039	38.6	13.7	36.4	<PQL	0.072	205
VFBR BS TCLP 3	0.003	1.33	<PQL	0.059	590	0.006	4.49	0.014	<PQL	1.98	10.6	0.041	39.7	13.9	35.9	<PQL	0.074	191
VRBR Bs TCLP Avg	**0.003**	**1.34**	**<PQL**	**0.061**	**582**	**0.007**	**4.61**	**0.016**	**<PQL**	**1.93**	**10.5**	**0.041**	**40.8**	**14.2**	**37.1**	**<PQL**	**0.073**	**205**
VFBR CCR TCLP 1	0.006	3.59	<PQL	0.093	1211	0.006	3.16	0.008	<PQL	0.874	12.5	0.053	61.8	12.1	26.9	<PQL	0.083	28.7
VFBR CCR TCLP 2	0.004	3.74	<PQL	0.079	1168	0.004	3.04	0.009	<PQL	0.883	12.4	0.054	63.0	11.2	26.2	<PQL	0.100	32.2
VFBR CCR TCLP 3	0.006	3.75	<PQL	0.080	1093	0.004	2.90	0.009	<PQL	0.934	12.3	0.053	61.9	10.8	25.0	<PQL	0.081	28.7
VRBR CCR TCLP Avg	**0.005**	**3.70**	**<PQL**	**0.084**	**1157**	**0.005**	**3.04**	**0.009**	**<PQL**	**0.897**	**12.4**	**0.054**	**62.2**	**11.4**	**26.0**	**<PQL**	**0.088**	**29.9**
VFBR C TCLP 1	0.004	1.15	<PQL	0.060	664	0.004	4.87	0.013	<PQL	2.42	10.2	0.044	39.2	15.7	39.9	<PQL	0.074	145
VFBR C TCLP 2	0.004	0.952	<PQL	0.058	573	0.003	4.45	0.013	<PQL	2.00	10.6	0.042	36.7	14.6	36.9	<PQL	0.064	114
VFBR C TCLP 3	0.004	0.944	<PQL	0.048	615	0.003	4.57	0.012	<PQL	2.40	10.5	0.040	36.8	14.7	37.7	<PQL	0.083	114
VRBR C TCLP Avg	**0.004**	**1.01**	**<PQL**	**0.055**	**618**	**0.004**	**4.63**	**0.013**	**<PQL**	**2.28**	**10.4**	**0.042**	**37.6**	**15.0**	**38.2**	**<PQL**	**0.074**	**125**

Table C-12: Elemental Concentrations in SPLP Leachate in mg L^{-1} from Southeast Commerce VFBR Solids Amended with Biochar (BC), Biosolids (BS), CCR, and the Unamended Control (C)

Sample	Ag	Al	As	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	Se	Zn
PQL	*0.0005*	*0.018*	*0.022*	*0.002*	*0.052*	*0.001*	*0.002*	*0.001*	*0.001*	*0.002*	*0.029*	*0.014*	*0.001*	*0.001*	*0.012*	*0.002*	*0.017*	*0.022*	*0.003*
VFBR BC SPLP 1	0.003	2.41	<PQL	0.068	304	0.011	6.62	0.011	0.007	36.5	20.8	0.049	39.8	14.7	15.2	62.8	0.038	0.111	314
VFBR BC SPLP 2	0.004	1.31	<PQL	0.068	237	0.004	5.36	0.026	0.004	2.66	40.2	0.056	42.3	13.0	verrang	50.5	0.056	0.360	304
VFBR BC SPLP 3	0.003	2.42	<PQL	0.051	287	0.008	6.50	0.013	0.003	34.5	21.0	0.049	42.5	14.8	15.3	62.2	0.041	0.083	320
VRBR Bc SPLP Avg	**0.004**	**2.04**	**<PQL**	**0.062**	**276**	**0.008**	**6.16**	**0.017**	**0.005**	**24.5**	**27.3**	**0.051**	**41.5**	**14.2**	**15.2**	**58.5**	**0.045**	**0.185**	**313**
VFBR BS SPLP 1	0.002	3.42	<PQL	0.061	296	0.014	6.54	0.008	0.004	43.6	8.37	0.047	46.3	15.4	15.0	60.8	0.038	0.134	387
VFBR BS SPLP 2	0.003	3.56	<PQL	0.063	302	0.014	6.74	0.007	0.003	44.6	8.49	0.050	49.0	16.0	15.5	62.8	0.044	0.099	391
VFBR BS SPLP 3	0.003	3.75	<PQL	0.056	324	0.013	7.07	0.013	0.003	43.8	9.30	0.052	53.4	17.1	16.6	65.6	0.062	0.047	394
VRBR Bs SPLP Avg	**0.003**	**3.58**	**<PQL**	**0.060**	**307**	**0.014**	**6.78**	**0.009**	**0.004**	**44.0**	**8.72**	**0.050**	**49.6**	**16.1**	**15.7**	**63.1**	**0.048**	**0.093**	**391**
VFBR CCR SPLP 1	0.003	0.109	<PQL	0.072	406	<PQL	1.55	<PQL	<PQL	0.036	8.61	0.048	68.8	2.96	19.4	15.6	<PQL	0.416	15.6
VFBR CCR SPLP 2	0.003	0.080	<PQL	0.073	446	<PQL	1.60	<PQL	<PQL	<PQL	9.91	0.054	75.9	3.00	22.8	16.0	<PQL	0.326	11.1
VFBR CCR SPLP 3	0.002	0.071	0.032	0.072	427	<PQL	1.49	<PQL	<PQL	<PQL	8.87	0.049	69.3	2.79	19.5	14.9	<PQL	0.372	10.6
VFBR CCR SPLP Avg	**0.003**	**0.087**	**0.032**	**0.073**	**426**	**<PQL**	**1.54**	**<PQL**	**<PQL**	**0.036**	**9.13**	**0.050**	**71.3**	**2.91**	**20.6**	**15.5**	**<PQL**	**0.371**	**12.4**
VFBR C SPLP 1	0.003	2.34	<PQL	0.072	286	0.009	6.11	0.010	0.001	48.1	7.95	0.047	35.9	14.1	14.7	58.9	0.043	0.131	290
VFBR C SPLP 2	0.004	2.65	<PQL	0.058	311	0.011	6.96	0.016	0.001	46.5	8.68	0.054	45.5	16.4	17.0	65.7	0.059	0.120	305
VFBR C SPLP 3	0.004	2.77	<PQL	0.050	354	0.011	7.18	0.017	0.001	52.5	9.02	0.058	49.2	17.4	18.3	69.1	0.054	0.091	311
VRBR C SPLP Avg	**0.004**	**2.58**	**<PQL**	**0.060**	**317**	**0.010**	**6.75**	**0.014**	**0.001**	**49.0**	**8.55**	**0.053**	**43.5**	**16.0**	**16.7**	**64.6**	**0.052**	**0.114**	**302**

Table C-13: Elemental Concentrations in FLT Leachate in mg L^{-1} from Southeast Commerce VFBR Solids Amended with Biochar (BC), Biosolids (BS), CCR, and the Unamended Control (C)

Sample	Ag	Al	Ar	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Pb	Se	Zn
PQL	*0.0005*	*0.018*	*0.022*	*0.002*	*0.052*	*0.001*	*0.002*	*0.001*	*0.001*	*0.002*	*0.029*	*0.014*	*0.001*	*0.001*	*0.012*	*0.002*	*0.017*	*0.022*	*0.003*
VFBR BC FLT 1	0.003	2.25	<PQL	<PQL	204	0.011	7.08	0.018	0.003	23.6	22.1	0.050	48.7	16.8	15.2	66.8	0.057	0.204	321
VFBR BC FLT 2	0.003	2.07	<PQL	<PQL	196	0.010	6.90	0.022	0.002	22.7	20.3	0.046	42.2	15.4	13.7	65.5	0.056	0.221	317
VFBR BC FLT 3	0.003	2.24	<PQL	<PQL	191	0.009	7.33	0.022	0.003	20.7	21.6	0.050	47.5	16.8	15.3	68.6	0.072	0.196	325
VRBR Bc FLT Avg	**0.003**	**2.19**	**<PQL**	**<PQL**	**197**	**0.010**	**7.10**	**0.021**	**0.003**	**22.3**	**21.3**	**0.049**	**46.1**	**16.3**	**14.7**	**66.9**	**0.061**	**0.207**	**321**
VFBR BS FLT 1	0.002	3.06	<PQL	<PQL	180	0.024	7.06	0.019	0.013	31.4	8.57	0.048	51.9	17.4	14.7	65.3	0.088	0.178	377
VFBR BS FLT 2	0.002	2.52	<PQL	<PQL	122	0.022	6.38	0.014	0.008	25.4	6.59	0.040	45.6	15.6	12.5	59.5	0.062	0.197	356
VFBR BS FLT 3	0.003	2.66	<PQL	<PQL	144	0.021	6.86	0.018	0.006	24.6	7.71	0.046	50.3	17.1	14.1	64.1	0.077	0.202	339
VRBR Bs FLT Avg	**0.003**	**2.75**	**<PQL**	**<PQL**	**149**	**0.023**	**6.77**	**0.017**	**0.009**	**27.1**	**7.62**	**0.044**	**49.3**	**16.7**	**13.8**	**62.9**	**0.076**	**0.192**	**357**
VFBR CCR FLT 1	0.001	0.077	<PQL	0.057	151	<PQL	0.539	<PQL	0.004	0.052	6.42	0.031	51.8	0.957	13.7	5.74	<PQL	0.283	4.27
VFBR CCR FLT 2	0.001	0.124	<PQL	0.051	164	<PQL	0.611	<PQL	0.002	0.028	6.59	0.032	53.1	1.06	14.5	6.54	<PQL	0.313	6.33
VFBR CCR FLT 3	0.001	0.113	<PQL	0.061	180	<PQL	0.593	<PQL	0.001	0.136	6.57	0.032	52.0	0.994	14.2	6.27	<PQL	0.323	5.01
VFBR CCR FLT Avg	**0.001**	**0.105**	**<PQL**	**0.056**	**165**	**<PQL**	**0.581**	**<PQL**	**0.003**	**0.072**	**6.52**	**0.032**	**52.3**	**1.00**	**14.1**	**6.19**	**<PQL**	**0.307**	**5.20**
VFBR C FLT 1	0.004	1.55	<PQL	<PQL	187	0.009	6.47	0.010	0.002	24.9	8.72	0.040	46.8	16.5	16.1	60.8	0.087	0.200	227
VFBR C FLT 2	0.004	1.52	<PQL	<PQL	172	0.009	6.38	0.014	0.003	24.1	8.50	0.040	45.8	16.4	16.2	60.0	0.079	0.267	223
VFBR C FLT 3	0.004	1.67	<PQL	<PQL	204	0.010	6.82	0.017	0.001	29.6	9.33	0.044	50.4	17.7	18.0	64.2	0.086	0.193	225
VFBR C FLT Avg	**0.004**	**1.58**	**<PQL**	**<PQL**	**187**	**0.009**	**6.56**	**0.014**	**0.002**	**26.2**	**8.85**	**0.041**	**47.7**	**16.9**	**16.8**	**61.7**	**0.084**	**0.220**	**225**