LEACHABILITY AND SORPTIVITY OF INCINERATED BIOSOLID ASH

by

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ABSTRACT

WILLIAM ANTHONY BOIVIN. Leachability and sorptivity of incinerated biosolid ash.
(Under the direction of DR. JOHN L. DANIELS)

The byproduct of incinerated biosolids (biosolid ash) was evaluated for land application through laboratory and field testing of leachability and sorption capacity. Field testing involved vacuum lysimeters that were installed to monitor the leachate composition. All constituents detected by these lysimeters were below regulatory limits with the exception of one sample with manganese and silver above the limit.

Laboratory column leaching tests were performed using the biosolid ash. Six elements, manganese, nickel, selenium, arsenic, lead, and silver, leached out of the columns at concentrations above the regulatory limits. All but arsenic returned to safe limits after the first 0.2 L/S ratio. Arsenic remained above the limit from 0 – 4.5 L/S ratio. Leachability results derived from the laboratory were different from field measurements during the first 2 L/S ratios collected. There were several field conditions which were not replicated in the laboratory and may explain the variance. In the field, biosolid ash was land applied six months prior to the installation of instrumentation and data collection. Based on precipitation records, estimated thickness, porosity, and using 100% infiltration (evapotranspiration rates not known for time period) approximately 1.8 pore volumes of infiltration passed through the biosolid ash prior to lysimeter installation resulting in no data for the first flush of the system. This would have been equivalent to a first flush where the pore fluids may contain higher constituent concentrations. Compacted dry biosolid ash density in the field was estimated at 7.775 kN/m^3 (49.5 pcf) while in the laboratory it was 9.897 kN/m^3 (63 pcf). This difference affects leachability results through concomitant changes in the seepage velocity and contaminant retardation. Similarly, column experiments were conducted under saturated conditions while in the field this degree of saturation varied from approximately 13% to 61%.

The leachate composition from field and laboratory leaching tests was compared with groundwater regulations to determine contaminants of concern. These contaminants (arsenic, manganese, phosphorus, and selenium) were then synthetically prepared by mixing with deionized (DI) water and used in laboratory column studies to evaluate the sorption capacity of site soils. The estimated Kd for selenium is between 2 and 4 mL/g. No Kd could be determined for the other constituents although their absence in the effluent suggests a value greater than this range.

Several physical characteristics were determined including particle size analysis, moisture content, proctor test, loss of ignition, permeability, and specific gravity. The values were similar to the literature.

A comparison between coal fly ash, municipal solid waste ash (MSW), and biosolid ash was conducted. The physical characteristics were all similar except particle size. Coal fly ash had significantly smaller particles passing a No. 200 sieve. The primary differences between the three ash categories was the elemental composition. Both coal fly ash and MSW ash had significantly higher concentrations of numerous constituents while biosolid ash was significantly higher only in phosphorus according to literature as well as these results.

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CHAPTER 1: INTRODUCTION

1.1 Background

The current world population is 7.4 billion people with the United States population approximately 321.4 million people. The impact on the environment was not realized until the 1960s and 1970s. Regulations and laws have been passed beginning with the Resource Conservation and Recovery Act (RCRA) adopted in 1976 to protect the environment from further devastation and misuse. In 1991 the United States Environmental Protection Agency (USEPA) promulgated the Biosolids Rules as 40 CFR Part 503 and these rules initiated a comprehensive, nationwide effort to manage biosolids.

The purpose of federal regulation 40 CFR Part 503 is to establish standards concerning the generation and disposal of domestic sewage sludge. The regulations establish standards for the pollutant limits, management practices, operational standards, and disposal of the biosolid sludge. However, there is room for improvement on the regulations. As 40 CFR Part 503 is currently written, regulations exist only governing issues such as air emissions, effluent discharge, and waste disposal for sewage sludge. The regulations do not specify how to re-use or dispose of the incinerated biosolid ash. Regulation 40 CFR Part 503 Subpart E set the standards for incineration of biosolids outlining the pollutant limits pertaining to air emissions. No federal regulations oversee the disposal or provide for the re-use of the biosolid ash nor does it disallow for beneficial use of incinerated biosolid ash such as for land amendment (EPA 2001).

In fact very few regulations oversee the disposal of incineration ash at all. Municipal solid waste (MSW) is governed by regulation 40 CFR Part 258 which oversees the operations, emissions, groundwater, and closure of the landfill. However, there is no reference as to the disposal of MSW ash nor are the concentration maximums of the regulatory metals specified beyond passing either Method 1311: Toxicity Characteristic Leaching Protocol (TCLP) or Method 1312: Synthetic Precipitation Leaching Procedure (SPLP). Regulation 40 CFR Part 60 outlines the operations and the emission standards for incinerating MSW. As with the biosolid ash regulations there is no specifications for either disposal or re-use of the MSW ash (EPA 1991).

The incineration ash that has garnered much public attention is coal combustion residuals (CCR). Over the past decade there have been three major coal ash spills: 1) Pennsylvania Power and Light, Martins Creek Station, 2) Tennessee Valley Authority, Kingston Fossil Plant, 3) Duke Energy, Dan River Station. This has spurred both government and environmental groups in pursuing more stringent regulations for disposal and re-use of CCRs (Daniels 2016). The EPA released 40 CFR Parts 257 and 261 in May, 2015 updating regulations for CCRs. The new regulations define how CCRs may be used although the maximum allowable concentrations of constituents of interest are controlled by both the drinking water and groundwater regulatory limits (EPA 2015).

In North Carolina, NCDEQ is currently classifying all ash, including biosolid sewage sludge ash, under the CCR regulations regardless of the concentrations of regulatory metals contained in the biosolid ash. Part of the motivation for this research is to explore the differences in both physical and chemical composition of biosolid ash, MSW ash, and coal fly ash.

As the population continues to grow, it requires an increase in water treatment, municipal waste collection and disposal, recycling, composting, and wastewater treatment. However, how should the waste be disposed of or should it be? Governments around the world have realized that what has traditionally been considered waste may be reused through recycling, incineration to energy capture, and reengineering. Many European countries, Germany, China, and Japan use incineration of waste as part of the energy recovery system to feed back into the grid (Schaum et al. 2007). The majority of waste used for energy recapture have been municipal waste however, scientists and engineers are investigating the possibilities of incinerating municipal sewage sludge/biosolids.

Traditionally, wastewater treatment facilities disposed of the sludge through two primary methods: landfills and agricultural land application. In 2015, approximately 28% of the biosolids were landfilled, 36% used for agricultural purposes, 11% for class A products, 15% incinerated, 2% reclamation and forestry, 2% for monofill, and 6% for other uses (Center for Sustainable Systems 2015). In many countries, the practice using biosolids for agricultural purposes is diminishing due to the high amount of phosphorus, nitrogen, and other constituents of concern. The high concentrations of phosphorus and nitrogen run off from farmland and find their way to surface bodies of water. The increase in available nutrients in the surface water may result in increased biological activity leading to possible depletion of dissolved oxygen in the water.

In 1999, concern for the excess nutrients running off of agricultural lands was essential in the development and implementation of the Comprehensive Nutrient Management Plan (CNMP) that would address the pollutants (Environmental Management Commission Raleigh 2006). Section C in the CNMP outlines the requirements for land application of nutrients and organic by-products (NRCS 2008). The criteria for nutrient management include:

- Meet policy in the general manual (Title 190, Part 402)
- Meet criteria from the nutrient management (Code 590), waste utilization (Code 633), and irrigation waste management (Code 449)
- Develop a nutrient budget for phosphorus, potassium, and nitrogen
- Document implementation activities of nutrient management plan

In the United States biosolid incineration started in the late 1960s however it fell from favor due to public disapproval (Hudson 2005; Roy et al. 2011). Therefore, research into the composition and environmental impact of biosolid incinerated ash was limited. Currently, there are no states that have regulations pertaining to biosolid ash land application or amendment. In North Carolina, Department of Environmental Quality (NCDEQ) currently classify all incinerated ash under Session Law 2014-122 Coal Ash Management Act.

This thesis will evaluate the potential for the biosolid incinerated ash to be used for land amendment. To determine the environmental impact of land amendment on the environment and groundwater 15A NCAC 02L.0202 Groundwater Quality Standard was used. The regulation states the maximum allowable concentration levels of regulated constituents (Environmental Management Commission Raleigh 2013). The re-use of the biosolid ash for land amendment will allow for biofuel crops to be grown however groundwater regulatory limits must be observed. Plants require sixteen nutrients to thrive: three nutrients available in the atmosphere, three macronutrients, three secondary nutrients, and seven micronutrients. Three of the nutrients come from the atmosphere and water including carbon, hydrogen, and oxygen. The primary nutrients also referred to the macro nutrients include nitrogen, phosphorus, and potassium usually requiring fertilizers to add necessary levels to the soil. The secondary nutrients include calcium, magnesium, and sulfur which are required in smaller quantities although with improvements in air emissions regulations there may be a need for additional quantities added to the soil. The micronutrients needed in small quantities include boron, chlorine, copper, iron, manganese, molybdenum, and zinc. The micronutrients are required for the plants to thrive and may need to be added to the soil (Tucker 1999). The biosolid ash contains all of the nutrients required except for nitrogen, sulfur, and chlorine.

The Water and Sewer Authority of Cabarrus County (WSACC) incinerates the sludge produced during regular operations and has proposed using the ash to amend land for biofuel crop production. The test site was located at the Rocky River Regional Wastewater Treatment Plant (RRRWWTP) in Cabarrus County, NC. Shown in Figure 1. Also shown on the drawing is the topography of the site, proposed grade modified for biosolid ash as fill, and sedimentation basins.

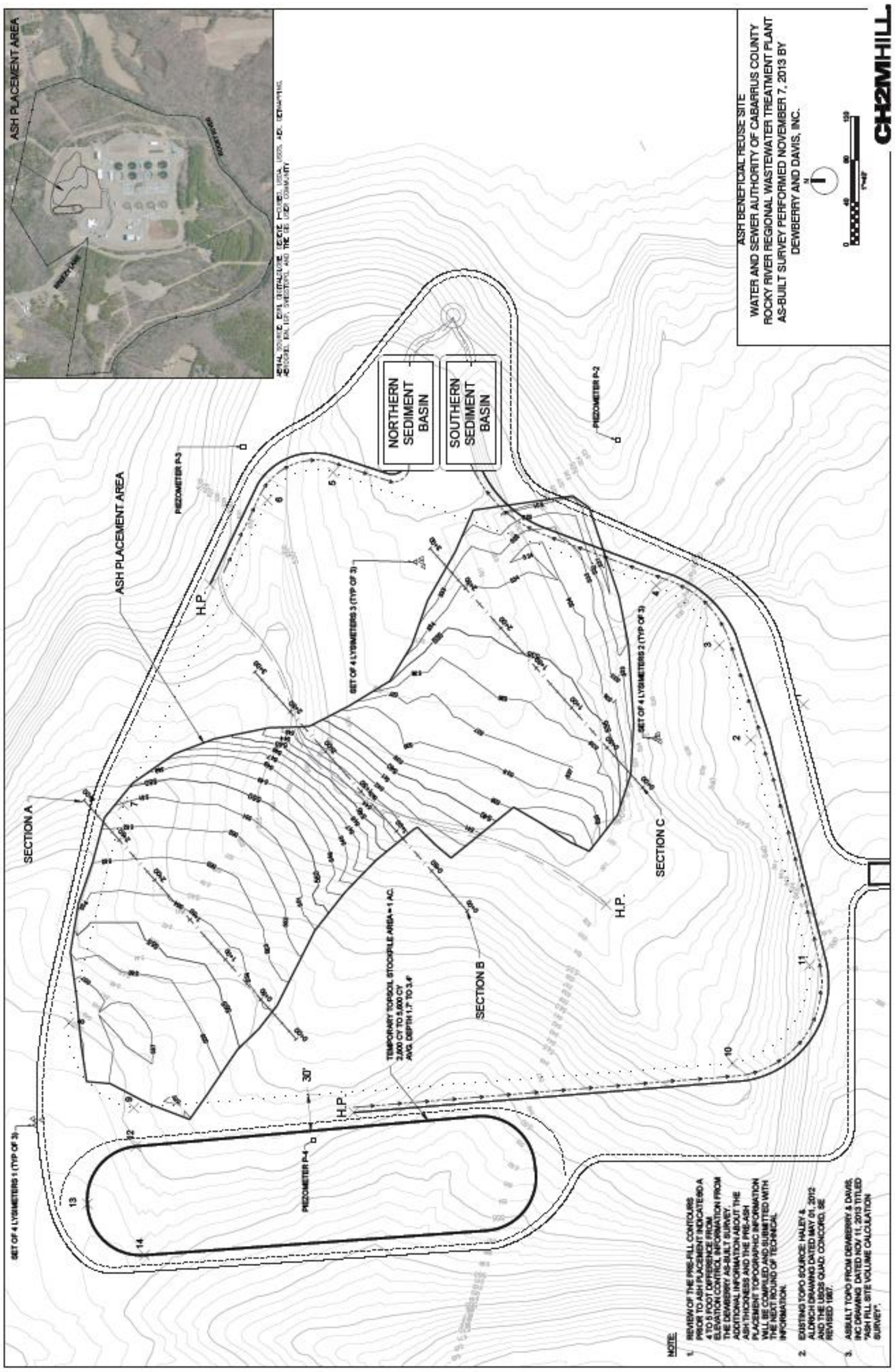


Figure 1: Rocky River Wastewater Treatment Plant biosolid ash application site plan view

1.2 Project Description

The RRRWWTP had reached the storage limit onsite of 19,114 m^3 for the biosolid incinerated ash and wanted to use it to amend the uneven landscape onsite shown in Figure *2*.

Figure 2: RRRWWTP biosolid ash application site during initial preparations before applying biosolid ash

Due to limitations from the permit issued by NCDEQ, WSACC needed an evaluation to determine the leaching characteristics of the biosolid ash. The leaching data combined with the physical characteristics of the biosolids ash were intended to inform both NCDEQ and WSACC to develop appropriate regulations concerning the use of biosolid ash for land amendment.

There are primarily two methods currently used for incineration, multiple hearth furnaces (MHF) and fluidized bed furnaces (FBF) (EPA 2005). RRRWWTP uses a seven tier hearth furnace to incinerate the biosolids similar to the one shown in Figure *3*.

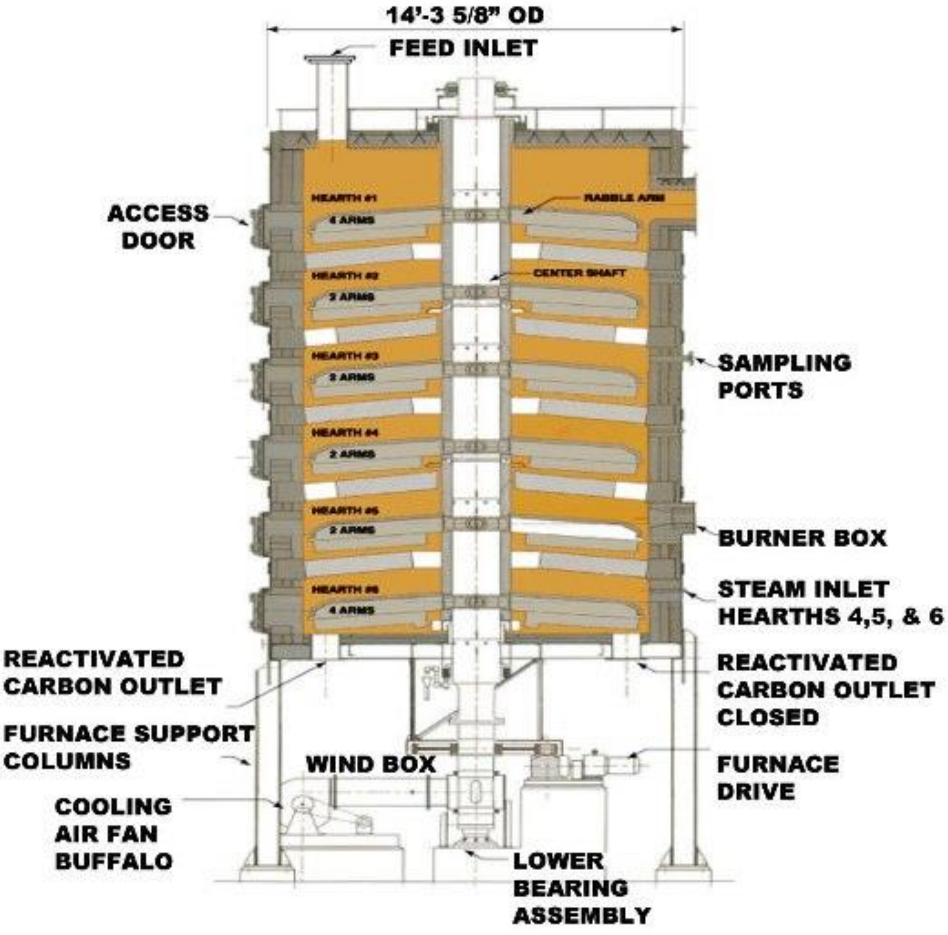


Figure 3: Multiple hearth furnace design

The multiple hearth furnace has an outer shell of steel lined with heat-resistant material. A hollow shaft runs through the center of the furnace allowing for cool air to flow upwards through the hearth levels. Each hearth level/tier is equipped with rabble arms used to rake the biosolids in a spiral motion that is alternated between tiers. The depth of sludge on each hearth tier is approximately 2.54 cm according the biosolids design flow rate. The dewatered biosolids is fed onto the perimeter of the upper most hearth tier and slowly raked towards the center and then dropped to the next tier through holes. The incineration process becomes self-sustaining with biosolids dewatered to less than 35% water content and optimized when dewatered to less than 15% (Spinosa et al. 2011).

The hearths are divided into three sections: upper (drying zone), middle (combustion zone), and the lower (cooling zone). The upper zone temperature is typically between 425° - 760° C and removes the remaining moisture from the biosolids. The temperature in the middle zone is approximately 925° C incinerating solids, volatile gases, and fixed carbon. The lower zone is cooled through heat exchange with the cooling air entering the system.

Once the ash is discharged from the furnace it is sluiced with water and pumped out to settling ponds. After a period of time (usually months) the water is pumped from the ponds and the ash is removed to a dry containment area to await relocation to a disposal location, a local Title D landfill or to be utilized as a soil amendment/soil builder.

Although the focus of research is to evaluate the land amendment applications of the ponded biosolid ash, it is important to understand how the composition of the ash varies throughout the incineration process. Samples of the biosolid ash were collected from three major steps during the process:

- fresh, dry biosolid ash (FBA), was collected after incineration before sluicing
- sluiced biosolid ash (SBA) collected where the sluiced ash enters the pond
- aged wet biosolid ash from the containment pond (PBA), collected from an older area of the pond

Although the FBA would have the highest concentration of constituents before leaching, the facility applies water to the fresh ash to cool and move the ash through the system. The SBA would then be placed in the pond. This material was used for lab experimentation to observe leaching after the material is sluiced and exits the hearth system.

1.3 Research Objectives

The objectives of this research were: 1) determine the leaching characteristics of the biosolid ash at natural pH including the concentrations of any regulatory metals and phosphorus, 2) compare the field leaching characteristics to laboratory leaching, 3) Compare field and laboratory sorption behavior, 4) Compare biosolid incineration ash, municipal solids ash, and coal fly ash.

CHAPTER 2: LITERATURE REVIEW

2.1 Biosolid Sludge

Biosolids have been used for decades for agricultural land applications due to the high phosphorus and nitrogen concentrations (Zvomuya et al. 2005). Much concern has been raised about the heavy metals and nutrients mobility that might contaminant the ground water or surface water. Phosphorus mobility is low compared to other nutrients and the retention of phosphorus in most soils is high (Jalali and Karamnejad 2011). Phosphorus losses due to agricultural drainage results in an inefficient utilization of fertilizer and increases the likelihood that the phosphorus will contribute to eutrophication of rivers and estuaries (Weaver et al. 1988). The water-extractable phosphorus content in biosolids is typically less than five percent. However, the phosphorus is not necessarily agronomically available (Chinault and O'Connor 2008). The characterization of biosolids vary significantly depending on wastewater composition, the treatment process, and the age of the biosolids (Arulrajah et al. 2011).

2.2 Biosolid Incineration Ash

There has been research performed on several beneficial reuses of the biosolid ash in Europe, Germany, Japan, and the U.S. The biosolid ash has been used as a filler in both cement and brick manufacturing, road construction in the subbase material, used as pellets for landfill covers, and ingredients in the footing at athletic facilities (EPA 2005; Tempest and Pando 2013).

The incineration of biosolid ash has several advantages and a few disadvantages. The primary benefit to incineration is a significant volume reduction of up to 95% (EPA 2005; Roy et al. 2011). The organic matter and the majority of carbon has been removed through the incineration process (Biswas et al. 2009; Pettersson et al. 2008). The odor normally associated with wastewater sludge is minimized. The more stringent emissions regulations alleviate most of the public skepticism surrounding incineration. The multiple hearth furnace is most energy efficient if continually run and fed biosolids. While continually operating there is potential for energy recovery allowing for even more efficiency in the incineration system (Stillwell et al. 2010). Biosolids may become a sought after as a source for renewable energy and produce carbon credits (Wang et al. 2008).

The disadvantages of the incineration process includes a high capital investment and the annual operating cost depends on fuel cost (EPA 2005). The consumption of non-renewable resources by definition makes the process unsustainable long term. There is limited possibilities for use in areas of poor air quality. Downtime for repairs could potentially cost treatment plants significantly. The characteristics of biosolids from even the same treatment plant may vary over time resulting in different biosolid ash compositions (Arulrajah et al. 2011). Some experts believe that the potential for land application of biosolid ash may be limited (Wang et al. 2008).

2.3 Biosolid Ash Characteristics

As mentioned previously there will be some variation in the physical characteristics. The particle size distribution of the incinerated biosolid ash was 35% 75-150 μm and 34% 53-75 μm. The particle surface area is approximately 4.7 m^2/g (Biswas et al. 2009). The pH of incinerated biosolid ash ranges between 6 – 12 but mainly alkaline (Ai-Sharif and Attom 2014). These authors have noted that the biosolid ash is a silty-sand material containing very low organic content. And they have indicated that there is no plasticity, the permeability is approximately 10^{-6} cm/sec. Several studies have been conducted that have concluded that trace metal concentrations are not a source of measureable leaching issues (Ai-Sharif and Attom 2014). The loss of ignition ranged between 1.3% to 13% by weight (Cheeseman et al. 2003; Tempest and Pando 2013).

Table 1 summarizes relevant findings on the characterization of biosolids ash. It lists the authors, topic, and findings of each paper with similar topics grouped together alphabetically.

Table 1: Literature Review

Authors/Year	**Topic/Focus/ Purpose**	**Findings**
Biosolid Incinerated Ash		
(Ai-Sharif and Attom 2014)	Geoenvironmental applications of biosolid incinerated ash	Soil stabilizing agent Incineration eliminated N and organic matter Increased P, Ca, and Mg No plasticity Numerous studies indicate that the trace metal concentrations are not excessive and will not be a measureable leaching problem

(Arulrajah et al. 2011)	Chemical and engineering properties of biosolids	Characteristics of biosolids vary around the world based on numerous factors
(Benitez et al. 2001)	Biosolid ash as source of heavy metal in plant-soil systems	Incineration produces sterile ash (organics destroyed) Study used wheat plants with digested biosolids, composted biosolids, and biosolid ash The addition of biosolid ash significantly increased root growth compared to the other two types of biosolid
(Dangtran et al. 2000)	Comparison of fluid bed and multiple hearth biosolid incineration	Multiple hearth system sensitive to any changes in the feed such as moisture and speed Multiple hearth furnace system specifications
(Federal Highway Administration Research and Technology Coordinating 1997)	Sewage sludge ash characteristics	Gradation, particle size, LOI, moisture content, specific gravity, plasticity index, and permeability Elemental concentrations
(Krogmann et al. 1997)	Biosolids management	Significant overlap of the drying, devolatilization, and combustion processes Up to 80% of sludge carbon is volatile Sludge combustion was dominated by gas phase combustion of the volatiles
(Paramasivam et al. 2003)	Elemental transport in soil amended with biosolid ash	Results indicate that biosolid ash may be used for soil amendment at low to medium rates without potential loading of metals into the groundwater Metal concentrations increased in the column leaching studies with increased soil amendment 60-70% of cumulative leaching occurred during the first 6-8 leaching events
(Roy et al. 2011)	Biosolid management options	Major constraint in the widespread use of incineration is the public concern Landfill more costly disposal option Biosolid incineration offers advantages compared to other treatment alternatives such as significant volume reduction and minimizing odor

(Tempest and Pando 2013)	Characterization and demonstration of re-use applications of biosolid ash	Two beneficial re-use options: admixture for fired clay brick and geotechnical ground improvement soil admixture Possible re-use non-human consumption agricultural application
(Wang et al. 2008)	Technological options for biosolid management	Multiple-hearth furnace Issues associated with biosolid incineration include quality inconsistency, need for biosolid handling system, and reduced boiler capacity because of high moisture Majority of biosolid incineration operations are net energy users
(Yoshida et al. 2013)	Life cycle assessment of sewage sludge management	Sewage sludge management poses both financial and planning challenges for wastewater treatment plants
Phosphorus		
(Esteller et al. 2009)	Nitrate and phosphorus leaching from biosolids	Biosolid characteristics
(Franz 2008)	Phosphate fertilizer from biosolid ash	Phosphates are a limited non-renewable resource The amount of phosphorus in biosolid ash is as high as in natural occurring ore
(Ito et al. 2013)	Separation of metals and phosphorus from biosolid ash	Direct application of biosolid ash to agricultural land Possible phosphorus recovery from biosolid ash
(Jacobs and McCreary 2003)	Utilizing biosolids on agricultural land	Incineration reduces biosolid volume, kills pathogens, and destroys most organic chemicals Majority of phosphorus in biosolids are in inorganic form
(Jeanmaire and Evans 2001)	Feasibility of phosphorus recovery from municipal wastewater	Phosphorus recovery from wastewater sludge would reduce incineration ash by 12-48%
(Kiggundu et al. 2010)	Phosphorus adsorption by ceramic suction lysimeters	Phosphorus concentrations are lower with ceramic lysimeters due to adsorption. The lysimeters must be soaked in phosphorus bath to minimize adsorption
(NCSU)	Phosphorus criteria for North Carolina	Phosphorus limits for surface water bodies in NC Phosphorus analytical techniques

(Tan and Lagerkvist 2011)	Phosphorus recovery from biosolid ash	Sustainable methods for phosphorus recovery Phosphorus is enriched in fly ash along with trace metals Biosolid ash has a relatively high phosphorus concentration
MSW Ash		
(Alhassan 2012)	MSW bottom ash characteristics and beneficial use	Excavated MSW, characterized it, then incinerated it (Nigeria) Geotechnical properties of the bottom ash including specific gravity, optimum moisture content, maximum dry density, gradation, particle size, Atterberg limit, permeability, and CBR Chemical composition
(Jung et al. 2004)	Identify the distribution of metals and the influential factors in MSW ash (Japan)	Shredded bulky waste has higher concentrations of Cd and Pb Considerable amount of metal is lost when residues landfilled Lithophilic metals remained mostly in the bottom ash
(Kida et al. 1996)	Chemical properties of MSW bottom and fly ash (Japan)	Constituents separated into two groups: silica-like lithophilic elements and constituents that were volatile and inversely proportional to Si concentration Both bottom and EP ashes are highly alkaline Leaching results for neutral or less alkaline ash Relate binding energies between standards and samples
(Li et al. 2004)	Municipal solid waste ash characterization	MSW sampled from China MSW physical and chemical characteristics depends on several factors: composition of feed, type of incinerator, air pollution controls, operating conditions, etc. The phenomenon of relative enrichment probably due to high combustion temperatures and excellent burnout Ash particle properties linked to its leaching behavior Heavy leachability of heavy metals

(Lima et al. 2008)	Characterization of two MSW ashes, straw ash, and co-combustion of wood and oil	MSW ash and biosolid ash highly soluble due to high concentrations of salts MSW ash had higher concentrations of Cr Fuel is main factor in influencing Cd and Cr form Cadmium solubility independent of fuel and flue gas temperature Each ash should be examined independently due to the variation in characteristics
(Mangialardi et al. 1998)	MSW physical and chemical characterization	Leaching tests showed that lead, chromium, cadmium, antimony, and arsenic leach in acidic conditions Cadmium, lead, and chromium leach in distilled water
Coal Fly Ash		
(EPRI 2009)	Coal ash characteristics	Specific gravity, bulk density, optimum moisture content, hydraulic conductivity, and porosity Chemical composition
(Goodarzi 2006)	Mineralogies and elemental composition of coal fly ash	Comparison of electrostatic precipitator and baghouse fly ash from seven plants Classification based on the intersection of their major oxides Major difference in minerology is in mullite content Large variation based on source of coal
(Hudson 2005)	Feasibility of incineration	Incineration plants became popular in the 1960s Environmental impact statement required now. Includes a comprehensive review of all aspects which may impact the local community
(Kim et al. 2005)	Geotechnical properties of mixture of fly and bottom ash	Grain size analysis, specific gravity, compaction, hydraulic conductivity, one-dimensional compression and triaxial tests Environmental tests compared with state regulatory requirements
(Moreno 2006)	Chemical composition, mineralogy and physical properties of	Fly ash classification by ASTM C618-92a Classified based on major oxide content

	European coal fly ash	Comparison between European fly ash and UK fly ash Major phases present in the fly ash Physical properties of the coal fly ash Chemical composition of the glass matrix Leaching results from coal fly ash
(Ugurlu 2004)	Leaching characteristics of coal fly ash	Comparison between fresh fly ash and weathered fly ash Cation concentrations decrease after each extraction The leachate conductivity varied significantly with temperature pH for both ashes was alkaline Ca, Na, K, Mn, Fe, S, Pb showed maximum leachability Cd, Mg, Cu, Cr, Zn, and Co showed minimum leachability Modeling of the constituents in soil and groundwater
Regulations		
(Environmental Management Commission Raleigh 2013)	N.C. ground water standards	Regulations for ground water for regulatory constituents of concern in North Carolina
(Environmental Management Commission Raleigh 2006)	Waste no disposed into surface water bodies	Regulations for waste residuals in North Carolina
(EPA 1991)	MSW regulations	Regulations for municipal solid waste landfills and disposal
(EPA 2001)	Sewage sludge	Regulations for use and/or disposal of sewage sludge
(EPA 2015)	Coal fly ash	Regulations for the management and disposal of coal combustion residuals
(Legislature 2014)	Coal ash	North Carolina regulations for coal ash management and disposal

CHAPTER 3: METHODOLOGY

3.1 Lysimeter Preparation & Installation

The material listed below per test site shown on Figure *4* and then the total material needed for the installation of the suction lysimeters was listed (based on three sample sites). The equipment and material was obtained from Soil Moisture Equipment Corporation.

Test Site Material:

- 4-1923 Large Volume "Ultra" Soil Water Samplers
- 12.2 meters of PVC piping 2.54 cm O.D.
- 1.33-22.68 kg. bags of silica flour
- 1.33-22.68 kg. bags of bentonite clay
- 14.11 meters of neoprene tubing 4.76 mm I.D.
- 1.33-clamping rings 6.35 mm tubing

Total Material:

- 12-1923 Large Volume "Ultra" Soil Water Samplers
- 36.58 meters of PVC piping 2.54 cm O.D.
- 4 bags 0930W050 Silica Flour, 200 Mesh, 22.68 kg. bags
- 4 bags 0922W050 Granular Bentonite, 22.68 kg. bags
- 130 feet MRT003 Neoprene Tubing 4.76 mm I.D. by 4.76 mm wall
- 4 bags 2031G2 Clamping Ring for 6.35 mm tubing, per dozen
- Drilling rig

- Hard hats
- Safety glasses
- Safety boots

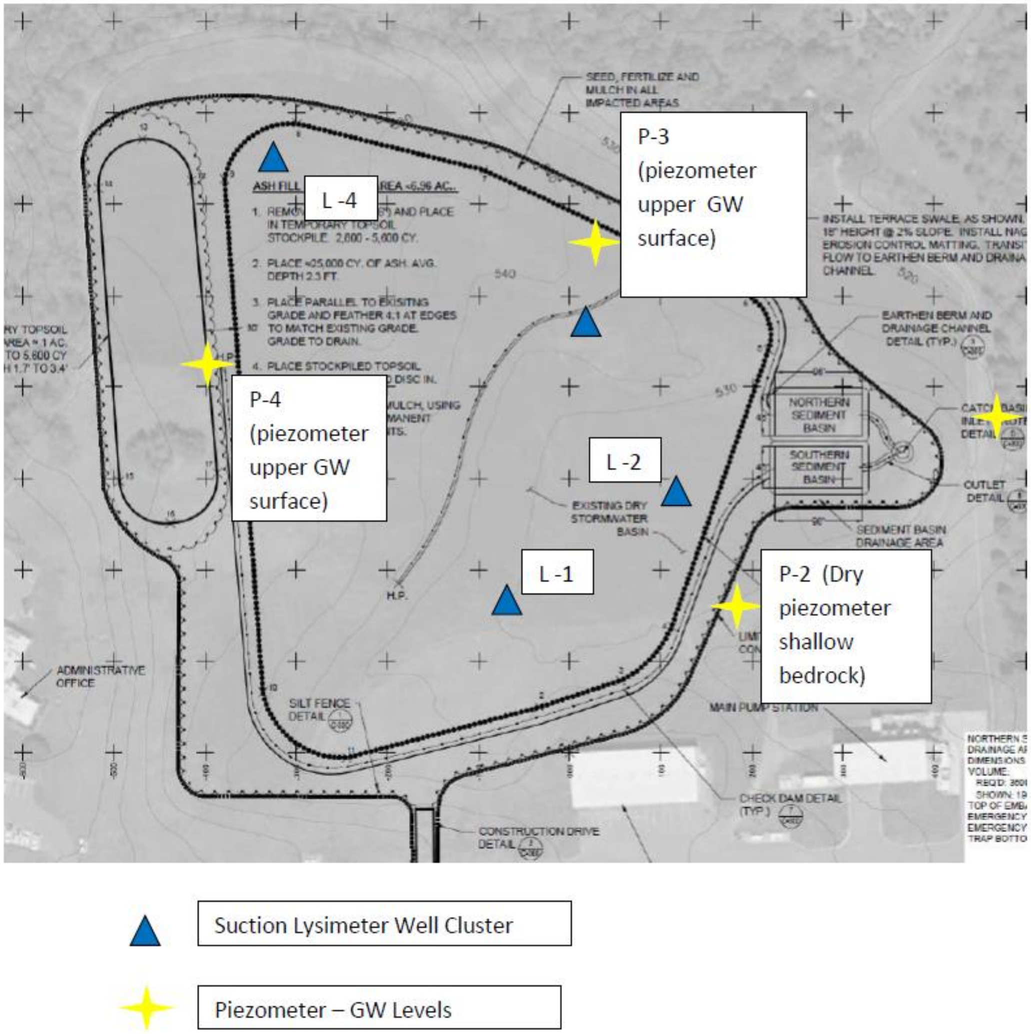


Figure 4: WSACC incinerator ash test site showing Piezometric well locations and lysimeter locations

The 1923 Large Volume "Ultra" Soil Water Samplers shown in Figure *5*, referred to as “suction lysimeters” or “lysimeters” throughout this thesis, were assembled and tested at the factory. They were tested for leaks once received at the lab. The procedures for testing and decontaminating the lysimeters followed *ASTM D4696-92 Standard Guide for Pore-Liquid Sampling from the Vadose Zone* (ASTM 2008). To prevent dust that may have gotten into the pores of the ceramic cup a decontamination process was conducted.

Figure 5: 1923 Large Volume "Ultra" Soil Water Samplers

The lysimeters were flushed with hydrochloric acid (HCl) 8N followed by running DI water through the ceramic cup until the conductivity between the inflow and the outflow were within two percent of each other. This process removes cations from the lysimeter allowing for a more accurate sample being retrieved. In order to control the adsorption of phosphorus by the ceramic cup, a solution containing 40 mg/L concentration of phosphorus was prepared (Kiggundu et al. 2010). The lysimeters were soaked for twenty-four hours in the phosphorus solution while under a vacuum to allow the ceramic cup, inside and out, to be exposed to the phosphorus. The solution concentration was measured after twenty-four hours to ensure that the ending phosphorus concentration was less than the initial concentration. The lysimeters were exposed an additional twenty-four hours to determine if any more phosphorus was loss due to adsorption. The next step was to verify that there were no leaks that would have allowed air entry during sampling. The lysimeters were also tested for their bubbling pressure, pressure tested, and vacuum tested. The process to test the seals followed the procedures developed by L. G. Everett (Wilson et al. 1995).

The installation of the suction lysimeters occurred in July 2013 and followed the steps described below to ensure uniformity in the placement, seals, and contact at sample test sites L-1, L-2, and L-3. The location of the four lysimeters at each sample test site were marked by metal stakes with the top one foot spray painted orange. The first lysimeter was placed into the 2 foot ash layer. The three other lysimeters were located approximately two feet radius from the ash layer lysimeter as shown in Figure *6*.

The boring for each lysimeter was drilled using an eight inch diameter auger to a depth approximately six inches lower than the desired depth of the suction lysimeter. The six inches below the lysimeter allowed for the loose soil at the bottom and included space for the bentonite bottom seal. The borehole of the ash layer lysimeter was drilled to a depth of 0.76 m. The three other boreholes were drilled an equal distance from each other surrounding the ash layer lysimeter to a depth of 1.37 m, 1.8 m, and 2.71 m as shown in Figure 6. The placement of the lysimeters was chosen so that the drawdown of each lysimeter would not impact the others (Bumb et al. 1988). The overall installation process followed ASTM D4696 – 92 (ASTM 1992) with the following exceptions. No risers or centralizers were used during installation however the lysimeters were lowered into the hole using a supporting string. At the installation site the neoprene tubing and PVC tubes were cut to length for each lysimeter and attached using the clamping rings to the lysimeters. The bentonite was mixed with water to 20% solid by weight in the proportion of nine pounds of water and 1.02 kg of bentonite. The slurry was then poured down into the borehole to create a six inch low permeable barrier with a hydraulic conductivity of 10^{-7} cm/sec. The bentonite plug would restrict the flow of water from below the suction lysimeter so that the sample is collected from just the depth desired.

The next layer above the bentonite plug was a silica flour slurry mixing 7.26 kg silica flour with 2.37 liters of water. Then pour the slurry in to the borehole to a depth of two inches. Place the lysimeter in to the borehole located approximately in the center of the hole. The rest of the silica flour slurry was poured around the lysimeter to ensure a uniform contact layer with the ceramic cup.

The next layer consisted of native soil that had been screened using a #4 sieve to remove any larger particles such as pebbles and stones. The native soil was backfilled until the suction lysimeter had a three inch cover. While the soil was backfilled it was tamped, using a metal bar, to compact the soil.

The last layer before soil was added consisted of a bentonite plug resembling the lower plug. The bentonite was mixed with water to 20% solid by weight in the proportion of 4.08 kg of water and 1.02 kg bentonite. The slurry was then poured down into the borehole to create a six inch low permeable barrier with a hydraulic conductivity of 10^{-7} cm/sec. The bentonite plug restricts the flow of water from above the suction lysimeter so that the sample is collected from the just the depth desired.

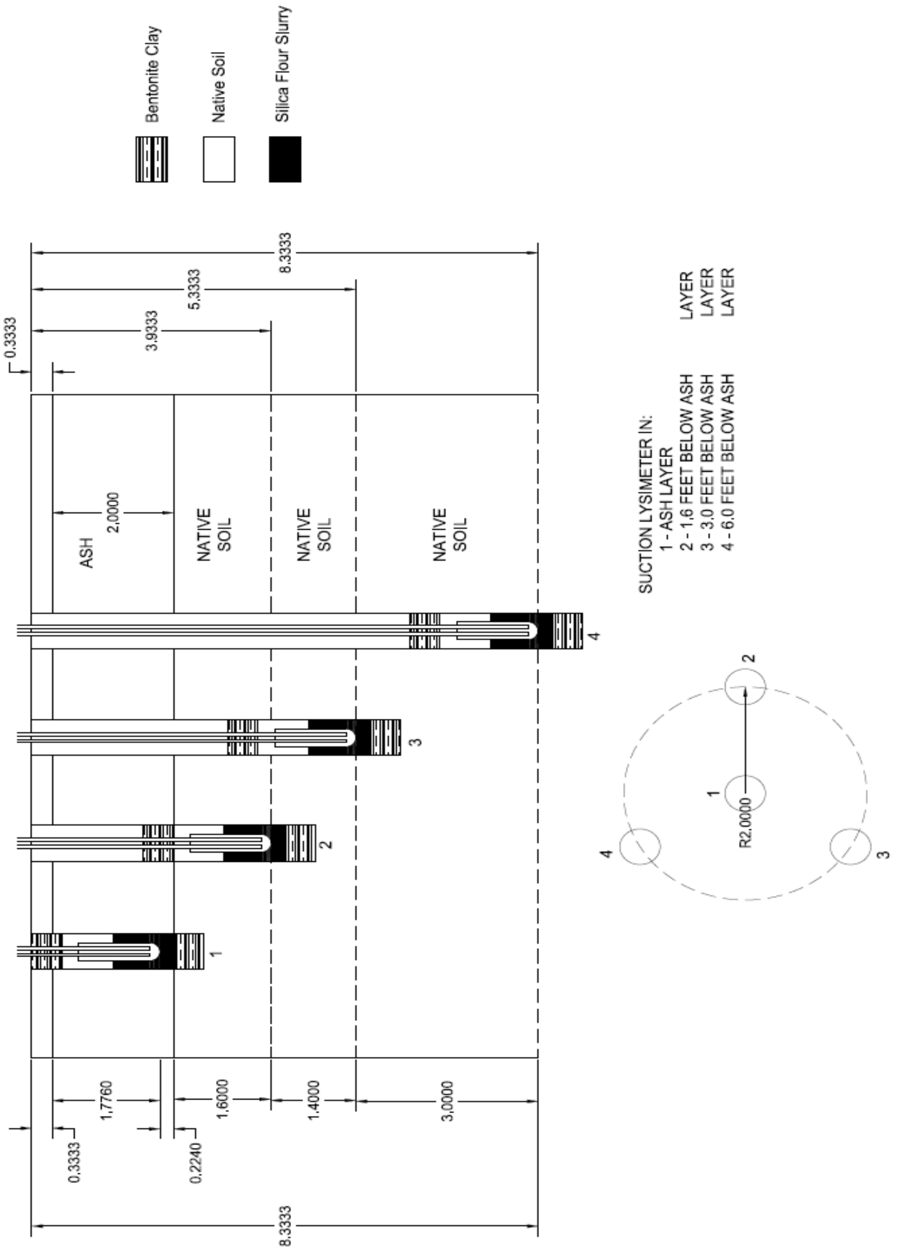


Figure 6: Lysimeter implementation design layout with depth and spacing

Once the bentonite plug had been created above the lysimeter the rest of the borehole was backfilled with the extracted native soil, tamping it to a compaction resembling the surrounding undisturbed soil.

3.2 Collection of Lysimeter Samples

Each lysimeter had two neoprene tubing lines, one vacuum (green) and one extraction (blue), extending approximately 1.22 m above the ground level with a PVC pipe encasing them. A platform was attached to the PVC pipe with the two lines extended above the platform to assist in the extraction of samples. The neoprene tubing had shutoff valves attached through a compression fitting to allow the lines to be opened and closed as needed.

The extraction line was initially closed while the vacuum line was open. A pressure/vacuum hand pump with gauge, shown in Figure *7*, from Soil Moisture Corporation was used to apply a vacuum of 70 centibars. ASTM 4696-92 specifies that the vacuum pressure may range between 60-80 centibars (ASTM 1992). However, there are two issues with increasing the vacuum above 80 centibars. Applied suction greater than 80 centibars may rupture the meniscus of fluid resulting in a break of hydraulic contact allowing only air to enter the lysimeter (ASTM 2008). The second concern with suction greater than 80 centibars in fine soils cause increases in the pore-liquid tensions resulting in a decrease in the hydraulic gradient effectively reducing flow rates to zero (ASTM 2008).

After each rain event an attempt to collect samples from the lysimeters were made. The vacuum and extraction lines were opened, a 500 ml collection bottle was placed under the extraction valve, and pressure was pumped into the lysimeters forcing any leachate collected to flow through the extraction line and into the collection bottle. After the collection was finished the extraction line was closed and a vacuum was reapplied through the vacuum line.

Figure 7: Pressure/vacuum hand pump with gauge

3.3 Piezometric Well

Once a month during the leachate collection period the elevation of groundwater was measured for depth from ground surface to water surface and recorded using previously installed wells P2, P3, and P4 shown on Figure *4*. Each well had a metal protective casing that extended approximately .91 m – 1.22 m above the ground surface with a locking top cover. The top cover was used to prevent tampering and the key remained in the writer's possession during the monitoring period.

A pressure transducer similar to the one shown in Figure *8* was used to determine the distance from the top of the protective casing to the surface of the groundwater. The height of the protective casing and the distance measured to the surface of the groundwater were recorded for each well. The difference between the two measurements was the distance from the ground surface to the water surface.

Figure 8: Water contact meters

3.4 Laboratory Leaching Tests

The laboratory leaching tests were conducted following EPA Method 1314 from SW 846 (EPA 1996). Method 1314 was designed to obtain the liquid-solid partitioning information as a function of the liquid-solid (L/S) ratio (Garrabrants 2012). The cumulative volume of solution passing through a column with a known mass represents the liquid-solid ratio. The first samples collected at L/S 0.2 mL/g-day provide insight into the pore water composition. The cumulative volume of L/S collected gives an estimate of the cumulative mass release from the samples.

The biosolid ash was compacted in lifts in glass columns 30 cm in length by 5 cm inner diameter by hand using a tamper. The process used for compaction followed the steps provided in Method 1314 resulting in a bulk dry density 9.27 kN/m^3. A sand layer approximately 2 cm thick was used between the ash and the filters to prevent blockage of filters and the influent and effluent lines. The sand used was Ottawa sand and had a round shape, an average grain size of 0.45 mm, specific gravity of 2.65, $k_s = 1.54 \times 10^{-1}$ cm/s, and non-reactive (CEN/TS14405 2004). The flow rate was controlled using a peristaltic pump at a rate of 0.51 liquid-solid per day (1.22 pore volumes) with a residence time of 0.61 days (153 mL/day). Leachate was collected at cumulative liquid-solid values ranging from L/S 0.2 to 10 L/S. The collection of the leachate was performed by replacing the collection bottles at the specified time each day, where the specified time was calculated based on the flow rate and volume required for each L/S. Once samples were collected the pH, temperature, and conductivity were measured. The test was run in triplicate using ponded biosolid ash as the medium. The column test setup is shown in Figure *9*.

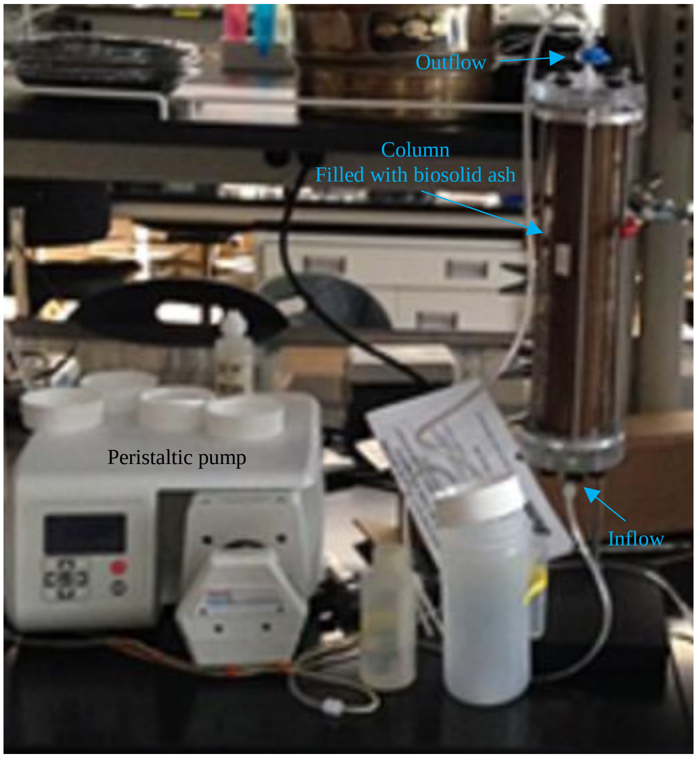


Figure 9: Method 1314 column test setup with peristaltic pump

3.5 Laboratory Soil Attenuation

A soil attenuation study was performed using soil from WSACC research site. The field and laboratory leachate samples shown in Table 2 and Table 4 respectively, indicate several constituents with maximum concentrations higher than NC ground water standards. Silver and lead were excluded from the attenuation study due to minimal concentrations except in one sampling. High concentrations of Phosphorus in the biosolid ash warranted its inclusion in the attenuation study. A spiked solution containing selenium, arsenic, manganese, and phosphorus was used based on the lab results from the Method 1314 column leaching test. One liter of DI water was used in combination with 2.5 mg selenium, 2.5 mg arsenic, 2.5 mg manganese, and 11 mg sodium phosphate (orthophosphate). The regulatory metals were added to DI water, the pH was lowered to 4.5 therefore sodium hydroxide was added to adjust the pH to 6.8. There was no visible precipitate formed in the spiked solution. The spiked solution was analyzed by Pace Laboratory to verify the concentrations of the regulatory metals.

The attenuation study was designed so that there would be breakthrough of at least two of the constituents within a reasonable time. Two replicates were run with samples collected for each pore volume of leachate. The column was packed with 15.24 cm of Ottawa sand, $k_s = 1.54 \times 10^{-1}$cm/s, with 7.62 cm of soil, $k_s = 2.63 \times 10^{-4}$ cm/s, manually compacted to a density of 8.011 kN/m^3. The final 15.24 cm of the column was filled with sand. A Mariotte’s tube was filled with the spiked solution and then connected to the bottom of the column. The tube was placed at a higher vertical position than the columns allowing for the difference in head of 91.44 cm with a hydraulic gradient of 0.028 to enable the spiked solution to enter the sample. There was no visible sidewall leakage during the experiment as determined by a visible inspection. The adsorption capacity of the sand was not determined, however the Ottawa quartz sand is typically used due to its non-reactive nature (CEN/TS14405 2004), and the native soil was a much more reactive sandy silt with approximately three percent clay. The resulting attenuation is for the combined sand/soil. The test ran one week with six samples collected.

A plot of concentration versus time can be fitted with a solution to the Ogata Banks equation (Ogata and Banks 1961) given by Equations 1 and 2.

$$C = \frac{C_0}{2}\left[erfc\left(\frac{L-\frac{v}{R}t}{2\sqrt{\frac{D}{R}t}}\right) + \exp\left(\frac{vL}{D}\right) erfc\left(\frac{L+\frac{v}{R}t}{2\sqrt{\frac{D}{R}t}}\right)\right] \tag{1}$$

Where:

C = concentration at a specific location and time, µg/L

C_0 = initial concentration, µg/L

t = time of interest, s

L = distance down gradient location of interest, m

v = velocity, m/s

D = dispersion coefficient, m^2/s

R = retardation factor, dimensionless

$$R = \left(\frac{\rho_b}{\theta}\right) K_d \qquad (2)$$

Where:

K_d = distribution coefficient, cm^3/g

R = retardation factor, dimensionless

P_b = dry bulk density. g/cm^3

θ = volumetric moisture content, dimensionless

Equation 3 shows the relationship between dispersivity, diffusion coefficient, seepage velocity, and the dispersion coefficient. Adjusting the K_d term will shift the curve to align with the constituent breakthrough on the graph while modifying the dispersivity will alter the shape of the curve.

$$D_L = a_L v_s + D^* \qquad (3)$$

Where:

D_L = the longitudinal coefficient of hydrodynamic dispersion

a_L = the dynamic dispersivity

v_s = seepage velocity

D^* = the effective molecular diffusion coefficient

3.6 Double Ring Infiltrometer

The double ring infiltrometer was installed per the instructions outlined in ASTM D 3385-09 (ASTM 2009). The double ring infiltrometer is traditionally used to determine an infiltration rate of water or fluid into the soil. The hydraulic conductivity of the soil may was measured using the infiltrometer, $k_s = 2.63 \times 10^{-4}$ cm/s. However, the device was used to determine how arsenic, selenium, manganese, and phosphorus attenuated in the in-situ soil. Note that the fluid used in the Mariotte tubes contained DI water spiked with the four constituents of concern at concentrations of 2.5 mg/L, 2.5 mg/L, 2.5 mg/L, and 11 mg/L respectively.

The two rings were installed in the field centered over a vacuum lysimeter that was buried two feet below the ground surface. The outer ring has a diameter of 60.96 cm and the inner ring has a diameter of 30.48 cm. The outer ring was installed to a depth of six inches using a 1.36 kg sledge and a 5.08 cm x 10.16 cm piece of wood. The level of the outer ring was checked using a level to insure uniform depth. The process was repeated sinking the inner ring to a depth of 5.08 cm. There was some vegetation in the installation area however it was trimmed as to not interfere with the infiltration of the spiked solution. The double ring infiltrometer is shown in Figure 10. Two 18.93 liters buckets were used to fill the two rings; the inner ring was filled with the spiked solution and the outer ring was filled with tap water. The rings were filled to an inch from the top and Mariotte tubes were hooked up to the rings to keep a constant head. A total of 70 liters of fluid was used over twelve days. The vacuum lysimeter sample was collected every twenty-four hours to determine how the soil was attenuating the constituents of concern. The samples were then processed using an ICP for the cations and the phosphorus was sent to Pace Laboratory for analysis.

Figure 10: Double ring infiltrometer used for field attenuation study

3.7 Water Content

The water content was determined following ASTM D2216-10 (ASTM 2010). The mass of the specimen container was noted. Then the sample of ash was placed in a tin can with a specimen identification number. An initial mass of container plus wet ash was determined using a balance according to ASTM standards. The sample was then placed in an oven at 110° C for approximately 16 hours. The specimen was then removed from the oven and placed into a desiccator until cooled. Once cooled the mass of the dry biosolid ash plus the container was determined. Equation (4) shows the calculations required to determine the water content of the biosolid ash.

$$w = \left[\frac{M_{cms} - M_{cds}}{M_{cds} - M_c}\right] \times 100 = \left(\frac{M_w}{M_s}\right) \times 100 \qquad (4)$$

Where:

W = water content, %

M_{cms} = mass of container and moist specimen, g

M_{cds} = mass of container and oven dry specimen, g

M_c = mass of container, g

M_w = mass of water ($M_w = M_{cms} – M_{cds}$), g

M_s = mass of oven dry specimen ($M_s = M_{cds} – M_c$), g

3.8 Atterberg Limits

The Atterberg Limits test was conducted in accordance with ASTM D 4318 using the wet preparation. The test method describes the quantitative effect of varying water content on the consistency of fine-grained materials. The upper (liquid) limit and lower (plastic) limit is defined by the water content that produces a specified consistency. The first step was to process the biosolid ash through a #40 sieve to remove any large particles. The Liquid Limit (LL) is defined as the water content at which a trapezoidal groove of specified shape, cut in moist soil held in a standardized cup, is closed 1.27cm after 25 taps on a hard rubber plate as shown in Figure *11*. The water content at which the material begins to break apart and crumble when rolled by hands into threads .3175 cm in diameter is the Plastic Limit (PL) (ASTM 2010). The Plasticity Index (PI) is the difference between the Liquid and Plastic Limits shown in Equation (5) and indicates the range in water contents through which the material is in the plastic state (ASTM 2010).

$$LL - PL = PI \tag{5}$$

Figure 11: Casagrande apparatus

3.9 Specific Gravity of Biosolid Combustion Residuals

Specific gravity is used to determine the density of soil solids by multiplying the density of water by the specific gravity. Furthermore, specific gravity is used to determine characteristics in phase relationships such as void ratio and the degree of saturation. For particles passing a #4 sieve ASTM D 854-14 is used to determine the specific gravity of natural soil particles. The method may be used for other particles like biosolid ash as long as the specific gravity is greater than one (ASTM 2014).

The first step in determining the specific gravity required the pycnometer to be calibrated following the steps outlined in the ASTM. After the completion of the pycnometer calibration the following procedures were used to calculate the specific gravity of the biosolid ash. The mass of the pycnometer was recorded and then using Method A – Procedure for Moist Specimens the water content of the sample was measured and recorded.

A sample of biosolid ash was collected with 100 mL of DI water used to disperse the soil. The slurry was thoroughly mixed using a blender and then poured into a pycnometer. DI water was added until the pycnometer was filled to the half way mark of the body. The sample was deaired using a vacuum pump for two hours while continuously agitated to ensure all the entrapped air from the sample. After removing the entrapped air, deaired water was added to the pycnometer to the calibration mark.

The pycnometer and a pipet was placed into a covered insulated container overnight to achieve thermal equilibrium. The pycnometer was removed and the mass measured using a balance. The temperature was also measured and recorded to the closest 0.1 °C. A drying pan was weighed and the soil slurry mix was transferred to the container. The drying pan was placed in an oven at 110°C until dried. The container was then placed in a desiccator to cool and then the mass was measured. The mass of the pycnometer and water was calculated using Equation (6).

$$M_{pw,t} = M_p + \left(V_p \rho_{w,t}\right) \tag{6}$$

Where:

$M_{pw,t}$ = mass of the pycnometer and water at the test temperature (T_t), g

M_p = the average calibrated mass of the dry pycnometer, g

V_p = the average calibrated volume of the pycnometer, mL

$\rho_{w,t}$ = the density of water at the test temperature (T_t), g/mL

The specific gravity of the soil solids at the test temperature using Equation (7).

$$G_s = \frac{\rho_s}{\rho_{w,t}} = \frac{M_s}{\left(M_{\rho w,t} - \left(M_{\rho ws,t} - M_s\right)\right)} \tag{7}$$

Where:

ρ_s = the density of the soil solids, Mg/m^3 or g/cm^3

$\rho_{w,t}$ = the density of water at the test temperature (T_t), g/mL or g/cm^3

M_s = the mass of the oven dry soil solids, g

$M_{\rho ws,t}$ = the mass of pycnometer, water, and soil solids at test temperature (T_t), g

Specific gravity is usually reported at 20°C as a standard therefore the calculated specific gravity was multiplied by a temperature coefficient as shown in Equation (8).

$$G_{20°\mathrm{C}} = K \cdot G_s \tag{8}$$

Where:

K = the temperature coefficient, no units (Table 2 in ASTM 854-14)

3.10 Particle Size Distribution

The grain size particle distribution affects the engineering properties of the soil as well as compaction, maximum bulk density, and permeability (Bodman and Constantin 1965). The grain size with hydrometer test was performed in accordance with ASTM D 422 (Reapproved 2007) (ASTM 2007). The grain size with hydrometer test is used to determine the particle size and distribution of a material. The coarser soil particle size was determined by passing the ash sample though a standard set of nested sieves retaining particles not passing through a No. 200 sieve. A hydrometer analysis is necessary to determine the particle size and distribution of those particles that pass the No. 200 sieve. The hydrometer method is governed by Stoke's equation for the terminal velocity of a falling sphere through a fluid with a known viscosity. The percentage of soil, by weight, passing the No. 200 sieve is dispersed into a solution, and the rate at which the individual particles fall out of suspension is recorded.

The biosolid ash was dried in an oven at 110°C ± 5°C for twenty-four hours. The mass of each sieve used was recorded using a balance. The ash was then scooped into a nested sieve stack with sieves No. 4, No. 10, No. 40, No. 100, and No. 200. The nested sieves were placed in a mechanical sieve shaker and allowed to run for 20 minutes to allow maximum separation of particles. The mass of the sieve and retained ash was recorded and the fraction of mass retained was calculated. The sum of the sieve fractions should add up to the original mass.

A specific gravity hydrometer meeting ASTM 152H specifications was used. The hydrometer was calibrated at 20°C. Approximately 100 grams of ash was weighed out, placed in a 250 mL beaker, and then covered the ash with 125 mL of sodium hexametaphosphate solution (40 g/L) to ensure separation of the fine ash particles (ASTM 2007). The sample was left to soak for 24 hours to ensure the ash was thoroughly wetted. The sample was dispersed further through stirring with a blender (Magic Bullet) for five minutes. The ash-water slurry was transferred to the one liter glass sedimentation cylinder. The cylinder was covered with a wax seal and inverted continuously for one minute. The wax seal was removed and then hydrometer readings were taken at intervals 2 and 5 minutes, then the cylinder was placed into a bath of water at room temperature while readings were taken at 15, 30, 60, 250, and 1440 minutes. The temperature of the suspension should be recorded after each reading. The percentage of soil in suspension was calculated using Equation (9).

$$P = (Ra/W) \times 100 \tag{9}$$

Where:

a = correction factor to be applied to the reading of hydrometer 152H (Table 1 ASTM 422-07)

P = percentage of soil remaining in suspension at the level at which the hydrometer measures the density of the suspension

R = hydrometer reading with composite correction applied

Using Stokes' law, the diameter of the particle at each reading was calculated using Equation (10).

$$D = \sqrt{[30n/980(G_S - G)] \times L/T} \tag{10}$$

Where:

D = diameter of particle, mm

n = coefficient of viscosity of the suspending medium

L = distance from the surface of the suspension to the level at which the density of the suspension is being measured, cm

T = interval of time from beginning of sedimentation to the taking of the reading, min.

G_s = specific gravity of soil particles

G = specific gravity of suspending medium

3.11 Standard Proctor Compaction Test

The Standard Proctor compaction test was performed in accordance with ASTM D 698 (ASTM 2012). The Standard Proctor compaction test is defined as twenty-five blows of a 2.49 kg hammer falling 30.48 cm on each of 3 equal material layers in a 10.16 cm diameter, 934.5 cm^3 cylinder. The effort is 600 $kN\text{-}m/m^3$, which is comparable to light rollers or very thorough tamping in thin layers. The Standard Proctor compaction test is used to determine the compaction characteristics of a material, including the maximum dry density and optimum moisture content.

The biosolid ash sample all passed a No. 4 sieve therefore the first step was to determine the natural water content of the sample through oven drying. The natural water content was used in determining how much water was added to each specimen to achieve the desired water contents. Five samples at different water contents were used to determine the maximum dry density and the optimum moisture content: 25%, 30%, 35%, 40%, 45%, 50%. Each sample was mixed thoroughly and placed in a plastic bag and sealed to mellow for twenty-four. A sample from each desired moisture content was collected and dried in an oven to verify the actual moisture content.

The mass of the 10.16 cm diameter mold and base plate was measured and recorded. The ash sample was compacted in three lifts of equal thickness following the blow pattern outlined in ASTM 698 (ASTM 2012). The top of the first and second lifts was scored to allow the next layer of soil to bond with the lower layer. The proctor hammer was used twenty-five times for each layer of ash. Once the compaction was completed the top collar was removed and a knife was used to remove any excess sample from the mold. A straightedge was used to level the sample with the top of the mold. The mass of the mold and sample was measured and recorded. The sample was extracted and then a portion was used to determine the moisture content of the sample. The moist density is calculated by using Equation (11).

$$\rho_m = K \times \frac{(M_t - M_{md})}{V} \tag{11}$$

Where:

ρ_m = moist density of compacted specimen, g/cm^3

M_t = mass of moist soil in mold and mold, g

M_{md} = mass of compaction mold, g

V = volume of compaction mold, cm^3

K = conversion constant, depending on density units and volume units

The dry density was determined using Equation (12).

$$\rho_d = \frac{\rho_m}{1 + \frac{w}{100}} \tag{12}$$

Where:

ρ_d = dry density of compaction point, g/cm^3

w = molding water content of compaction point

The dry unit weight is calculated by multiplying the dry density conversion factor depending on the units used as shown in Equation (13).

$$\gamma_d = K_n \times \rho_d \tag{13}$$

Where:

γ_d = dry unit weight

K_n = conversion constant

The zero air voids curve was plotted using points developed through Equation (14).

$$w_{sat} = \frac{(\gamma_w)(G_s) - \gamma_d}{(\gamma_d)(G_s)} \times 100 \tag{14}$$

Where:

w_{sat} = water content for complete saturation

γ_w = unit weight of water at 20°C

G_s = specific gravity of sample

3.12 Permeability

Permeability is an important property of soil and ash that measures the ability of the soil's ability to permit water and air to flow through the continuous pore spaces. The permeability is used when considering numerous engineering projects. Due to approximately fifty percent of the ash passing a No. 200 sieve a constant head test would not be appropriate to use ASTM D2434-68 (ASTM 2006). Therefore, a Falling Head Permeability Test was performed per industry standards using a remolded sample of biosolid ash.

The column used was 7.569 cm diameter, a pore stone was placed in the bottom in the bottom of the cylinder and a height of 12.383 cm. The biosolid ash was compacted into the column in 1.27 cm lifts and then a pore stone was placed on top of the ash. The top of the column was secured using the column tie rods. The sample was compacted to approximately 95% of maximum dry density using a Harvard Miniature Compaction Hammer. The mass of the column and pore stones was noted before and after the sample was added. The diameter and length of the samples were measured and recorded. The height of the reservoir from the ash sample was measured and recorded at 104.14 cm. The valves were open on top and bottom of the column to allow saturation of the sample. Once the sample was saturated the valves were closed and the heights of the reservoir and outflow were recorded. The final step was to open the valves again and allow the water to flow for two hours. At the end of the two hours the new heights were recorded and the permeability calculated using equation (15).

$$k = \frac{aL}{At}\ln\frac{h_0}{h_1} \tag{15}$$

Where:

K = coefficient of permeability

a = area of burette

L = length of soil column

A = area of soil column

h_0 = initial height of water

h_1 = final height of water

t = time required to get head drop of Δh

3.13 Loss of Ignition

The loss of ignition (LOI) test is used to determine the amount of mass loss when exposed to high temperatures and the tests were performed following ASTM D 7348-13 (ASTM 2013). The primary reason for performing this test on the biosolid ash is that organic phosphorus is more mobile in water than inorganic phosphorus (Jacobs and McCreary 2003). The lower the loss of ignition the less likely that organic phosphorus is present in the ash sample. Organic phosphates volatilize at significantly lower temperatures than inorganic phosphates (Yokota et al. 2003). The loss may be due to the loss of moisture, carbon, sulfur, or other combustible material. To remove moisture from the sample the biosolid ash sample was placed in an oven at 110°C for twenty-four hours.

Method A from the ASTM was used in the LOI determination. The tin was weighed and then an ash sample was placed in the tin and the weight of the tin and sample were measured and recorded. The temperature in a muffle furnace was raised from 20°C to 500°C over the course of an hour and then from 500°C to 750°C over the next hour. The specimen was exposed to the high temperature for twenty-four hours to ensure that all carbon had been volatilized. The sample was removed from the muffle furnace and placed in a desiccator until cooled. Then the sample and tin were weighed and recorded. The LOI was determined using Equation (16).

$$LOI = [(W - B)/W] \times 100 \tag{16}$$

Where:

W = mass of test specimen used, g

B = mass of test specimen after heating 750°C

CHAPTER 4: RESULTS AND ANALYSIS

4.1 Field Lysimeter Samples

The field leachate samples were collected using 1923 Ultra Pure Soil Water Samplers from Soil Moisture Corp. Five sets of samples were collected from the three lysimeter nests during the period from September 2013 to April 2014. The pH, conductivity, and the ORP were recorded for all samples during the sampling periods. All of the regulatory metals evaluated were below 15A NCAC 02L.0202 groundwater regulatory limits with the exception of manganese and silver which are highlighted in Table 2Table *1*. One sample from lysimeter #4 had a maximum manganese concentration of 134 μg/L. An additional sample from lysimeter #11 had a maximum silver concentration of 37.14 μg/L. The spikes in concentration may be the result of the ash and/or soil being heterogeneous but more likely contamination occurred during transport, storage, or testing of the sample.

The leachate samples that were collected from the vacuum lysimeters were analyzed for total phosphorus using a Lachat Flow Injection Analyzer (FIA). The total phosphorus concentrations were less than 0.6 mg/L in all but one sample. The vacuum lysimeter that was installed in center of the test site on February 2014 had a total phosphorus concentration of 1.68 mg/L shown in Figure 16. The total phosphorus concentrations evaluated from the field samples were significantly lower than the Method 1314 test. This discrepancy may be due to the soil attenuating the constituents that leach from the ash combined with precipitates settling out of the leachate.

Geochemist’s Workbench was used to determine the species of the constituents of concern. Aqueous phases depicted in blue while solid phases shown in light brown on the Pourbaix diagrams. The equilibrium conditions and predominant species presented are for standard temperature of 25 °C. Variation in temperature may result in different solids and species formed. The field samples collected had a pH between 6.82 and 8.47 and an Eh ranging from 270-386 mV.as shown on graphs in Appendix B.

Aluminum

The species of aluminum present according to the Eh-pH diagram, shown in Figure 30, was lead phosphate mineral, plumbogummite ($PbAl_3(PO_4)_2(OH)_5 \cdot H_2O$). Aluminum should precipitate out as plumbogummite due to poor solubility (Strawn et al. 2007). The ions may form aluminate salts when dissolved in strong bases, however aluminum in alkaline solutions may become rhizotoxic (inhibit root elongation) according to Thomas Kinraide (Kinraide 1990).

Arsenic

Anhydrous copper (II) arsenate (Lammerite) $Cu_3(AsO_4)_2$ is the main species of arsenic present per Figure 38. Lammerite has a solubility product of 7.95×10^{-36} resulting in the mineral precipitating out of the solution. Arsenates are inorganic and strongly absorb onto mineral surfaces. The main environmental concern of arsenates is that they inhibit the oxidative phosphorylation.

Barium

Barium ions [2+] is the primary species present in the samples according to Figure 43 Eh-pH diagram.

Cadmium

Chromium spinel ($CdCr_2O_4)_{(s)}$ is the main species of cadmium that would be present in the samples as represented on the Eh-pH diagram in Figure 42. This form of cadmium is insoluble and should precipitate out of the solution.

Chromium

Zinc chromite ($ZnCr_2O_{4(s)}$) is the most prevalent species of chromium in the samples according to Eh-pH diagram depicted in Figure 32. While zinc is present in the ash chromium should completely precipitate out of the solution (Noyes and Swift 1942).

Copper

The Pourbaix diagram shown in Figure 36 indicate two primary species will be present in solid form, copper (II) dichromium (III) tetraoxide ($CuCr_2O_{4(s)}$) and ferrite-Cu ($CuFe_2O_{4(s)}$). The two species are not soluble in solution and should precipitate out.

Iron

Figure 34 of the Eh-pH for iron emphasizes that the primary species present in the samples would be chromite ($FeCr_2O_4$) and hercynite ($FeAl_2O_4$). Chromite is used in industrial plating and not soluble in water precipitating out of the solution.

Lead

The Eh-pH diagram shown in Figure *44* indicates that the primary species of lead in the samples plumbogummite ($PbAl_3(PO_4)_2(OH)_5 \cdot H_2O$). Aluminum should precipitate out as plumbogummite due to poor solubility (Strawn et al. 2007).

Manganese

The primary species of manganese present per Figure 33 Eh-pH diagram is the Mn^{2+} ion. In organic life manganese ions combine with enzymes in the detoxification of superoxide free radicals.

Molybdenum

Molybdate MoO_4(2-) is the main species of molybdenum present in the samples based on the Eh-pH diagram in Figure 40. Molybdates may bond with other constituents resulting in some species of molybdenum that would detrimentally impact organic life.

Nickel

According to the Eh-pH diagram shown in Figure 35 trevorite ($NiFe^{3+}{}_2O_{4(s)}$) is the primary species of nickel present. Nickel above levels commonly found normal flora areas may result in in stunted plant growth. Trevorite is insoluble in most acids and should precipitate out of the solution. This is seen particularly around nickel mines where the flora is limited to one or two species (Warhurst and Noronha 1999).

Phosphorus

Total phosphorus species present according to the Eh-pH diagrams, Figure 31, is plumbogummite ($PbAl_3(PO_4)_2(OH)_5{\cdot}H_2O$). The current phosphorus composition of U.S. municipal wastewater sludge is 80% orthophosphates and 20% organic phosphates (Strom 2006). A LOI test was performed on the biosolid ash following ASTM D7348-13 with a result of 4% LOI. Therefore, it is reasonable to postulate that the organic phosphates were consumed during the incineration process thus the remaining phosphorus would be of an orthophosphate species. The solubility product of most orthophosphates are less than 10^{-6}

moles/liter therefore the phosphorus that leaches at the test site should precipitate out or attenuate in the soil (NCSU).

Selenium

According to the Pourbaix diagram for selenium, shown in Figure 39, the major species present would be naumannite ($Ag_2Se_{(s)}$) and cadmium selenite ($CdSeO_{3(s)}$). It should be noted that selenium is needed in small concentrations however selenium poisoning may occur resulting in both acute and chronic health issues. No selenium was detected in the field samples collected at the test site.

Zinc

Zinc chromite ($ZnCr_2O_{4(s)}$) is the main zinc species present according to Figure 37 Eh-pH diagram. Zinc chromite is insoluble in water and should precipitate out of the solution. Zinc is considered relatively nontoxic however at concentrations approximately 10-20 times the recommended daily allowance symptoms such as anemia and copper deficiencies are observed (Fosmire 1990).

Table 2: Constituent maximum concentration in leachate

Constituent	Max. Concentration (µg/L)	15A NCAC 02L.0202 Regulatory Limit (µg/L)
Aluminum	174	-
Arsenic	4.4	10
Barium	279	700
Cadmium	ND	2
Chromium	1.85	10
Copper	22	1000
Iron	86.74	300
Lead	1.41	15
Manganese	134	50
Molybdenum	61	-
Nickel	12.07	100
Selenium	ND	20
Silver	37.14	20
Zinc	38	1000

4.2 Laboratory Column Leaching

The analysis of EPA Method 1314 include comparing the concentrations of the constituents versus the cumulative liquid to solid ratio and then calculating the total mass release over the cumulative L/S. The pH for each sample at each L/S ratio was measured and shown in Figure 45. The overall mean pH for the samples was 7.93 with a standard deviation of 0.46. The red dotted line marks the mean pH of the collected samples while the solid black lines denote the upper and lower standard deviation bounds. Much of the data lies within one standard deviation of the mean.

Further analysis into the release mechanism may be described as either first-flush response or a lagged-flush response. The first-flush response identified as a constituent of concern that is soluble during initial pore volumes then decreases either solubility due to pH decrease or concentration decrease in the soil. The lagged-flush response is initially insoluble during permeation then increases in solubility as the pH decreases (Bin-Shafique et al. 2002; Edil et al. 1992).

The maximum concentrations for each regulatory metal constituent is shown in Table *2*. There were several constituents above the 15A NCAC 02L.0202 Groundwater Quality Standard: manganese, nickel, selenium, arsenic, silver, and lead. Both lead and silver had one sample that was above the drinking water regulations which may be an example that the biosolid ash may not be homogeneous.

Manganese

Manganese exhibited first-flush response with maximum concentrations of 77.15 μg/L, 117.60 μg/L, and 573.80 μg/L in columns 1, 2, and 3 respectively during the first 0.20 L/S. The leachate concentration reaches equilibrium at 2 μg/L. The first 2 L/S ratios of the column leaching test may not representative of what will leach out of the material but rather provides insight into the initial pore water composition. The sample was tested in triplicate with a relative standard deviation of 1.10% indicating s high level of precision between the three tests. At L/S ratios greater than one had concentrations significantly below 15A NCAC 02L.0202 ground water regulatory limits as shown in Figure 49. The average total mass released during the column test was 0.013 mg/kg-dry.

Nickel

Nickel exhibited first-flush response with maximum concentrations during the first 0.20 L/S ratio of 139 µg/L and 186.5 µg/L in columns 1 and 2 respectively. Column 3 concentration was below the regulatory limits. Equilibrium was achieved at 9.5 L/S of 1.1 µg/L. Samples extracted at higher L/S ratios had concentrations well below 15A NCAC 02L.0202 ground water regulatory limits as shown in Figure 51. The average total mass released during leaching was 0.085 mg/kg-dry resulting in 0.16% of the total mass of nickel released over the 10 L/S ratios.

Selenium

Selenium exhibited first-flush response with maximum concentrations during the first 0.20 L/S ratio of 50.91 µg/L, 53.01 µg/L, and 22.33 µg/L in columns 1, 2, and 3 respectively. However there is a second peak at L/S 10 which may indicate a second mineral phase of selenium which is less soluble, this is usually due to a pH or alkalinity decrease. Selenium does not reach a concentration equilibrium. As with previous constituents, the first 2 L/S ratios resulted in concentrations of selenium were above 15A NCAC 02L.0202 ground water regulatory limits as shown in Figure 55. After the first flush, L/S ratios > 1, were below the regulatory limits. The mean total mass released was 0.065 mg/kg-dry.

Arsenic

Arsenic exhibited a lagged-flush response reaching peak between 2 and 4.5 L/S with maximum concentrations of 14.81 µg/L (column 1), 15.31 µg/L (column 2). Arsenic does not reach equilibrium although does begin to decrease after 4.5 L/S. The maximum concentration of arsenic exceeded 15A NCAC 02L.0202 ground water regulatory limits in columns 1 and 2. Column 3 concentrations were below the regulatory limit as shown in Figure 54. The mean total mass released was 0.10 mg/kg-dry.

Phosphorus

There are no ground water regulatory standards for phosphorus, however, many states are implementing surface runoff maximum loading lbs/acre/year. In Wisconsin, NR 217 rule sets maximum total phosphorus discharge from point sources at 1.0 mg/L and NR 151 outlines best practices for maximum loading of agricultural lands although it currently does not give numerical values. Numerous states have developed best management practices for phosphorus loading of agricultural lands near surface water bodies. NCDEQ has expressed concern with regards to the quantity of phosphorus in the biosolid ash. According to previous tests conducted by Pace Analytical Services the biosolid ash contains 46 g/kg of phosphorus.

Phosphorus exhibited a first-flush response then concentrations increased during the first L/S reaching a peak of 8.88 mg/L. The concentration of phosphorus slowly decreased beyond 5 L/S with a concentration of 3.2 mg/L. The concentration of phosphorus ranged between 0.1 mg/L to 8.88 mg/L in all three columns shown in Figure 47. The average total mass of phosphorus released was 71.7 mg/kg-dry or 0.18% of the total mass of phosphorus in the sample released. Overall the phosphorus demonstrated limited transport in water.

The column tests were a worst-case scenario with regards to determining the concentrations of constituents in the leachate. The biosolid ash used for the column tests was gathered from the ponded ash onsite. Also of note, the biosolid ash applied onsite was removed from the ash ponds and applied January 2013, lysimeter installation and data collection was July 2013. To determine how many pore volumes of infiltrated water was leached through the biosolid ash a sample volume of the area was calculated and the pore volume noted as shown in Figure *93*. The porosity of the biosolid ash was 0.59, biosolid ash depth 0.61 m, and an area 182.88 m x 182.88 m. The pore volume was approximately 12194 m^3, precipitation from 1/1/2013 – 6/30/2013 was 65.8 cm resulting in a total precipitation volume of 22,002 m^3. The number of pore volumes of water infiltrated through the biosolid ash was 1.804 or 1.21 L/S. As noted in the column test, that would have resulted in the first flush of the system. Therefore, the filed samples collected were representative of what constituents would leach out of the biosolid ash. The initial field samples did not include the pore fluid which may explain why the field leaching samples had considerably lower constituent concentrations. Further investigation into the mechanisms that may attenuate the contaminants should be pursued.

The cumulative release of each constituent over the cumulative liquid to solid ratio is shown in Figure 61 through Figure 75. An average of the cumulative release of the three column tests was calculated to determine the mg/kg-dry of each constituent that was released over the 10 L/S shown in Table 3. The only constituent with an average cumulative release greater than 1 mg/kg-dry was phosphorus with 54.76 mg/kg-dry. Aluminum, iron, copper, zinc, and molybdenum average cumulative release between 0.700 and 0.100 mg/kg-dry with the remaining constituents less than 0.100 mg/kg-dry.

Table 3: L/S average cumulative release of constituents

Constituent	Average Cumulative Release (mg/kg-dry)
Aluminum	0.684
Arsenic	0.077
Barium	0.025
Cadmium	0
Chromium	0.0002
Copper	0.169
Iron	0.289
Lead	0.01
Manganese	0.082
Molybdenum	0.524
Nickel	0.065
Phosphorus	54.67
Selenium	0.046
Silver	0.021
Zinc	0.111

Table 4: Maximum concentration of constituents

Constituent	Max. Concentration (µg/L)	15A NCAC 02L.0202 Regulatory Limit (µg/L)
Aluminum	1469	-
Arsenic	15.31	10
Barium	46	700
Cadmium	1.495	2
Chromium	1.639	10
Copper	137	1000
Iron	174.6	300
Lead	58.37	15
Manganese	573.8	50
Molybdenum	973	-
Nickel	186.5	100
Selenium	53.01	20
Silver	28.51	20
Zinc	67	1000

4.3 Laboratory Soil Attenuation

The initial Kd estimate for each constituent was obtained from literature and used to determine the time required for breakthrough. The distribution coefficients, dispersivity, retardation, diffusion coefficients, and seepage velocity are shown in Appendix D Table 27. Two replicates were run with samples collected each pore volume of leachate. The column was packed with 15.24 cm of Ottawa sand, $k_s = 1.54 \times 10^{-1}$ cm/s, with 7.62 cm of soil, $k_s = 2.63 \times 10^{-4}$ cm/s, manually compacted. The final 7.62 cm of the column was filled with sand. Note that the Ottawa sand, considered non-reactive, was not tested for attenuation therefore the results are for soil-sand attenuation. A Mariotte's tube was filled with the feed solution and then connected to the bottom of the column. The feed solution contained 2.5 mg/L selenium, 2.5 mg/L arsenic, 2.5 mg/L manganese, and 11 mg/L sodium phosphate (orthophosphate). The four constituents used during the test were chosen based on what constituents were present in the field lysimeters. The tube was placed at a higher vertical position than the columns allowing for the difference in head to cause the spiked solution to enter the sample. There was no visual sidewall leakage during the experiment determined by visible inspection. The test ran one week with six samples collected with the pH, ORP, conductivity, and concentrations shown in Table 26.

There are four primary release patterns that may occur when using a feed solution. The first two pore volumes of effluent collected are considered transitional fluids between pore fluid and feed solution and may not represent chemical leaching (Edil et al. 1992).

1. The effluent concentration decreased to equilibrium at the feed solution concentration (leaching occurs at concentrations greater than feed solution).
2. The effluent concentration decreased to equilibrium below feed solution concentration.
3. A breakthrough curve that reached equilibrium at feed solution concentration.
4. A breakthrough curve that reached equilibrium above feed solution concentration.

The results from the soil attenuation test indicated that the first flush of the soil contained 149 µg/L of selenium, 40 µg/L of manganese, and 60 µg/L of phosphorus. The second pore volume did not detect concentrations of arsenic, manganese, or phosphorus, however, selenium increased to 363-495 µg/L shown in Figure *76*. By the third pore volume of leachate there was a selenium concentration of 502 µg/L and a manganese concentration of 6.9 µg/L. As shown in Figure 76 the estimated Kd for selenium is between 2 and 4 mL/g. This compares with values ranging from 8 to 6,600 mL/g for soil samples collected near Salisbury, NC (Langley and Oza 2015). No Kd could be determined for the other constituents although their absence in the effluent suggests a value greater than this range. Values from Langley and Kim suggests that the Kd for arsenic should be greater than 67 mL/g and the Kd for manganese should be greater than 60 mL/g (Langley and Oza 2015). The release pattern appears to follow type 3, and given sufficient time the mermeant level should be reached. After six pore volumes of leachate the only constituents that were present were selenium and manganese. In 6 L/S the total volume of solution leached was 1.84 liters with a selenium mass of 4608.36 µg. Approximately 15.8% (727µg) of selenium leached out of the system resulting in a concentration 395.2 µg/L, well above 15A NCAC 02L.0202 groundwater regulatory limits. Manganese approximately 0.83% (20.8µg) leached from the column. There was no breakthrough of arsenic or phosphorus during the test. The soil appears to attenuate arsenic and phosphorus very well and manganese to a lesser extent.

The initial phosphorus present in the first pore volume represents the presence of phosphorus in the pore fluid. The lack of phosphorus breakthrough may represent either the soil attenuating the phosphorus or 24 pore volumes did not allow enough time for phosphorus to reach breakthrough although the Ogata-Banks curve indicates breakthrough should occur. There was no arsenic present in the laboratory soil attenuation leachate. Arsenic is naturally attenuated in soils that have hydroxides of iron, aluminum, manganese, clay and sulfides, known to be arsenic adsorbents (Wang and Mulligan 2006). The ORP and pH of the leachate, shown in Figure 34, indicate that the species of iron present would be $Fe(OH)_3$. Therefore, the arsenic most likely bonded with the iron and precipitated out of the leachate.

The differences between field and laboratory leaching tests may in part be influenced based on different water characteristics in the influent. The influent in the field was due to precipitation while the laboratory testing was performed with DI water. The field samples' pH ranged from 6.82 – 8.39 while the laboratory samples' pH was 7.04 – 9.17. The conductivity in the field was 3.19 – 1140 µs/cm and the laboratory samples' conductivity was 44.20 – 1885 µs/cm. The filed samples ORP was 281 – 386 and the laboratory samples' ORP was 250 – 355. The variance between the two influents was not great but may have impacted the solubility of the COCs. One other difference was that the field used soil for attenuation while the lab samples was biosolid ash.

4.4 Field Attenuation Test

The field attenuation study used a double ring infiltrometer to monitor the amount of spiked solution that was released into the test area. The soil is a silty sand with a small amount of clay present and has a permeability of 3.14×10^{-5} cm/s or approximately 0.113 cm/hr. It should be noted that the soil at the test site was used for construction purposes elsewhere on the property and did not exhibit much homogeneity throughout the relatively small test area. Therefore, the permeability and void ratio may vary depending on where the test is performed. The hydraulic conductivity of the soil was 2.63×10^{-4} cm/s. The void ratio of the soil is 0.37 with a unit weight of 2.018 g/cm^3. The depth of the lysimeter used during the test was two feet therefore the volume of soil below the infiltrometer inner ring down to the lysimeter is 43,092 cm^3 with a void volume of 11,638 cm^3. Samples were collected at 0.5 pore volumes or once a day for the twelve day period as shown in Figure *77*. The transport parameters are shown in Table 27.

Arsenic was not detected in any field attenuation samples. As with the lab samples and given the ORP and pH of the samples it is most likely that the arsenic bonded with the hydroxide iron. Phosphorus was present in two samples during the first flush of the system with at low concentrations less than 0.09 mg/L. The phosphorus used was an orthophosphate with a low solubility product resulting in negligible transport through the soil. The majority of leachate containing manganese was collected during first flush although 2.11 mg (0.47%) of the initial mass leached out of the soil. The manganese concentration of the leachate was 11.71 μg/L. The maximum manganese concentration during the field study was 10.8 μg/L and well below the 15A NCAC 02L.0202 ground water regulatory limits. The total mass of selenium released during the study was 137.7 mg (30.4%) with a concentration of 763.1 μg/L. Selenium followed a similar pattern during the field study as the laboratory shown in Figure 76. The initial sample had a concentration of 114 μg/L and slowly increased to 500 μg/L over the six pore volumes.

The laboratory test and field test had similar leaching patterns for selenium shown in Figure 76 and Table 27. Both the field cumulative mass per L/S ratio and the percentage of the total constituent mass was twice the laboratory results. There should have been some correlation between depth of soil and attenuation although the author believes that this was not obvious due to samples being pulled both in the laboratory and field by the pore volume. One possible avenue to pursue in future research would be to take samples at timed intervals rather than based on fractional pore volume. Using the ash, soil, and hydraulic properties combined with collection of samples are specific time intervals may provide more insight in relating field attenuation and soil attenuation studies.

4.5 Water Content

The water content was determined using gravitational water content. The field samples of biosolid ash are from the ash pond therefore the samples have a higher water content than typical biosolid ash. The biosolid ash was tested when received and then samples were left to air dry and tested again following the ASTM. The average moisture content of the ponded sample is 110% with a standard deviation of 1.79%. The air-dried sample of biosolid ash has an average moisture content of 2% with a standard deviation of 0.24%. Note that the oven dried samples were dried at 110 °C. Some literature indicates that mass loss may be contributed to solids with a low volatilization point. In the future, to determine if the mass loss is due to water loss or volatilization of solids a thermal gravimetric study should be completed.

4.6 Particle Size Analysis

The particle size analysis was performed using both sieves mechanically shaken and a hydrometer for the finer particles. Six tests were performed on May 12, 2014 and the figures are in the Appendix. The percent passing the No. 200 sieve has an average of 53.22 with a standard deviation of 1.01. The D85 particle size is 0.3156 mm and the D15 particle size is 0.0093 mm. the particle distribution curve is shown in Figure 12.

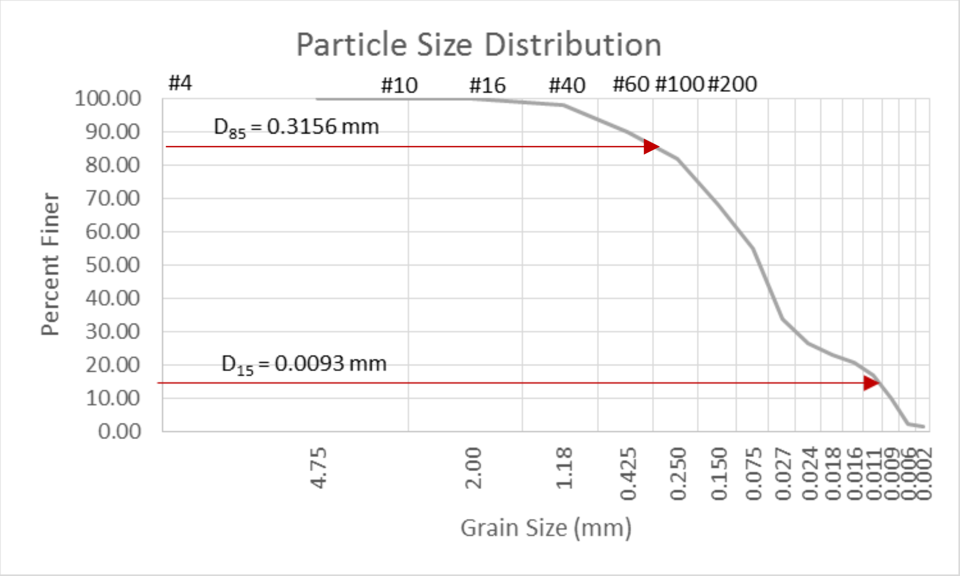


Figure 12: Particle size distribution curve

4.7 Atterberg Limit

The wastewater biosolid ash has a light brownish red tint and is comprised primarily (74%) of a sand (2 mm) and silt (0.002 mm) particles resulting in no plasticity .The sample is classified ML using the USCS classification system. The liquid limit, plastic limit, and plasticity index all are NP (non-plastic).

4.8 Specific Gravity

The specific gravity of six samples were taken with the average specific gravity of 2.488 with a standard deviation of 0.110. The data may be seen in Appendix G Figure *86*.

4.9 Proctor Test

Three samples of biosolid ash were tested using the proctor test. The average optimal water content is 36.7% with a standard deviation of 0.25%. The average maximum dry unit weight at the optimal water content is 9.80 kN/m^3 with a standard deviation of 0.71 kN/m^3. The figures may be found in Appendix H in Figure *88*.

4.10 Permeability

The biosolid ash permeability was determined using the Falling Head Permeability Test (Fetter 2014). Six trials were run to determine the average permeability of the biosolid ash at the optimum water content of 36.7% and the maximum dry unit weight 9.80 kN/m^3. The average permeability is 2.36 x 10^{-04} cm/sec with a standard deviation of 1.74x10^{-05}. The permeability of the samples are indicative of a silty material and/or clayey sand. As mentioned earlier the biosolid ash sample is a mix of sand and silt with 74% of the particle sizes ranging from 2 mm to 0.002 mm with a very small amount of clay-sized particles.

4.11 Loss of Ignition

To determine the amount of material remaining in the biosolid ash that would volatilize, a Loss of Ignition test was conducted. Six samples were run during this procedure to ensure that an accurate result. The average loss on ignition is 4.21% with a standard deviation of 0.44%. The data for the samples run is in Appendix J. This indicates that the seven tier hearth system that is used to incinerate the dewatered biosolid sludge is efficient. In the past, hearth systems were not very efficient at burning the waste and had issues achieving high enough temperatures to ensure that the majority of the waste was incinerated.

4.12 Comparison of Biosolid Ash, Municipal Ash, and Coal Ash

This section will be comparing several physical characteristics and the general elemental composition of sewage sludge biosolid ash (SSBA), municipal ash, and coal fly ash. It should be noted that the comparison will use ranges of values both with the physical characteristics and in the discussion of elemental composition due to how dependent the three ash types are to geographic location, demographics, and where the coal was excavated. Local regions around the world vary in what food they consume, how the consumables are packaged, and even what holidays are celebrated. This is important in determining what elemental constituents may be present in the ash. Two main sources of regulatory metals in biosolid waste, MSW and SSBA, are industrial waste incinerated and the quantity of processed goods consumed/used. The more processed goods like kitchen waste, plastic, and paper the larger quantities of regulatory metals present (Long et al. 2011).

The physical characteristics that will be compared are shown in Figure 13. The particle size distribution differed between the three ashes where MSW incinerated ash had the lowest percentage passing a No. 200 sieve. This indicates that the MSW ash had significantly more coarse particles that the coal fly ash and the biosolid ash. Biosolid ash had the next lowest percentage passing a No. 200 sieve where approximately half the particles pass the sieve. The smallest particles were found in the coal fly ash where 60% to 90% passing No. 200 sieve. This would lead to a higher impact on the surrounding areas where coal fly ash was used or landfilled. It is possible that the smaller particles may easily be transported by winds outside the disposal area.

The specific gravity was relatively equal for all three ash types. MSW ash was slightly lower resulting in similar bulk densities between the three ashes. There is significant differences in the maximum dry density of coal fly ash, MSW ash, and biosolid ash. Coal fly ash has the highest maximum density which may be due to how much smaller the particles are than in the other two ash types. The biosolid ash has the lowest maximum dry density which, by the logic used for the coal ash, does not seem likely. However, the biosolid ash does not have a good gradation of particles. The MSW Ash has a much more defined particle gradation resulting in lower void volume and a higher maximum dry density.

The hydraulic conductivity is approximately equal for all three ash types. Water moves relatively easily through all ash types with a permeability range of 10^{-3} to 10^{-4} cm/s which correspond to a fine sand or silt. All three ashes are also non-plastic acting similar to coarser particles of sand. The last property is the loss on ignition (LOI) to determine how much potential carbon and other organic elements may be present. Loss on ignition is highly dependent on how efficient the process may be. MSW ash has the highest loss on ignition ranging from 4.3% to 13.36% by weight. This may be due to a lower temperature used during the incineration process and how efficient the process is. The biosolid ash has the next highest LOI with 1.4% to 9.3% although the higher end was found in earlier hearth systems. The coal fly ash has the lowest LOI ranging from 2% to 7% and may be due to the temperature at which coal burns or more efficient processes for incineration.

	Coal Fly Ash	MSW Ash	WW Biosolid Ash
% passing No. 200 sieve	60% - 90%	5% - 30%	38% - 66%
Moisture Content (% by weight)	10% -45%	17% - 76%	17% - 38%
Specific Gravity	2.3 - 2.9	1.86 - 2.37	2.39 - 2.99
Permeability (cm/sec)	10^{-4} - 10^{-6}	10^{-3} - 10^{-4}	$10^{-3.40}$ -10^{-4}
Maximum Dry Density (pcf)	66.2 - 114	79-108	65-90
Loss of Ignition	2% - 7%	4.3 - 13.36	1.4- 9.3
Plasticity Index	NP	NP	NP

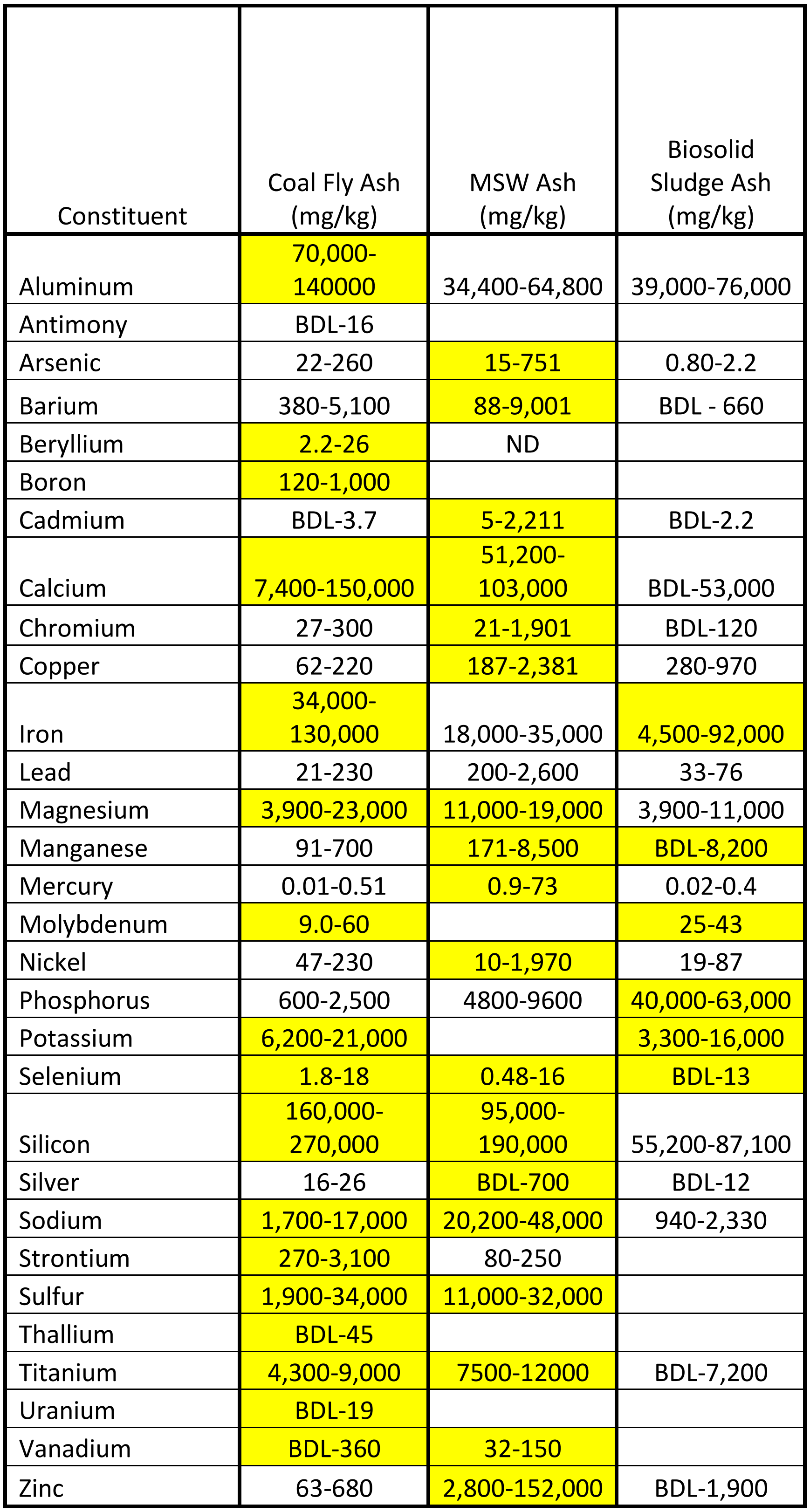
Figure 13: Ash physical characteristics (Alhassan 2012; EPRI 2009; Federal Highway Administration Research and Technology Coordinating 1997)

Overall, there is not a significant difference, except particle size, between the three ash types. The next area to look at is the elemental composition in each ash type. The mg/kg of each constituent of concern is shown in Figure 14. Biosolid incinerated ash has significantly lower concentrations of most constituents except phosphorus 40,000-63,000 mg/kg, iron 4,500-92,000 mg/kg, manganese below detectable limits (BDL)-8,200, and zinc BDL-1,900. The phosphorus concentration is approximately seven times higher than in either coal fly ash or MSW ash.

MSW ash has the highest concentrations of arsenic, barium, cadmium, chromium, copper, lead, manganese, mercury, nickel, silver, sodium, titanium, and zinc. The majority of the elements MSW is highest in concentration are orders of magnitude higher than in biosolid ash. Specifically, arsenic is 350 times higher than in biosolids and three times higher than in coal fly ash. Chromium concentrations are fifteen times greater than in biosolids and six times greater than in coal fly ash. The high concentrations of the constituents in MSW ash may cause environmental issues if not properly monitored.

Coal fly ash has the highest concentrations of aluminum, antimony, boron, calcium, iron, magnesium, molybdenum, potassium, selenium, silicon, strontium, sulfur, thallium, uranium, and vanadium. The concentrations of many of the constituents shown in Figure 14 were significantly higher than in biosolid ash. Coal fly ash was the only ash type reviewed that has uranium, boron, antimony, and thallium present.

It is not clear as to whether coal fly ash or MSW ash may have a greater impact on the population and environment if contamination occurs. Further evaluation through leaching tests may be required to rank the three ash types in order of environmental impact.



Constituent	Coal Fly Ash (mg/kg)	MSW Ash (mg/kg)	Biosolid Sludge Ash (mg/kg)
Aluminum	70,000-140000	34,400-64,800	39,000-76,000
Antimony	BDL-16		
Arsenic	22-260	15-751	0.80-2.2
Barium	380-5,100	88-9,001	BDL - 660
Beryllium	2.2-26	ND	
Boron	120-1,000		
Cadmium	BDL-3.7	5-2,211	BDL-2.2
Calcium	7,400-150,000	51,200-103,000	BDL-53,000
Chromium	27-300	21-1,901	BDL-120
Copper	62-220	187-2,381	280-970
Iron	34,000-130,000	18,000-35,000	4,500-92,000
Lead	21-230	200-2,600	33-76
Magnesium	3,900-23,000	11,000-19,000	3,900-11,000
Manganese	91-700	171-8,500	BDL-8,200
Mercury	0.01-0.51	0.9-73	0.02-0.4
Molybdenum	9.0-60		25-43
Nickel	47-230	10-1,970	19-87
Phosphorus	600-2,500	4800-9600	40,000-63,000
Potassium	6,200-21,000		3,300-16,000
Selenium	1.8-18	0.48-16	BDL-13
Silicon	160,000-270,000	95,000-190,000	55,200-87,100
Silver	16-26	BDL-700	BDL-12
Sodium	1,700-17,000	20,200-48,000	940-2,330
Strontium	270-3,100	80-250	
Sulfur	1,900-34,000	11,000-32,000	
Thallium	BDL-45		
Titanium	4,300-9,000	7500-12000	BDL-7,200
Uranium	BDL-19		
Vanadium	BDL-360	32-150	
Zinc	63-680	2,800-152,000	BDL-1,900

Figure 14: Elemental composition of coal fly ash, MSW ash, and biosolid ash

CHAPTER 5: CONCLUSION

The research began as a project to determine if applying biosolid incinerated ash for land amendment might result in exceedances of groundwater standards. Specifically, phosphorus was a concern due to the relatively high concentration (46 g/kg) and how it may impact surface water bodies. Many states, including North Carolina, have adopted phosphorus regulations including nutrient management plans with regards to biosolid sludge applied to agricultural lands (NCDEQ 2015). The excess phosphorus would run off into surface water and stimulate plant growth. Therefore, North Carolina Department of Environmental Quality questioned if phosphorus would leach into the soil and groundwater.

The concentrations of phosphorus collected in the field vacuum lysimeters were below 0.6 mg/L in all but one sample. One sample had a phosphorus concentration of 1.6 mg/L, 2.5 times higher than any other sample collected. The laboratory column leaching tests had maximum concentrations of 8.88 mg/L. During the soil attenuation tests no phosphorus was collected indicating that little or no transport occurred.

The field study also had one sample with a manganese concentration of 134 μg/L and silver concentration of 37.14 μg/L, while exceeding 15A NCAC 02L.0202 drinking water regulations both fall within the background levels detected in Cabarrus County, NC. (Environmental Management Commission Raleigh 2013; UNC 2013). During the column test there were six elements that exceeding the drinking water regulations during the first 0.2 L/S; manganese, nickel, selenium, arsenic, lead, and silver. However, arsenic remained above the limit for the first 4.5 L/S indicating that without soil to attenuate arsenic there would be an issue with contamination. Greater concentrations were observed in laboratory tests than in the field, ostensibly because leaching had already occurred, i.e., an estimated 1.8 pore volumes of infiltration had passed through the field-placed ash prior to instrumentation and data collection.

Both the laboratory and field attenuation studies demonstrated that phosphorus and arsenic did not leach through the soil for duration of the testing. Selenium leached from the beginning and released 15% of the total mass in the spiked solution. Fitting the Ogata-Banks equation to the data yielded a column derived Kd in the range of 2-4 mL/g. Manganese concentrations were below maximum allowable limits with maximum concentration that leached in six pore volumes of 11.71 μg/L. The field attenuation had similar concentrations of selenium and manganese in relation to pore volumes. However, collection of leachate at smaller increments of time may reveal the relationship of attenuation with depth.

The physical characteristics that were tested had similar results to previous tests conducted by Pace Laboratories and from literature. The results were used as part of the comparison between coal fly ash, municipal solid waste ash, and biosolid incinerated ash. The only significant different between the three ash types were in particle size passing a No. 200 sieve. The elemental composition showed a significant difference between biosolid ash and both MSW ash and coal fly ash. The majority of elements in biosolid ash were orders of magnitude lower than in either of the other two ash categories.

Recommended future research is:

- Mechanisms of soil attenuation of phosphorus, arsenic, selenium, and manganese should be determined.
- The field and laboratory attenuation should be done in time increments and/or by depth to determine the relationship between depth and attenuation.
- More laboratory leaching tests conducted varying the pH to determine how the ash would react to a change in pH.
- A comparison between column leaching of biosolid ash, MSW ash, and coal fly ash to determine the order of environmental impact.

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APPENDIX A: FIELD LYSIMETERS

Table 5: Field lysimeter 9-17-2013

Date	Lysimeter	Volume Collected (mL)	pH	Conductivity (µs/cm)	ORP (mV)	Al (27) (µg/L)	P (31) (mg/L)	Cr (52) (µg/L)	Mn (55) (µg/L)	Fe (56) (µg/L)	Ni (60) (µg/L)	Cu (65) (µg/L)	Zn (66) (µg/L)	As (75) (µg/L)	Se (82) (µg/L)	Mo (95) (µg/L)	Ag (107) (µg/L)	Cd (111) (µg/L)	Ba (137) (µg/L)	Pb (208) (µg/L)
9/17/2013	1	2	sample amount too small																	
9/17/2013	2	231	7.62	421	281	ND	0.1221	ND	9.2	36.1	ND	ND	ND	ND	ND	9.4	ND	ND	54.1	ND
9/17/2013	3	1000	7.81	501	310	ND	0.2900	ND	9.8	50.1	ND	ND	ND	ND	ND	17.7	5.4	ND	162	ND
9/17/2013	4	1000	7.83	419	357	ND	0.4800	ND	134	111	ND	ND	ND	ND	ND	53.4	ND	ND	77.9	ND
9/17/2013	5	3	sample amount too small																	
9/17/2013	6	241	7.30	490	336	ND	0.2700	ND	20.9	ND	ND	ND	ND	ND	ND	19.6	ND	ND	279	ND
9/17/2013	7	678	7.38	590	342	ND	0.2000	ND	23.7	ND	ND	ND	ND	ND	ND	21.3	ND	ND	65.4	ND
9/17/2013	8	1000	7.20	587	368	ND	0.4400	ND	27.6	ND	5.7	ND	16.1	ND	ND	33.9	ND	ND	207	ND
9/17/2013	9	2	sample amount too small																	
9/17/2013	10	123	7.65	319	363	ND	0.0315	ND	11.2	ND	ND	ND	ND	ND	ND	17.8	ND	ND	89.4	ND
9/17/2013	11	754	7.47	546	352	ND	0.4300	ND	10.7	ND	ND	ND	ND	ND	ND	22.4	ND	ND	127.1	ND
9/17/2013	12	1000	7.32	528	343	ND	0.1328	ND	18.5	ND	ND	ND	ND	ND	ND	26.7	ND	ND	73.6	ND
9/17/2013	13	N/A																		
			TCLP Regulatory Limits					5000						5000	1000		5000	1000	100000	5000
			NC 2L groundwater					10	50	300	100	1000	1000	10	20		20	2	700	15
			15A NCAC 2T.1203 (mg/kg)								420	4300	7500	75	100	75		85		840
			Prism Report (mg/kg)			70000		68			53	430	1300	BRL	BRL	26	12	2.2	660	44

Table 6: Field lysimeter 10-14-2013

Date	Lysimeter	Volume Collected (mL)	pH	Conductivity (µs/cm)	ORP (mV)	Al (27) (µg/L)	P (31) (mg/L)	Cr (52) (µg/L)	Mn (55) (µg/L)	Fe (56) (µg/L)	Ni (60) (µg/L)	Cu (65) (µg/L)	Zn (66) (µg/L)	As (75) (µg/L)	Se (82) (µg/L)	Mo (95) (µg/L)	Ag (107) (µg/L)	Cd (111) (µg/L)	Ba (137) (µg/L)	Pb (208) (µg/L)
10/14/2013	1	15	7.75	671	282	sample amount too small														
10/14/2013	2	543	7.92	1140	293	ND	0.1588	ND	7.8	ND	ND	ND	ND	ND	ND	16.4	ND	ND	75.8	ND
10/14/2013	3	1000	7.28	546	347	ND	0.2800	ND	39.2	ND	ND	ND	10.7	ND	ND	27.9	ND	ND	99.2	ND
10/14/2013	4	1000	7.25	517	297	ND	0.2800	ND	8.1	ND	ND	ND	ND	ND	ND	17.3	ND	ND	164	ND
10/14/2013	5	14	7.32	492	286	sample amount too small														
10/14/2013	6	471	7.92	738	352	ND	0.0960	ND	ND	ND	ND	ND	ND	ND	ND	17	ND	ND	188	ND
10/14/2013	7	1000	7.89	805	288	ND	0.2100	ND	ND	ND	ND	ND	ND	ND	ND	23.4	ND	ND	192	ND
10/14/2013	8	1000	7.28	490	286	ND	0.3841	ND	38.6	ND	ND	ND	ND	ND	ND	45.6	ND	ND	201	ND
10/14/2013	9	21	8.08	537	293	no sample														
10/14/2013	10	214	7.38	544	286	ND	0.0262	ND	17.1	ND	ND	ND	ND	ND	ND	15.9	ND	ND	167	ND
10/14/2013	11	674	7.65	528	303	ND	0.4125	ND	19.5	ND	ND	ND	ND	ND	ND	17.8	ND	ND	192	ND
10/14/2013	12	issues with line leaking																		
10/14/2013	13	N/A																		
			TCLP Regulatory Limits					5000						5000	1000		5000	1000	100000	5000
			NC 2L groundwater					10	50	300	100	1000	1000	10	20		20	2	700	15
			15A NCAC 2T.1203 (mg/kg)								420	4300	7500	75	100	75		85		840
			Prism Report (mg/kg)			70000		68			53	430	1300	BRL	BRL	26	12	2.2	660	44

Table 7: Field lysimeter 12-22-2013

Date	Lysimeter	Volume Collected (mL)	pH	Conductivity (µs/cm)	ORP (mV)	Al (27) (µg/L)	P (31) (mg/L)	Cr (52) (µg/L)	Mn (55) (µg/L)	Fe (56) (µg/L)	Ni (60) (µg/L)	Cu (65) (µg/L)	Zn (66) (µg/L)	As (75) (µg/L)	Se (82) (µg/L)	Mo (95) (µg/L)	Ag (107) (µg/L)	Cd (111) (µg/L)	Ba (137) (µg/L)	Pb (208) (µg/L)
12/22/2013	1	247	7.64	674	343	ND	0.3062	ND	7.2	ND	ND	ND	ND	ND	ND	6.5	ND	ND	47.8	ND
12/22/2013	2	784	7.45	517	386	ND	0.1827	ND	9.8	ND	ND	ND	ND	ND	ND	9.8	ND	ND	67	ND
12/22/2013	3	1000	7.89	624	357	ND	0.2214	ND	15.4	ND	ND	ND	ND	ND	ND	15.7	ND	ND	97.3	ND
12/22/2013	4	1000	7.92	801	302	ND	0.2332	ND	20.3	ND	ND	ND	ND	ND	ND	25.6	ND	ND	111.3	ND
12/22/2013	5	287	7.31	394	343	ND	0.1341	ND	8.2	ND	ND	ND	ND	ND	ND	7.9	ND	ND	53.9	ND
12/22/2013	6	721	7.42	486	352	ND	0.2879	ND	13.4	ND	ND	ND	ND	ND	ND	15.1	ND	ND	71.1	ND
12/22/2013	7	1000	7.39	647	368	ND	0.4788	ND	21.6	ND	ND	ND	ND	ND	ND	19.8	ND	ND	92.9	ND
12/22/2013	8	1000	8.01	587	291	ND	0.3642	ND	27.4	ND	ND	ND	ND	ND	ND	26.3	ND	ND	157.2	ND
12/22/2013	9	311	7.68	565	283	ND	0.3013	ND	9.7	ND	ND	ND	ND	ND	ND	10.2	ND	ND	51.1	ND
12/22/2013	10	802	7.85	741	295	ND	0.0885	ND	18.4	ND	ND	ND	ND	ND	ND	13.7	ND	ND	59.7	ND
12/22/2013	11	1000	7.65	601	301	ND	0.4477	ND	21.9	ND	ND	ND	ND	ND	ND	19.3	ND	ND	83.8	ND
12/22/2013	12	1000	7.87	657	314	ND	0.1874	ND	25.7	ND	ND	ND	ND	ND	ND	22.5	ND	ND	101.4	ND
12/22/2013	13	N/A																		
			TCLP Regulatory Limits					5000						5000	1000		5000	1000	100000	5000
			NC 2L groundwater					10	50	300	100	1000	1000	10	20		20	2	700	15
			15A NCAC 2T.1203 (mg/kg)								420	4300	7500	75	100	75		85		840
			Prism Report (mg/kg)			70000		68			53	430	1300	BRL	BRL	26	12	2.2	660	44

Table 8: Field lysimeter 2-14-2014

Date	Lysimeter	Volume Collected (mL)	pH	Conductivity (µs/cm)	ORP (mV)	Al (27) (µg/L)	P (31) (mg/L)	Cr (52) (µg/L)	Mn (55) (µg/L)	Fe (56) (µg/L)	Ni (60) (µg/L)	Cu (65) (µg/L)	Zn (66) (µg/L)	As (75) (µg/L)	Se (82) (µg/L)	Mo (95) (µg/L)	Ag (107) (µg/L)	Cd (111) (µg/L)	Ba (137) (µg/L)	Pb (208) (µg/L)
2/14/2014	1	314	7.83	1049	302	ND	0.0829	ND	ND	ND	ND	ND	ND	ND	ND	5.1	ND	ND	48.7	ND
2/14/2014	2	754	8.37	606	310	ND	0.1100	ND	2.14	ND	ND	ND	ND	ND	ND	8.8	ND	ND	69.9	ND
2/14/2014	3	1000	7.99	601	357	58	0.2521	0	4.419	ND	2.619	4	10	1.157	ND	10	ND	ND	133	0
2/14/2014	4	1000	7.38	738	336	59	0.2048	1.175	4.029	11.53	1.51	22	9	1.311	ND	13	0	ND	78	0
2/14/2014	5	Lysimeter not working																		
2/14/2014	6	698	7.28	490	368	123	0.0890	0	1.453	23.02	0	3	6	ND	ND	0	ND	0	116	0
2/14/2014	7	1000	7.38	590	363	ND	0.0887	ND	6.31	ND	ND	ND	ND	ND	ND	11.2	ND	ND	158.1	ND
2/14/2014	8	1000	7.65	567	352	94	0.2857	0	14.24	38.61	3.807	2	17	2.586	ND	52	0	0	193	0
2/14/2014	9	297	7.30	536	343	ND	0.2101	ND	1.256	ND	ND	ND	ND	ND	ND	4.1	ND	ND	31.7	ND
2/14/2014	10	754	7.00	587	310	ND	0.0974	ND	1.861	ND	ND	ND	ND	ND	ND	9.7	ND	ND	89.6	ND
2/14/2014	11	1000	7.38	599	302	ND	0.3614	ND	4.12	ND	ND	ND	ND	ND	ND	15.9	ND	ND	108.7	ND
2/14/2014	12	1000	7.50	606	343	ND	0.1973	ND	9.78	ND	ND	ND	ND	ND	ND	21.3	ND	ND	122.3	ND
2/14/2014	13	N/A																		
			TCLP Regulatory Limits					5000						5000	1000		5000	1000	100000	5000
			NC 2L groundwater					10	50	300	100	1000	1000	10	20		20	2	700	15
			15A NCAC 2T.1203 (mg/kg)								420	4300	7500	75	100	75		85		840
			Prism Report (mg/kg)			70000		68			53	430	1300	BRL	BRL	26	12	2.2	660	44

Table 9: Field lysimeter 3-11-2014

Date	Lysimeter	Volume Collected (mL)	pH	Conductivity (µs/cm)	ORP (mV)	Al (27) (µg/L)	P (31) (mg/L)	Cr (52) (µg/L)	Mn (55) (µg/L)	Fe (56) (µg/L)	Ni (60) (µg/L)	Cu (65) (µg/L)	Zn (66) (µg/L)	As (75) (µg/L)	Se (82) (µg/L)	Mo (95) (µg/L)	Ag (107) (µg/L)	Cd (111) (µg/L)	Ba (137) (µg/L)	Pb (208) (µg/L)
3/11/2014	1	289	8.07	358	279	167	0.2018	ND	11.6	56.56	2.976	9	14	ND	ND	1	5.09	ND	97	ND
3/11/2014	2	547	8.24	735	276	116	0.155	ND	1.989	21.98	2.862	7	9	ND	ND	4	ND	ND	141	ND
3/11/2014	3	1000	6.82	270	325	72	0.0662	ND	1.707	24.77	1.436	2	3	ND	ND	4	ND	ND	61	ND
3/11/2014	4	1000	8.39	647	270	99	0.5749	1.145	6.475	NR	1.65	3	8	1.281	ND	11	ND	ND	79	ND
3/11/2014	5	Lysimeter not working																		
3/11/2014	6	587	8.09	482	288	86	0.0994	ND	ND	25.5	1.328	2	7	ND	ND	ND	ND	ND	131	ND
3/11/2014	7	1000	7.57	586	310	80	0.0877	ND	2.488	24.05	2.073	2	11	ND	ND	ND	ND	ND	153	ND
3/11/2014	8	1000	7.72	392	290	174	0.4706	ND	2.924	31.99	3.198	2	18	1.724	ND	22	ND	ND	192	ND
3/11/2014	9	301	8.29	592	304	139	0.1634	1.269	1.216	NR	3.18	9	15	4.403	ND	ND	ND	ND	147	1.074
3/11/2014	10	674	8.37	840	292	93	0.1481	ND	3.599	34	2.307	7	7	1.019	ND	39	ND	ND	103	ND
3/11/2014	11	1000	8.47	903	282	101	0.3067	1.849	2.333	15.18	2.208	6	2	1.828	ND	61	ND	ND	201	ND
3/11/2014	12	1000	7.83	911	279	112	0.2347	ND	2.014	29.41	1.458	5.1	ND	1.912	ND	54.2	ND	ND	209.1	ND
3/11/2014	13	N/A																		
			TCLP Regulatory Limits					5000						5000	1000		5000	1000	100000	5000
			NC 2L groundwater					10	50	300	100	1000	1000	10	20		20	2	700	15
			15A NCAC 2T.1203 (mg/kg)								420	4300	7500	75	100	75		85		840
			Prism Report (mg/kg)			70000		68			53	430	1300	BRL	BRL	26	12	2.2	660	44

Table 10: Field lysimeter 4-11-2014

Date	Lysimeter	Volume Collected (mL)	pH	Conductivity (µs/cm)	ORP (mV)	Al (27) (µg/L)	P (31) (mg/L)	Cr (52) (µg/L)	Mn (55) (µg/L)	Fe (56) (µg/L)	Ni (60) (µg/L)	Cu (65) (µg/L)	Zn (66) (µg/L)	As (75) (µg/L)	Se (82) (µg/L)	Mo (95) (µg/L)	Ag (107) (µg/L)	Cd (111) (µg/L)	Ba (137) (µg/L)	Pb (208) (µg/L)
4/11/2014	1	414	7.32	410	286	98	0.0729	ND	2.317	33.24	2.806	13	7	ND	ND	1	1.415	ND	122	ND
4/11/2014	2	847	7.11	300	293	80	0.073	ND	4.599	53.56	2.352	4	2	ND	ND	3	1.144	ND	182	ND
4/11/2014	3	1000	8.03	546	293	NR	0.1983	ND	8.488	46.16	3.631	7	11	1.158	ND	8	2.17	ND	187	ND
4/11/2014	4	1000	7.69	540	283	161	0.3003	1.506	20.91	74.3	12.07	4	38	1.182	ND	11	1.474	ND	100	1.045
4/11/2014	5	321	7.64	544	282	61	0.0541	ND	1.987	16.78	2.478	5	9	ND	ND	ND	ND	ND	109	ND
4/11/2014	6	799	7.25	492	316	88	0.1166	ND	ND	21.08	2.359	3	19	ND	ND	ND	ND	ND	161	1.414
4/11/2014	7	1000	7.42	604	296	81	0.0821	ND	1.47	21.42	1.529	1	14	ND	ND	ND	ND	ND	194	ND
4/11/2014	8	1000	7.80	541	296	88	0.2514	ND	2.03	19.78	2.689	2	11	ND	ND	ND	ND	ND	201	ND
4/11/2014	9	379	7.75	677	303	92	0.1923	1.104	2.133	ND	3.649	1	13	2.955	ND	25	4.624	ND	212	ND
4/11/2014	10	815	7.89	671	288	115	0.1615	ND	4.15	35.46	3.98	5	15	ND	ND	ND	ND	ND	203	ND
4/11/2014	11	1000	7.92	853	293	152	0.334	1.687	8.129	86.74	4.302	11	18	1.85	ND	53	37.14	ND	193	ND
4/11/2014	12	Lysimeter not working																		
4/11/2014	13	379	7.75	541	308	78	1.679	ND	2.98	19.47	3.01	3.1	8.5	ND	ND	ND	ND	ND	118	ND
			TCLP Regulatory Limits					5000						5000	1000		5000	1000	100000	5000
			NC 2L groundwater					10	50	300	100	1000	1000	10	20		20	2	700	15
			15A NCAC 2T.1203 (mg/kg)								420	4300	7500	75	100	75		85		840
			Prism Report (mg/kg)			70000		68			53	430	1300	BRL	BRL	26	12	2.2	660	44

Table 11: Field lysimeter - Aluminum

	Al (27) (µg/L)												
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		ND	ND	ND		ND	ND	ND		ND	ND	ND	
10/14/2013		ND	ND	ND		ND	ND	ND		ND	ND		
12/22/2013	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
2/14/2014	ND	ND	58	59		123	ND	94	ND	ND	ND	ND	
3/11/2014	167	116	72	99		86	80	174	139	93	101	112	
4/11/2014	98	80	NR	161	61	88	81	88	92	115	152		13

Table 12: Field lysimeter - Phosphorus

	P (31) (mg/L)												
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		0.1221	0.2900	0.4800		0.2700	0.2000	0.4400		0.0315	0.4300	0.1328	
10/14/2013		0.1588	0.2800	0.2800		0.0960	0.2100	0.3841		0.0262	0.4125		
12/22/2013	0.3062	0.1827	0.2214	0.2332	0.1341	0.2879	0.4788	0.3642	0.3013	0.0885	0.4477	0.1874	
2/14/2014	0.0829	0.11	0.2521	0.2048		0.089	0.0887	0.2857	0.2101	0.0974	0.3614	0.1973	
3/11/2014	0.2018	0.155	0.0662	0.5749		0.0994	0.0877	0.4706	0.1634	0.1481	0.3067	0.2347	
4/11/2014	0.0729	0.073	0.1983	0.3003	0.0541	0.1166	0.0821	0.2514	0.1923	0.1615	0.334		1.679

Table 13: Field lysimeter - Chromium

	Cr (52) (µg/L)												
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		ND	ND	ND		ND	ND	ND		ND	ND	ND	
10/14/2013		ND	ND	ND		ND	ND	ND		ND	ND		
12/22/2013	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
2/14/2014	ND	ND	0	1.175		0	ND	0	ND	ND	ND	ND	
3/11/2014	ND	ND	ND	1.145		ND	ND	ND	1.269	ND	1.849	ND	
4/11/2014	ND	ND	ND	1.506	ND	ND	ND	ND	1.104	ND	1.687		ND

Table 14: Field lysimeter - Manganese

	Mn (55) (μg/L)												
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		9.2	9.8	134		20.9	23.7	27.6		11.2	10.7	18.5	
10/14/2013		7.8	39.2	8.1		ND	ND	38.6		17.1	19.5		
12/22/2013	7.2	9.8	15.4	20.3	8.2	13.4	21.6	27.4	9.7	18.4	21.9	25.7	
2/14/2014	ND	2.14	4.419	4.029		1.453	6.31	14.24	1.256	1.861	4.12	9.78	
3/11/2014	11.6	1.989	1.707	6.475		ND	2.488	2.924	1.216	3.599	2.6333	2.014	
4/11/2014	2.317	4.599	8.488	20.91	1.987	ND	1.47	2.03	2.133	4.15	8.129	2.98	2.98

Table 15: Field lysimeter - Iron

	Fe (56) (μg/L)												
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		36.1	50.1	111		ND	ND	ND		ND	ND	ND	
10/14/2013		ND	ND	ND		ND	ND	ND		ND	ND		
12/22/2013	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
2/14/2014	ND	ND	ND	11.53		23.02	ND	38.61	ND	ND	ND	ND	
3/11/2014	56.56	21.98	24.77	NR		25.5	24.05	31.99	NR	34	15.18	29.41	
4/11/2014	33.24	53.56	46.16	74.3	16.78	21.08	21.42	19.78	ND	35.46	86.74		19.47

Table 16: Field lysimeter - Nickel

	Ni (60) (μg/L)												
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		ND	ND	ND		ND	ND	5.7		ND	ND	ND	
10/14/2013		ND	ND	ND		ND	ND	ND		ND	ND	ND	
12/22/2013	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
2/14/2014	ND	ND	2.619	1.51		0	ND	3.807	ND	ND	ND	ND	
3/11/2014	2.976	2.862	1.436	1.65		1.328	2.073	3.198	3.18	2.307	2.208	1.458	
4/11/2014	2.806	2.352	3.631	12.07	2.478	2.359	1.529	2.689	3.649	3.98	4.302		3.01

Table 17: Field lysimeter - Copper

Cu (65) (µg/L)													
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		ND	ND	ND		ND	ND	ND		ND	ND	ND	
10/14/2013		ND	ND	ND		ND	ND	ND		ND	ND		
12/22/2013	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
2/14/2014	ND	ND	4	22		3	ND	2	ND	ND	ND	ND	
3/11/2014	9	7	2	3		2	2	2	9	7	6	5.1	
4/11/2014	13	4	7	4	5	3	1	2	1	5	11		3.1

Table 18: Field lysimeter - Zinc

Zn (66) (µg/L)													
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		ND	ND	ND		ND	ND	16.1		ND	ND	ND	
10/14/2013		ND	10.7	ND		ND	ND	ND		ND	ND		
12/22/2013	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
2/14/2014	ND	ND	10	9		6	ND	17	ND	ND	ND	ND	
3/11/2014	14	9	3	8		7	11	18	15	7	2	ND	
4/11/2014	7	2	11	38	9	19	14	11	13	15	18		8.5

Table 19: Field lysimeter - Arsenic

As (75) (µg/L)													
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		ND	ND	ND		ND	ND	ND		ND	ND	ND	
10/14/2013		ND	ND	ND		ND	ND	ND		ND	ND		
12/22/2013	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
2/14/2014	ND	ND	1.157	1.311		ND	ND	2.586	ND	ND	ND	ND	
3/11/2014	ND	ND	ND	1.281		ND	ND	1.724	4.403	1.019	1.828	1.912	
4/11/2014	ND	ND	1.158	1.182	ND	ND	ND	ND	2.955	ND	1.85		ND

Table 20: Field lysimeter - Selenium

Se (82) (µg/L)													
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		ND	ND	ND		ND	ND	ND		ND	ND	ND	
10/14/2013		ND	ND	ND		ND	ND	ND		ND	ND		
12/22/2013	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
2/14/2014	ND	ND	ND	ND		ND	ND	ND	ND	ND	ND	ND	
3/11/2014	ND	ND	ND	ND		ND	ND	ND	ND	ND	ND	ND	
4/11/2014	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND		ND

Table 21: Field lysimeter - Molybdenum

Mo (95) (µg/L)													
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		9.4	17.7	53.4		19.6	21.3	33.9		17.8	22.4	26.7	
10/14/2013		16.4	27.9	17.3		17	23.4	45.6		15.9	17.8		
12/22/2013	6.5	9.8	15.7	25.6	7.9	15.1	19.8	26.3	10.2	13.7	19.3	22.5	
2/14/2014	5.1	8.8	10	13		0	11.2	52	4.1	9.7	15.9	21.3	
3/11/2014	1	4	4	11		ND	ND	22	ND	39	61	54.2	
4/11/2014	1	3	8	11	ND	ND	ND	ND	25	ND	53		ND

Table 22: Field lysimeter - Silver

Ag (107) (µg/L)													
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		ND	5.4	ND		ND	ND	ND		ND	ND	ND	
10/14/2013		ND	ND	ND		ND	ND	ND		ND	ND		
12/22/2013	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
2/14/2014	ND	ND	ND	0		ND	ND	0	ND	ND	ND	ND	
3/11/2014	5.09	ND	ND	ND		ND	ND	ND	ND	ND	ND	ND	
4/11/2014	1.415	1.144	2.17	1.474	ND	ND	ND	ND	4.624	ND	37.14		ND

Table 23: Field lysimeter - Cadmium

	Cd (111) (µg/L)												
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		ND	ND	ND		ND	ND	ND		ND	ND	ND	
10/14/2013		ND	ND	ND		ND	ND	ND		ND	ND		
12/22/2013	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
2/14/2014	ND	ND	ND	ND		0	ND	0	ND	ND	ND	ND	
3/11/2014	ND	ND	ND	ND		ND	ND	ND	ND	ND	ND	ND	
4/11/2014	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND		ND

Table 24: Field lysimeter - Barium

	Ba (137) (µg/L)												
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		54.1	162	77.9		279	65.4	207		89.4	127.1	73.6	
10/14/2013		75.8	99.2	164		188	192	201		167	192		
12/22/2013	47.8	67	97.3	111.3	53.9	71.1	92.9	157.2	51.1	59.7	83.8	101.4	
2/14/2014	48.7	69.9	133	78		116	158.1	193	31.7	89.6	108.7	122.3	
3/11/2014	97	141	61	79		131	153	192	147	103	201	209.1	
4/11/2014	122	182	187	100	109	161	194	201	212	203	193		118

Table 25: Field lysimeter - Lead

	Pb (208) (µg/L)												
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13
9/17/2013		ND	ND	ND		ND	ND	ND		ND	ND	ND	
10/14/2013		ND	ND	ND		ND	ND	ND		ND	ND		
12/22/2013	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
2/14/2014	ND	ND	0	0		0	ND	0	ND	ND	ND	ND	
3/11/2014	ND	ND	ND	ND		ND	ND	ND	1.074	ND	ND	ND	
4/11/2014	ND	ND	ND	1.045	ND	1.414	ND	ND	ND	ND	ND		ND

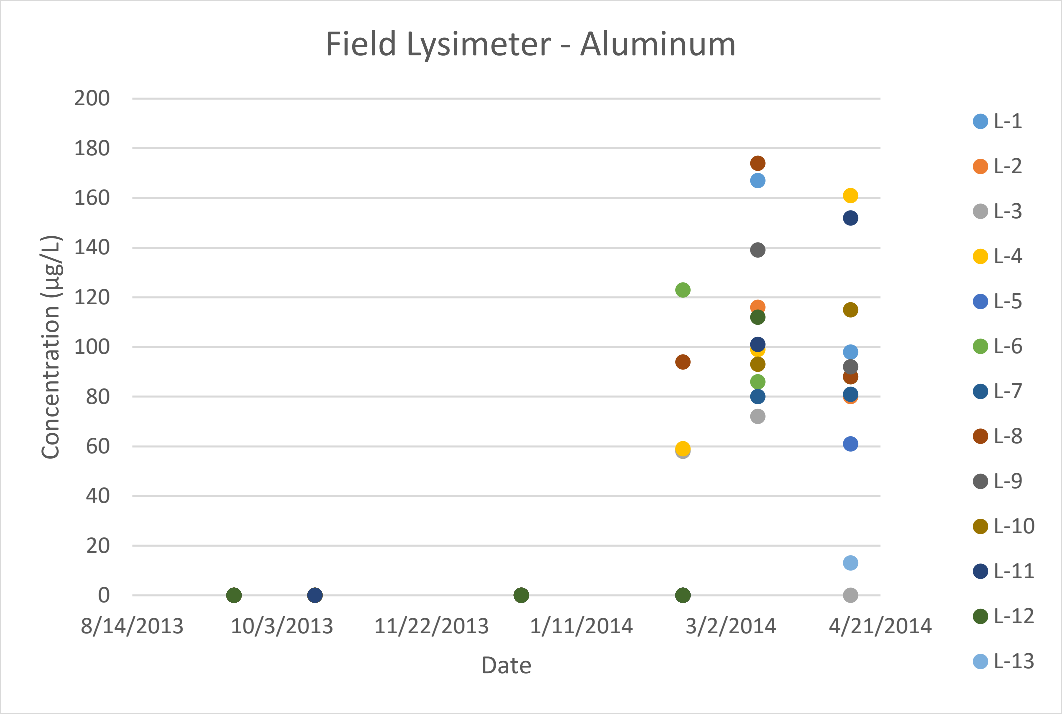


Figure 15: Field lysimeters – Aluminum

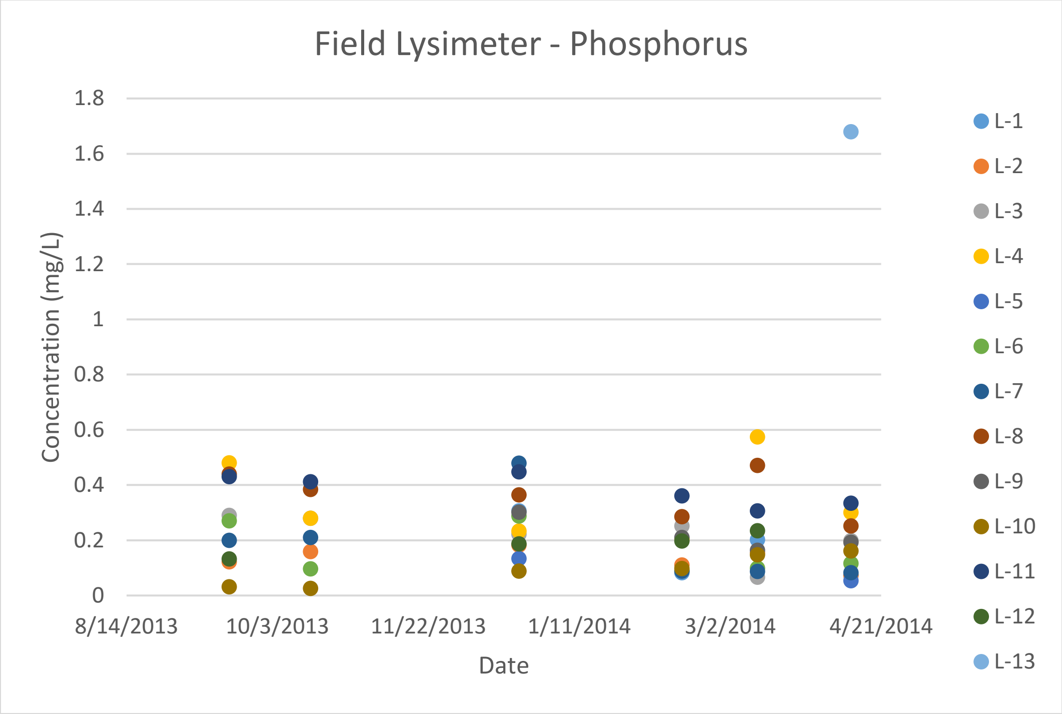


Figure 16: Field lysimeters – Phosphorus

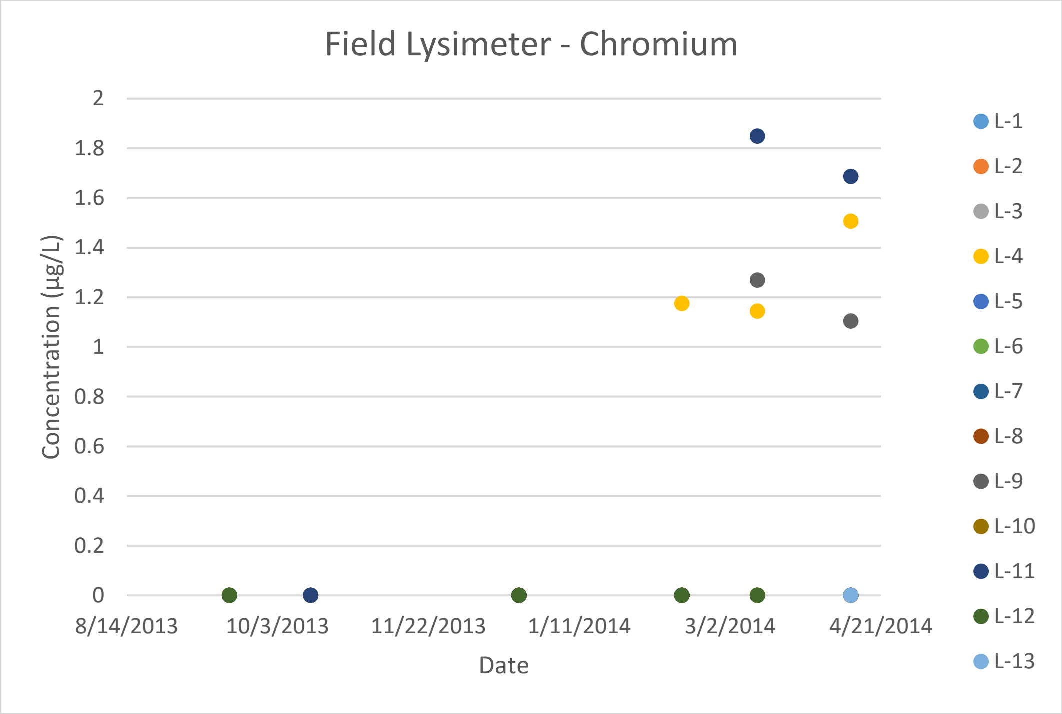


Figure 17: Field lysimeters – Chromium

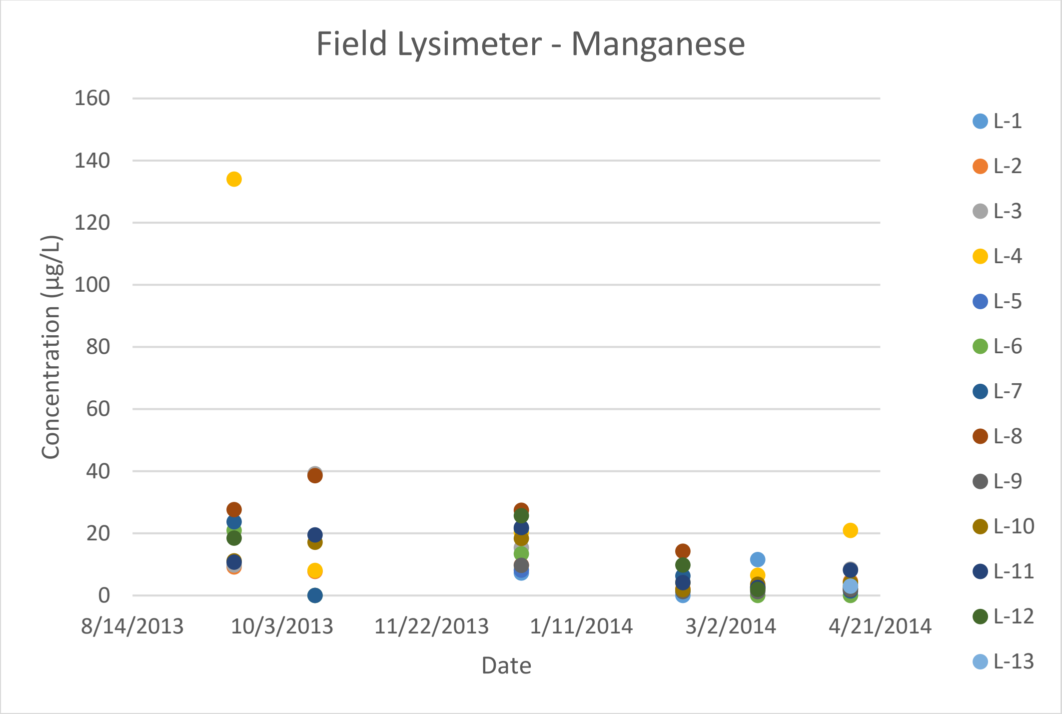


Figure 18: Field lysimeters – Manganese

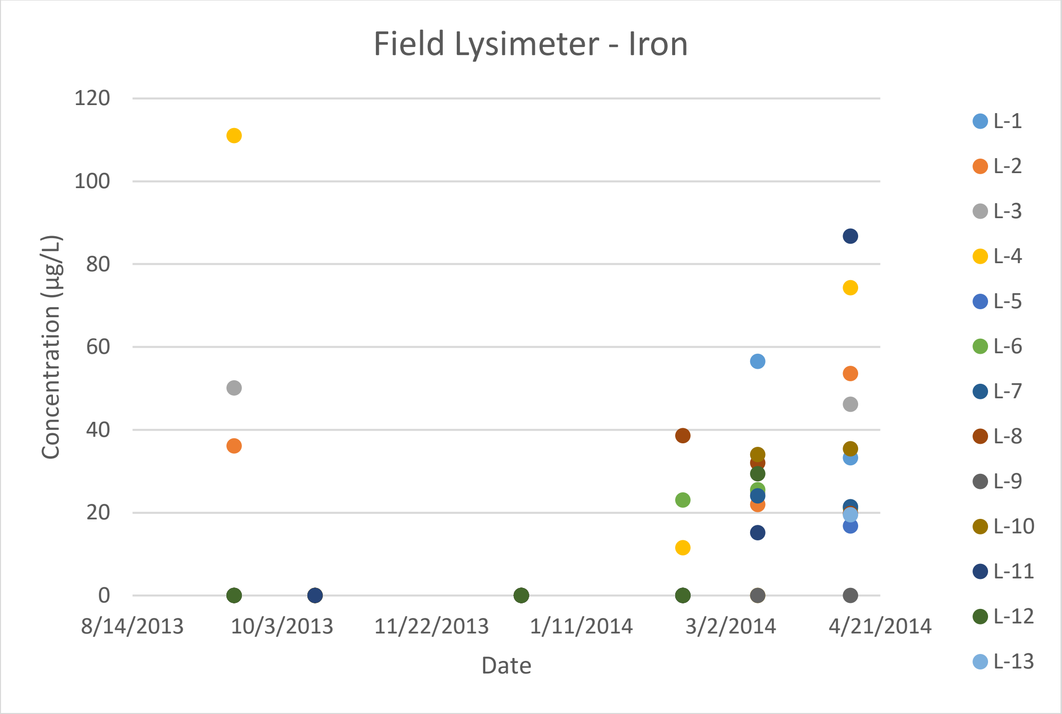


Figure 19: Field lysimeters – Iron

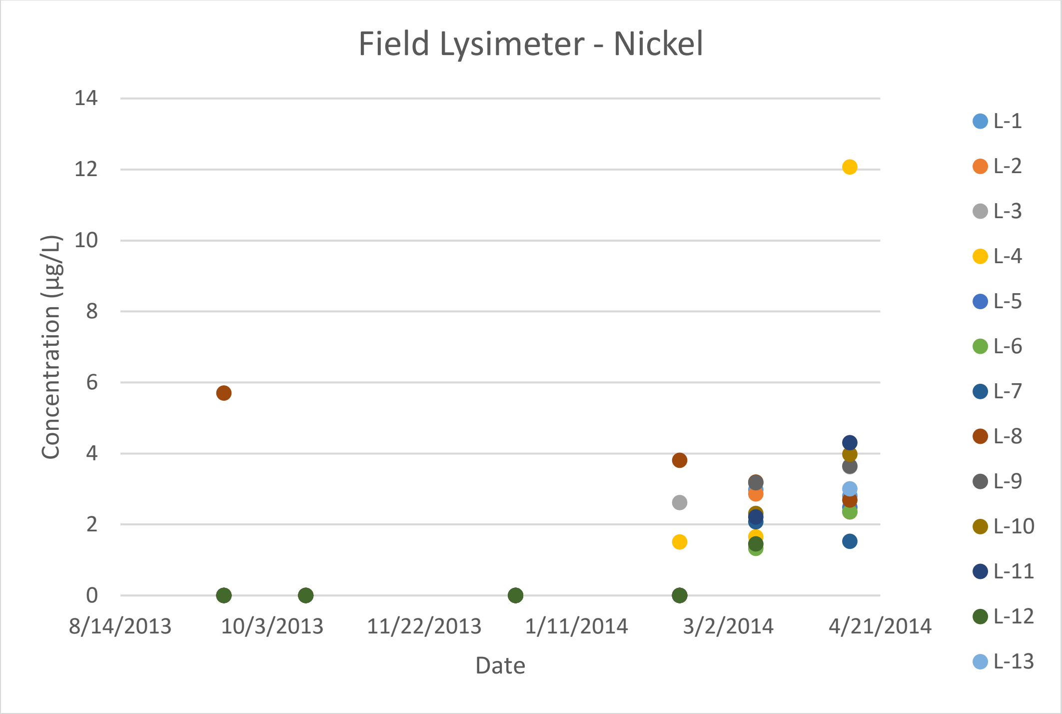


Figure 20: Field lysimeters – Nickel

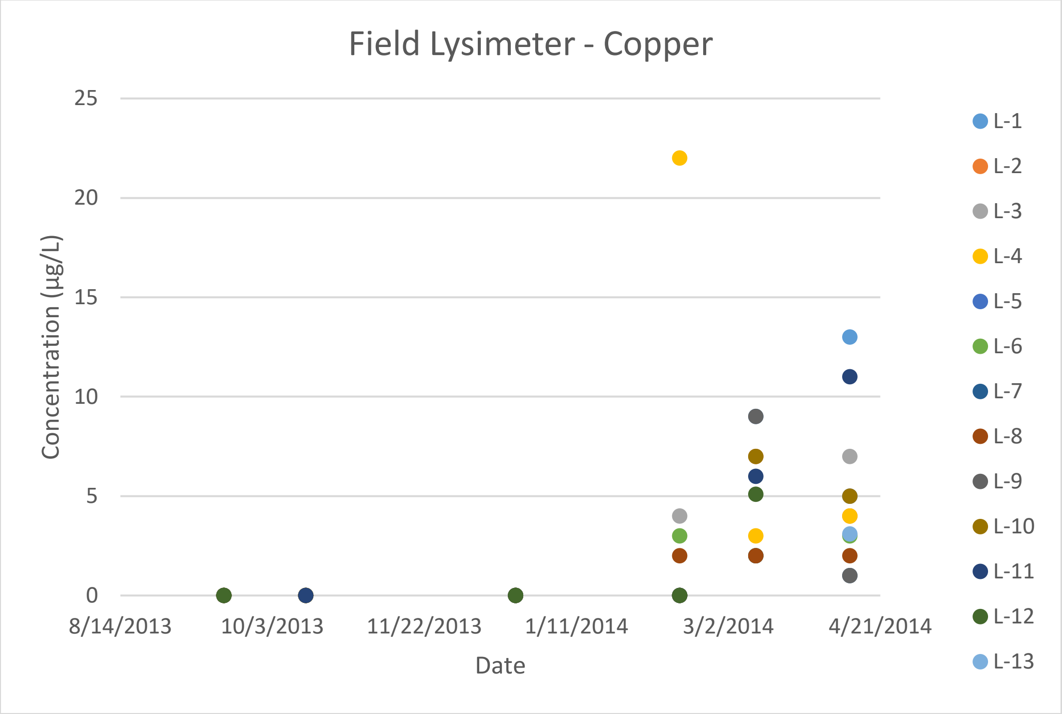


Figure 21: Field lysimeters – Copper

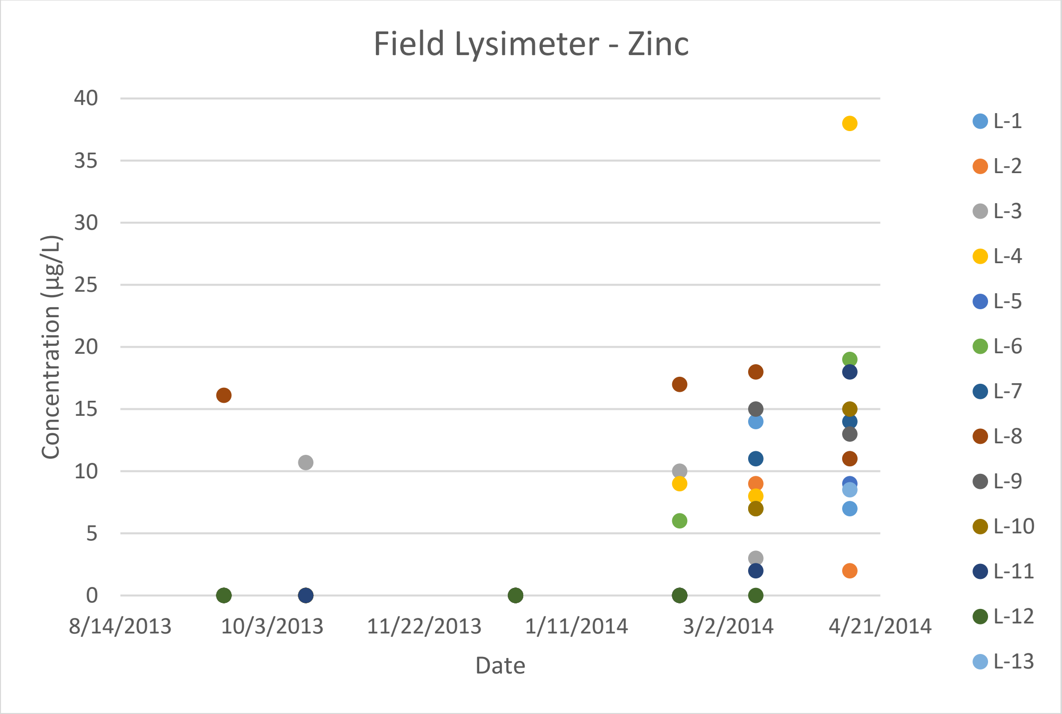


Figure 22: Field lysimeters – Zinc

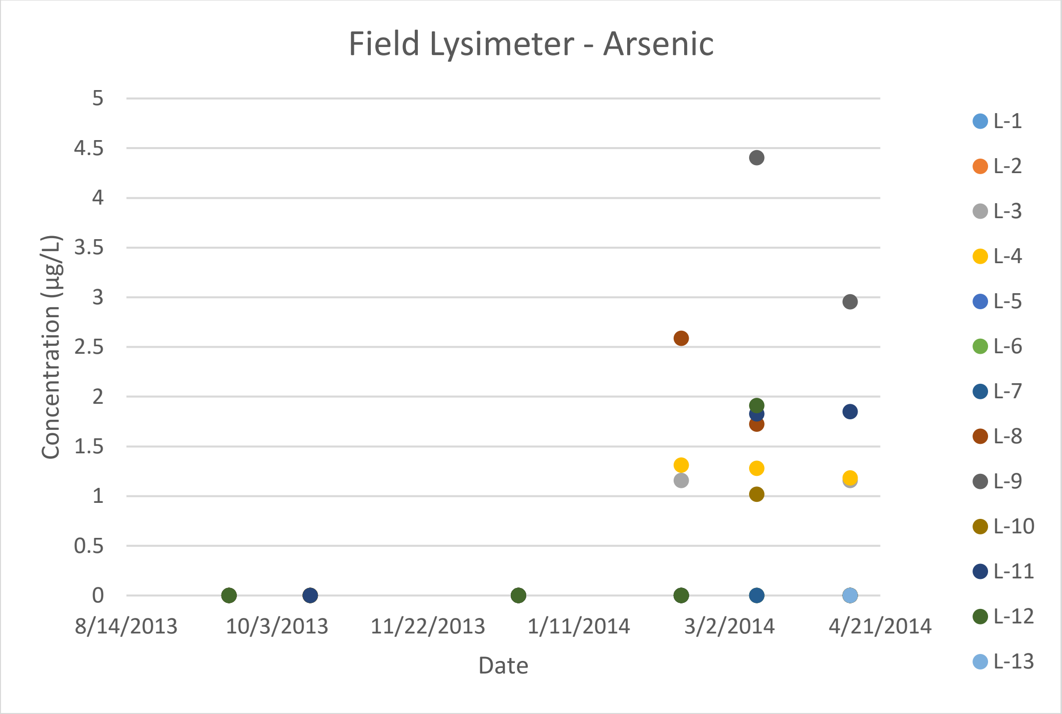


Figure 23: Field lysimeters – Arsenic

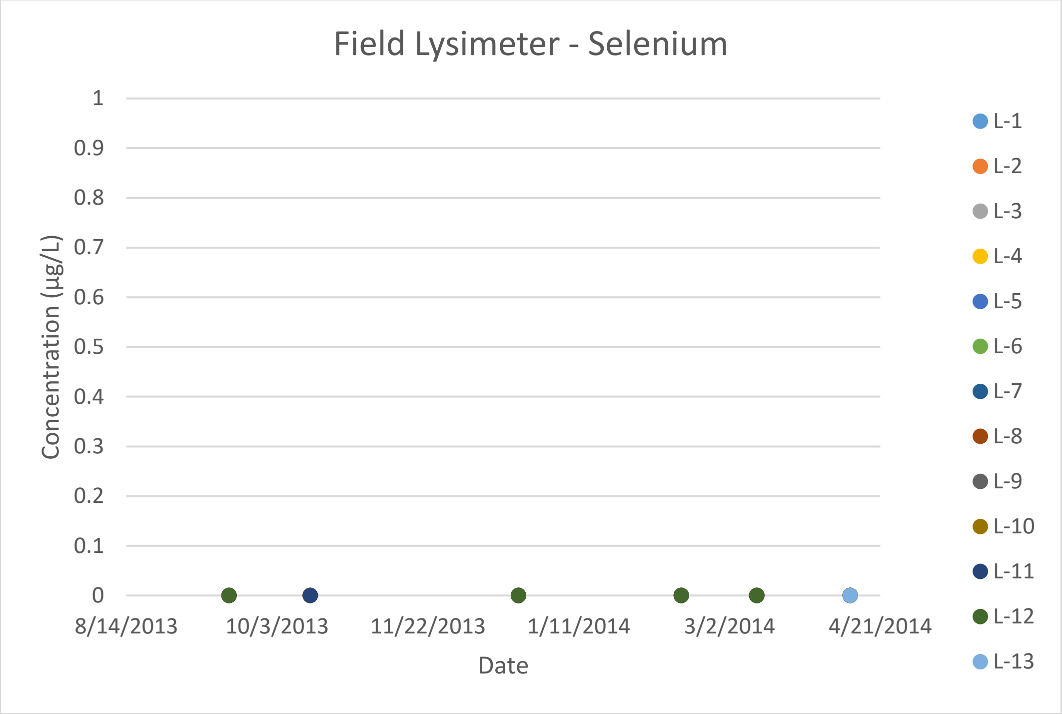


Figure 24: Field lysimeters – Selenium

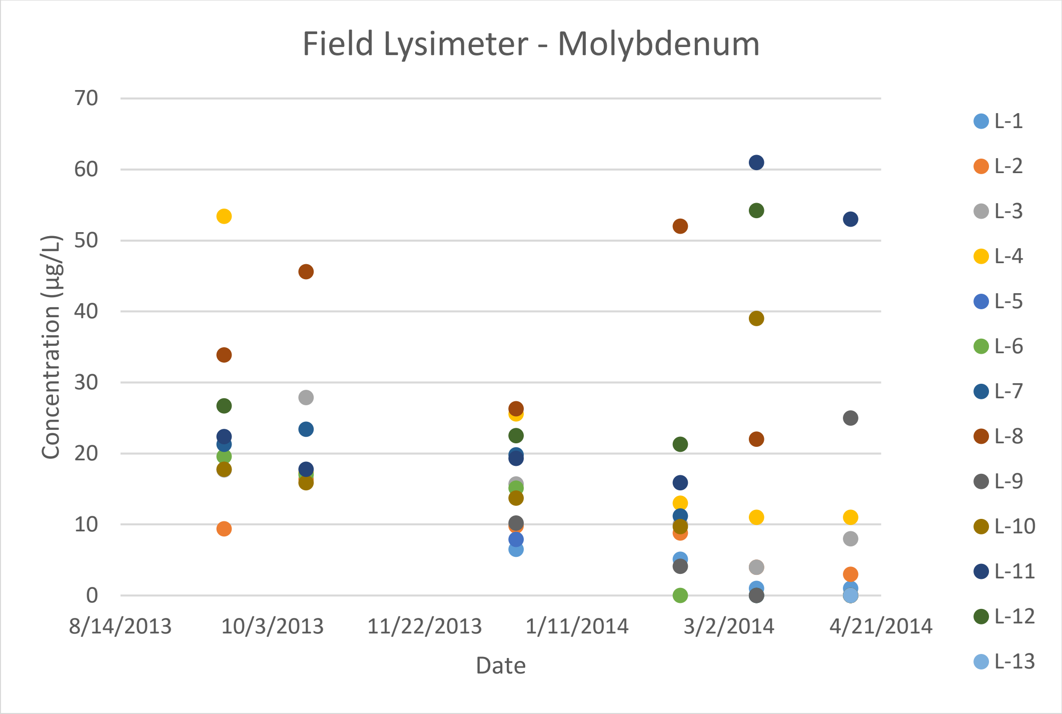


Figure 25: Field lysimeters – Molybdenum

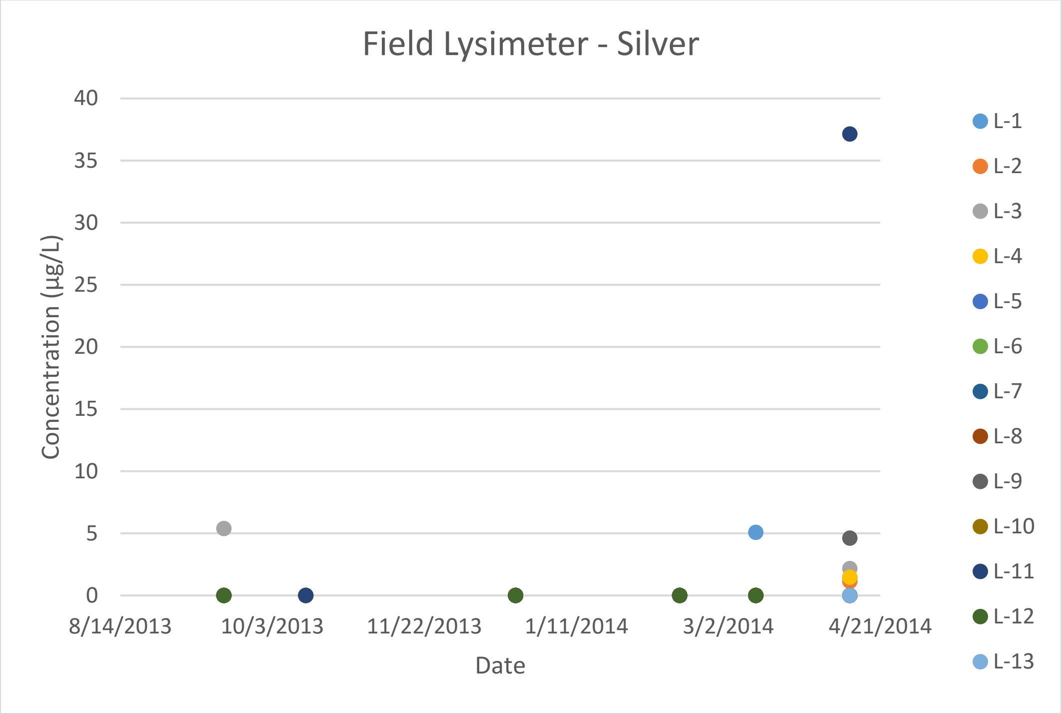


Figure 26: Field lysimeters – Silver

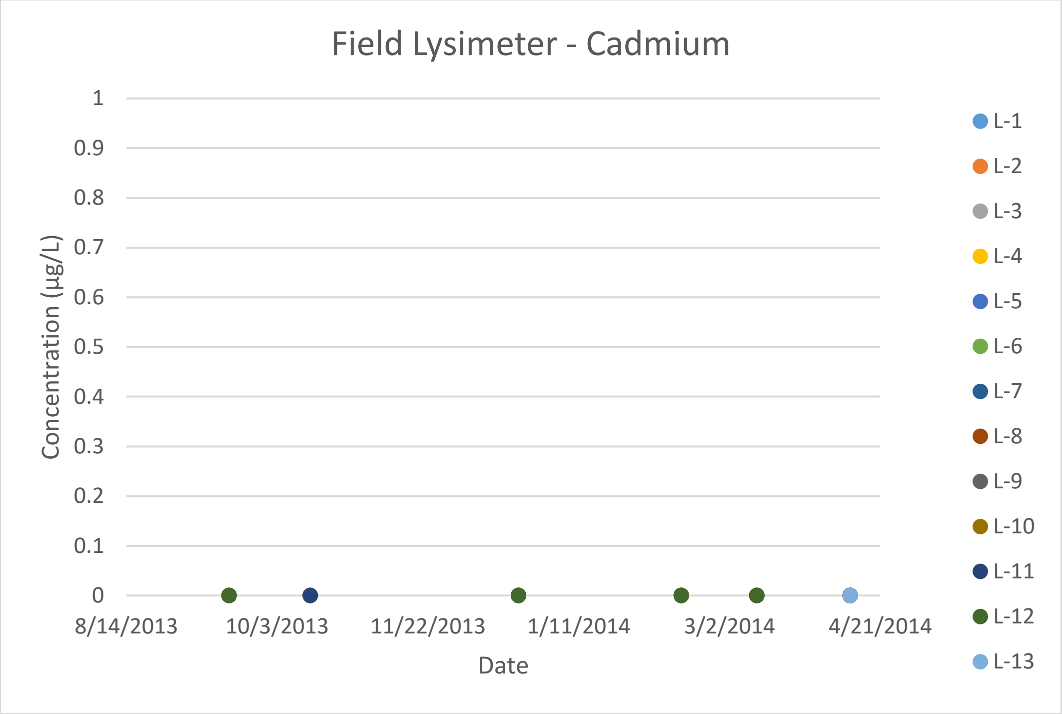


Figure 27: Field lysimeters – Cadmium

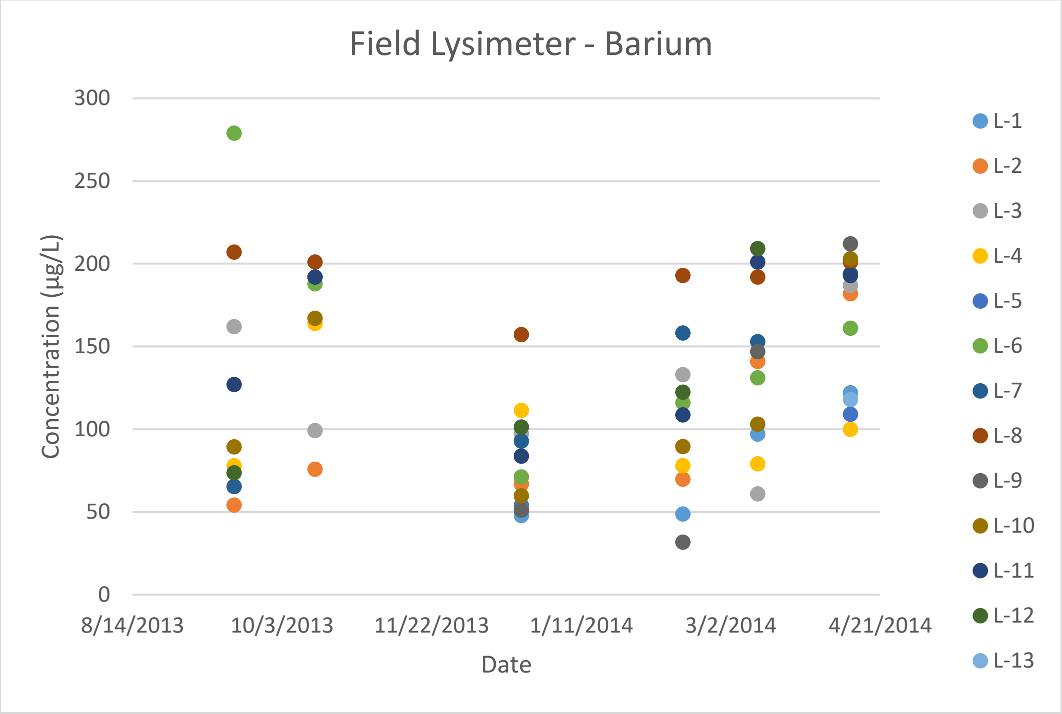


Figure 28: Field lysimeters – Barium

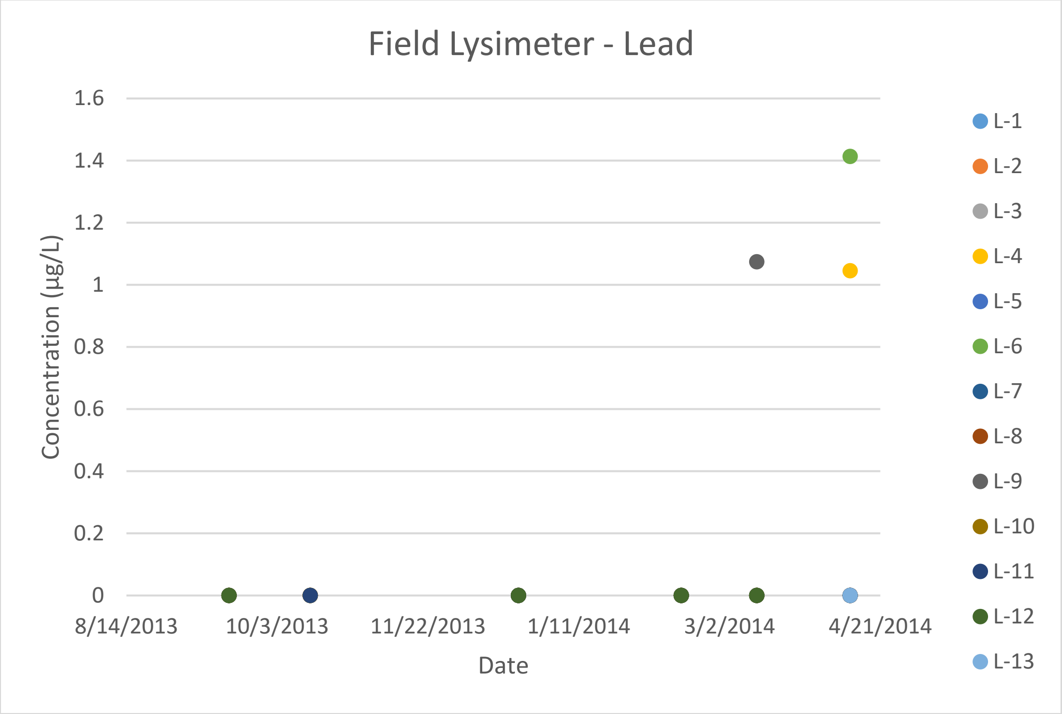


Figure 29: Field lysimeters – Lead

APPENDIX B: Eh-pH DIAGRAMS

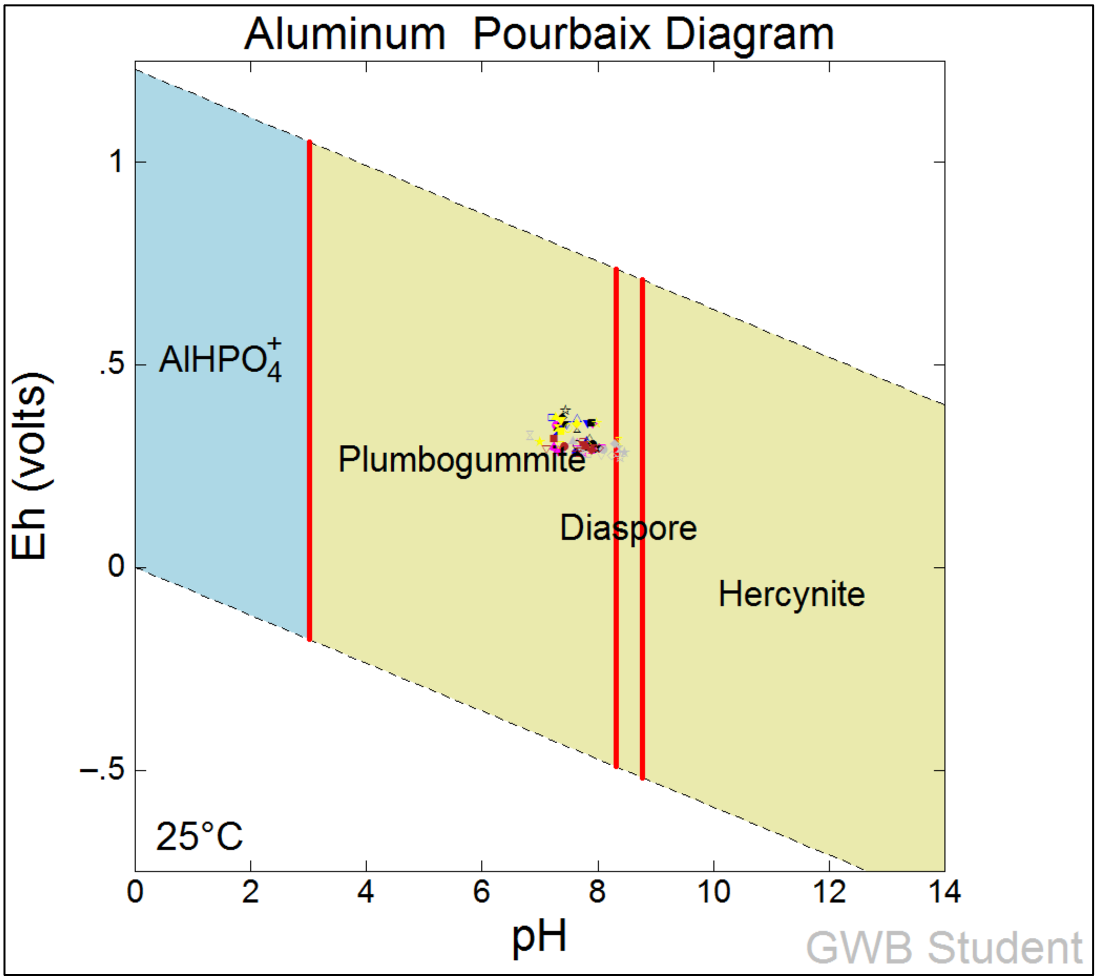


Figure 30: Field lysimeters – Eh-pH Aluminum

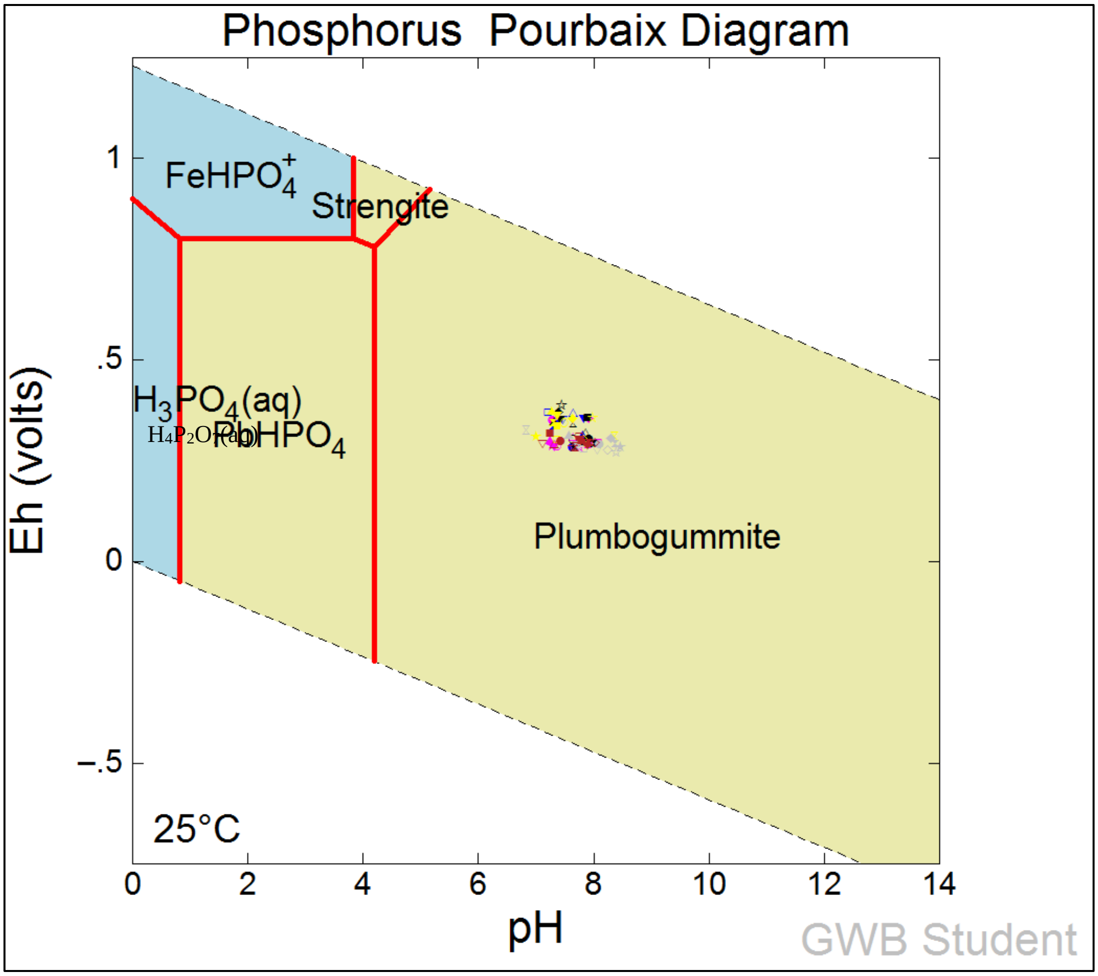


Figure 31: Field lysimeters – Eh-pH Phosphorus

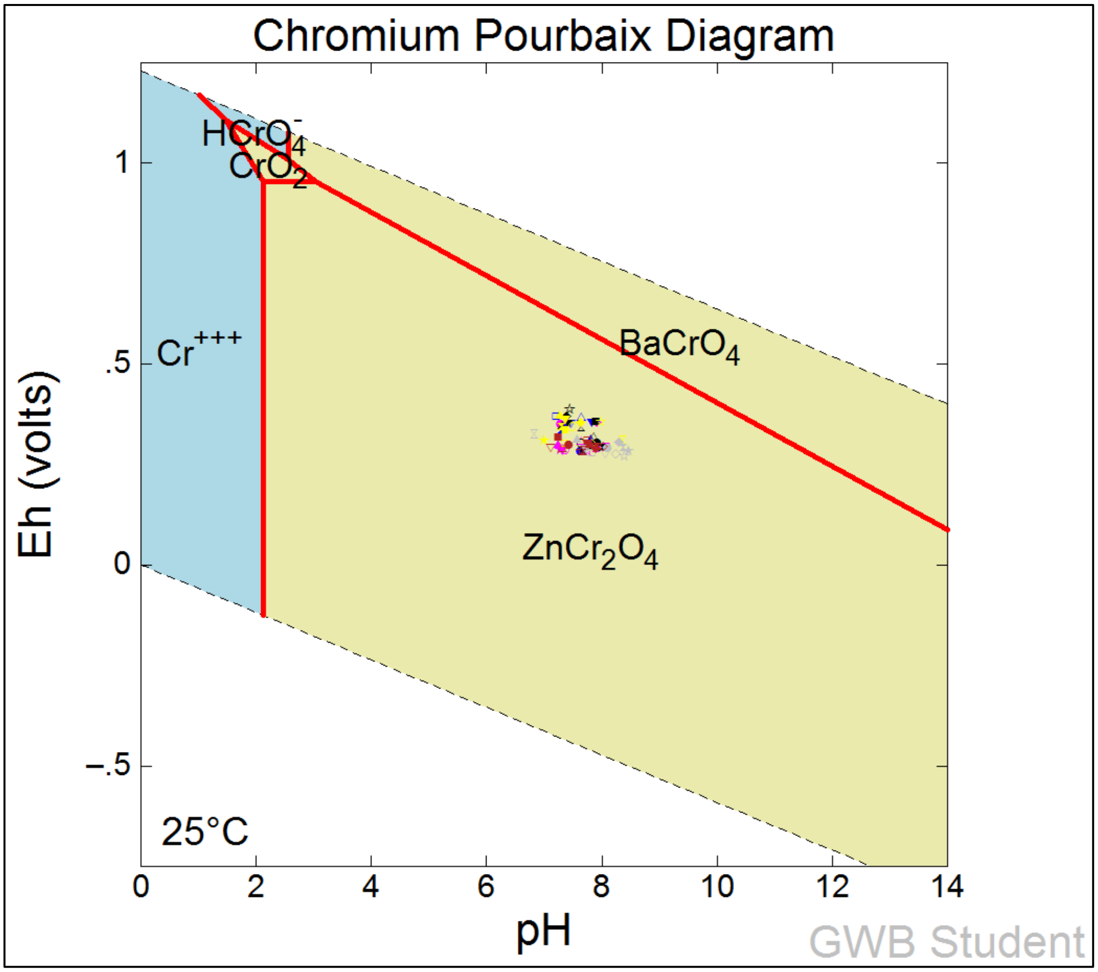


Figure 32: Field lysimeters – Eh-pH Chromium

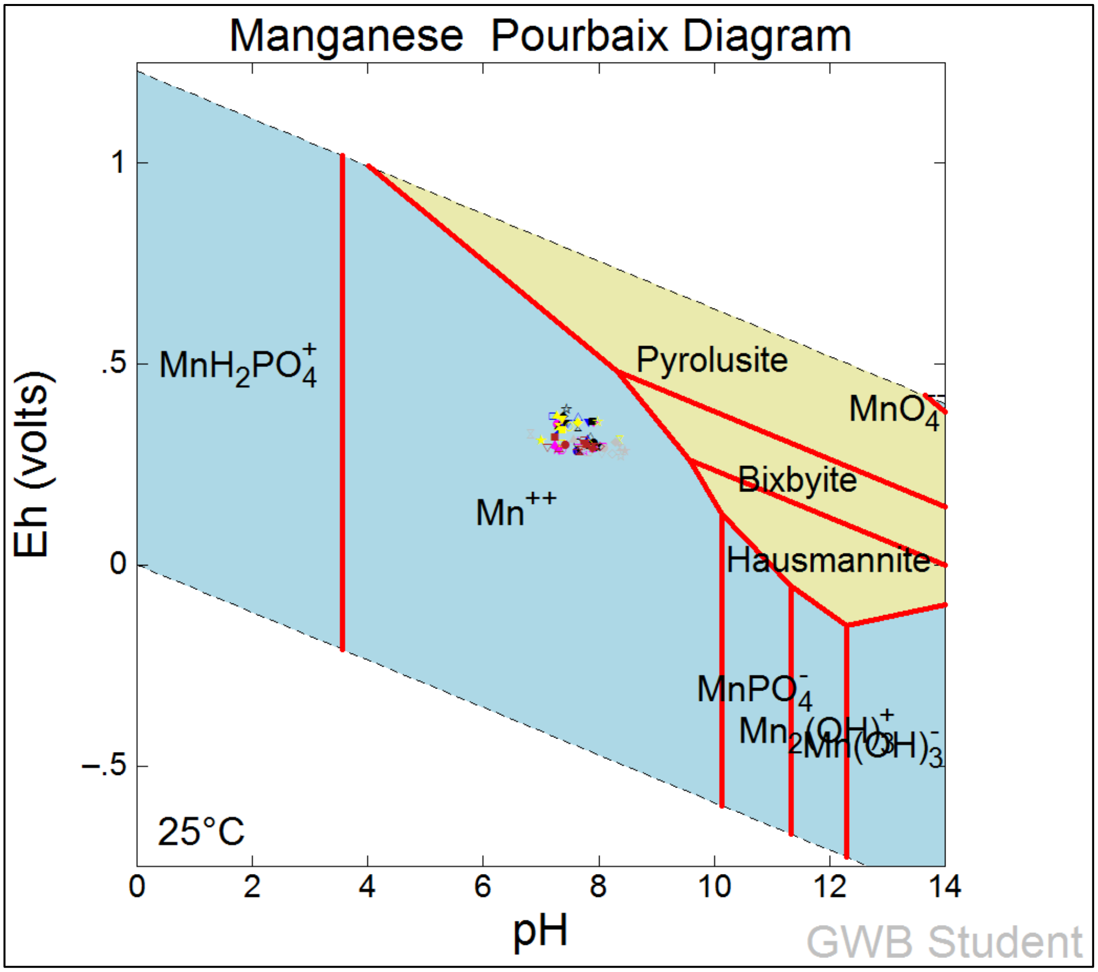


Figure 33: Field lysimeters – Eh-pH Manganese

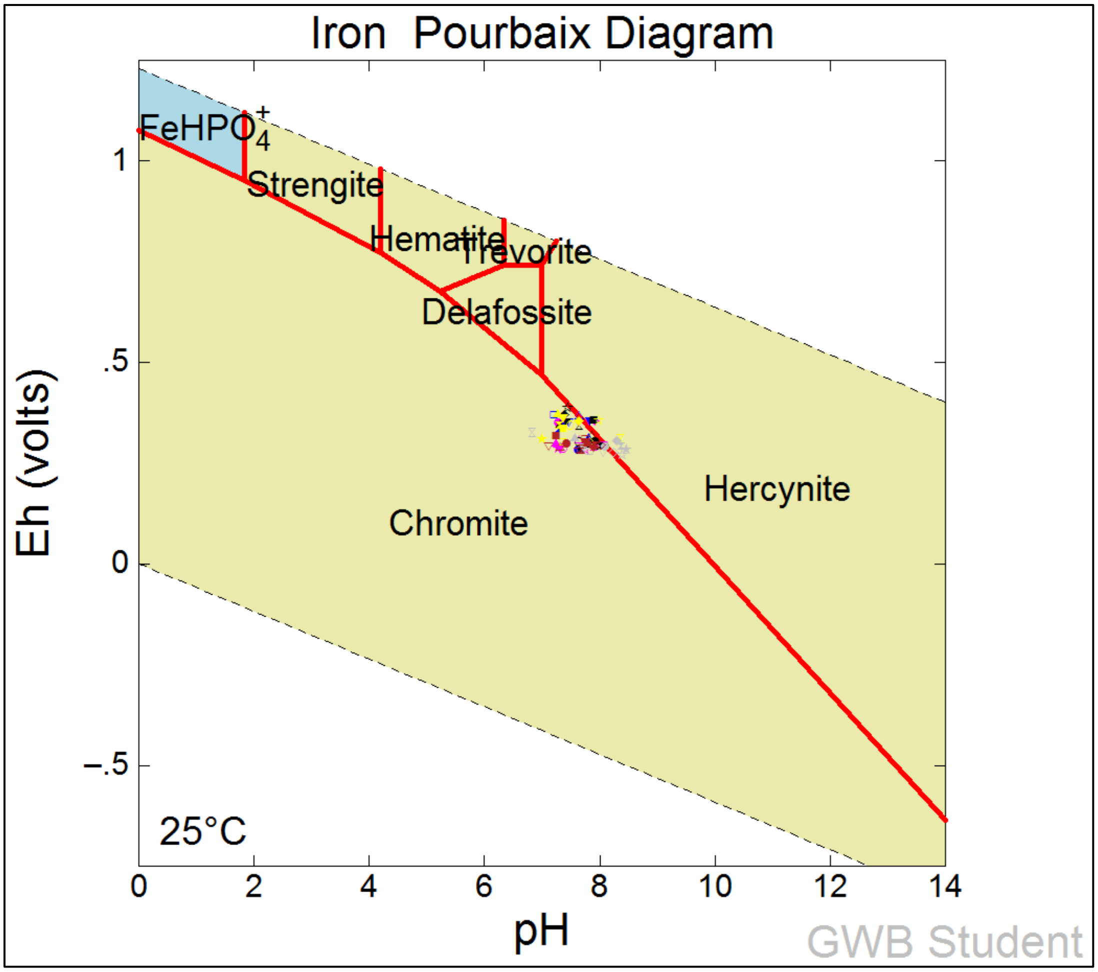


Figure 34: Field lysimeters – Eh-pH Iron

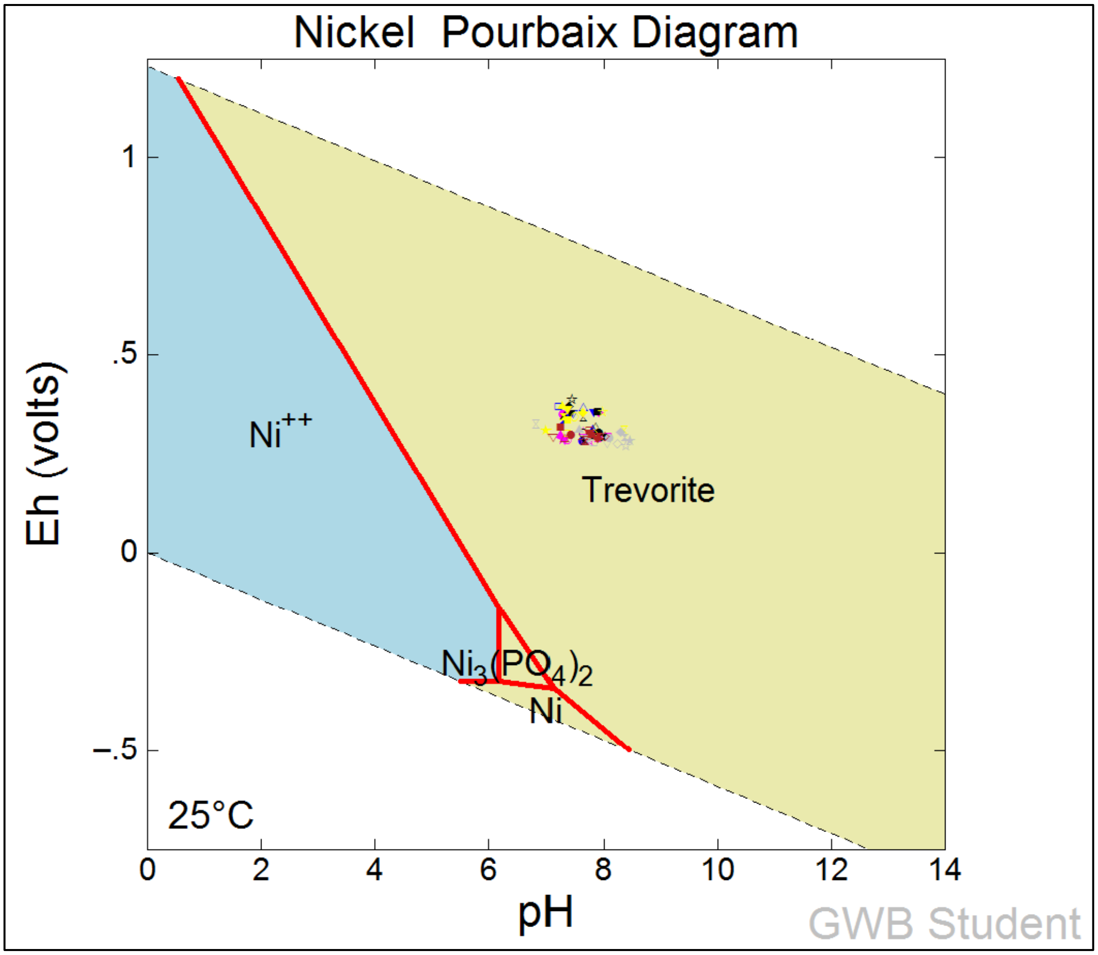


Figure 35: Field lysimeters – Eh-pH Nickel

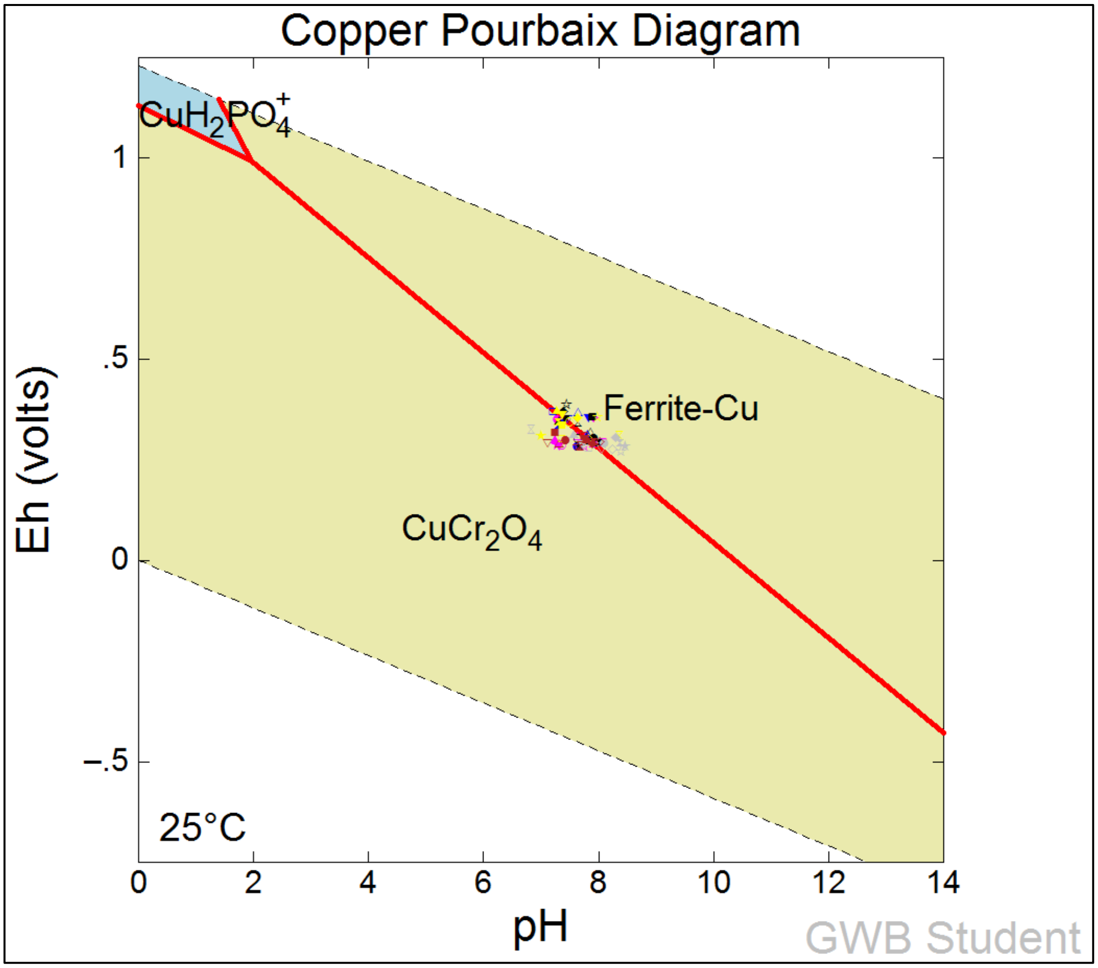


Figure 36: Field lysimeters – Eh-pH Copper

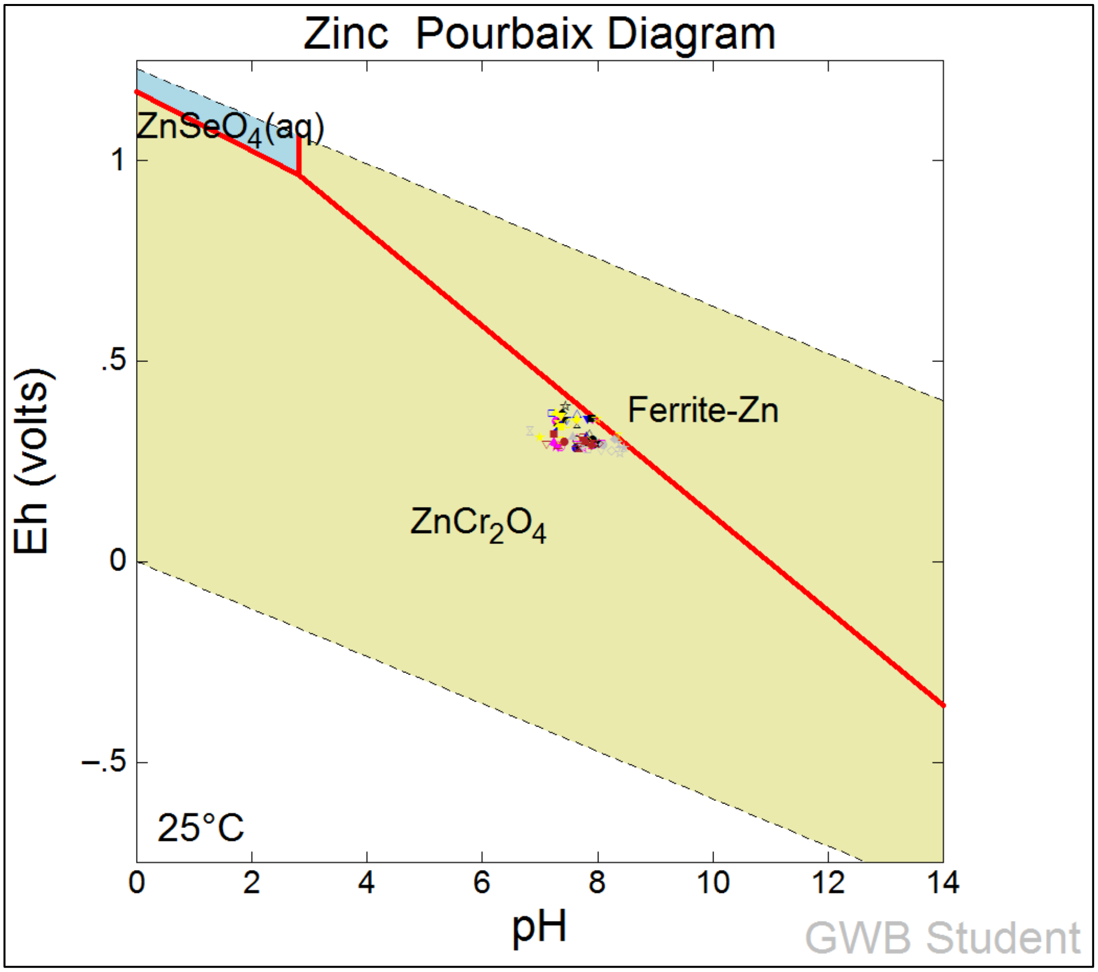


Figure 37: Field lysimeters – Eh-pH Zinc

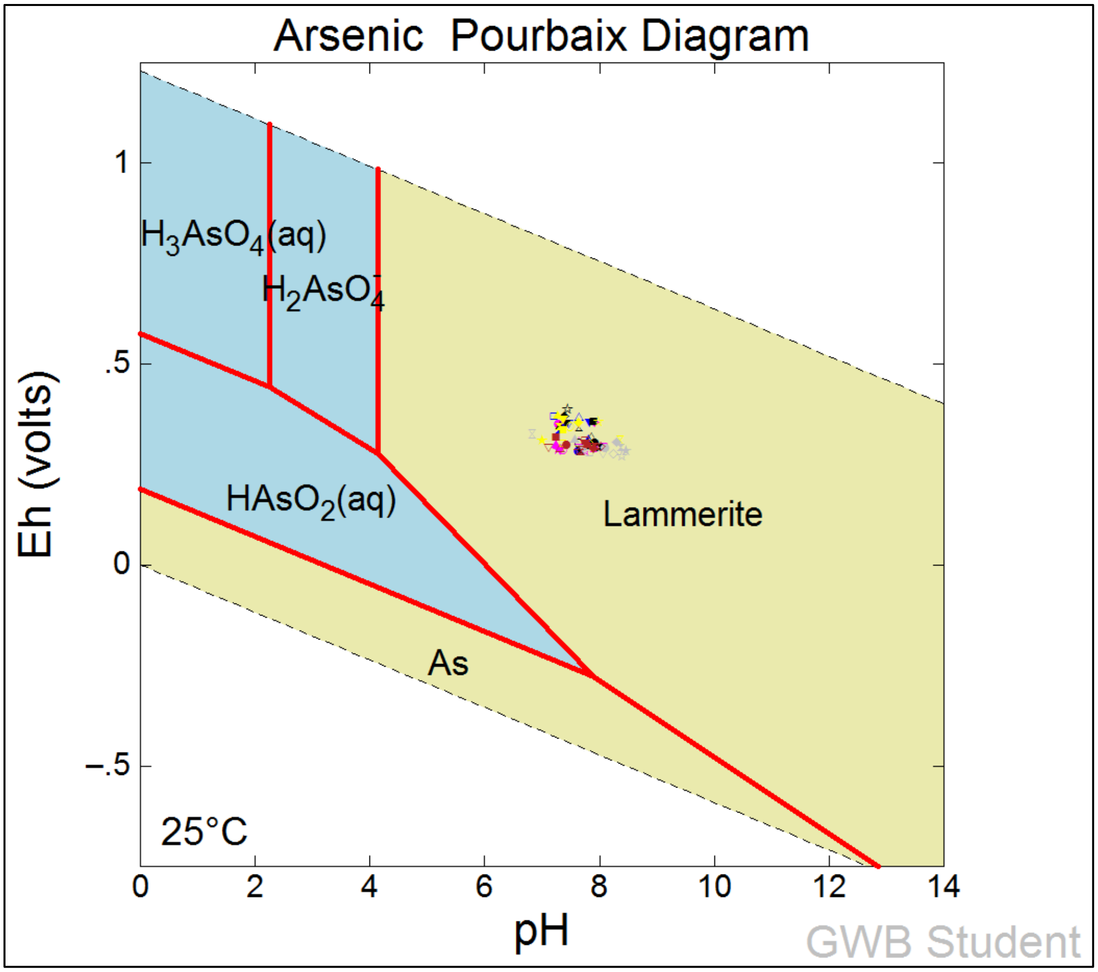


Figure 38: Field lysimeters – Eh-pH Arsenic

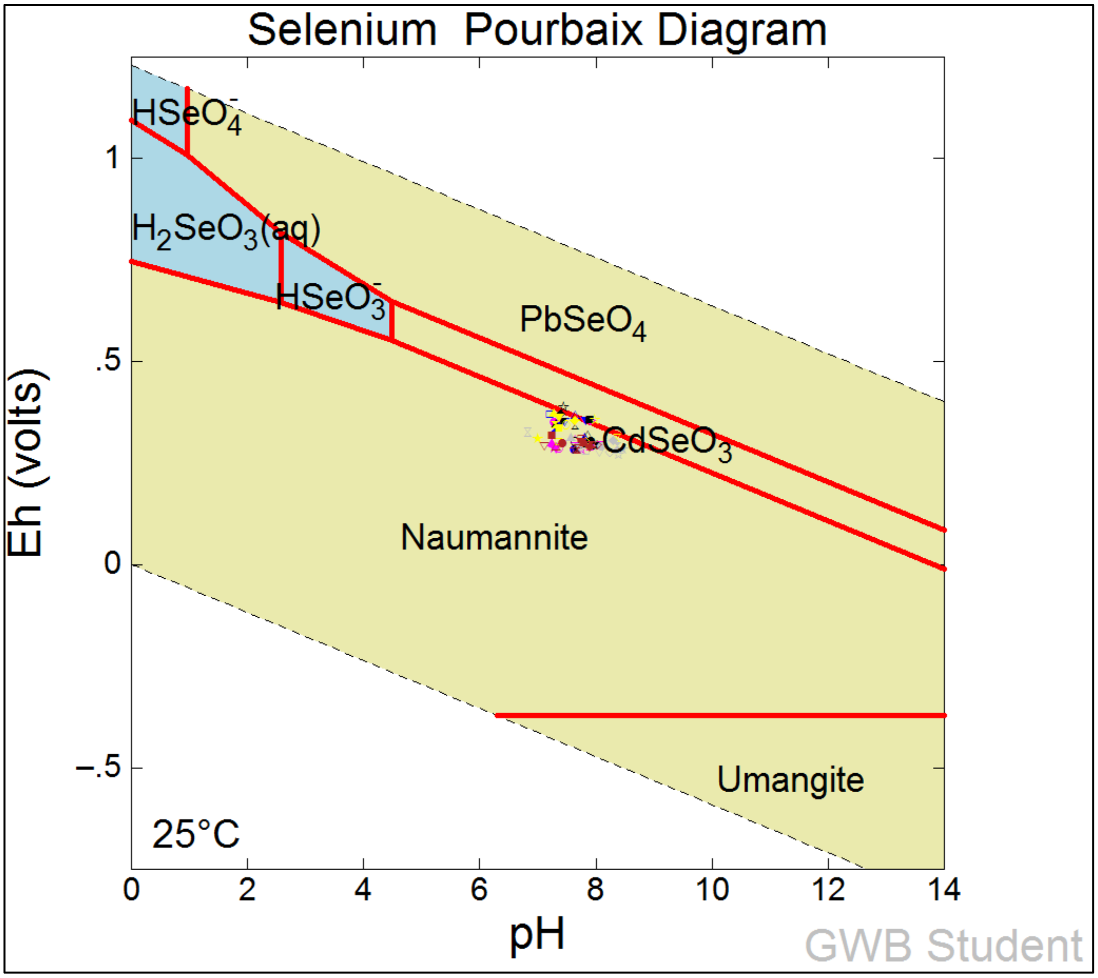


Figure 39: Field lysimeters – Eh-pH Selenium

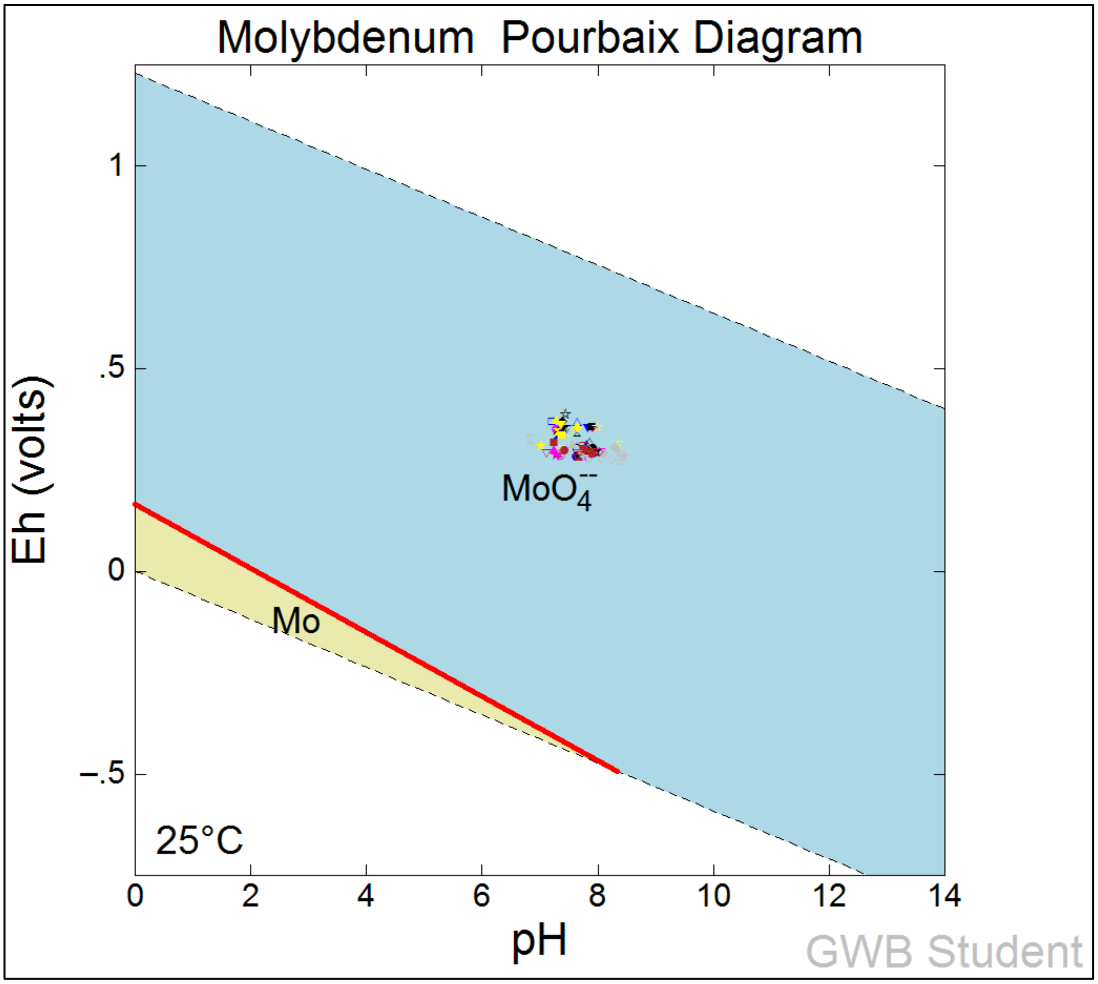


Figure 40: Field lysimeters – Eh-pH Molybdenum

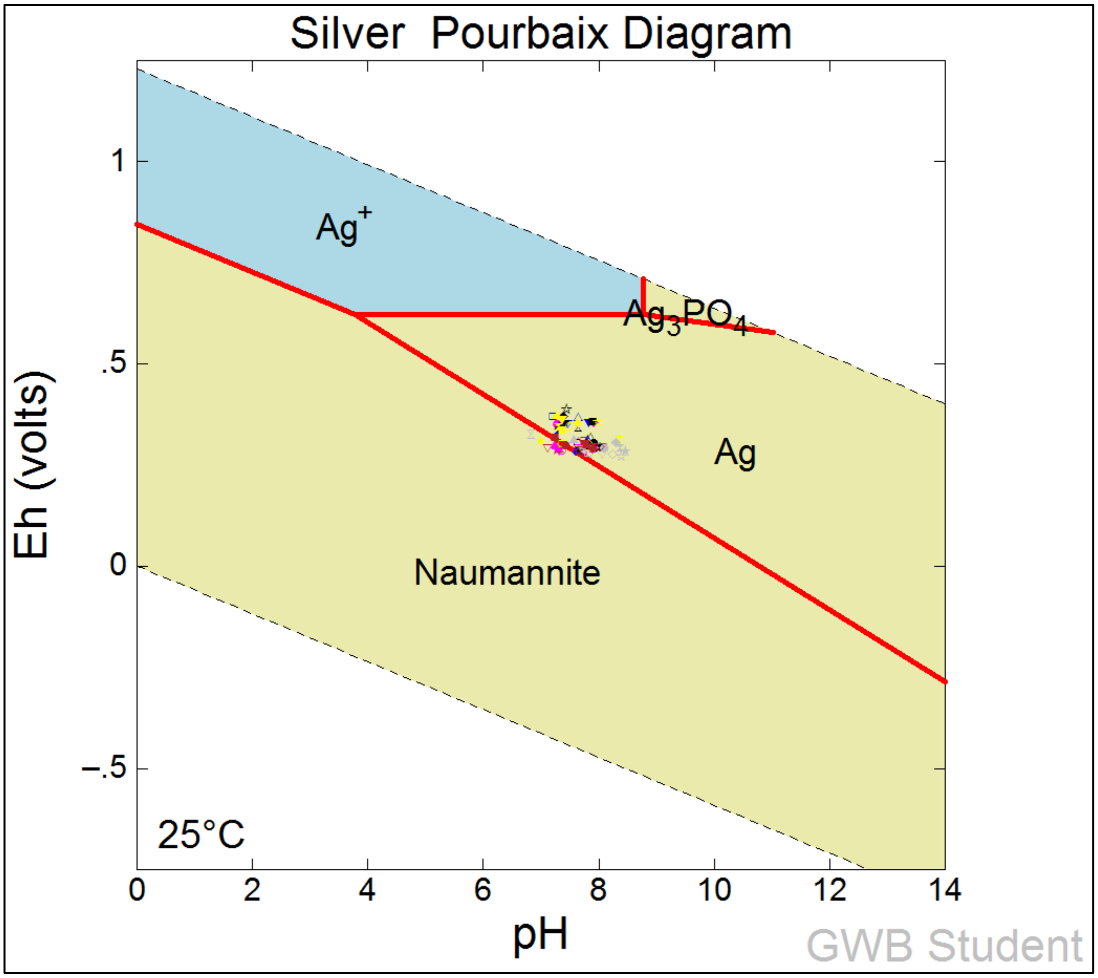


Figure 41: Field lysimeters – Eh-pH Silver

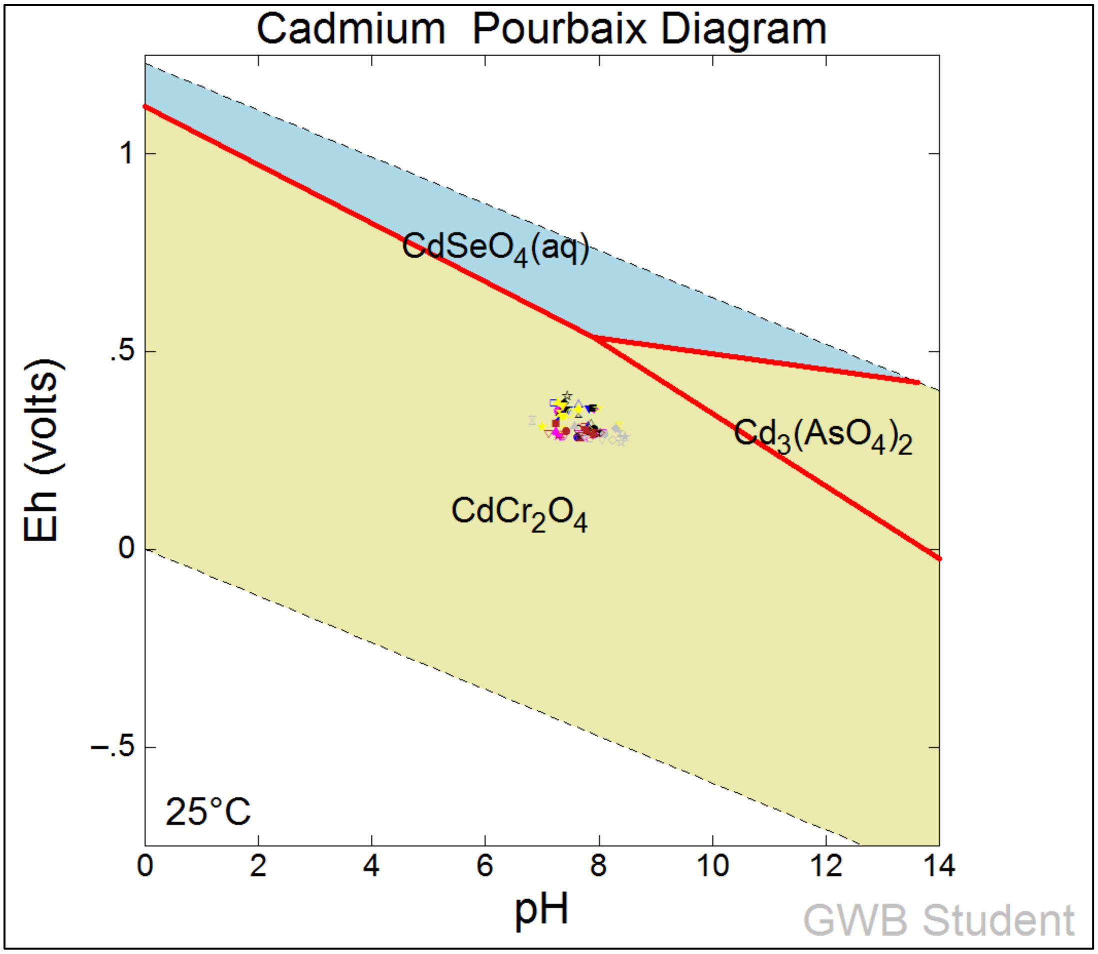


Figure 42: Field lysimeters – Eh-pH Cadmium

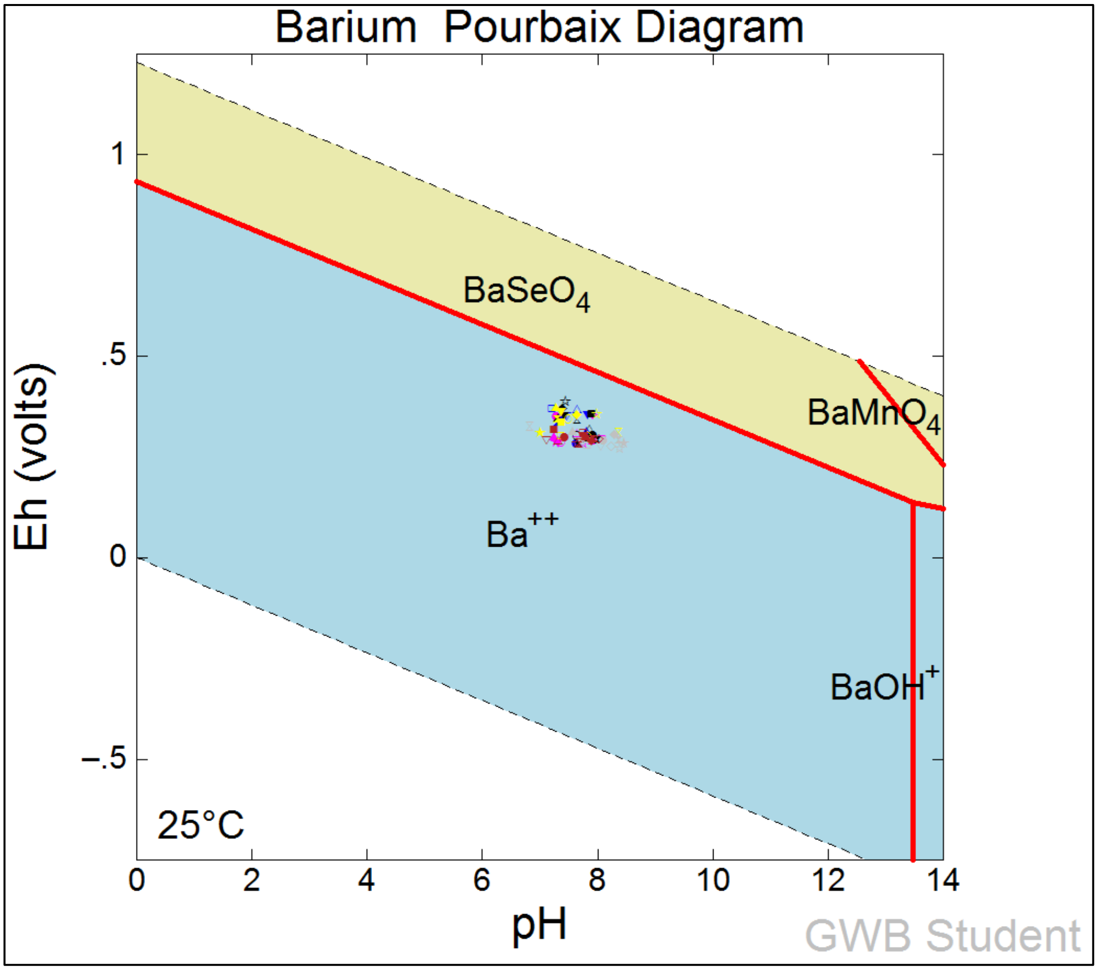


Figure 43: Field lysimeters – Eh-pH Barium

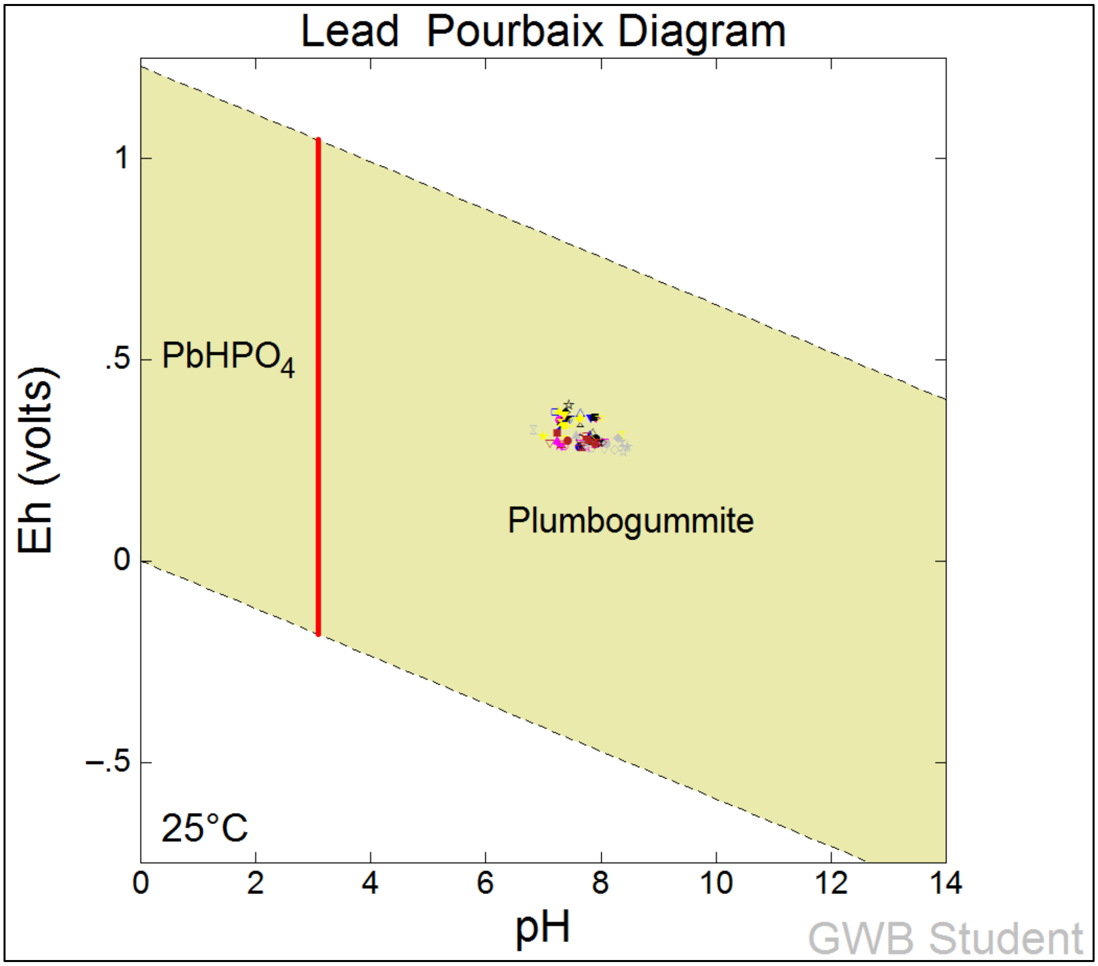


Figure 44: Field lysimeters – Eh-pH Lead

APPENDIX C: LABORATORY COLUMN TESTS

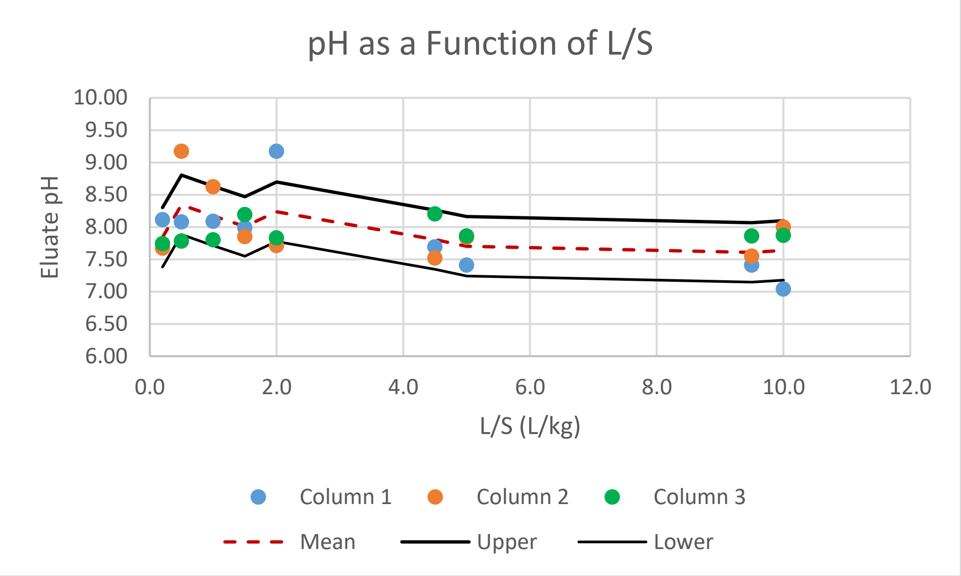


Figure 45: Laboratory column test: pH

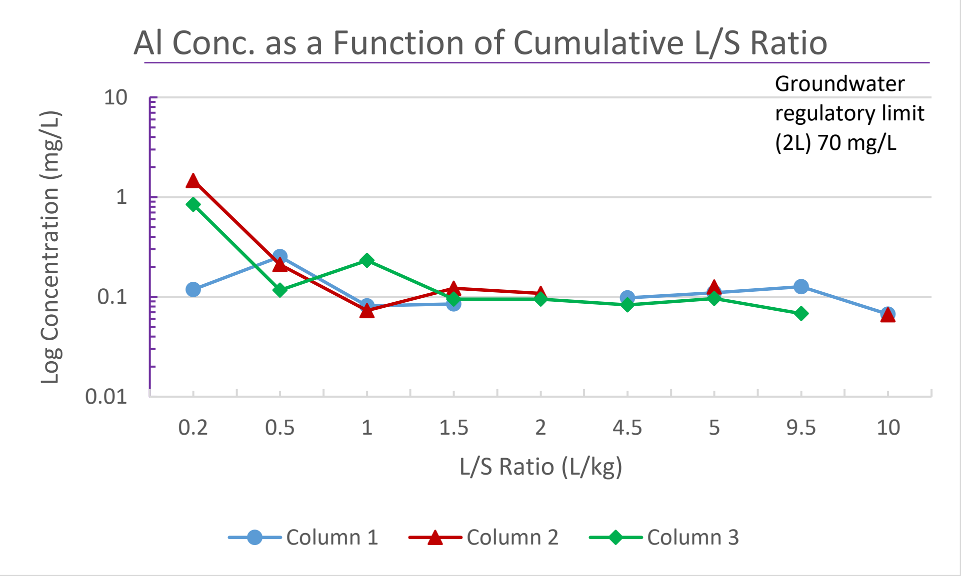


Figure 46: Laboratory column test – Aluminum

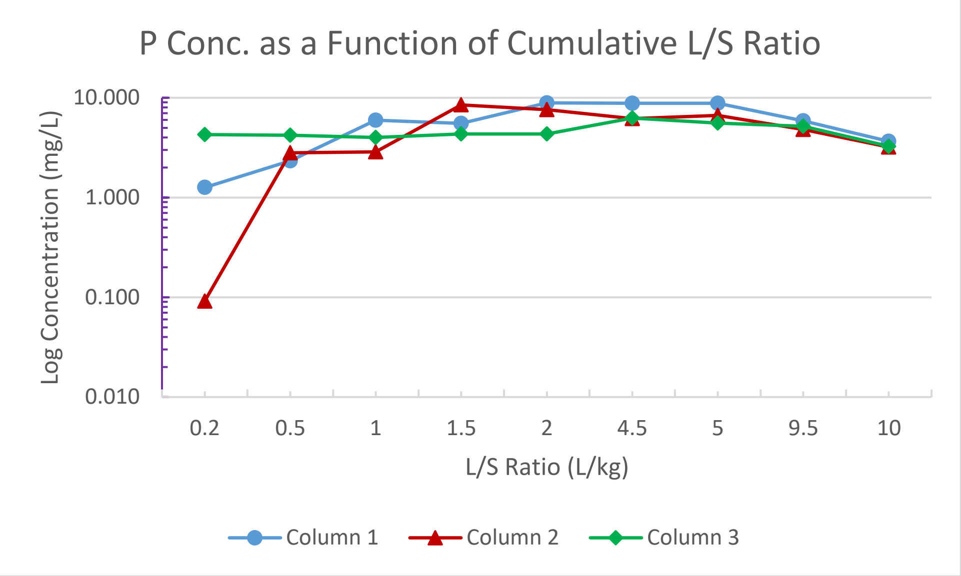


Figure 47: Laboratory column test – Phosphorus

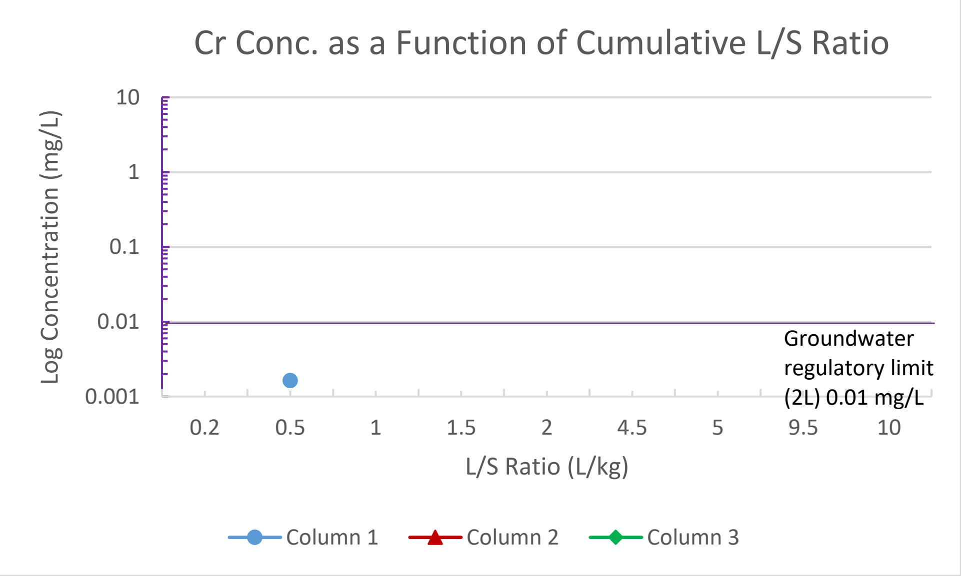


Figure 48: Laboratory column test – Chromium

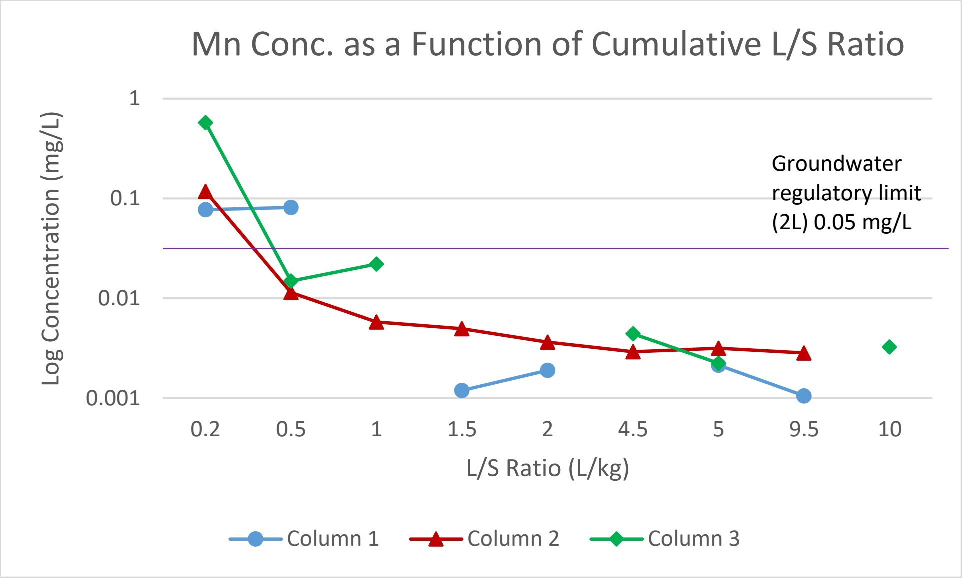


Figure 49: Laboratory column test – Manganese

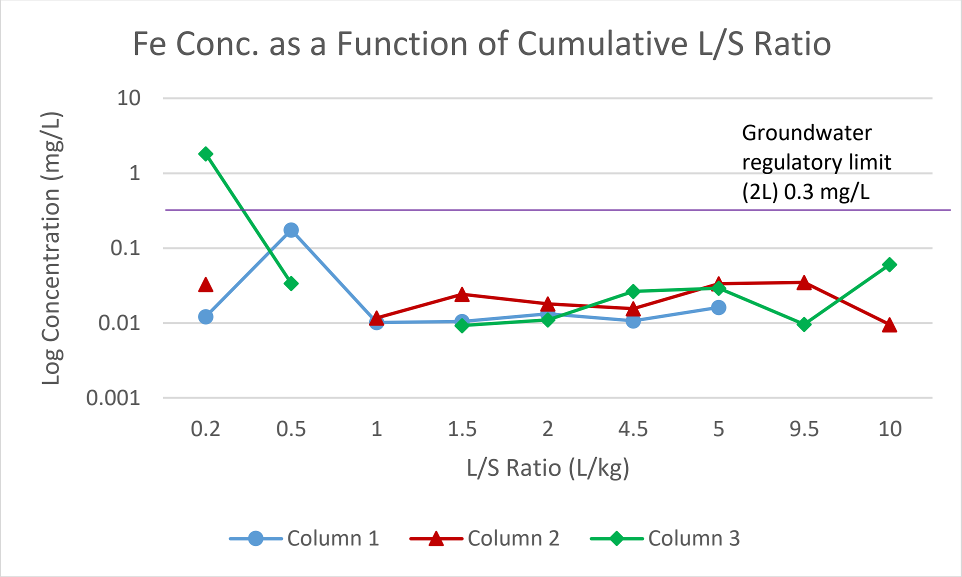


Figure 50: Laboratory column test – Iron

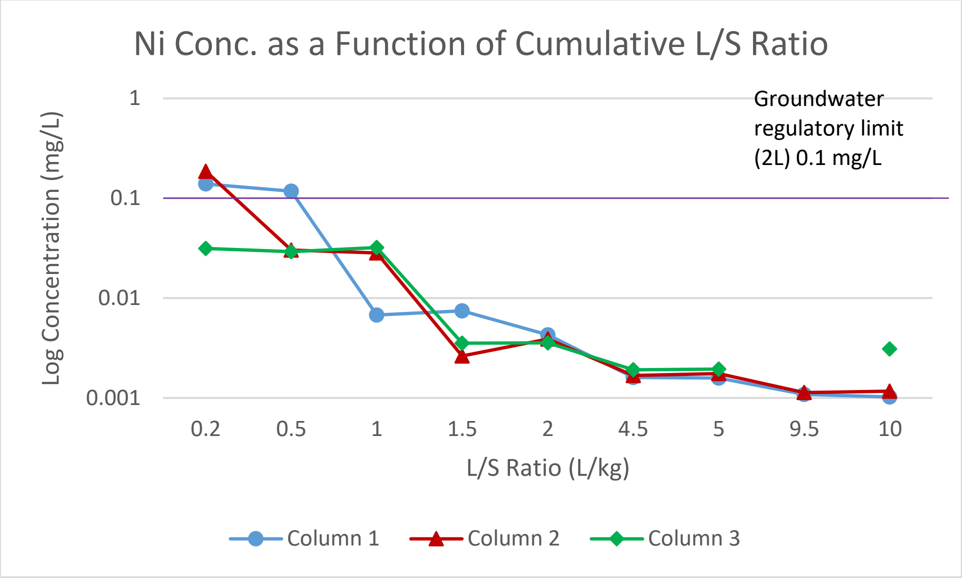


Figure 51: Laboratory column test – Nickel

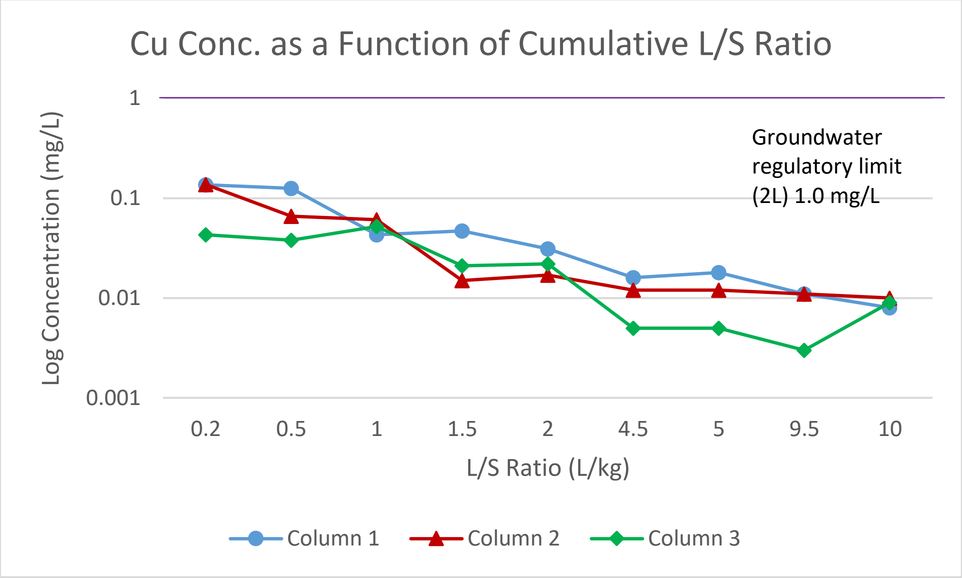


Figure 52: Laboratory column test – Copper

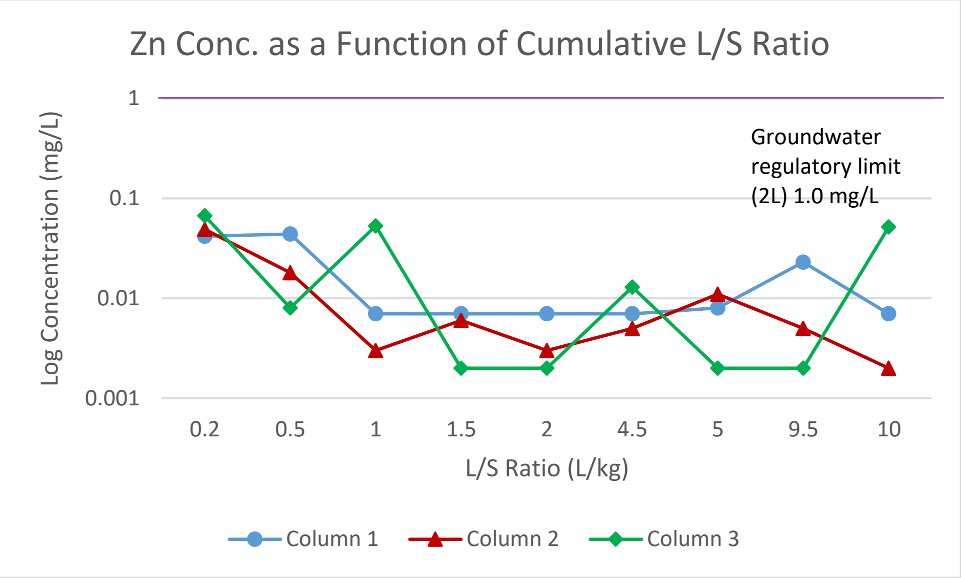


Figure 53: Laboratory column test – Zinc

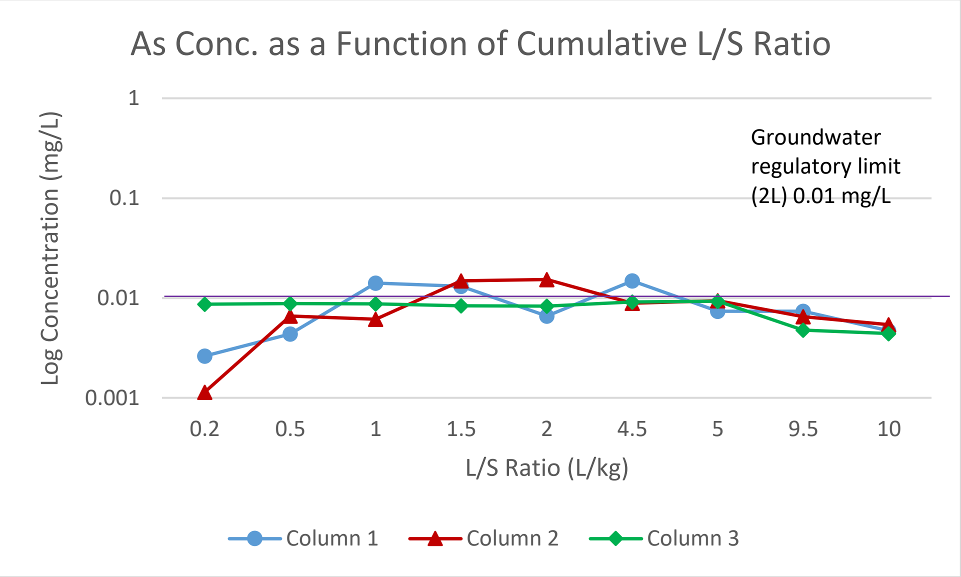


Figure 54: Laboratory column test – Arsenic

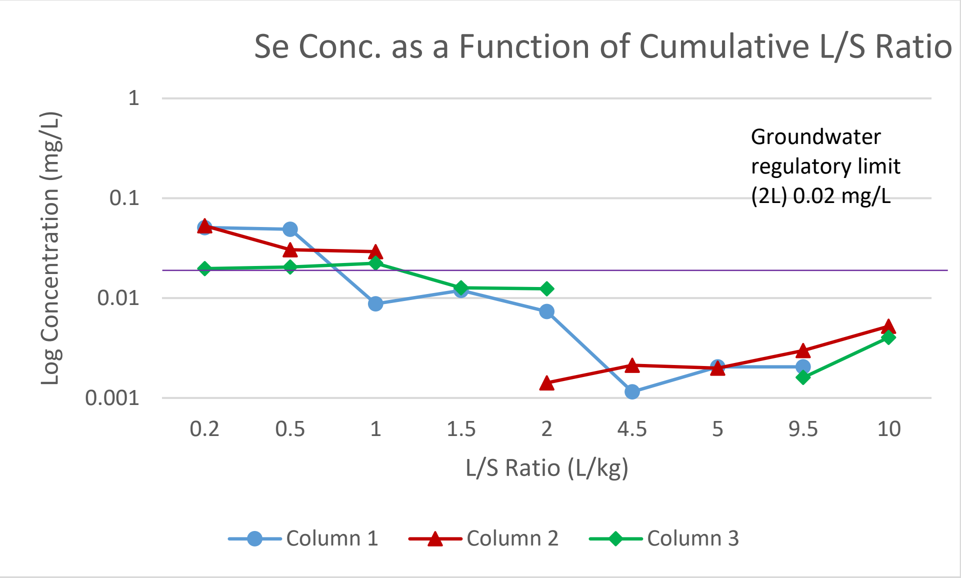


Figure 55: Laboratory column test – Selenium

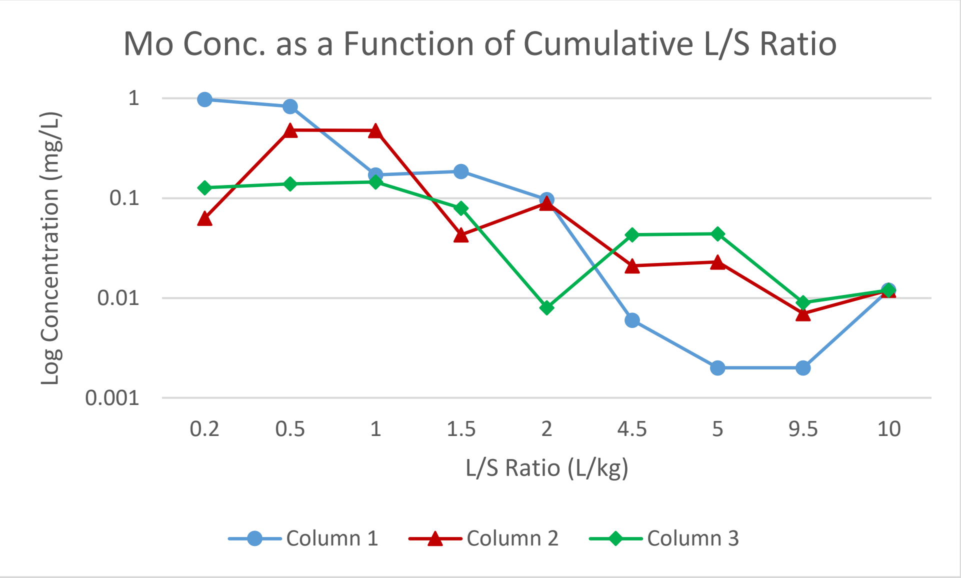


Figure 56: Laboratory column test – Molybdenum

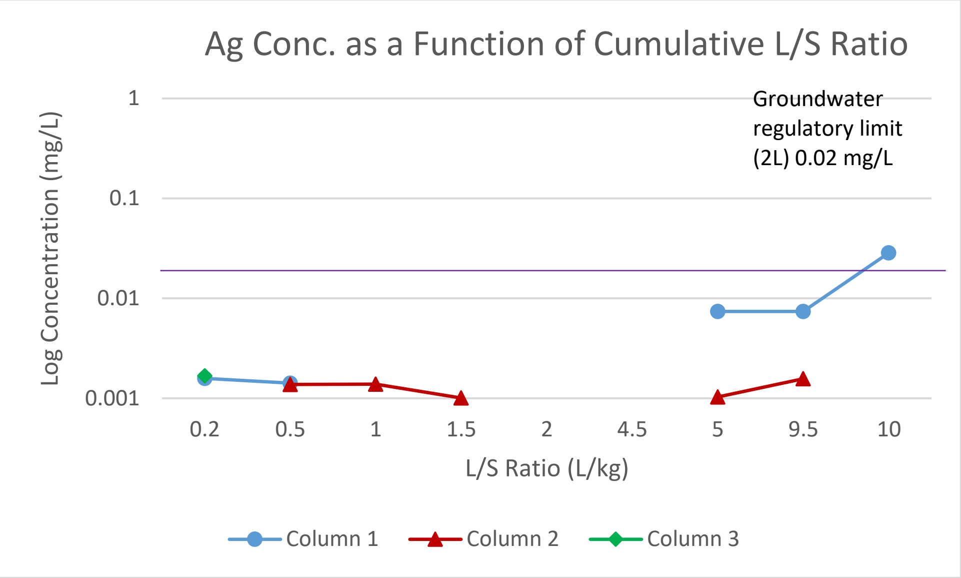


Figure 57: Laboratory column test – Silver

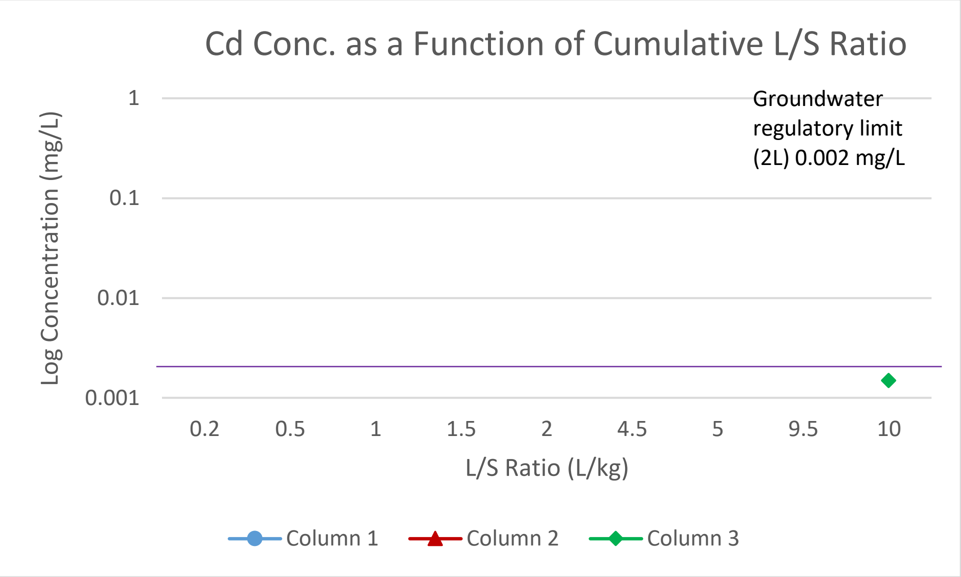


Figure 58: Laboratory column test – Cadmium

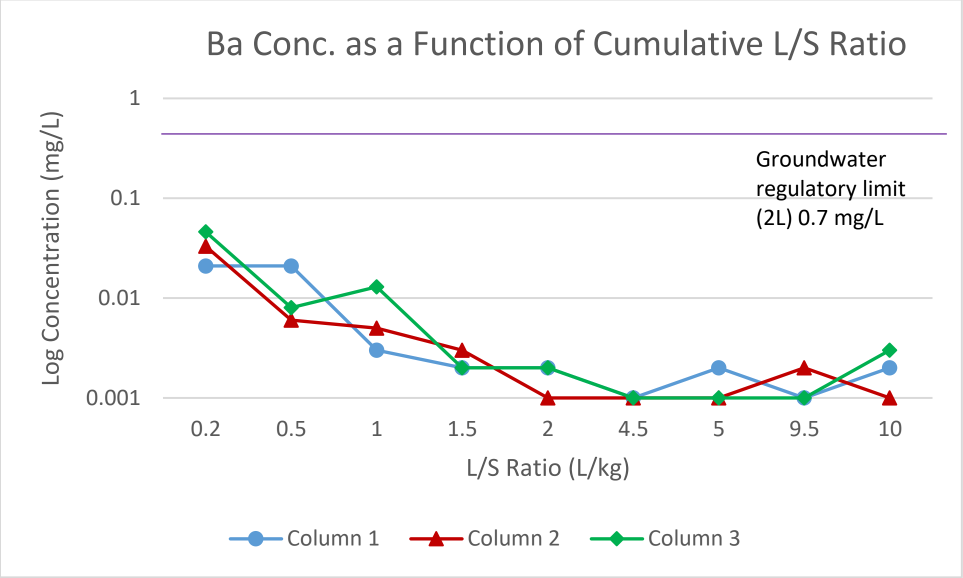


Figure 59: Laboratory column test – Barium

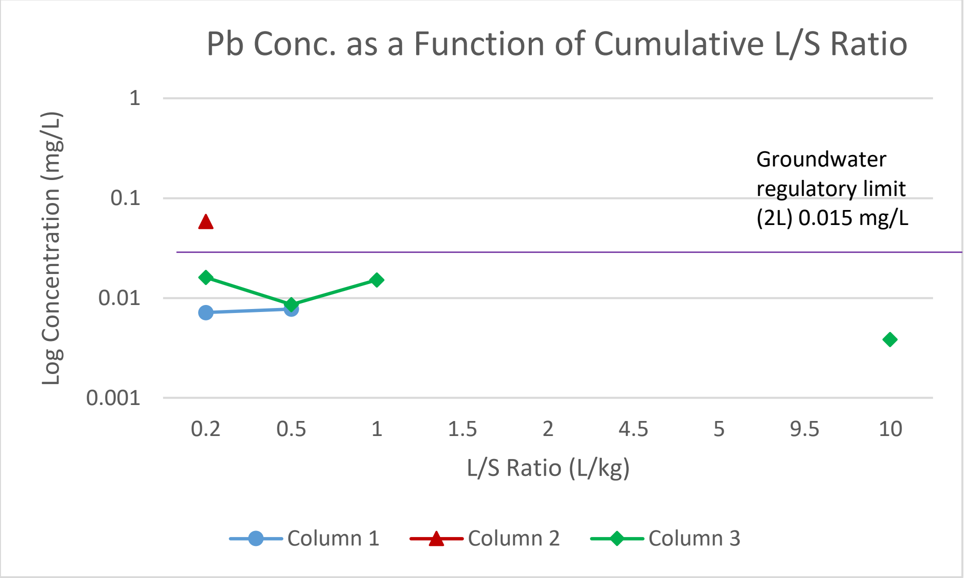


Figure 60: Laboratory column test – Lead

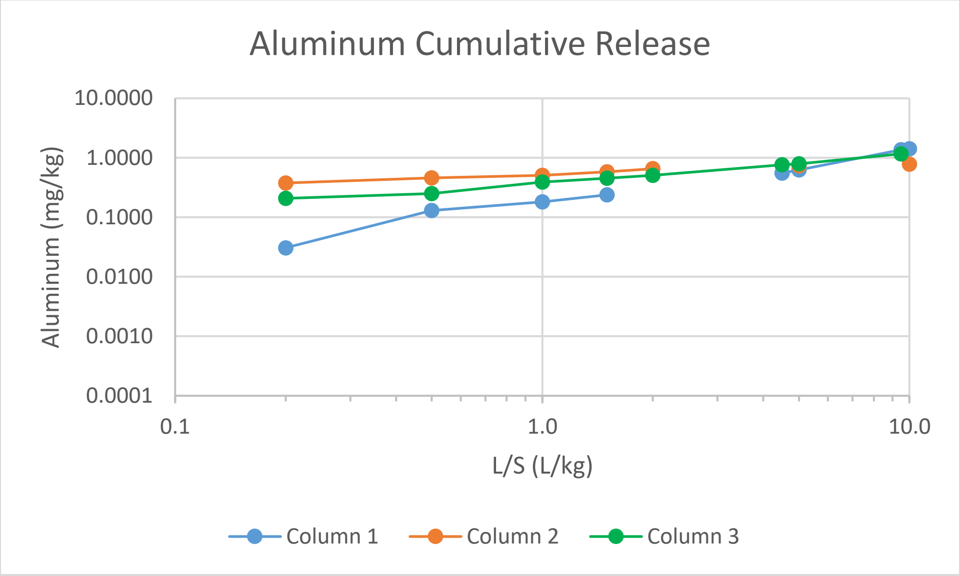


Figure 61: Cumulative release: Aluminum

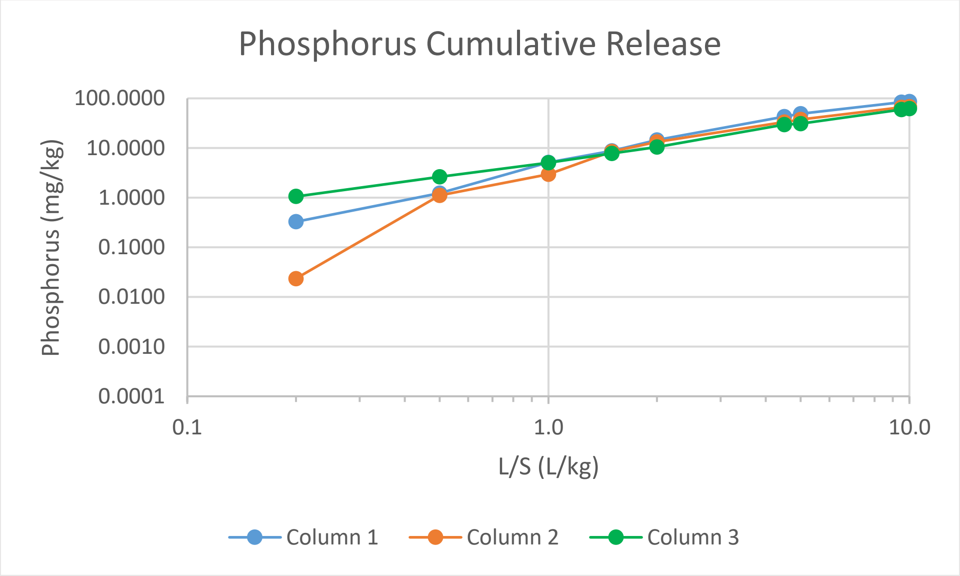


Figure 62: Cumulative release: Phosphorus

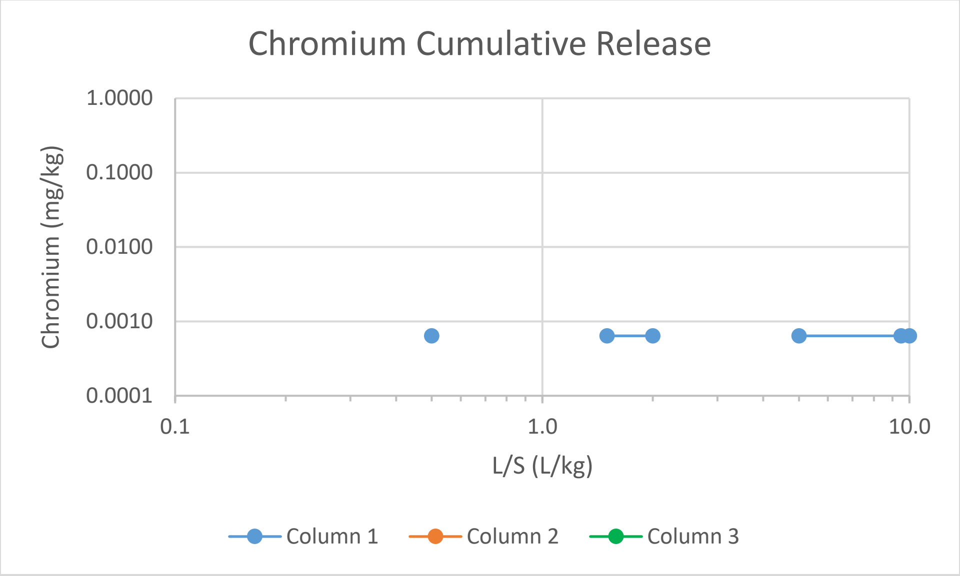


Figure 63: Cumulative Release: Chromium

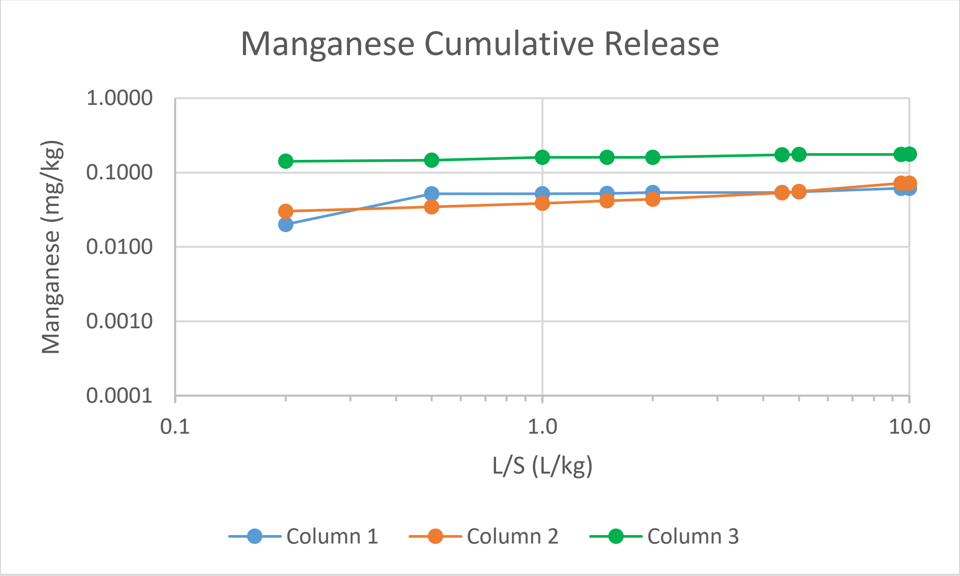


Figure 64: Cumulative Release: Manganese

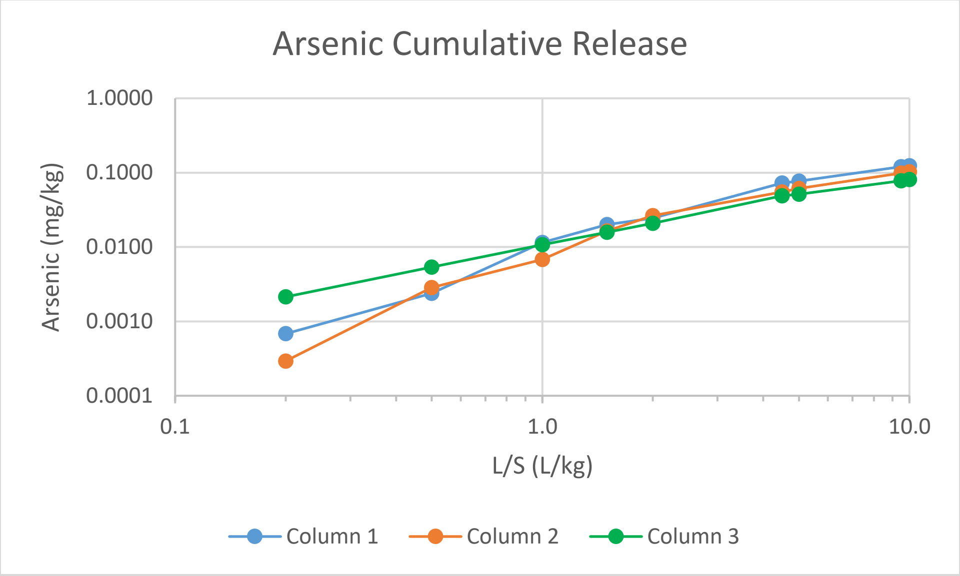


Figure 65: Cumulative Release: Arsenic

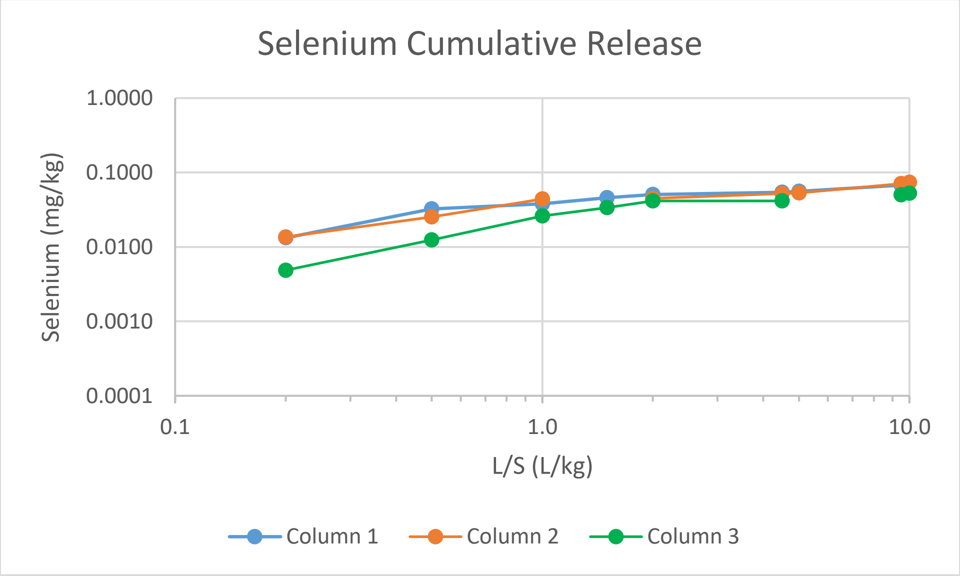


Figure 66: Cumulative Release: Selenium

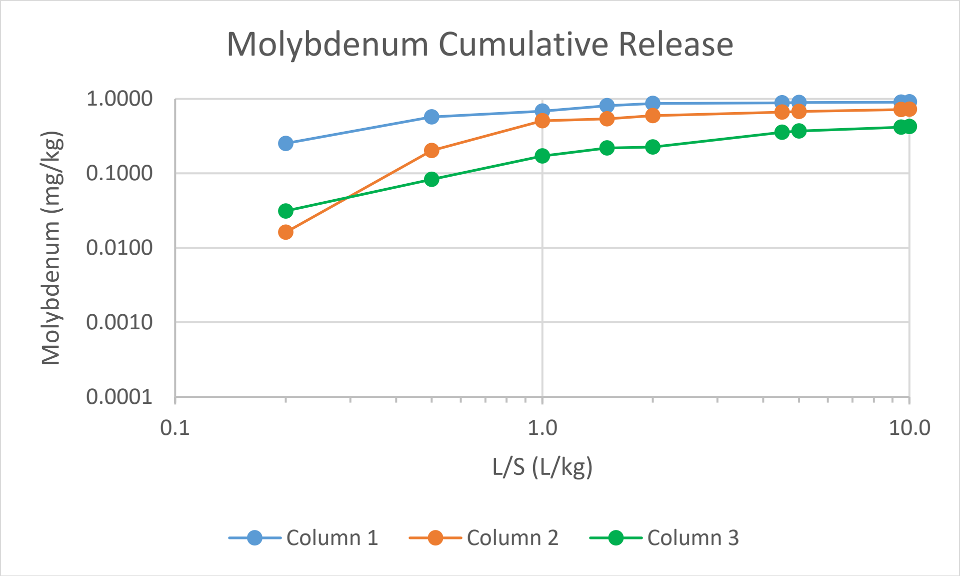


Figure 67: Cumulative Release: Molybdenum

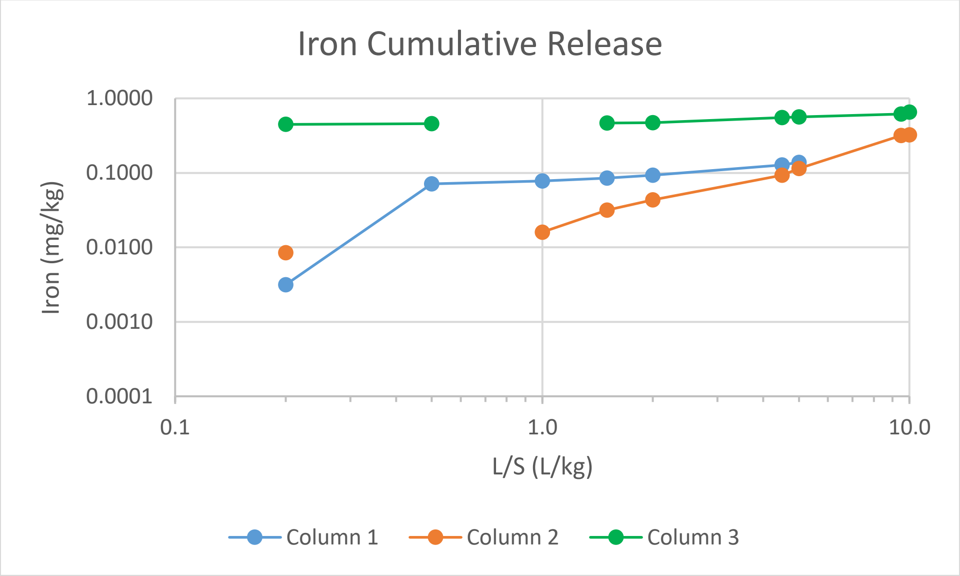


Figure 68: Cumulative Release: Iron

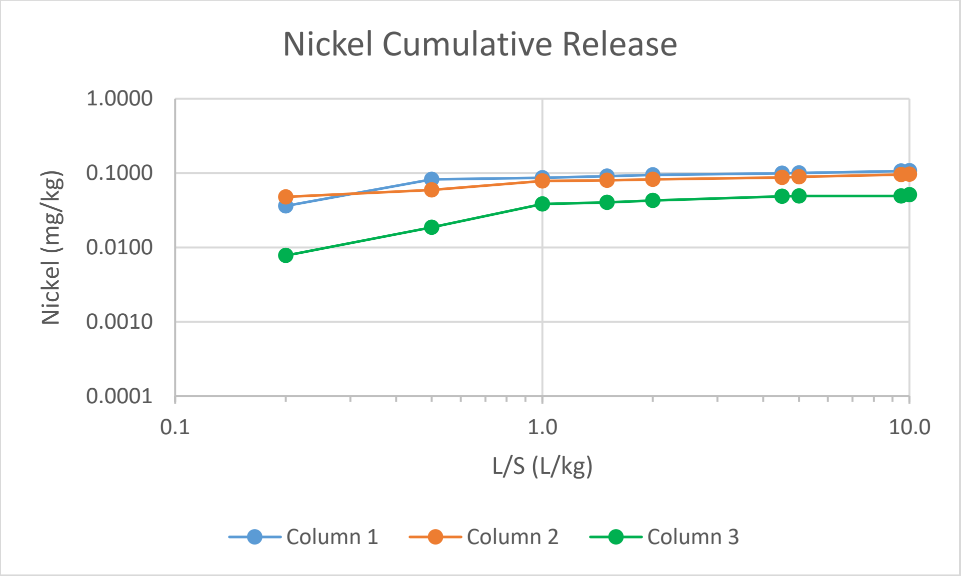


Figure 69: Cumulative Release: Nickel

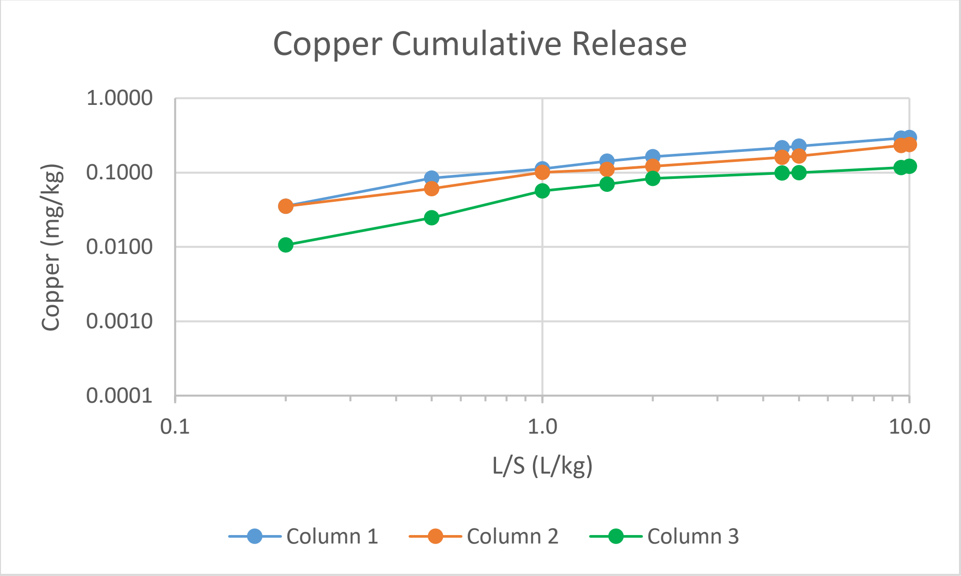


Figure 70: Cumulative Release: Copper

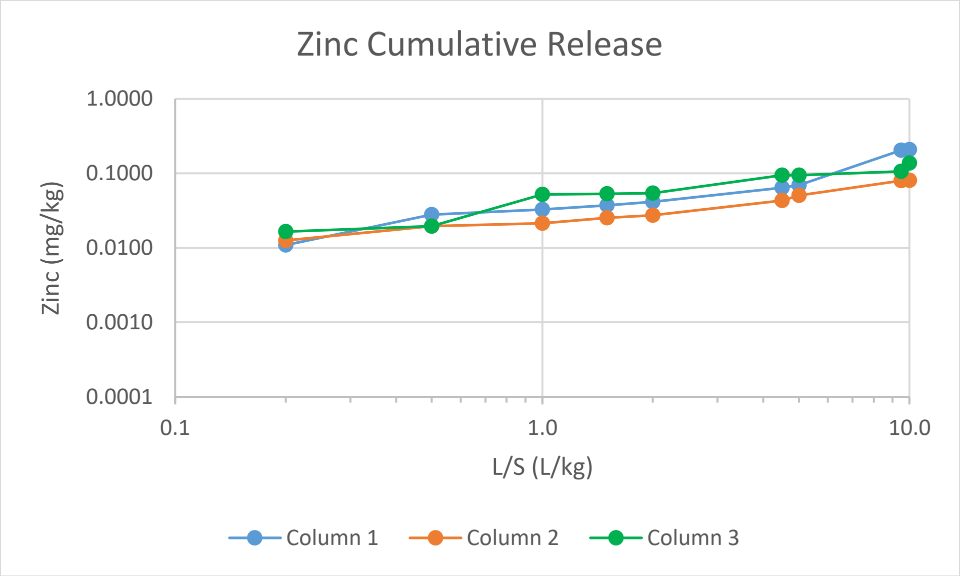


Figure 71: Cumulative Release: Zinc

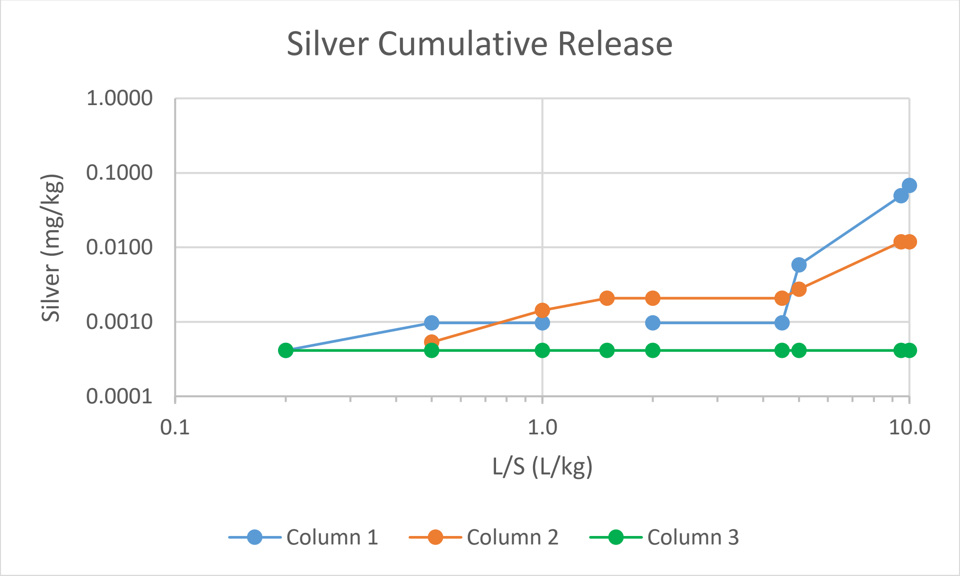


Figure 72: Cumulative Release: Silver

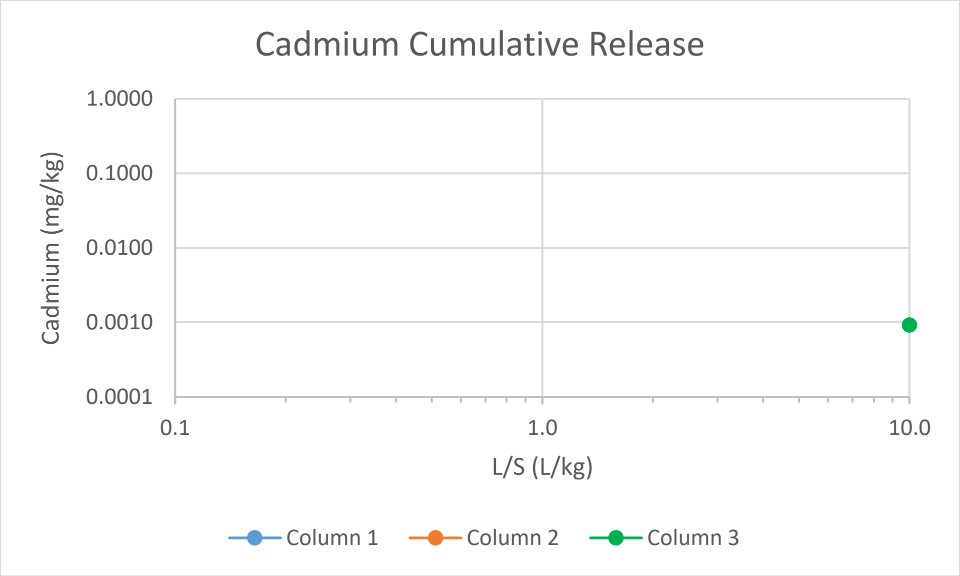


Figure 73: Cumulative Release: Cadmium

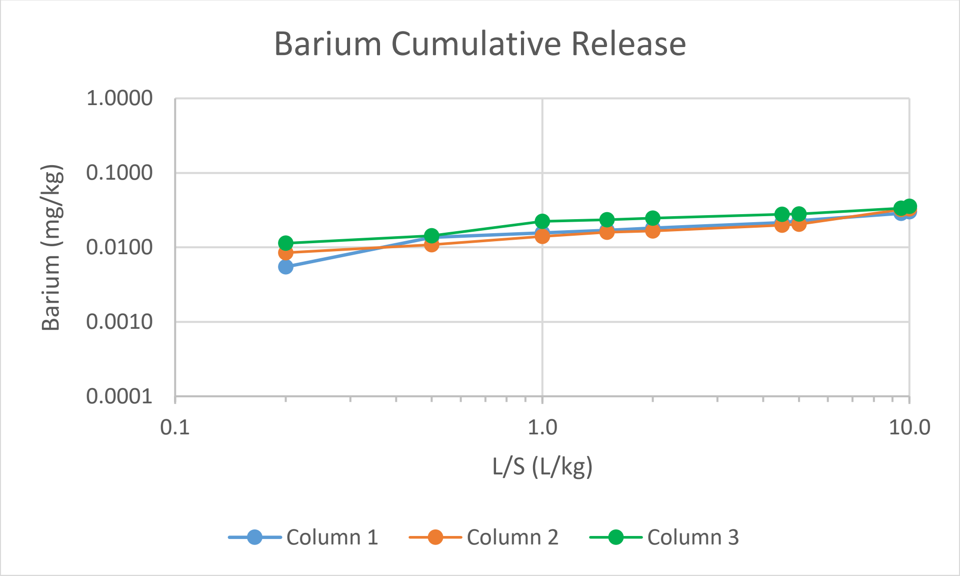


Figure 74: Cumulative Release: Barium

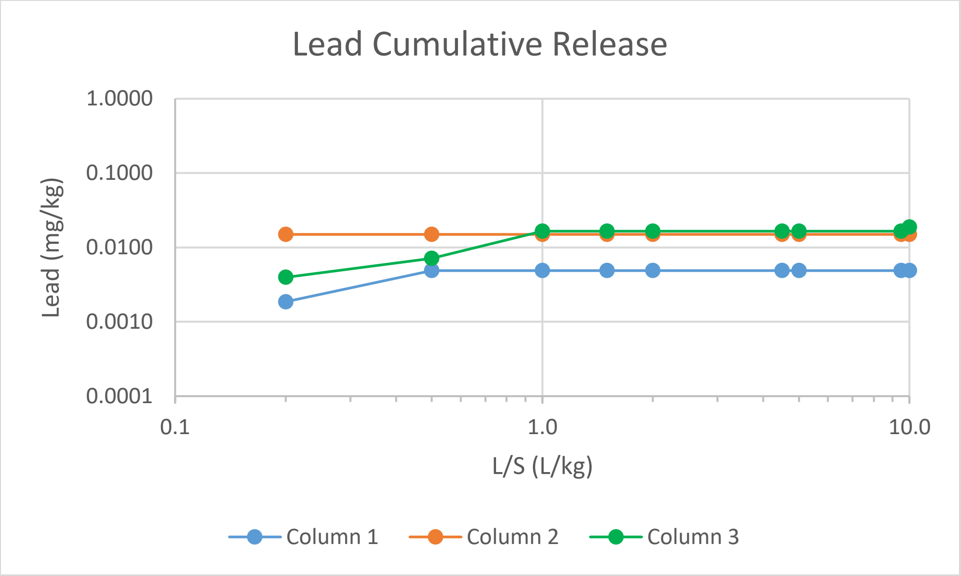


Figure 75: Cumulative Release: Lead

APPENDIX D: LABORATORY & FIELD SOIL ATTENUATION

Table 26: Laboratory soil attenuation

Sample #	ORP (mV)	pH	Conductivity (µs)	Arsenic (µg/L)	Selenium (µg/L)	Manganese (µg/L)	Phosphorus (mg/L)
Spike 091514 HM	239.0	2.47	962	2450	2510	2410	11
C1 091814 HM	-28.7	7.32	772	ND	149	40	ND
C1 091914 HM	-40.1	7.51	558	ND	363	ND	ND
C1 092014 HM	-65.0	7.97	571	x	x	x	ND
C1 092114 HM	-24.4	7.41	504	ND	495	ND	ND
C1 092214 HM	-13.7	7.20	471	ND	566	11.7	ND
C1 092314 HM	-23.4	7.14	496	ND	538	21.3	ND
C2 091814 HM	-29.3	7.34	987	ND	146	37.3	0.06
C2 091914 HM	-22.4	7.29	506	ND	495	ND	ND
C2 092014 HM	-39.8	7.55	518	ND	502	6.9	ND
C2 092114 HM	-12.8	7.13	465	ND	502	5	ND
C2 092214 HM	-24.0	7.32	495	ND	520	5.3	ND
C2 092314 HM	-12.3	7.11	471	ND	466	7.9	ND

Table 27: Laboratory & field constituents transport characteristics

Constituent	**Dispersivity (cm)**	**Diffusion Coefficient (cm^2/s)**	**Soil Diffusion Coefficient (cm^2/s)**	**Distribution Coefficient (mL/g)**	**Retardation Coefficient**	**Dispersion Coefficient (cm^2/s)**	**Seepage Velocity (cm/s)**
Arsenic	0.705207	3.34E-06	4.51E-07	>67	24.920	2.39E-04	3.34E-04
Manganese	0.134713	2.00E-09	2.70E-10	>60	7.055	4.50E-05	3.34E-04
Phosphorus	1.295114	6.94E-08	9.37E-09	>3000	22426	4.33E-04	3.34E-04
Selenium	8.835729	1.31E-08	1.60E-09	>2	15.948	2.95E-03	3.34E-04
Selenium - Field	87.559052	1.43E-08	1.72E-06	>8	15.607	1.89E-03	2.15E-05

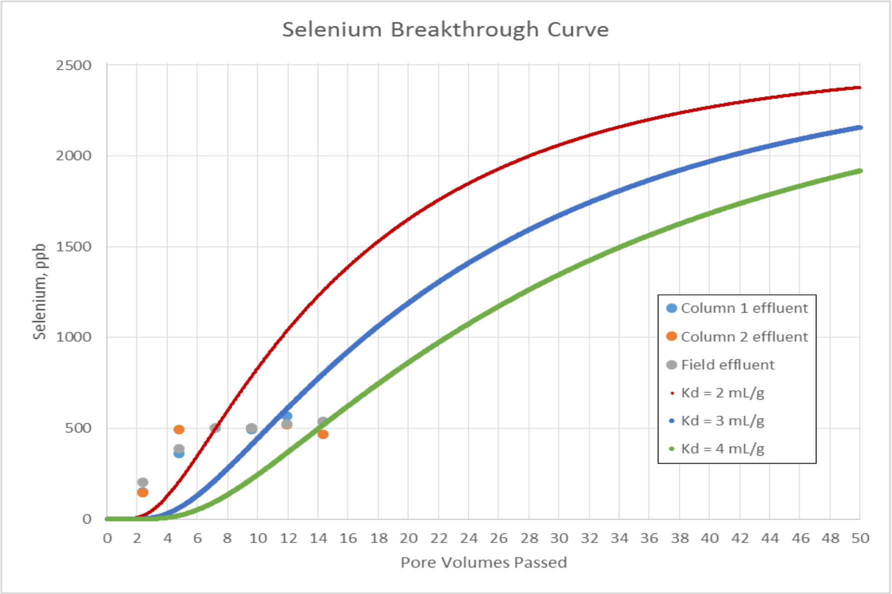


Figure 76: Selenium breakthrough curve

Project Identification: WSSAC
Test Location: Rocky River Wastewater Treatment Plant
Liquid Used: Spiked solution with DI water
Depth to Water Table: 17.65 feet

	Area (cm^2)	Depth of Liquid (cm)
Inner Ring	706	10
Outer Ring	2120	10

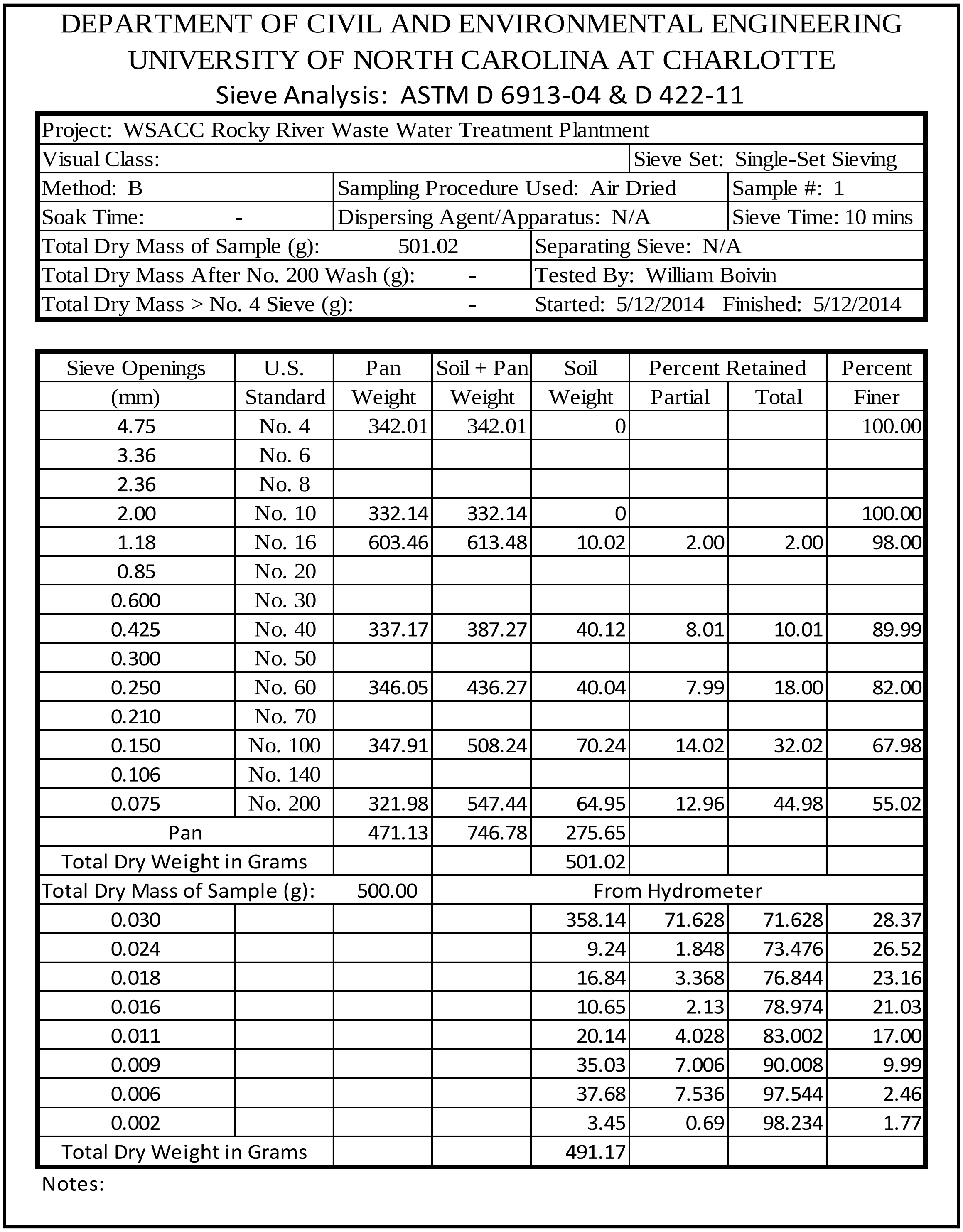
Soil Void Ratio:	0.37	
Volume of Void under inner ring:	11638	cm^3
Volume of Pore Vol.	11.6	L
γ_{Total}:	126	lbs/ft^3
Permeability	3.14 x 10^{-5}	cm/s
	0.113	cm/hr
Vol. of Infiltrate	239.7	mL/hr
Depth to Lysimeter:	2	ft

Note: One pore volume every 48 hours

Date	Time	Volume Collected (mL)	ORP (mV)	pH	Arsenic (µg/L)	Selenium (µg/L)	Manganese (µg/L)	Phosphorus (mg/L)
10/15/14 sp		50.0	254	2.61	2450	2510	2410	11
10/3/2014	9:00:00 AM	500	-36.1	7.04	ND	114	ND	0.09
10/4/2014	9:06:00 AM	496	-27.7	7.21	ND	201	8.1	ND
10/5/2014	9:03:00 AM	499	-34.9	7.18	ND	287	6.4	ND
10/6/2014	9:00:00 AM	500	-17.8	7.67	ND	389	10.8	ND
10/7/2014	9:01:00 AM	500	-13.9	7.31	ND	459	6.9	0.07
10/8/2014	9:00:00 AM	498	-27.6	7.54	ND	501	7.7	ND
10/9/2014	9:00:00 AM	498	-30.1	7.55	ND	499	5.2	ND
10/10/2014	9:09:00 AM	497	-29.7	7.13	ND	504	4.7	ND
10/11/2014	9:02:00 AM	500	-36.4	7.32	ND	518	6.8	ND
10/12/2014	9:00:00 AM	499	-32.7	7.19	ND	524	6.5	ND
10/13/2014	9:04:00 AM	500	-19.8	7.24	ND	541	5.9	ND
10/14/2014	9:00:00 AM	500	-22.4	7.41	ND	537	7.1	ND

Figure 77: Field attenuation data

APPENDIX E: PARTICLE SIZE DISTRIBUTION



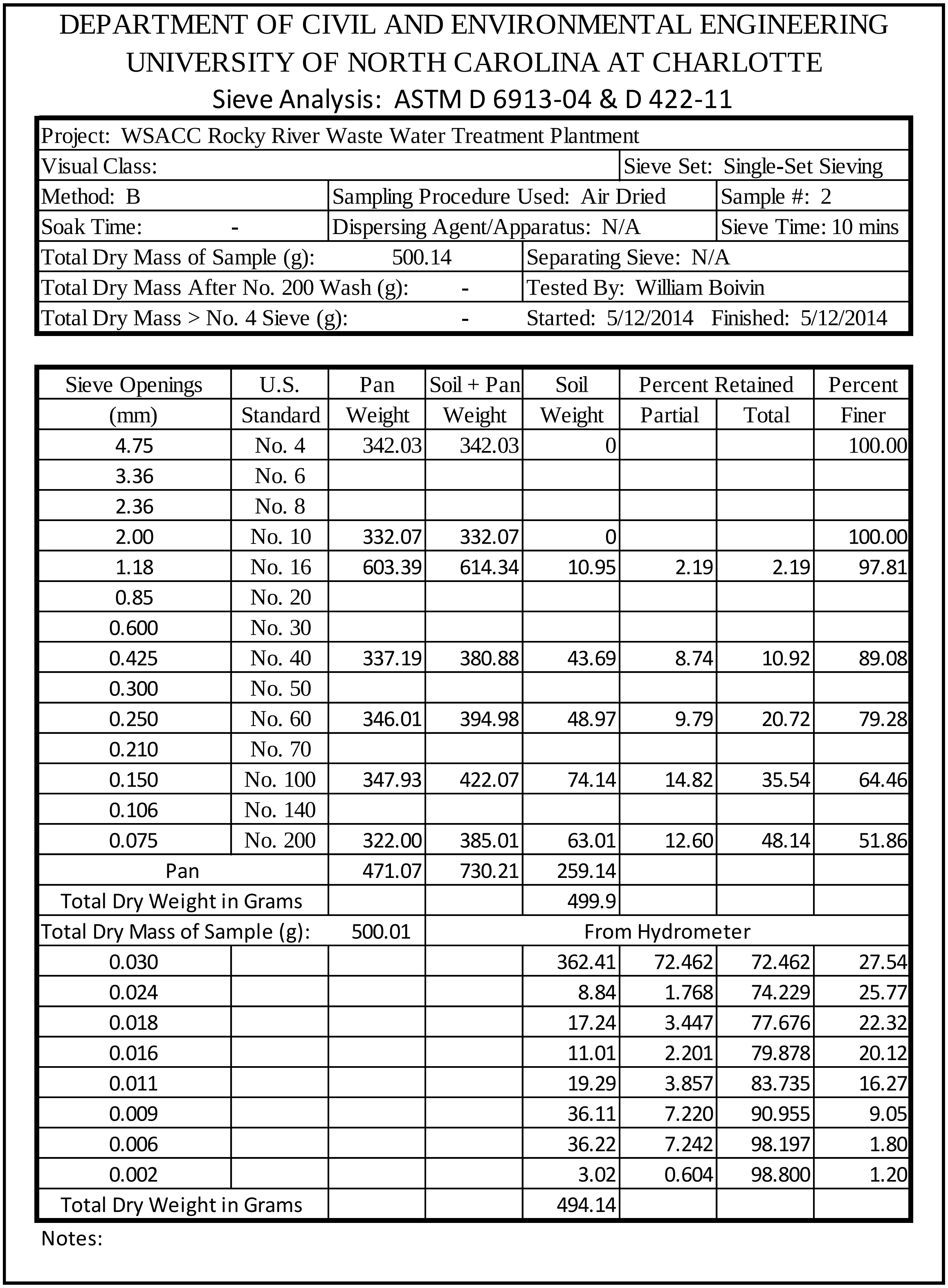
DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Sieve Analysis: ASTM D 6913-04 & D 422-11

Project: WSACC Rocky River Waste Water Treatment Plantment		
Visual Class:		Sieve Set: Single-Set Sieving
Method: B	Sampling Procedure Used: Air Dried	Sample #: 1
Soak Time: -	Dispersing Agent/Apparatus: N/A	Sieve Time: 10 mins
Total Dry Mass of Sample (g): 501.02	Separating Sieve: N/A	
Total Dry Mass After No. 200 Wash (g): -	Tested By: William Boivin	
Total Dry Mass > No. 4 Sieve (g): -	Started: 5/12/2014 Finished: 5/12/2014	

Sieve Openings	U.S.	Pan	Soil + Pan	Soil	Percent Retained		Percent
(mm)	Standard	Weight	Weight	Weight	Partial	Total	Finer
4.75	No. 4	342.01	342.01	0			100.00
3.36	No. 6						
2.36	No. 8						
2.00	No. 10	332.14	332.14	0			100.00
1.18	No. 16	603.46	613.48	10.02	2.00	2.00	98.00
0.85	No. 20						
0.600	No. 30						
0.425	No. 40	337.17	387.27	40.12	8.01	10.01	89.99
0.300	No. 50						
0.250	No. 60	346.05	436.27	40.04	7.99	18.00	82.00
0.210	No. 70						
0.150	No. 100	347.91	508.24	70.24	14.02	32.02	67.98
0.106	No. 140						
0.075	No. 200	321.98	547.44	64.95	12.96	44.98	55.02
Pan		471.13	746.78	275.65			
Total Dry Weight in Grams				501.02			
Total Dry Mass of Sample (g):		500.00	From Hydrometer				
0.030				358.14	71.628	71.628	28.37
0.024				9.24	1.848	73.476	26.52
0.018				16.84	3.368	76.844	23.16
0.016				10.65	2.13	78.974	21.03
0.011				20.14	4.028	83.002	17.00
0.009				35.03	7.006	90.008	9.99
0.006				37.68	7.536	97.544	2.46
0.002				3.45	0.69	98.234	1.77
Total Dry Weight in Grams				491.17			

Notes:

Figure 78: Particle size analysis - sample 1



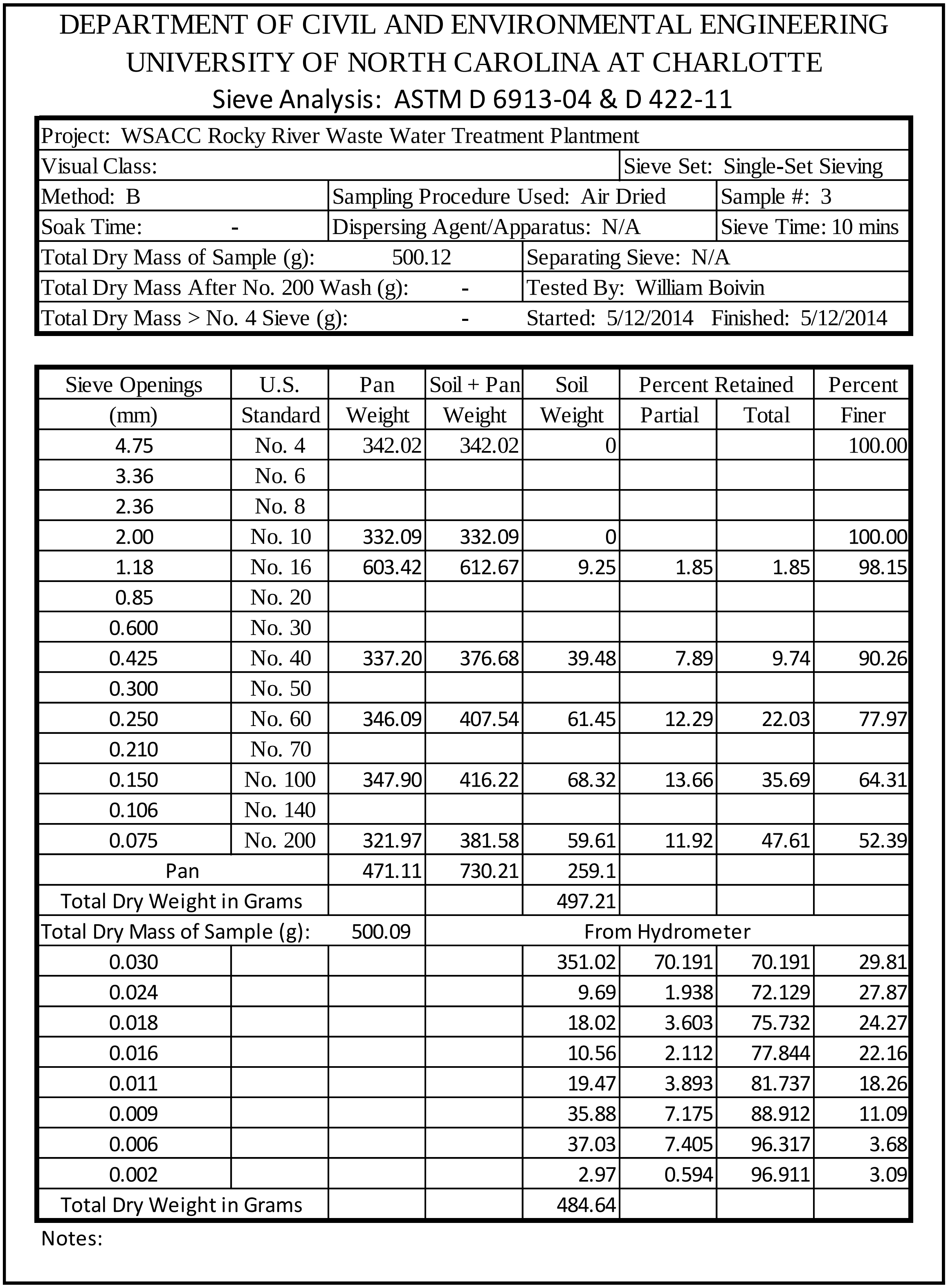
DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Sieve Analysis: ASTM D 6913-04 & D 422-11

Project: WSACC Rocky River Waste Water Treatment Plantment		
Visual Class:		Sieve Set: Single-Set Sieving
Method: B	Sampling Procedure Used: Air Dried	Sample #: 2
Soak Time: -	Dispersing Agent/Apparatus: N/A	Sieve Time: 10 mins
Total Dry Mass of Sample (g): 500.14	Separating Sieve: N/A	
Total Dry Mass After No. 200 Wash (g): -	Tested By: William Boivin	
Total Dry Mass > No. 4 Sieve (g): -	Started: 5/12/2014 Finished: 5/12/2014	

Sieve Openings	U.S.	Pan	Soil + Pan	Soil	Percent Retained		Percent
(mm)	Standard	Weight	Weight	Weight	Partial	Total	Finer
4.75	No. 4	342.03	342.03	0			100.00
3.36	No. 6						
2.36	No. 8						
2.00	No. 10	332.07	332.07	0			100.00
1.18	No. 16	603.39	614.34	10.95	2.19	2.19	97.81
0.85	No. 20						
0.600	No. 30						
0.425	No. 40	337.19	380.88	43.69	8.74	10.92	89.08
0.300	No. 50						
0.250	No. 60	346.01	394.98	48.97	9.79	20.72	79.28
0.210	No. 70						
0.150	No. 100	347.93	422.07	74.14	14.82	35.54	64.46
0.106	No. 140						
0.075	No. 200	322.00	385.01	63.01	12.60	48.14	51.86
Pan		471.07	730.21	259.14			
Total Dry Weight in Grams				499.9			
Total Dry Mass of Sample (g):		500.01	From Hydrometer				
0.030				362.41	72.462	72.462	27.54
0.024				8.84	1.768	74.229	25.77
0.018				17.24	3.447	77.676	22.32
0.016				11.01	2.201	79.878	20.12
0.011				19.29	3.857	83.735	16.27
0.009				36.11	7.220	90.955	9.05
0.006				36.22	7.242	98.197	1.80
0.002				3.02	0.604	98.800	1.20
Total Dry Weight in Grams				494.14			

Notes:

Figure 79: Particle size analysis - sample 2



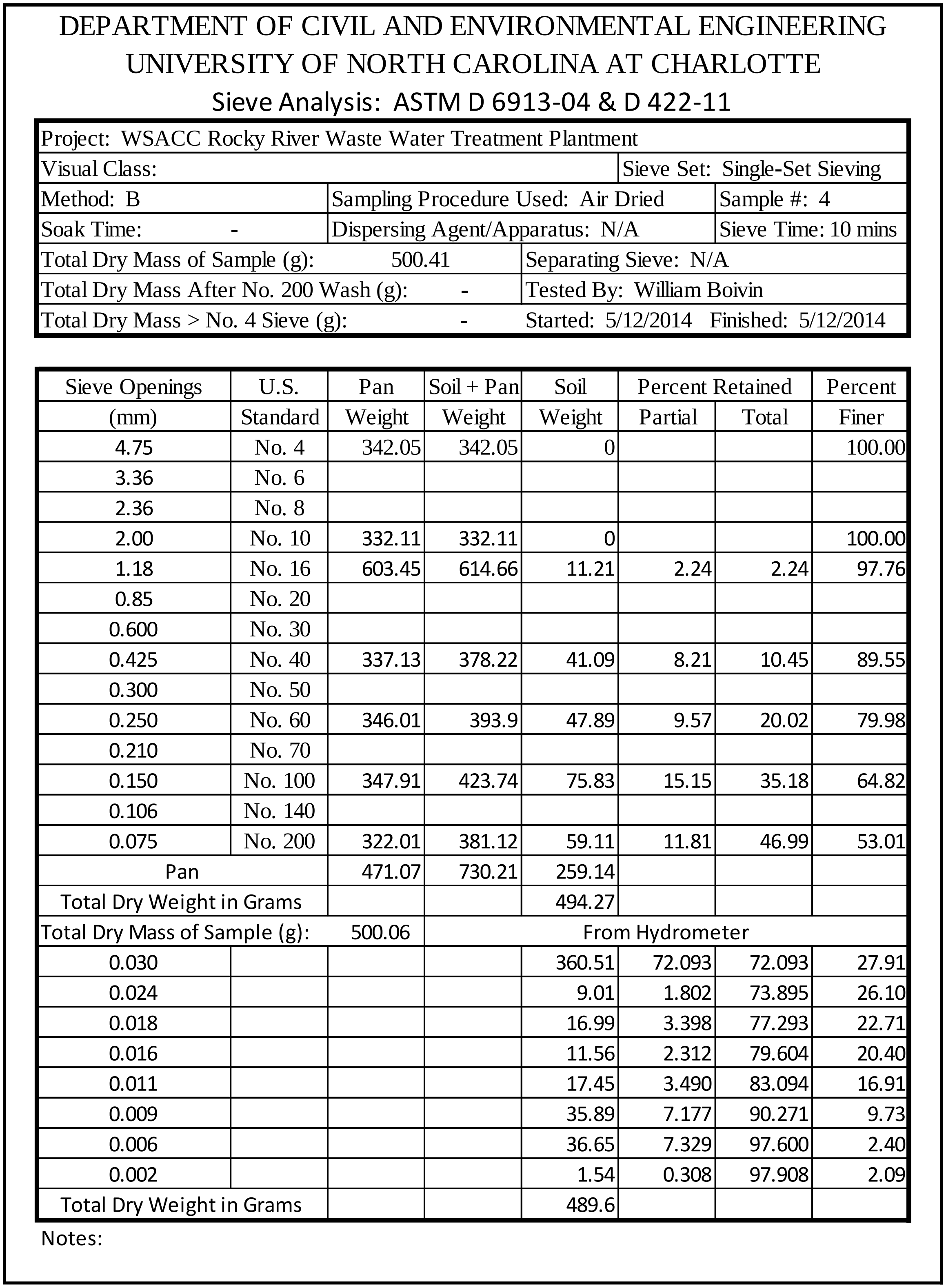
DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Sieve Analysis: ASTM D 6913-04 & D 422-11

Project: WSACC Rocky River Waste Water Treatment Plantment		
Visual Class:		Sieve Set: Single-Set Sieving
Method: B	Sampling Procedure Used: Air Dried	Sample #: 3
Soak Time: -	Dispersing Agent/Apparatus: N/A	Sieve Time: 10 mins
Total Dry Mass of Sample (g): 500.12	Separating Sieve: N/A	
Total Dry Mass After No. 200 Wash (g): -	Tested By: William Boivin	
Total Dry Mass > No. 4 Sieve (g): -	Started: 5/12/2014 Finished: 5/12/2014	

Sieve Openings (mm)	U.S. Standard	Pan Weight	Soil + Pan Weight	Soil Weight	Percent Retained Partial	Percent Retained Total	Percent Finer
4.75	No. 4	342.02	342.02	0			100.00
3.36	No. 6						
2.36	No. 8						
2.00	No. 10	332.09	332.09	0			100.00
1.18	No. 16	603.42	612.67	9.25	1.85	1.85	98.15
0.85	No. 20						
0.600	No. 30						
0.425	No. 40	337.20	376.68	39.48	7.89	9.74	90.26
0.300	No. 50						
0.250	No. 60	346.09	407.54	61.45	12.29	22.03	77.97
0.210	No. 70						
0.150	No. 100	347.90	416.22	68.32	13.66	35.69	64.31
0.106	No. 140						
0.075	No. 200	321.97	381.58	59.61	11.92	47.61	52.39
Pan		471.11	730.21	259.1			
Total Dry Weight in Grams				497.21			
Total Dry Mass of Sample (g):		500.09	From Hydrometer				
0.030				351.02	70.191	70.191	29.81
0.024				9.69	1.938	72.129	27.87
0.018				18.02	3.603	75.732	24.27
0.016				10.56	2.112	77.844	22.16
0.011				19.47	3.893	81.737	18.26
0.009				35.88	7.175	88.912	11.09
0.006				37.03	7.405	96.317	3.68
0.002				2.97	0.594	96.911	3.09
Total Dry Weight in Grams				484.64			

Notes:

Figure 80: Particle size analysis - sample 3



DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Sieve Analysis: ASTM D 6913-04 & D 422-11

Project: WSACC Rocky River Waste Water Treatment Plantment
Visual Class:
Sieve Set: Single-Set Sieving
Method: B
Sampling Procedure Used: Air Dried
Sample #: 4
Soak Time: -
Dispersing Agent/Apparatus: N/A
Sieve Time: 10 mins
Total Dry Mass of Sample (g): 500.41
Separating Sieve: N/A
Total Dry Mass After No. 200 Wash (g): -
Tested By: William Boivin
Total Dry Mass > No. 4 Sieve (g): -
Started: 5/12/2014 Finished: 5/12/2014

Sieve Openings	U.S.	Pan	Soil + Pan	Soil	Percent Retained		Percent
(mm)	Standard	Weight	Weight	Weight	Partial	Total	Finer
4.75	No. 4	342.05	342.05	0			100.00
3.36	No. 6						
2.36	No. 8						
2.00	No. 10	332.11	332.11	0			100.00
1.18	No. 16	603.45	614.66	11.21	2.24	2.24	97.76
0.85	No. 20						
0.600	No. 30						
0.425	No. 40	337.13	378.22	41.09	8.21	10.45	89.55
0.300	No. 50						
0.250	No. 60	346.01	393.9	47.89	9.57	20.02	79.98
0.210	No. 70						
0.150	No. 100	347.91	423.74	75.83	15.15	35.18	64.82
0.106	No. 140						
0.075	No. 200	322.01	381.12	59.11	11.81	46.99	53.01
Pan		471.07	730.21	259.14			
Total Dry Weight in Grams				494.27			
Total Dry Mass of Sample (g):		500.06	From Hydrometer				
0.030				360.51	72.093	72.093	27.91
0.024				9.01	1.802	73.895	26.10
0.018				16.99	3.398	77.293	22.71
0.016				11.56	2.312	79.604	20.40
0.011				17.45	3.490	83.094	16.91
0.009				35.89	7.177	90.271	9.73
0.006				36.65	7.329	97.600	2.40
0.002				1.54	0.308	97.908	2.09
Total Dry Weight in Grams				489.6			

Notes:

Figure 81: Particle size analysis - sample 4

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Sieve Analysis: ASTM D 6913-04 & D 422-11

Project: WSACC Rocky River Waste Water Treatment Plantment		
Visual Class:		Sieve Set: Single-Set Sieving
Method: B	Sampling Procedure Used: Air Dried	Sample #: 5
Soak Time: -	Dispersing Agent/Apparatus: N/A	Sieve Time: 10 mins
Total Dry Mass of Sample (g): 500.78	Separating Sieve: N/A	
Total Dry Mass After No. 200 Wash (g): -	Tested By: William Boivin	
Total Dry Mass > No. 4 Sieve (g): -	Started: 5/12/2014 Finished: 5/12/2014	

Sieve Openings	U.S.	Pan	Soil + Pan	Soil	Percent Retained		Percent
(mm)	Standard	Weight	Weight	Weight	Partial	Total	Finer
4.75	No. 4	342.05	342.05	0			100.00
3.36	No. 6						
2.36	No. 8						
2.00	No. 10	332.12	332.12	0			100.00
1.18	No. 16	603.39	614.28	10.89	2.18	2.18	97.82
0.85	No. 20						
0.600	No. 30						
0.425	No. 40	337.15	379.28	42.13	8.42	10.60	89.40
0.300	No. 50						
0.250	No. 60	346.08	392.85	46.77	9.35	19.95	80.05
0.210	No. 70						
0.150	No. 100	347.93	421.93	74	14.80	34.75	65.25
0.106	No. 140						
0.075	No. 200	321.97	381.96	59.99	11.99	46.74	53.26
Pan		471.12	730.21	259.09			
Total Dry Weight in Grams				492.87			
Total Dry Mass of Sample (g):		500.67	From Hydrometer				
0.030				364.01	72.705	72.705	27.30
0.024				8.09	1.616	74.320	25.68
0.018				16.16	3.228	77.548	22.45
0.016				10.87	2.171	79.719	20.28
0.011				17.38	3.471	83.191	16.81
0.009				35.41	7.073	90.263	9.74
0.006				30.85	6.162	96.425	3.58
0.002				3.52	0.703	97.128	2.87
Total Dry Weight in Grams				486.29			

Notes:

Figure 82: Particle size analysis - sample 5

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Sieve Analysis: ASTM D 6913-04 & D 422-11

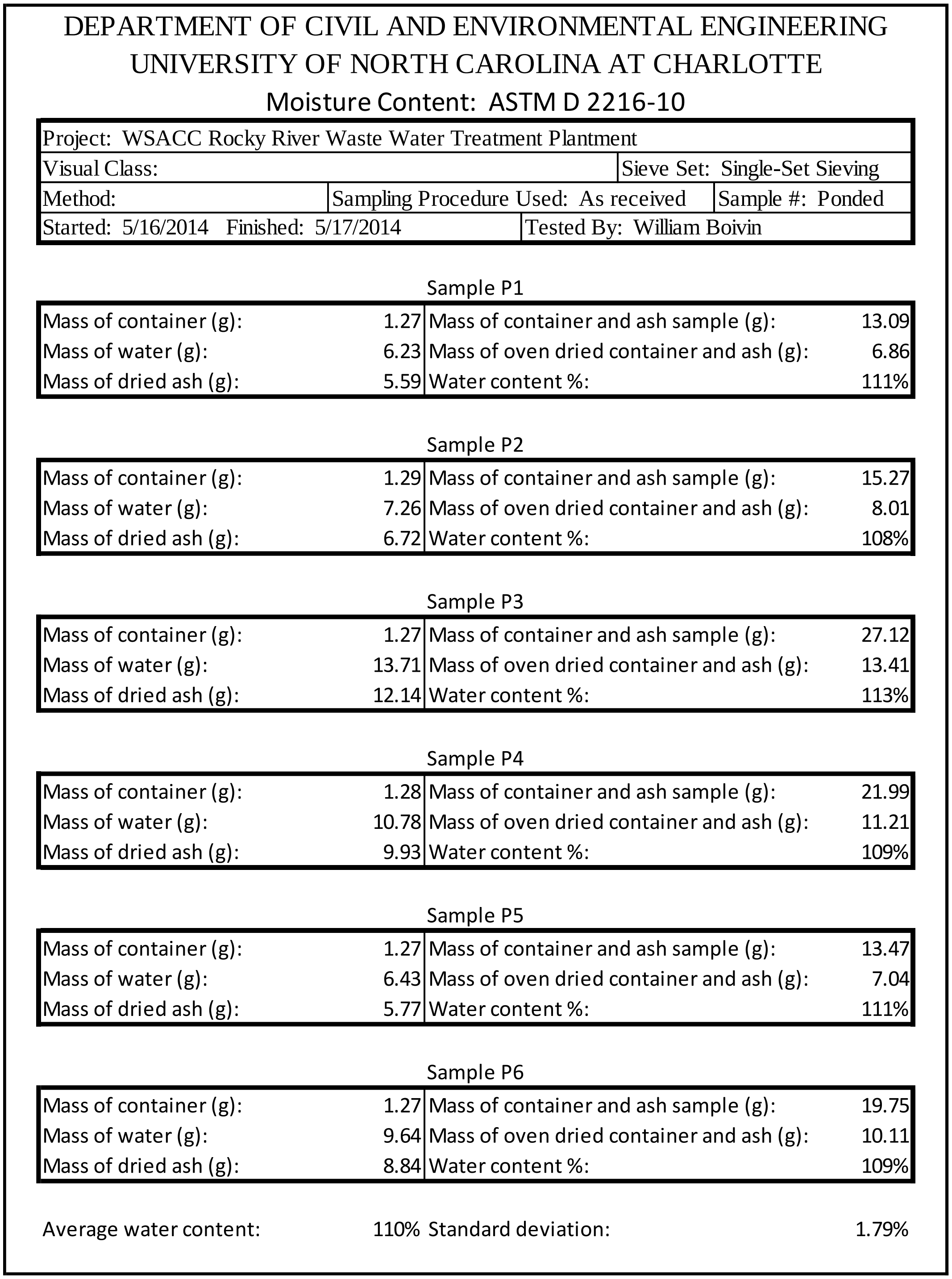
Project: WSACC Rocky River Waste Water Treatment Plantment		
Visual Class:		Sieve Set: Single-Set Sieving
Method: B	Sampling Procedure Used: Air Dried	Sample #: 6
Soak Time: -	Dispersing Agent/Apparatus: N/A	Sieve Time: 10 mins
Total Dry Mass of Sample (g): 500.67	Separating Sieve: N/A	
Total Dry Mass After No. 200 Wash (g): -	Tested By: William Boivin	
Total Dry Mass > No. 4 Sieve (g): -	Started: 5/12/2014 Finished: 5/12/2014	

Sieve Openings	U.S.	Pan	Soil + Pan	Soil	Percent Retained		Percent
(mm)	Standard	Weight	Weight	Weight	Partial	Total	Finer
4.75	No. 4	342.04	342.04	0			100.00
3.36	No. 6						
2.36	No. 8						
2.00	No. 10	332.09	332.09	0			100.00
1.18	No. 16	603.49	614.81	11.32	2.26	2.26	97.74
0.85	No. 20						
0.600	No. 30						
0.425	No. 40	337.21	375.82	38.61	7.71	9.97	90.03
0.300	No. 50						
0.250	No. 60	346.11	392.93	46.82	9.35	19.32	80.68
0.210	No. 70						
0.150	No. 100	347.91	421.28	73.37	14.65	33.98	66.02
0.106	No. 140						
0.075	No. 200	322.03	383.44	61.41	12.27	46.24	53.76
Pan		471.16	730.21	259.05			
Total Dry Weight in Grams				490.58			
Total Dry Mass of Sample (g):		500.23	From Hydrometer				
0.030				357.14	71.395	71.395	28.60
0.024				7.29	1.457	72.852	27.15
0.018				16.34	3.266	76.119	23.88
0.016				10.14	2.027	78.146	21.85
0.011				19.07	3.812	81.958	18.04
0.009				35.12	7.021	88.979	11.02
0.006				35.99	7.195	96.174	3.83
0.002				2.89	0.578	96.751	3.25
Total Dry Weight in Grams				483.98			

Notes:

Figure 83: Particle size analysis - sample 6

APPENDIX F: MOISTURE CONTENT



DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Moisture Content: ASTM D 2216-10

Project: WSACC Rocky River Waste Water Treatment Plantment		
Visual Class:		Sieve Set: Single-Set Sieving
Method:	Sampling Procedure Used: As received	Sample #: Ponded
Started: 5/16/2014 Finished: 5/17/2014	Tested By: William Boivin	

Sample P1

Mass of container (g):	1.27	Mass of container and ash sample (g):	13.09
Mass of water (g):	6.23	Mass of oven dried container and ash (g):	6.86
Mass of dried ash (g):	5.59	Water content %:	111%

Sample P2

Mass of container (g):	1.29	Mass of container and ash sample (g):	15.27
Mass of water (g):	7.26	Mass of oven dried container and ash (g):	8.01
Mass of dried ash (g):	6.72	Water content %:	108%

Sample P3

Mass of container (g):	1.27	Mass of container and ash sample (g):	27.12
Mass of water (g):	13.71	Mass of oven dried container and ash (g):	13.41
Mass of dried ash (g):	12.14	Water content %:	113%

Sample P4

Mass of container (g):	1.28	Mass of container and ash sample (g):	21.99
Mass of water (g):	10.78	Mass of oven dried container and ash (g):	11.21
Mass of dried ash (g):	9.93	Water content %:	109%

Sample P5

Mass of container (g):	1.27	Mass of container and ash sample (g):	13.47
Mass of water (g):	6.43	Mass of oven dried container and ash (g):	7.04
Mass of dried ash (g):	5.77	Water content %:	111%

Sample P6

Mass of container (g):	1.27	Mass of container and ash sample (g):	19.75
Mass of water (g):	9.64	Mass of oven dried container and ash (g):	10.11
Mass of dried ash (g):	8.84	Water content %:	109%

Average water content:	110%	Standard deviation:	1.79%

Figure 84: Moisture content - ponded sample

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Moisture Content: ASTM D 2216-10

Project: WSACC Rocky River Waste Water Treatment Plantment		
Visual Class:		Sieve Set: Single-Set Sieving
Method:	Sampling Procedure Used: air-dried	Sample #: Ponded
Started: 5/20/2014 Finished: 5/26/2014	Tested By: William Boivin	

Sample A1

Mass of container (g):	1.27	Mass of container and ash sample (g):	10.38
Mass of water (g):	0.12	Mass of oven dried container and ash	10.26
Mass of dried ash (g):	8.99	Water content %:	1.33%

Sample A2

Mass of container (g):	1.27	Mass of container and ash sample (g):	14.39
Mass of water (g):	0.2	Mass of oven dried container and ash	14.19
Mass of dried ash (g):	12.92	Water content %:	1.55%

Sample A3

Mass of container (g):	1.27	Mass of container and ash sample (g):	24.16
Mass of water (g):	0.41	Mass of oven dried container and ash	23.75
Mass of dried ash (g):	22.48	Water content %:	1.82%

Sample A4

Mass of container (g):	1.27	Mass of container and ash sample (g):	18.41
Mass of water (g):	0.24	Mass of oven dried container and ash	18.17
Mass of dried ash (g):	16.9	Water content %:	1.42%

Sample A5

Mass of container (g):	1.27	Mass of container and ash sample (g):	13.71
Mass of water (g):	0.25	Mass of oven dried container and ash	13.46
Mass of dried ash (g):	12.19	Water content %:	2.05%

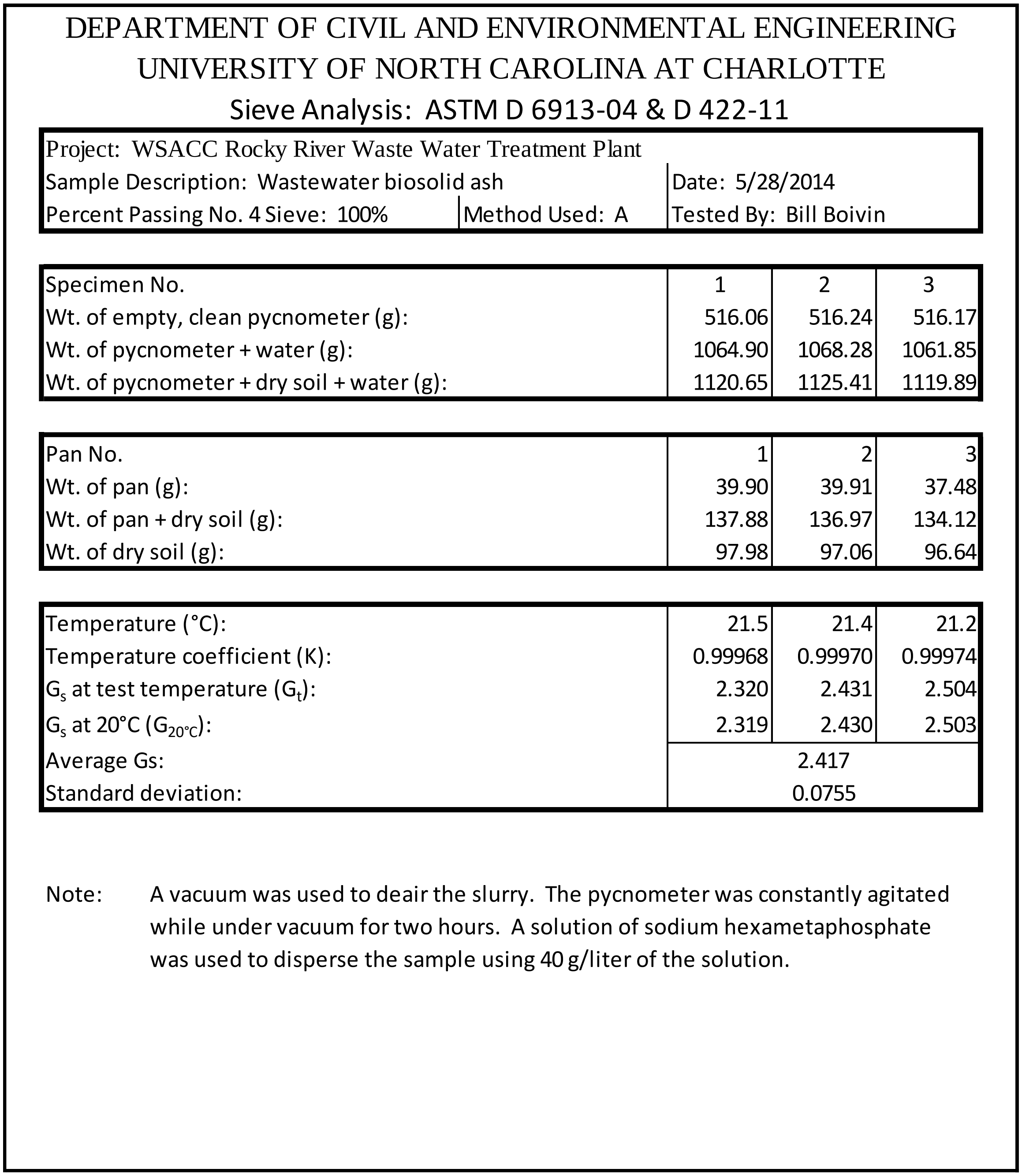
Sample A6

Mass of container (g):	1.27	Mass of container and ash sample (g):	15.42
Mass of water (g):	0.23	Mass of oven dried container and ash	15.19
Mass of dried ash (g):	13.92	Water content %:	1.65%

Average water content:	2%	Standard deviation:	0.24%

Figure 85: Moisture content - air-dried sample

APPENDIX G: SPECIFIC GRAVITY



DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Sieve Analysis: ASTM D 6913-04 & D 422-11

Project: WSACC Rocky River Waste Water Treatment Plant		
Sample Description: Wastewater biosolid ash		Date: 5/28/2014
Percent Passing No. 4 Sieve: 100%	Method Used: A	Tested By: Bill Boivin

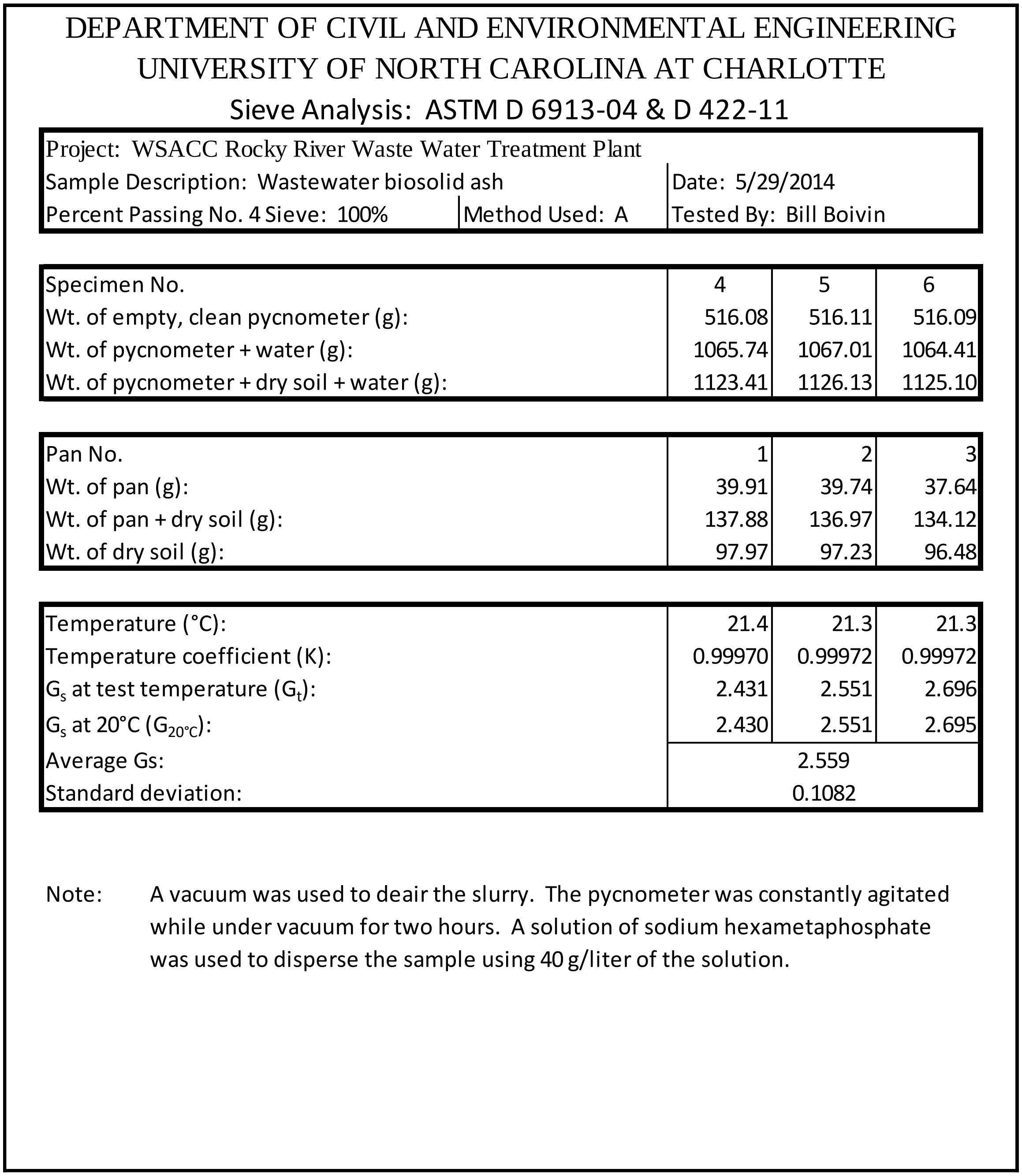
Specimen No.	1	2	3
Wt. of empty, clean pycnometer (g):	516.06	516.24	516.17
Wt. of pycnometer + water (g):	1064.90	1068.28	1061.85
Wt. of pycnometer + dry soil + water (g):	1120.65	1125.41	1119.89

Pan No.	1	2	3
Wt. of pan (g):	39.90	39.91	37.48
Wt. of pan + dry soil (g):	137.88	136.97	134.12
Wt. of dry soil (g):	97.98	97.06	96.64

Temperature (°C):	21.5	21.4	21.2
Temperature coefficient (K):	0.99968	0.99970	0.99974
G_s at test temperature (G_t):	2.320	2.431	2.504
G_s at 20°C ($G_{20°C}$):	2.319	2.430	2.503
Average Gs:	2.417		
Standard deviation:	0.0755		

Note: A vacuum was used to deair the slurry. The pycnometer was constantly agitated while under vacuum for two hours. A solution of sodium hexametaphosphate was used to disperse the sample using 40 g/liter of the solution.

Figure 86: Specific gravity of biosolid ash-1



DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Sieve Analysis: ASTM D 6913-04 & D 422-11

Project: WSACC Rocky River Waste Water Treatment Plant		
Sample Description: Wastewater biosolid ash		Date: 5/29/2014
Percent Passing No. 4 Sieve: 100%	Method Used: A	Tested By: Bill Boivin

Specimen No.	4	5	6
Wt. of empty, clean pycnometer (g):	516.08	516.11	516.09
Wt. of pycnometer + water (g):	1065.74	1067.01	1064.41
Wt. of pycnometer + dry soil + water (g):	1123.41	1126.13	1125.10

Pan No.	1	2	3
Wt. of pan (g):	39.91	39.74	37.64
Wt. of pan + dry soil (g):	137.88	136.97	134.12
Wt. of dry soil (g):	97.97	97.23	96.48

Temperature (°C):	21.4	21.3	21.3
Temperature coefficient (K):	0.99970	0.99972	0.99972
G_s at test temperature (G_t):	2.431	2.551	2.696
G_s at 20°C ($G_{20°C}$):	2.430	2.551	2.695
Average Gs:	2.559		
Standard deviation:	0.1082		

Note: A vacuum was used to deair the slurry. The pycnometer was constantly agitated while under vacuum for two hours. A solution of sodium hexametaphosphate was used to disperse the sample using 40 g/liter of the solution.

Figure 87: Specific gravity of biosolid ash -2

APPENDIX H: PROCTOR TEST

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE

Proctor Test: ASTM D 698

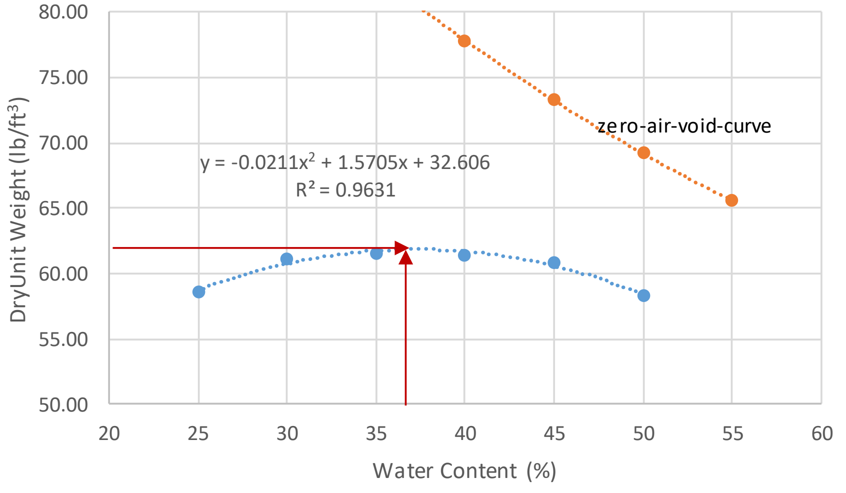
Project: WSACC Rocky River Waste Water Treatment Plant
Method Used: A Preparation Method Used: Moist Rammer: Manual
Material Description: Biosolid ash Oversize Fraction: 0% G_s: 2.49
Location: N/A Tested By: Bill Boivin Test Date: 6/1/2014

Determination of dry unit weight

Specimen No.	1	2	3	4	5	6
Water content, w%:	25%	30%	35%	40%	45%	50%
Mold volume (cm^3):	944	944	944	944	944	944
Wt. of mold (g):	4987.71	4987.68	4987.73	4987.71	4987.73	4987.71
Wt. of mold + soil (g):	5875.12	5914.94	5921.57	5920.1	5912.64	5874.1
Wt. of wet soil (g):	887.41	927.26	933.84	932.39	924.91	886.39
Wet density (g/cm^3):	0.940	0.982	0.989	0.988	0.980	0.939
Dry density (g/cm^3):	0.938	0.979	0.986	0.984	0.975	0.934
Wet unit weight (lb/ft^3):	58.69	61.32	61.76	61.66	61.17	58.62
Dry unit weight (lb/ft^3):	58.54	61.14	61.54	61.41	60.89	58.33

Determination of zero-air-void curve

Water content, w%:	25	30	35	40	45	50
Dry density (g/cm^3):	1.533	1.424	1.329	1.246	1.173	1.108
Dry unit weight (lb/ft^3):	95.72	88.90	82.99	77.81	73.25	69.19



Optimum water content (%)
36.7
Maximum dry unit weight (lbs/ft^3)
62.4

Figure 88: Proctor test – 1

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE

Proctor Test: ASTM D 698

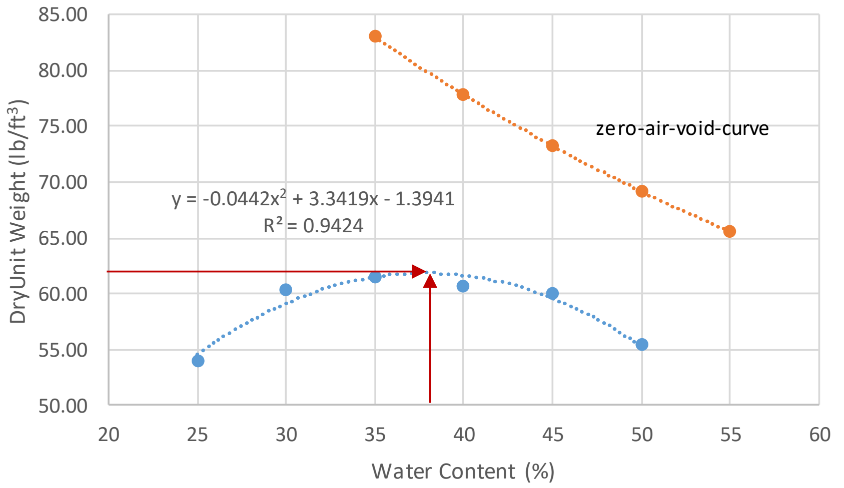
Project: WSACC Rocky River Waste Water Treatment Plant
Method Used: A Preparation Method Used: Moist Rammer: Manual
Material Description: Biosolid ash Oversize Fraction: 0% G_s: 2.49
Location: N/A Tested By: Bill Boivin Test Date: 6/2/2014

Determination of dry unit weight

Specimen No.	1	2	3	4	5	6
Water content, w%:	25%	30%	35%	40%	45%	50%
Mold volume (cm^3):	944	944	944	944	944	944
Wt. of mold (g):	4987.68	4987.69	4987.71	4987.7	4987.72	4987.71
Wt. of mold + soil (g):	5806.14	5901.74	5919.89	5908.41	5899.37	5829.09
Wt. of wet soil (g):	818.46	914.05	932.18	920.71	911.65	841.38
Wet density (g/cm^3):	0.867	0.968	0.987	0.975	0.966	0.891
Dry density (g/cm^3):	0.865	0.965	0.984	0.971	0.961	0.887
Wet unit weight (lb/ft^3):	54.13	60.45	61.65	60.89	60.29	55.64
Dry unit weight (lb/ft^3):	53.99	60.27	61.43	60.65	60.02	55.36

Determination of zero-air-void curve

Water content, w%:	25	30	35	40	45	50
Dry density (g/cm^3):	1.533	1.424	1.329	1.246	1.173	1.108
Dry unit weight (kN/m^3):	95.72	88.90	82.99	77.81	73.25	69.19



Optimum water content (%)
36.1
Maximum dry unit weight (lbs/ft^3)
62

Figure 89: Proctor test – 2

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Proctor Test: ASTM D 698

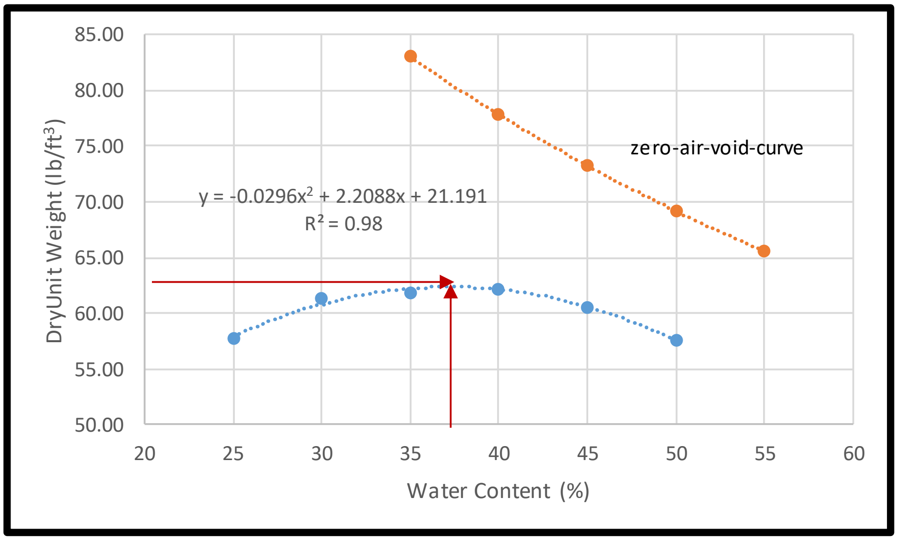
Project: WSACC Rocky River Waste Water Treatment Plant
Method Used: A Preparation Method Used: Moist Rammer: Manual
Material Description: Biosolid ash Oversize Fraction: 0% G_s: 2.49
Location: N/A Tested By: Bill Boivin Test Date: 6/2/2014

Determination of dry unit weight

Specimen No.	1	2	3	4	5	6
Water content, w%:	25%	30%	35%	40%	45%	50%
Mold volume (cm^3):	944	944	944	944	944	944
Wt. of mold (g):	4987.7	4987.71	4987.7	4987.7	4987.71	4987.71
Wt. of mold + soil (g):	5861.99	5917.52	5926.88	5931.05	5907.1	5863.36
Wt. of wet soil (g):	874.29	929.81	939.18	943.35	919.39	875.65
Wet density (g/cm^3):	0.926	0.985	0.995	0.999	0.974	0.928
Dry density (g/cm^3):	0.924	0.982	0.991	0.995	0.970	0.923
Wet unit weight (lb/ft^3):	57.82	61.49	62.11	62.39	60.80	57.91
Dry unit weight (lb/ft^3):	57.67	61.31	61.89	62.14	60.53	57.62

Determination of zero-air-void curve

Water content, w%:	25	30	35	40	45	50
Dry density (g/cm^3):	1.533	1.424	1.329	1.246	1.173	1.108
Dry unit weight (kN/m^3):	95.72	88.90	82.99	77.81	73.25	69.19



Optimum water content (%)
37.2
Maximum dry unit weight (lbs/ft^3)
63.1

Figure 90: Proctor test – 3

APPENDIX I: PERMEABILITY

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Falling Head Permeability Test

Project: WSACC Rocky River Waste Water Treatment Plant
Sample Description: Wastewater biosolid ash | Date: 6/7/2014
Dry Density (pcf): 48.1 | Method Used: N/A | Tested By: Bill Boivin

Sample 1			
Area of burette (cm^2):	1.695	Initial height of water (cm):	104.14
Length of soil column (cm):	10.32	Final height of water (cm):	102
Area of soil column (cm2):	44.867	Time required to get headdrop of Δh (s):	37
k (cm/sec):	2.19E-04		

Sample 2			
Area of burette (cm^2):	1.695	Initial height of water (cm):	102
Length of soil column (cm):	10.32	Final height of water (cm):	99.94
Area of soil column (cm2):	44.867	Time required to get headdrop of Δh (s):	30
k (cm/sec):	2.65E-04		

Sample 3			
Area of burette (cm^2):	1.695	Initial height of water (cm):	99.94
Length of soil column (cm):	10.32	Final height of water (cm):	98.12
Area of soil column (cm2):	44.867	Time required to get headdrop of Δh (s):	31
k (cm/sec):	2.31E-04		

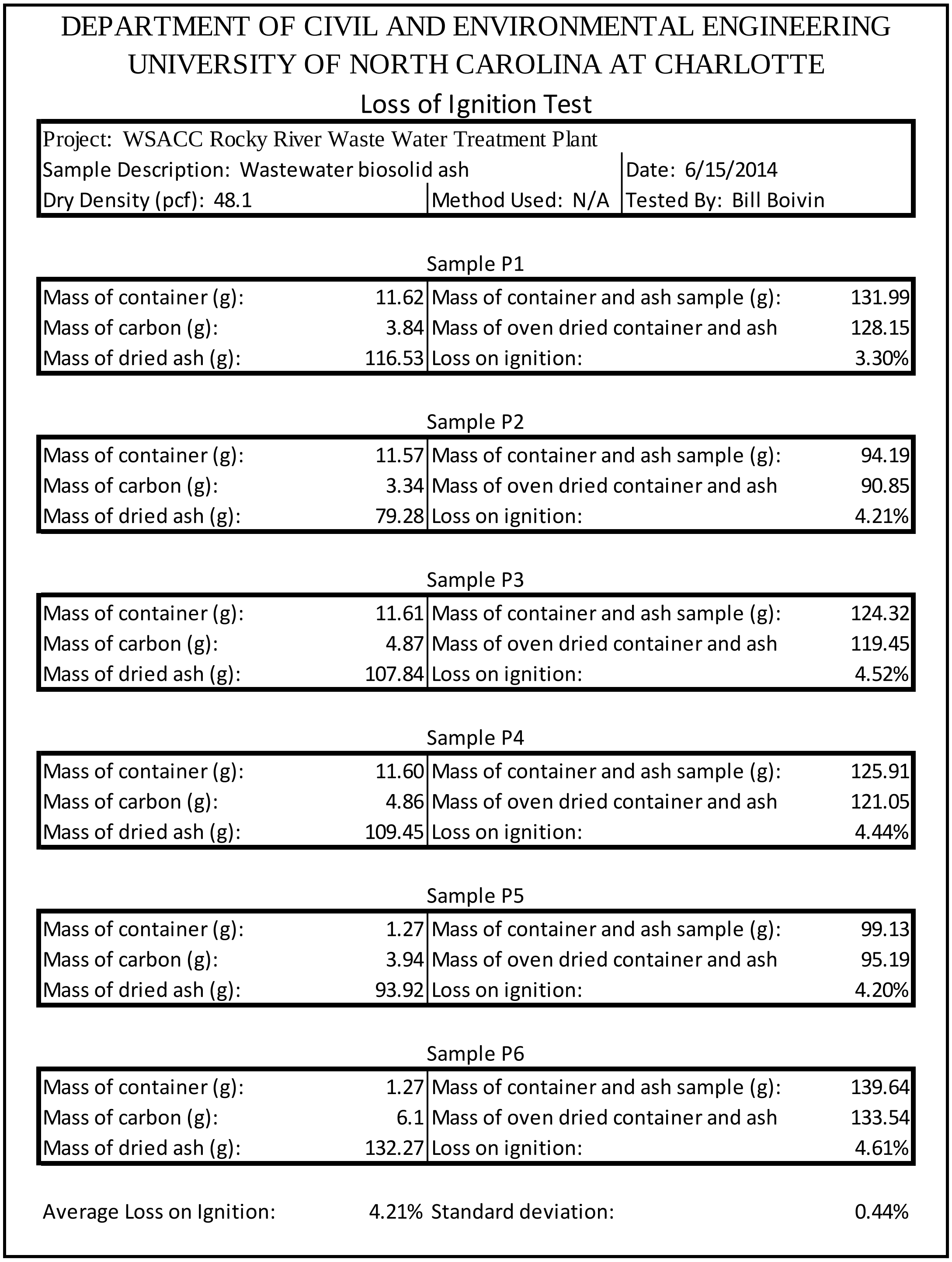
Sample 4			
Area of burette (cm^2):	1.695	Initial height of water (cm):	98.12
Length of soil column (cm):	10.32	Final height of water (cm):	96.51
Area of soil column (cm2):	44.867	Time required to get headdrop of Δh (s):	30
k (cm/sec):	2.15E-04		

Sample 5			
Area of burette (cm^2):	1.695	Initial height of water (cm):	96.51
Length of soil column (cm):	10.32	Final height of water (cm):	94.78
Area of soil column (cm2):	44.867	Time required to get headdrop of Δh (s):	30
k (cm/sec):	2.35E-04		

Sample 6			
Area of burette (cm^2):	1.695	Initial height of water (cm):	94.78
Length of soil column (cm):	10.32	Final height of water (cm):	92.85
Area of soil column (cm2):	44.867	Time required to get headdrop of Δh (s):	32
k (cm/sec):	2.51E-04		

Figure 91: Biosolid ash permeability

APPENDIX J: LOSS OF IGNITION



DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Loss of Ignition Test

Project: WSACC Rocky River Waste Water Treatment Plant		
Sample Description: Wastewater biosolid ash		Date: 6/15/2014
Dry Density (pcf): 48.1	Method Used: N/A	Tested By: Bill Boivin

Sample P1

Mass of container (g):	11.62	Mass of container and ash sample (g):	131.99
Mass of carbon (g):	3.84	Mass of oven dried container and ash	128.15
Mass of dried ash (g):	116.53	Loss on ignition:	3.30%

Sample P2

Mass of container (g):	11.57	Mass of container and ash sample (g):	94.19
Mass of carbon (g):	3.34	Mass of oven dried container and ash	90.85
Mass of dried ash (g):	79.28	Loss on ignition:	4.21%

Sample P3

Mass of container (g):	11.61	Mass of container and ash sample (g):	124.32
Mass of carbon (g):	4.87	Mass of oven dried container and ash	119.45
Mass of dried ash (g):	107.84	Loss on ignition:	4.52%

Sample P4

Mass of container (g):	11.60	Mass of container and ash sample (g):	125.91
Mass of carbon (g):	4.86	Mass of oven dried container and ash	121.05
Mass of dried ash (g):	109.45	Loss on ignition:	4.44%

Sample P5

Mass of container (g):	1.27	Mass of container and ash sample (g):	99.13
Mass of carbon (g):	3.94	Mass of oven dried container and ash	95.19
Mass of dried ash (g):	93.92	Loss on ignition:	4.20%

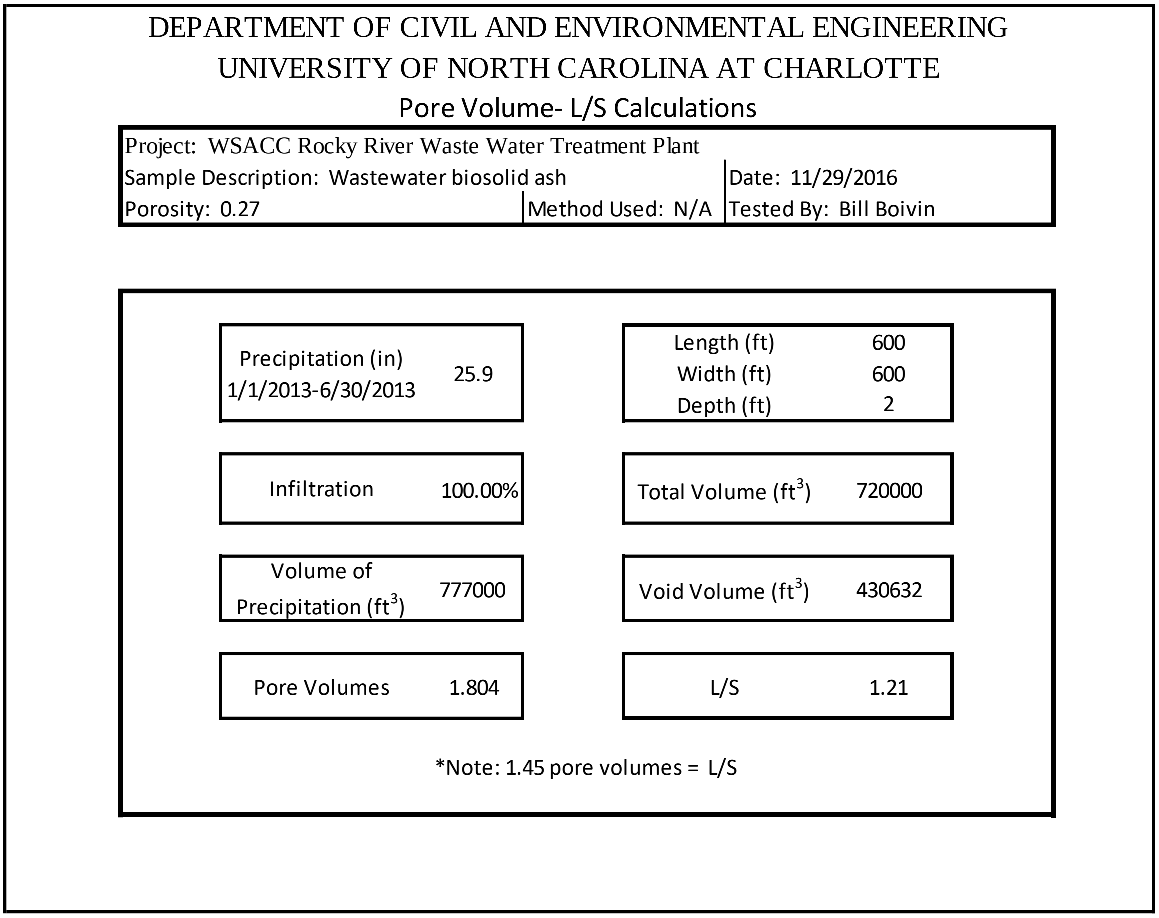
Sample P6

Mass of container (g):	1.27	Mass of container and ash sample (g):	139.64
Mass of carbon (g):	6.1	Mass of oven dried container and ash	133.54
Mass of dried ash (g):	132.27	Loss on ignition:	4.61%

Average Loss on Ignition:	4.21%	Standard deviation:	0.44%

Figure 92: Loss on ignition

APPENDIX K: CALCULATIONS



DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
Pore Volume- L/S Calculations

Project: WSACC Rocky River Waste Water Treatment Plant
Sample Description: Wastewater biosolid ash
Date: 11/29/2016
Porosity: 0.27
Method Used: N/A
Tested By: Bill Boivin

Precipitation (in) 1/1/2013-6/30/2013	25.9	Length (ft) Width (ft) Depth (ft)	600 600 2
Infiltration	100.00%	Total Volume (ft^3)	720000
Volume of Precipitation (ft^3)	777000	Void Volume (ft^3)	430632
Pore Volumes	1.804	L/S	1.21

*Note: 1.45 pore volumes = L/S

Figure 93: Pore volume - L/S calculations