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# Alkalinity Enhanced Mass Reduction of Uranium Contaminated Sediment

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# ALKALINITY ENHANCED MASS REDUCTION OF URANIUM CONTAMINATED SEDIMENT

by

Cullen Meurer

A Thesis Submitted in  
Partial Fulfillment of the  
Requirements for the Degree of

Master of Science  
in Geosciences

at

The University of Wisconsin-Milwaukee

May 2022

# ABSTRACT

## ALKALINITY ENHANCED MASS REDUCTION OF URANIUM CONTAMINATED SEDIMENT

by

Cullen Meurer

The University of Wisconsin-Milwaukee, 2022  
Under the Supervision of Dr. Charles Paradis

Uranium is a toxic and radioactive metal that is naturally occurring in the Earth's crust. The uranium mining boom of the 1950's produced many contaminated aquifers throughout the United States. Monitoring of groundwater data suggests that uranium concentrations may take 100's of years to naturally attenuate to below the maximum contamination limit. This project examines a potential and novel remediation technique of groundwater contaminated with uranium through alkalinity enhanced desorption from the solid phase. Alkalinity enhances the desorption of uranium by complexing uranyl ( $\text{UO}_2^{2+}$ ) with Ca and  $\text{CO}_3$  which allows for further desorption. Since remediation is time consuming and expensive, it is vital to understand the mechanisms of uranium transport to enhance the effectiveness of remediation strategies.

This study conducted six 1-dimensional flow through experiments using sediment from a contaminated aquifer near Riverton, Wyoming. The columns tests were completed to address four scientific questions: 1) What effect does increasing alkalinity have on the mass transport of uranium? 2) Does increasing alkalinity decrease the flushing time of uranium? 3) What is the dominant mechanism of uranium mobility at the study site 4) Is increasing alkalinity to enhance uranium mobility applicable at other contaminated aquifers?

Results indicated that: 1) There is an increase in uranium mass flushed when alkalinity is added to the influent. 2) Increasing alkalinity decreased the flushing time at the field scale but the decrease in flushing time should be viewed as an upper bound. 3) The dominant mechanism of uranium mobility at the site is desorption but where Ca- $\text{SO}_4$  minerals are present, dissolution dominates uranium mobility. 4) Under certain conditions alkalinity enhanced desorption is a viable remediation approach.

Laboratory based column experiments have shown that alkalinity enhanced flushing could be a promising remediation approach for contaminated aquifers. Field scale flushing is relatively untested and contains large limitations. Future field scale experiments and geochemical modeling need to be completed before alkalinity enhanced flushing of uranium can be considered a viable remediation approach.

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## Introduction

Uranium is naturally occurring in the Earth's crust as a potentially toxic metal. Uranium can contribute to low levels of background radiation in the environment (EPA, 2022). The 1950's brought along a uranium mining boom that greatly increased the number of uranium mining and milling sites throughout the United States. This boom contaminated groundwater aquifers in and around these now decommissioned uranium mining and milling sites (Mudd et al. 2014). These sites are actively managed by the United States Department of Energy (DOE) as part of the Legacy Management program. The main goal of this project is to examine the feasibility and applicability of a relatively novel uranium remediation approach. Since remediation is time consuming and expensive, it is vital to understand the dominant mechanism of uranium mobility to enhance the effectiveness of remediation strategies.

Uranium transport is generally dominated by adsorption and desorption (Dam et al. 2015) but other transport mechanisms can also play a large role in uranium mobility through groundwater. Mineral dissolution can release contaminants that are adsorbed or complexed to minerals (Laxen et al. 1972). When mineral dissolution occurs, bound uranium can become mobile in the groundwater. The precipitation and dissolution of these minerals may play an even larger role in the mobility of uranium at mill tailing sites due to the possible presence of co-precipitated uranium in minerals that are formed as mill tailing byproducts (Lin et al. 2017). Changes in groundwater geochemistry that produce under-saturation with respect to these minerals, may then mobilize co-precipitated uranium through mineral dissolution. The dissolution of these uranium-rich salts can be a continuous source of uranium contamination in groundwater (DOE, 2014).

The correct approach to model uranium mobility and specifically adsorption in reactive transport models is still open for debate. Most assessments conducted by the United States government utilized a linear equilibrium distribution co-efficient, or  $K_d$ , approach (EPA, 1999). However, temporal, and spatial variability of groundwater chemistry introduces uncertainty in uranium retardation when using a  $K_d$  approach (Read, 1998). Another note is that the partial pressure of carbon dioxide can play a large role in the  $K_d$  values of U(VI) (Curtis et al. 2004). In lab experiments, where the system is exposed and in equilibrium with the atmosphere,  $K_d$  values can be ten-times higher than in natural groundwater environments (Fox et al 2012).

Uranium mobility is also significantly enhanced by the addition of highly alkaline water. As carbonate concentrations increase in the water, uranyl, or  $UO_2^{2+}$ , in solution complexes to form carbonate-uranyl species (Guillaumont et al. 2003). Complexed carbonate-uranyl species are unlikely to adsorb to minerals (Geipel et al. 1998, Davis et al. 1998). As the concentration of uranyl decreases, uranium continues to desorb until a new equilibrium is reached. Therefore, increasing the alkalinity in uranium-contaminated groundwater may substantially mobilize uranium and thus contribute to enhanced natural attenuation via physically flushing of uranium mass. In addition, when calcium concentrations in the columns are elevated, calcium-carbonate-uranyl complexes form instead of carbonate-uranyl species (Dong et al. 2006). Calcium-carbonate-uranyl complexes have larger pKa values than carbonate-uranyl complexes (Dong et al. 2006) and therefore are bound together better. This increase in bond strength leads to even less uranyl adsorption (Bernhard et al. 2001).

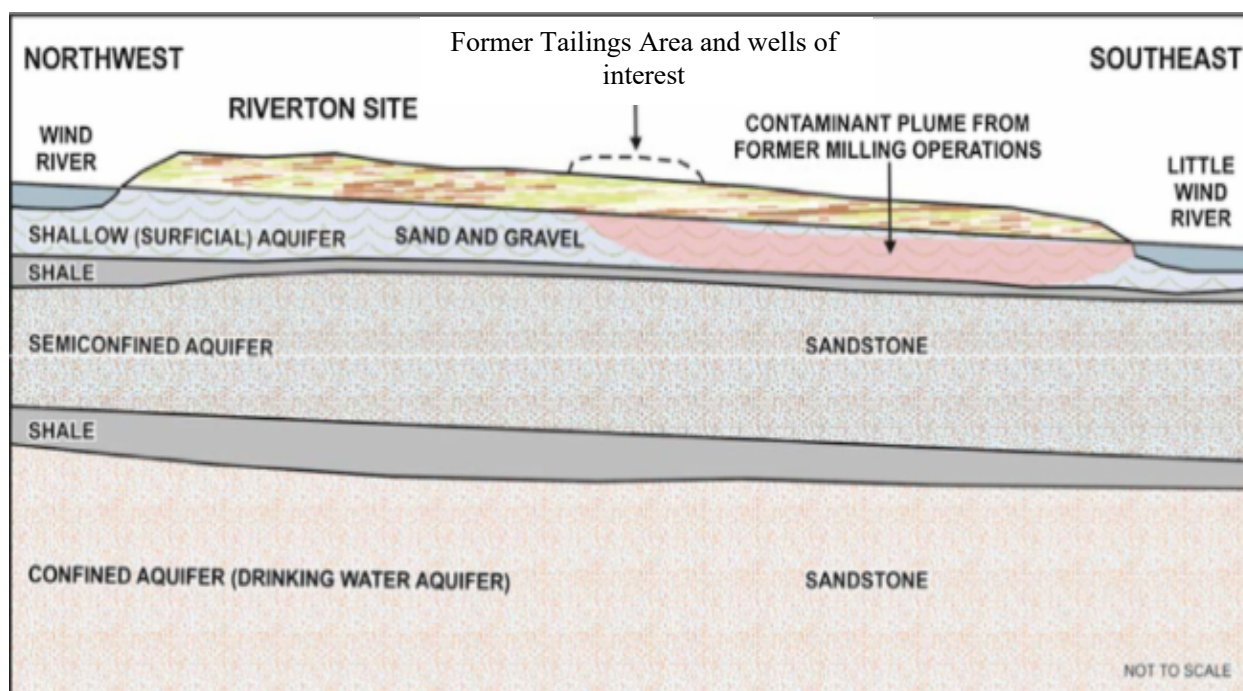
The DOE's Legacy Management manages over 100 sites throughout the United States, many of which contain uranium contaminated groundwater. The Riverton, Wyoming site is a

former uranium ore processing mill that was in operation from the late 1950's to early 1960's. The milling operations created uranium mill tailings (Fig. 1). In 1988 the contaminated material was removed from the site and surface remediation was completed in 1989 (DOE, 2021). Groundwater contamination of an unconfined surficial aquifer is present in much of the site with concentrations of uranium measuring 150 times greater than the maximum concentration limit, 44 ppb (Fig. 1). The transport of the uranium plume is generally from the former tailings area, or FTA, to downgradient and towards the Little Wind River (Fig. 1). The uranium plume largely resides in the alluvial aquifer from approximately 12 to 17 feet below ground surface (bgs) (Fig. 1).

Predictions from a conceptual site model (CSM) that was completed in the 1990's (DOE. 1998) stated that the natural attenuation of uranium to below the maximum contamination limit (MCL) would be reached within 100 years. (Fig. 2). However, a recent flooding event mobilized uranium that resulted in a dramatic spike in groundwater concentrations, indicating that the 1990's CSM needed to be refined (Dam et al. 2015) (Fig. 2). The original CSM assumed that once the tailings source was removed from the site, advection, dispersion, and sorption would be the dominant forces migrating the uranium plume. The plume was predicted to continue to migrate away from the source tailings (FTA) and to flush into the Little Wind River down gradient (Figs. 1 and 2) with sorption as the dominant mechanism controlling uranium mobility. In fact, the initial decade of groundwater monitoring, from 1995 to 2005, largely corroborated the CSM (Fig. 2) (DOE. 2008).

However, in June of 2010, the coupling of intense regional rainfall and rapid snowmelt in the Wind River Range, created a 75-year flooding event. The infiltration of the floodwater raised the water table and mobilized uranium present in the unsaturated zone as well as uranium

throughout the aquifer (Dam et al. 2015). The DOE recorded an immediate spike in uranium concentrations where flooding occurred (Fig. 2). Uranium concentrations increased over 300% in well 707 after the 2010 flood compared to the predicted decline of uranium concentrations from the original CSM (Fig. 2). It is important to note that large amounts of evaporite minerals that contain coprecipitated uranium have been found downgradient of the FTA near the Little Wind River in the vadose zone (Fig. 1) (Dam et al. 2015). As the water table rises or precipitation infiltrates into the aquifer, evaporite minerals dissolve along with the coprecipitated uranium. The FTA also contains isolated evaporite lenses in the alluvial aquifer, but desorption is still considered to be the primary mechanism of uranium mobility at the FTA (Dam et al. 2015).



**Fig. 1** Site conceptual model by Dam et al. (2015) showing original uranium source from former tailing pile and uranium plume migration downgradient towards Little Wind River.

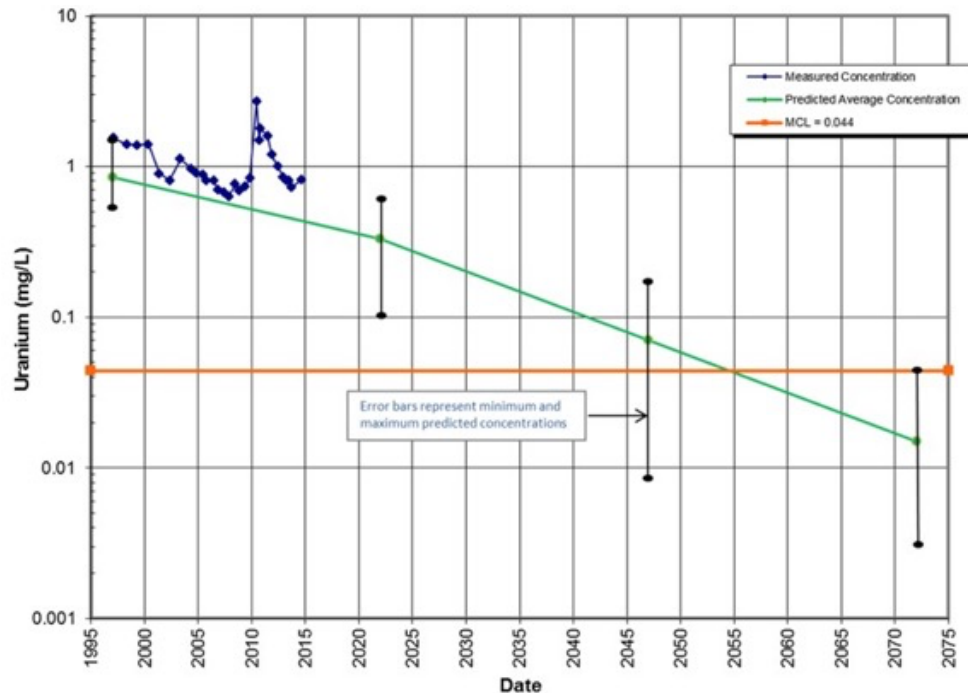
The 2010 flood and observations made in multiple site reports afterwards (Dam et al. 2015) (DOE. 2016) revealed that the original site CSM did not accurately depict uranium mobility at the Riverton site and needs to be revised. The new CSM accounted for multiple



deficiencies of the original CSM and included a continuous source of solid phase uranium in the alluvial aquifer below the FTA. However, due to the revision of the initial CSM, the current remediation strategy, which is attenuation to below the MCL via natural groundwater flushing in around 100 years, needs to be re-evaluated.

The current site remediation plan includes natural groundwater flushing as well as institutional controls. Controls include the following: 1) an alternate drinking water system provides potable water to residents within an institutional control boundary, 2) Legacy Management collects annual ground and surface water samples to monitor contamination in the site, and 3) groundwater flushing of the contaminated alluvial aquifer. Groundwater flushing occurs naturally as upgradient water that was not contaminated flows through the site and mobilizes the contaminate downgradient.

The natural flushing strategy is viable if five of the following parameters can be continuously met: 1) the source can be completely decoupled from the groundwater, 2) advective, dispersive and geochemical processes will be active enough to reduce or dilute contaminant, 3) the groundwater source is not a public drinking water source, 4) monitoring and enforcement of institutional controls will be in place for the necessary time and 5) adequate site characterization has been completed and approved (Metzler et al. 2002).



**Fig. 2** Uranium data from well 707 versus model simulations from Dam et al. (2015)

To decrease the time required to remediate the uranium contaminated aquifer at the Riverton site, other uranium remediation strategies are being considered. An alternative approach to natural flushing of uranium may involve injecting alkalinity into the aquifer to enhance the mobility of uranium from the sediments and decrease the flushing time. As uranium-contaminated aquifers become better understood, many CSM's are being rethought. Contaminants are simply not naturally attenuating to below MCL in the timeframe that was originally predicted from the CSM's, thus natural flushing as a remediation approach is being reconsidered. Utilizing increased alkalinity along with natural flushing may in fact lower the time required for uranium-contaminated aquifers to flush below the MCL.

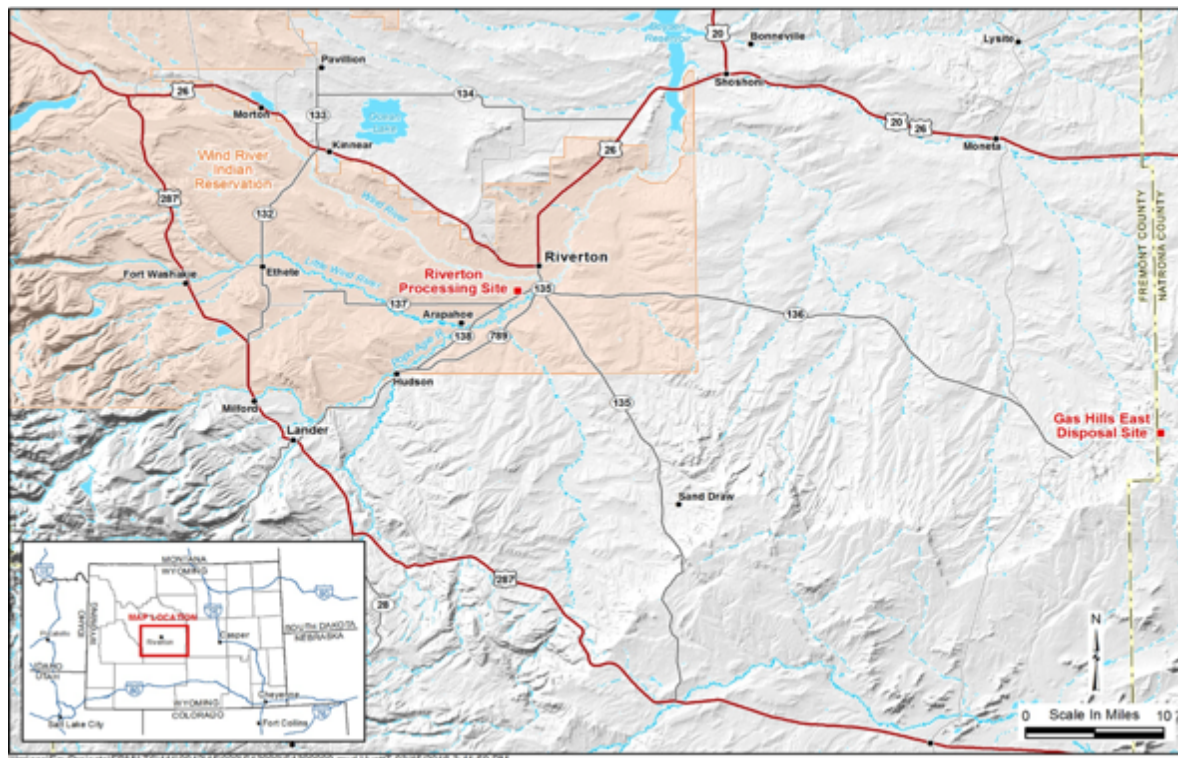
### *Scientific questions*

This research project addresses challenges that Dam et al., (2015) summarized by answering the following questions: 1) What effect does increasing alkalinity have on the mass

transport of uranium? 2) Does increasing alkalinity decrease the clean-up time of uranium at the FTA? 3) What is the dominant mechanism of uranium mobility at the FTA 4) Can alkalinity enhanced flushing be applied to other contaminated aquifers? Answering these questions will help characterize the uranium mobility in the FTA and evaluate the feasibility of alkalinity enhanced uranium mobility.

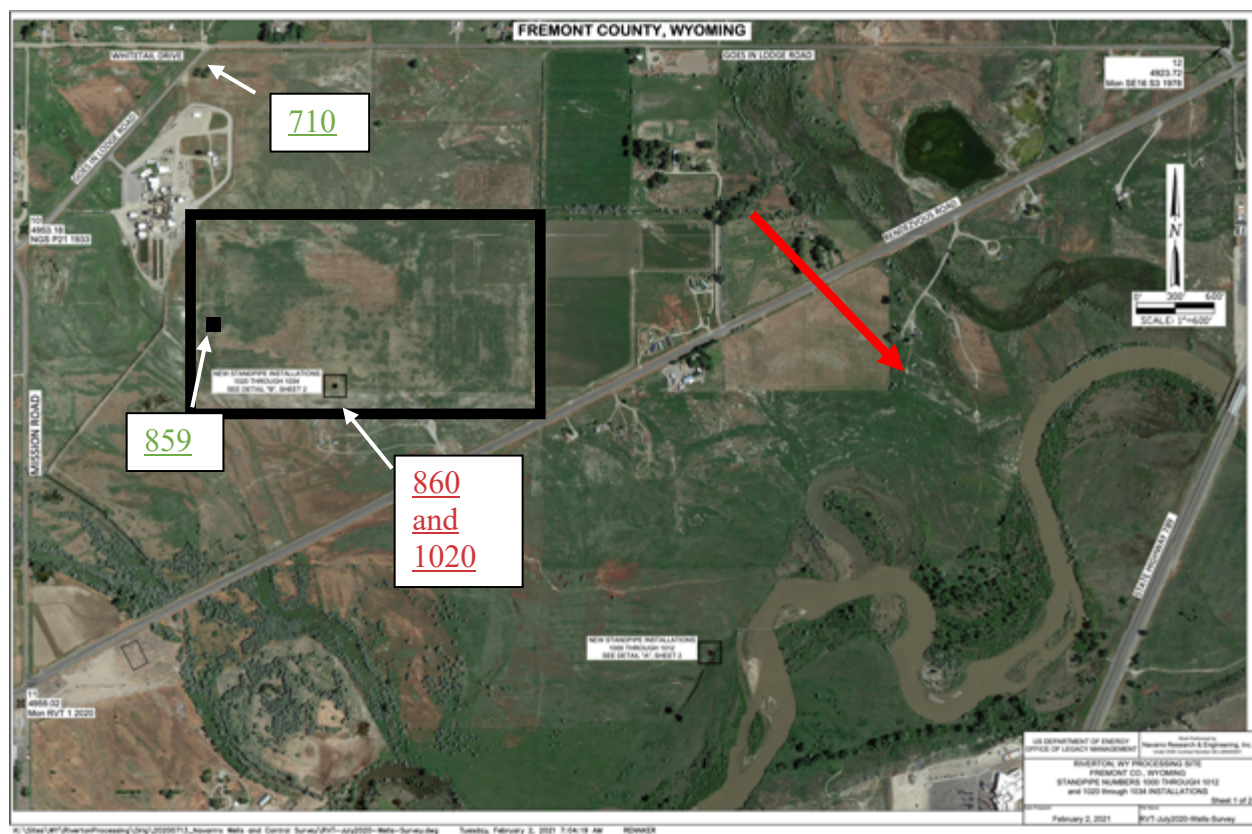
## Site Background and Location

The Department of Energy office of Legacy Management, Riverton site is in Fremont County, a little over 2 miles southwest of Riverton, Wyoming (Fig. 3). The Riverton site is within the boundaries of the Wind River Indian Reservation (Northern Arapahoe and Eastern Shoshone). The land is now owned by Chemtrade Refinery Services. Chemtrade runs an active sulphuric acid plant adjacent to the Riverton site shown in the top left corner in Fig 4. The site is the location of a former uranium and vanadium ore processing mill that was operational from 1958 to 1963. The mill processed uranium rich ore from the Gas Hills Wyoming mining district roughly 50 miles to the east from the site as shown in Figure 3. In the five years that the mill was operational, 816,470 tons of uranium ore was processed. Past milling operations produced radioactive mill tailings that contaminated the underlying soil with uranium.



**FIG 3** - Overview map of the Riverton Study Area. From the LM Persistence Secondary Contaminant Sources Project Tracer Testing Field Work plan.

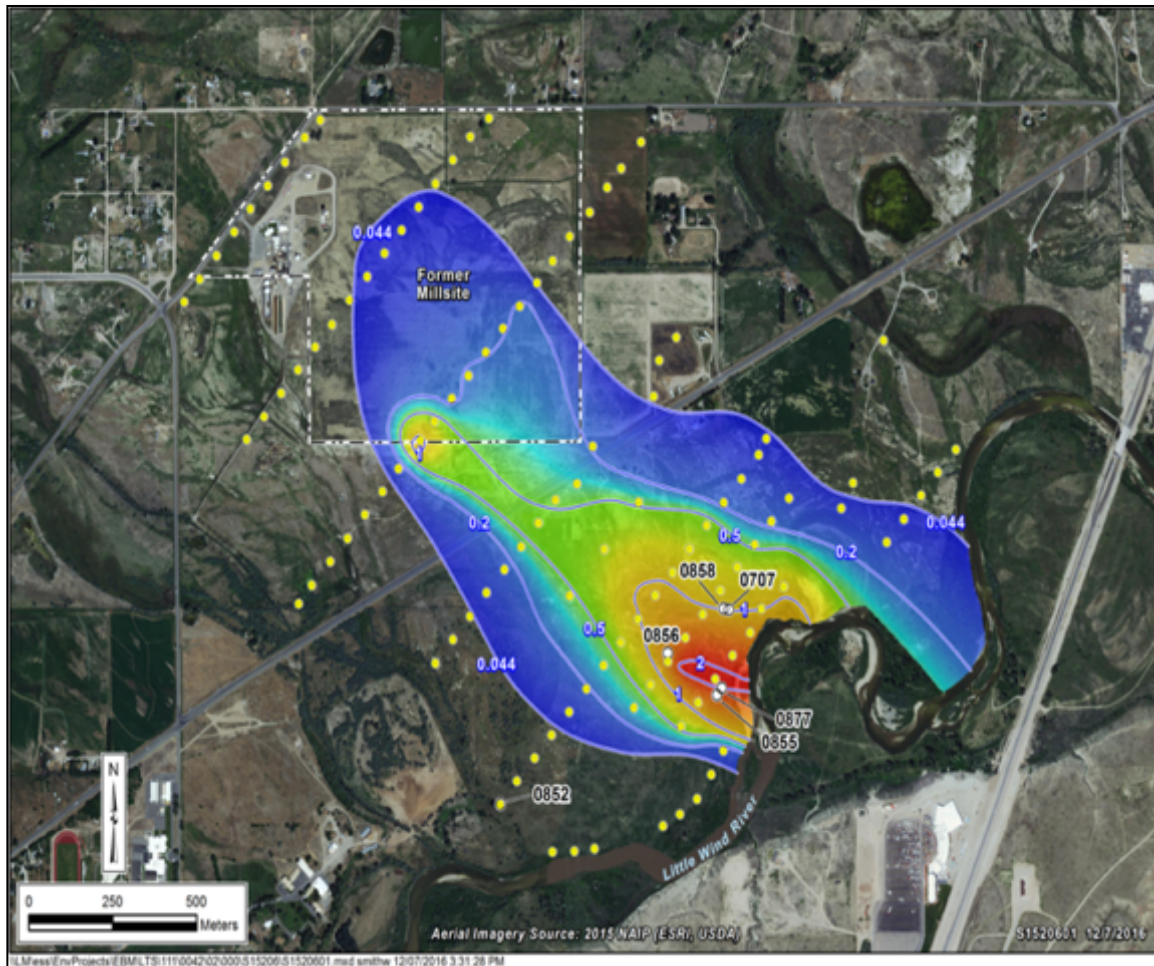
The mill tailings were stored in an area now called the Former Tailing Area (FTA) denoted by the rectangle in figure 4. A tailings pile covered around 72 acres of the 140-acre site. The tailings and associated debris were the primary and original source of contamination at the Riverton site (DOE, 2016). In 1988 and 1989 the tailings piles were excavated to an average depth of four feet bgs. The surface remediation resulted in the removal of 1.8 million cubic yards of tailings, associated material, and contaminated soil from the site. The excavated material was transported and encapsulated at the Gas Hills East Disposal Site 45 miles away shown in figure 3.



**Fig 4 -** Map of the Riverton site. New well galleries are shown. Adapted from DOE office of Legacy Management



## Hydrogeology



**Fig 5** -The Riverton DOE LM site. The uranium plume is overlaid onto the arial imagery of the site. Adapted from DOE – Legacy Management

The Riverton site is located on an alluvial terrace that sits between the Wind River and the Little Wind River. Both rivers are fed from snowmelt and precipitation from the Wind River Range 25 miles to the East of the site in Figure 3. Groundwater is located in three aquifers beneath the site: 1) An upper surficial unconfined alluvial aquifer, 2) a middle semiconfined aquifer, and 3) a deeper confined aquifer (DOE, 1998). The alluvial aquifer is roughly 15 – 20 feet thick throughout the site.

The surficial aquifer consists of mainly sands and gravel with lesser amounts of clay sized to cobble sized clasts (Dam, 2015). Depth to groundwater is typically 7 – 10 feet bgs, with some seasonal variation. Groundwater flow is typically to the southeast from the Wind River to the Little Wind River, denoted by the red arrow (Fig. 4). The middle semiconfined aquifer consists of a 15- to 30-foot-thick sandstone layer from the Eocene Wind River Formation. The middle aquifer is separated from the top surficial aquifer by a discontinuous 5-to-10-foot-thick layer of Wind River shale (Dam, 2015). The deeper confined aquifer is composed of shales and sandstones from the upper units of the Wind River formation (DOE, 2016). Only groundwater in the surficial alluvial aquifer has been contaminated by ore processing operations at the site (Dam, 2015).

The location of the site, on an alluvial terrace between the Wind River and the Little Wind River, means that site conditions are influenced by the periodic flooding of these rivers (DOE, 2016). These influences have included the formation of an oxbow lake off the Little Wind River in 1995 and post flooding spikes in groundwater contaminant concentrations. Contaminant distributions at the site are likely affected when either the Wind River or the Little Wind River exceeds 8,000 cubic feet per second (cfs) (DOE, 2016).

Shallow groundwater beneath the FTA and downgradient of the site was contaminated because of the uranium-processing activities in the 1950's and 1960's. The plumes center of mass has migrated downgradient of the initial contaminant source below the FTA near the Little Wind River (Fig. 5).

A persistent secondary contaminant source in the FTA is located near wells 860 and 1020 (Fig 4) and produces the resulting uranium plume (Fig. 5). Contaminants of potential concern in the ground water at the Riverton site are molybdenum, manganese, sulfate, and uranium. These contaminants were selected because the concentrations were above the maximum contamination limit (MCL) and pose potential human and environmental health risks. The uranium MCL at the Riverton site is 30 picocuries per Liter (DOE, 2016). To provide consistency with historical and new data the MCL has been converted to 0.044 mg/L or 44 parts per billion (ppb).

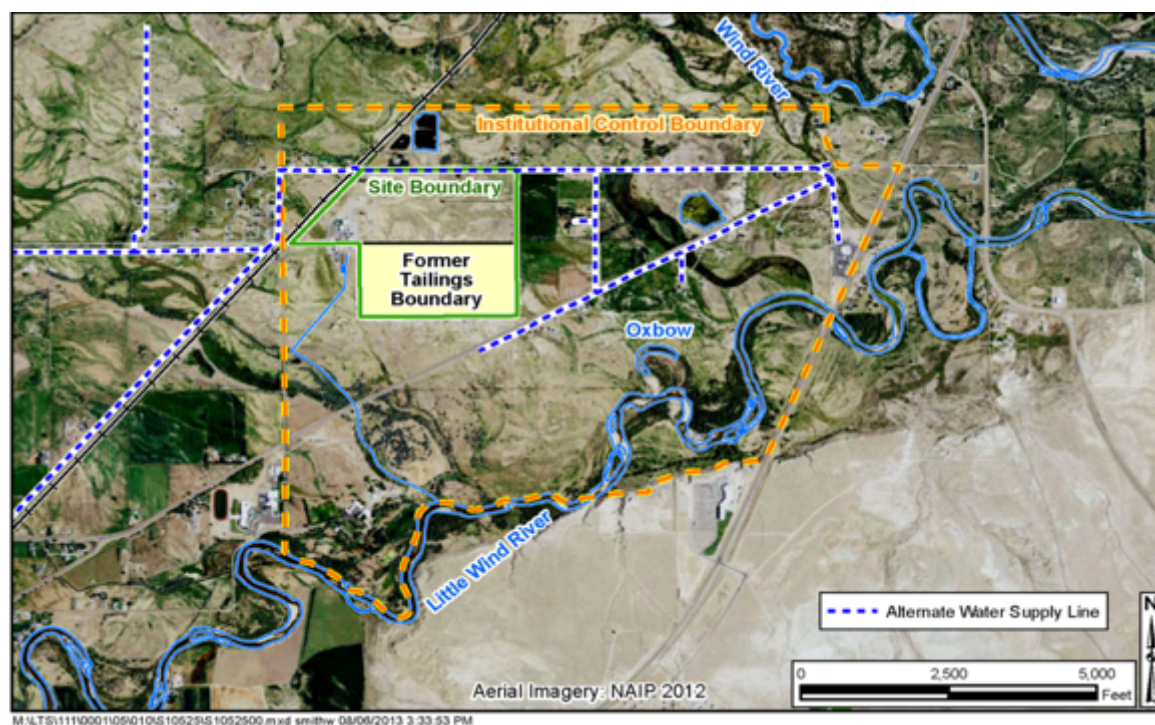
**Table 1** - Concentrations of contaminants of concern and their respective MCL at well 859 and well 860 (DOE, 2016).

Location	Uranium Concentration (mg/L)	Uranium MCL (mg/L)	Molybdenum Concentration (mg/L)	Molybdenum MCL (mg/L)
FTA – Wells 859 and 860	0.58 (0.08 - 0.91)	0.044	0.25 (0.20 - 0.29)	0.10



## Current Site Compliance Strategy and Institutional Controls

The groundwater compliance strategy at the Riverton site since the 1990's is 100-year natural flushing in conjunction with institutional controls and monitoring (DOE, 2018). Past groundwater modeling predicted that site wide levels of uranium in the contaminated surficial aquifer would flush to levels below the MCL with in a 100-year time frame as allowed by the Environmental Protection Agencies Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings (40 CFR Part 192).



**Fig. 6** - Institutional Control Boundary, Site Boundary, Former Tailings Boundary. (DOE, 2018)

Institutional controls (ICs) are required at many contaminated sites to protect human health, the environment and prevent any exposure to contaminated groundwater during natural flushing. An IC boundary was established around the site, delineating the area that requires protection (Fig. 6). Institutional controls at the Riverton site include: 1) a water line that provides a supply of

potable water to residents inside the IC, 2) warning signs around the oxbow lake, 3) ordinance on the installation of new wells inside of the IC boundary, 4) notification of existing groundwater contaminant to relevant parties, and 5) ongoing groundwater monitoring. (DOE, 2016)

## Methodology

Six 1-dimensional continuous flow through columns packed with sediment from the Riverton site were completed (Table 2). Two columns switched influent chemistry four times while the other four columns switched chemistry influent once, during the runtime of the column experiments.

Column	Sediment/Water	Influent A/B
Phase 1 Column 1 (P1C1)	Well 860/Well 710	No Alk/ Yes Alk
Phase 1 Column 2 (P1C2)	Well 860/Well 710	Yes Alk/No Alk
Phase 1 Column 3 (P1C3)	Well 1020/Well 710	No Alk/ Yes Alk
Phase 1 Column 4 (P1C4)	Well 1020/Well 710	Yes Alk/No Alk
Column	Sediment/Water	Influent A/B/C/D/E
Phase 2 Column 1 (P2C1)	Well 859/Synthetic Well	↑SO <sub>4</sub> /↓SO <sub>4</sub> /↓Alk/Alk/↑Alk
Phase 2 Column 2 (P2C2)	Well 860/Synthetic Well	↑SO <sub>4</sub> /↓SO <sub>4</sub> /↓Alk/Alk/↑Alk

**Table 2** - Experimental design of the six 1-D flow through columns. Alk = Alkalinity added to influent

### *Core Sampling and Collection*

Sediment cores were collected from the FTA at borehole 859, 860 and 1020 (Fig. 4). All wells were surveyed by the Legacy Management (LM) survey group. Horizontal coordinates and top of casing and ground surface elevations were noted. A total station was utilized to survey each location in the project. All wells were drilled using a rotasonic Geoprobe rig. The drilling method allowed for the collection of high-quality core samples in unconsolidated sediment (DOE, 2016) where small drilling diameter and gravelly sediment can make retrieving cores difficult. Care was taken to not penetrate the confining layer between the alluvial aquifer

and the semi-confined aquifer below. An eight-inch bit drilled through the surficial alluvial. The wells were all constructed with 5-foot long, 1.5-inch prepacked PVC filter screens with a 0.01-in slot size and end caps, 20 pounds of 20-40 silica sand wrapped with stainless steel mesh, and 50 pounds of No. 16 granular bentonite (DOE, 2018). Approximate well completion depths and screen intervals are included in the well bore logs in Appendix A. The aquifer formation collapsed around the 5-foot prepack screen, silica sand was added and any voids remaining were filled with bentonite pellets to the surface. Three-foot stickups were added to each well.

Well 859 (Fig. 4) is directly downgradient of the Chemtrade evaporation pond at coordinates, 848885.03 ft N and 590039.45 ft. E. The well was drilled in 2015 in an effort to increase the monitoring of uranium contamination in the surficial aquifer after the recent flooding events. The boring log, well construction and lithologic description are shown in Appendix A 1. Depth to the bottom (dtb) of the well was 12.50 ft bgs in the semi-confining layer below the contaminated aquifer. The depth to water (dtw) was 7.0 feet bgs. Sediment was taken from 8.4-10 feet bgs. The sediment is roughly 50% gravel with clasts up to 4.0 inches. The sand matrix is medium grained and grayish brown (DOE, 2018). Sediment has a petrochemical odor that may be associated with a thin clayey lens in the gravel as well as possible calcium sulfate minerals. Well 859 on the FTA is in an area of elevated sulfate concentrations (DOE, 2018).

Well 860 (Fig. 4) is in the south-central part of the FTA at coordinates, 848283.00 ft N and 590879.17 ft E. Well 860 is located 0.20 miles down-gradient from well 859. The well was drilled at the same time as well 859 using the same methods. The boring log, well construction and lithologic description are shown in appendix A 2. The dtb and dtw are 18 ft and 10 ft respectively. The column sediment comes from 12.5 to 17 ft. Well 860 column sediment is classified as a sandy gravel and is 50-60% gravel with clasts, the sand matrix is fine to medium

grained and grayish brown. Very coarse cobbles, up to 6.0 inches in diameter, are present and the sand matrix becomes dominantly gray as depth increases. Well 860 on the FTA is located near the remaining uranium source area.

Well 1020 (Fig. 4) is located 50 feet north west of well 860. Well 1020 was drilled at the start of the 2020 summer field season. The boring log, well construction and lithologic description are shown in appendix A 3. The dtb and dtw are 17.0 ft and 7.0 ft bgs respectively. The sediment used in the column is from 15.0 to 16.5 ft bgs. Well 1020 column sediment is classified as a gravel and sand. The sediment is well graded, and the sand is fine to medium grained. There are trace roots, large clasts up to 2.0 inches make up 50% of the sediment is rounded to subangular and grayish brown.

The water used as influent in the P1 column experiments was collected from well 710 (Fig. 4). The well was utilized as a background and is located upgradient of the FTA so it does not have any contamination from the processing plant or mill tailings. Water was collected using a peristaltic field pump and stored in airtight containers at 4° C. Water quality parameters for well 710 are provided in Table 3.

**Table 3** – Well 710, background water used as the column influent, general water chemistry.

Chemistry	Concentration	Units
pH	7.77	
Alkalinity	234	mg/L as CaCO <sub>3</sub>
Uranium	7.4	ppb
Sulfate	170	ppm
Calcium	110	ppm
Magnesium	27	ppm
Sodium	76	ppm
Potassium	3	ppm

### *Column preparation*

Two columns were run simultaneously in November of 2019 and denoted by phase 2 (P2). Four columns were run simultaneously in July of 2020 and are denoted by phase 1 (P1). Laboratory notes with exact time frames, steps, flow rates and other information is available in Appendix C. The P1 and P2 columns were both completed using very similar methodology; the sediment and influent changes were the only differences between the phases. All column experiments were completed at the Legacy Management Science Laboratory in Grand Junction, Colorado. All columns were constructed out of clear plastic and were 6 inches long and 2 inches in diameter with a total volume of 0.31 L. Sediment was first sieved to remove large clasts and gravel and then mixed to homogenize and break up any remaining pieces. Sediment was then dry packed incrementally into the columns. A round dampening tool was utilized during packing to simulate field conditions. A ½ inch layer of sediment was added to the column one at a time. The dampening tool was placed on top of the column and allowed to slide down the column using its own weight to pack the column. Column weights were taken before and after packing to calculate soil volume and soil density. Based on dry weight measurements and the volumes of the columns, porosities for the columns were calculated to be between 0.16 and 0.22. Filters were placed in specially constructed sleeves above and below the column to reduce dead space and not reduce the volume of sediment in the columns.

Columns were set up to low-flow, individual peristaltic pumps, and auto samplers to allow for continuous running and sampling of columns until they were completed. Small diameter tubing and column influent and effluent hardware were utilized to decrease dead space in the system. Influent solutions were delivered to the columns at around 0.15 ml/minute to simulate the FTA groundwater velocity of 1 ft/day. The soil volume and density were used to

calculate the void space or pore volume (PV) of each column. The auto sampler was programmed to collect one pore volume of effluent in 25 mL over the course of 3.5 hours. Pore volumes, residence times, and flow velocities for each column experiment are given in table 4.

**Table 4** – Physical properties of each column experiment.

Column	Pore Volumes	Flow Velocities	Residence Time
P1C1	83.16 mL	0.147 ml/min	566 min
P1C2	79.8 mL	0.15 ml/min	532 min
P1C3	95.93 mL	0.155 ml/min	619 min
P1C4	73.5 mL	0.15 mL/min	490 min
P2C1	76 mL	0.144 mL/min	528 min
P2C2	129 mL	0.15mL/min	860 min

Influent water in phase 1 was collected from well 710 and transported to the Grand Junction Science Lab (Table 2). Influent water in phase 2 was created to simulate well 710 background water (Table 2). Synthetic water was prepared by matching the concentrations of major ions with that of well 710 groundwater. General ionic constituents for the 710 water are shown in Table 3, while Table 5 shows changes made to the influent chemistry of the 710 water for the P1 and P2 experiments.

**Table 5** – Influent chemistry for each column.

Influent	Alkalinity mg/L CaCO <sub>3</sub>	pH	Calcium (ppb)	Sulfate (ppm)	Sodium (ppm)	Uranium (ppb)
Phase 1 BA	234	7.77	109.6	170	75.69	7.4
Phase 1 AA	1754	8.05	67.97	170	697	5.9
Phase 2 A	165	7.46	355.6	960	78.19	.2
Phase 2 B	94	8.14	74.24	170	42.9	.2
Phase 2 C	918	7.67	41.16	170	473.2	.2
Phase 2 D	2512	7.96	68.95	134	1229	.4
Phase 2 E	5014	8.24	62.67	141	2315	.4

### *Column Operation*

Phase 1 columns utilized two different influent chemistries: (A) well 710 water with background alkalinity (BA) and (B) well 710 water with added alkalinity (AA) using NaHCO<sub>3</sub>. Phase 1 influent waters were prepared by adding NaHCO<sub>3</sub> to the water to produce 2,500 mg/L as CaCO<sub>3</sub>. In two of the phase 1 columns, P1C2 and P1C4, the alkalinity-enriched water was added initially followed by the 710 water with background alkalinity after ~12 pore volumes. In the other two columns, P1C1 and P1C3, well 710 water was used as influent first, while alkalinity-enriched water was added to the influent halfway through the experiment (~12 pore volumes). Phase 2 columns utilized five different influents: (A) Synthetic 710 water with high sulfate concentrations, (B) synthetic 710 water, (C) synthetic 710 water with 1000 mg/L CaCO<sub>3</sub> of added alkalinity (LAA), (D) synthetic 710 water with 2,500 mg/L CaCO<sub>3</sub> of added alkalinity (AA), and (E) synthetic 710 water with 5,000 mg/L CaCO<sub>3</sub> of added alkalinity (HAA). The phase 2 high sulfate influent waters were bubbled with CO<sub>2</sub> to get the pH to be within field



conditions of 7.6. The columns were allowed to equilibrate with the influent solution for 24 hours before introducing flow conditions.

Influent solutions were delivered to the columns at a rate of 0.15 ml/minute (Table 4). Phase 1 Columns were fed Influent 1 water (Phase 1 BA in Table 5) for 12 – 13 pore volumes (roughly 4 days) after which the influent was switched to Influent 2 water (Phase 1 AA in Table 5) for 9 – 16 pore volumes (Table 2). Phase 2 Columns were fed influent in the following sequence 1) Influent 1 water for 5 – 7 pore volumes (roughly 2.5 days) 2) Influent 2 water for 5 – 6 pore volumes, 3) Influent 3 water for 6 pore volumes, 4) Influent 4 for 5 - 6 pore volumes, and 5) Influent 5 for 4 – 5 pore volumes.

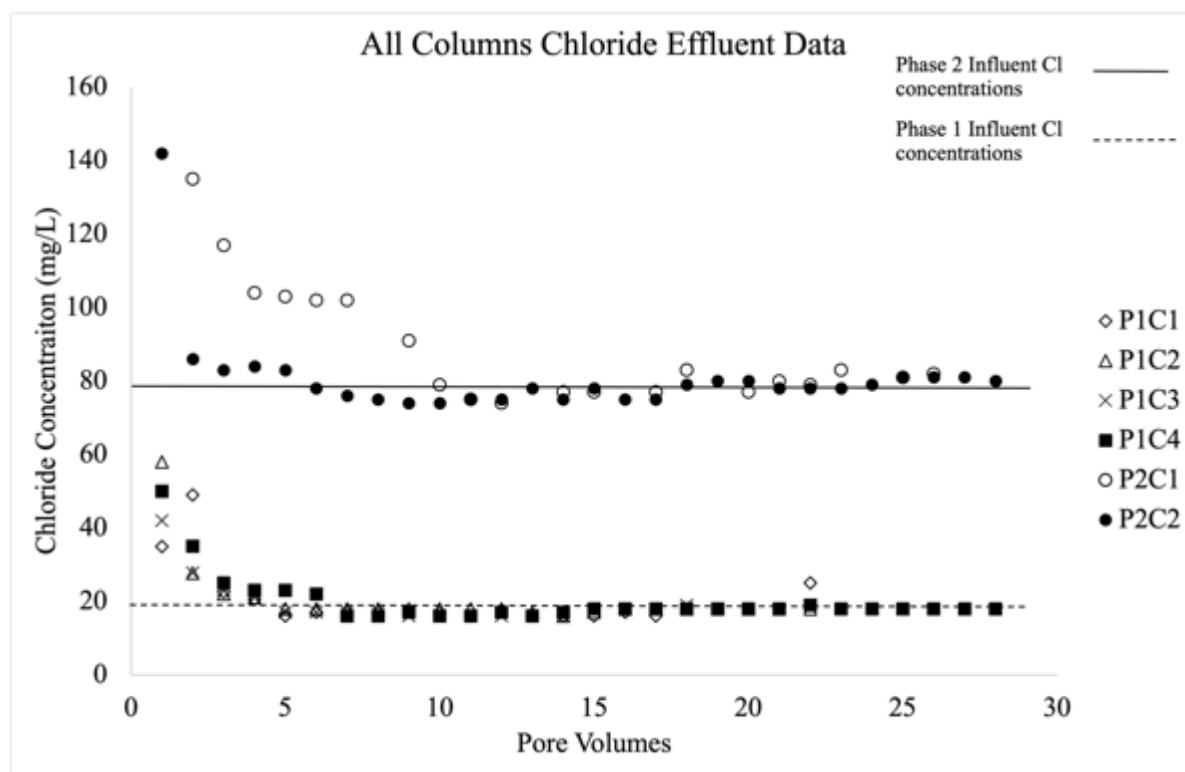
Samples were collected on a daily basis and stored at 4° C prior to chemical analysis. Uranium concentrations were measured at the DOE office of Legacy Management Environmental Science Laboratory (DOE-LM ESL) on a Kinetic Phosphorescence Analyzer (KPA). pH and alkalinity were measured at the DOE-LM ESL on a Hach Automatic Laboratory Analyzer (AT1000 Series). Anions were measured at the DOE-LM ESL an IC (ThermoFisher Aquion). Trace metals were measured by ICP-OES (Perkin Elmer DV7000). Solid phase uranium data for sediment from wells 859 and 860 were completed during the 2015 Advanced Site Investigation (DOE, 2016). Sediment from well 1020 solid phase uranium data was completed using a 5% nitric acid extraction based on a modified extraction described in (Orabi, 2013).

## Results

### *Solid Phase Data*

The solid phase extractions on the sediments showed that uranium content in the column sediment was at least 480% higher than uranium in the background sediments upgradient from the site (composed of gravel and silt). Results for the solid phase extractions are shown in Appendix A 2. Background concentrations in the sand and gravel were 0.6 mg/kg whereas well 859 and well 860 had 2.4 mg/kg of sediment uranium content and well 1020 sediment concentrations of uranium were 6.34 mg/kg.

### *Column Effluent Data*

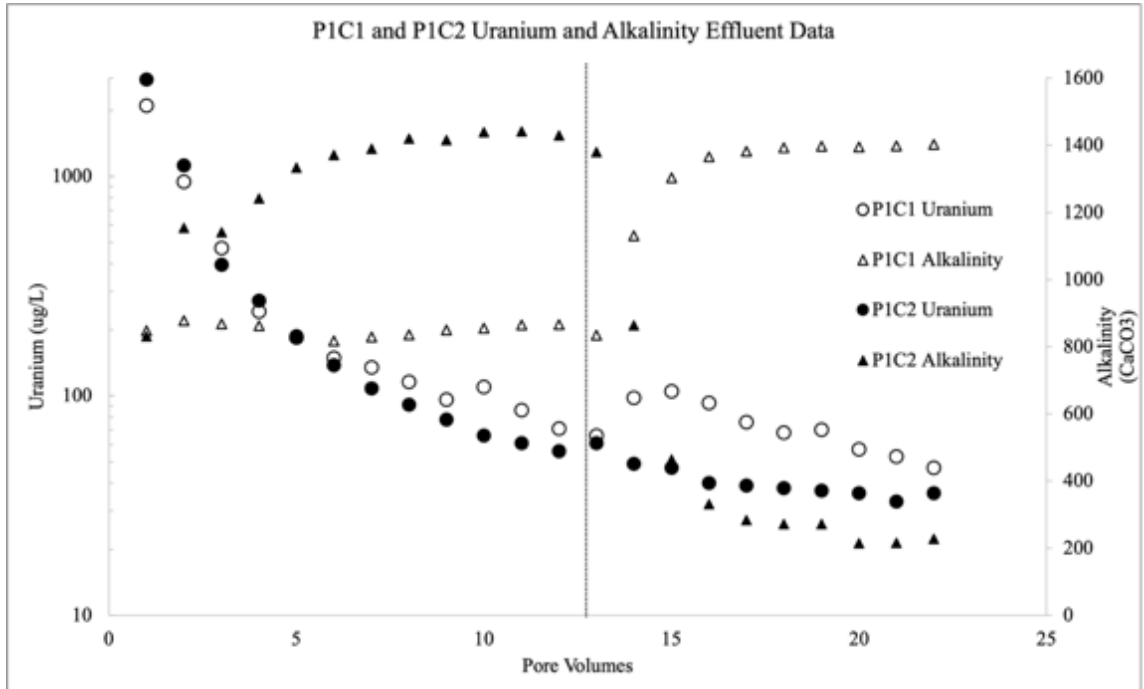


**Fig. 7** - Chloride concentrations of each concentration. Lines indicate influent chloride concentrations.

Initial chloride concentrations in the effluent were elevated due to equilibration and dissolution during the 24h equilibration period. Chloride concentrations leveled off to influent concentrations after 2 to 4 pore volumes for all columns except P2C1, which leveled off at background levels after 9 pore volumes (Fig. 7). Effluent concentrations for magnesium and sodium for all columns are shown in the appendix A 3 through 8.  $\text{SO}_4$  and Ca concentrations for each column are provided in Appendix A 3 through 8.

#### *Effluent Data for P1C1 and P1C2*

Detailed effluent results for experiment P1C1 are shown in Appendix A 3. Uranium concentrations per pore volume for columns P1C1 along with the effluent uranium concentrations are given in figure 8. Uranium concentrations in the first pore volumes are much higher so a semi-log graph is used to visualize the uranium concentrations in the effluent (Fig. 8) P1C1 uranium data in the first pore volume was 2,100 ppb. By pore volume 11 the uranium concentration had dropped below 100 ppb. At pore volume 13, the influent water was switched to well 710 with added alkalinity There was a 161% increase in the effluent uranium concentration in the following 4-5 pore volumes compared to PV directly before the influent switch. Alkalinity was stable at around 200 mg/L  $\text{CaCO}_3$  during the first influent when there was no additional alkalinity added (Fig. 8). When the influent switched to well 710 with 2,500 mg/L as  $\text{CaCO}_3$ , alkalinity values in the effluent went up to around 1,350 mg/L as  $\text{CaCO}_3$ . Sulfate and calcium concentrations were both 400% higher in the first few pore volumes than in pore volume five and after (Appendix A 3).



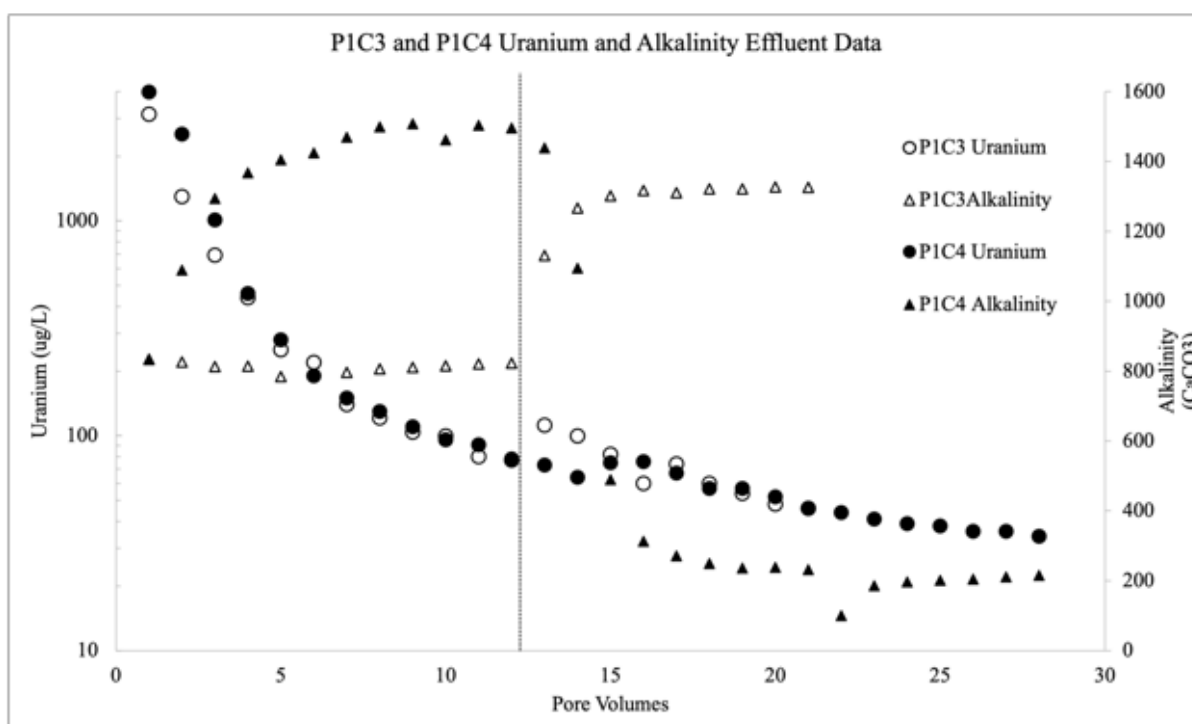
**Fig. 8** - P1C1 and P1C2 uranium and alkalinity effluent data. Black dotted line denotes influent switch

Phase 1 Column 2, (P1C2) effluents are shown in Appendix B. P1C2 uranium data for PV 1 was 2,760 ug/L. By pore volume 11 it had gone below 70 ug/L. When the influent was switched to well 710 BA there was an immediate bump in uranium concentration of 8.9% (Fig. 8) in the following pore volume. The alkalinity in the effluent of P1C2 during the first influent was around 1,400 mg/L as CaCO<sub>3</sub>. The alkalinity dropped to around 200 mg/L as CaCO<sub>3</sub> when the influent was switched to 710 BA water. Sulfate and calcium concentrations were both 400% higher in the first few pore volumes than in pore volume five and after (Appendix B 1).

#### *Phase 1 Column 3 and 4*

Phase 1 Column 3 and 4 are similar to column's 1 and 2 except they utilize sediment from well 1020 instead of well 860. The influents utilized in columns 1 and 2 were also used in column 3 and 4. P1C3 and C4 effluent results for major cations and anions are shown in

Appendix B. Uranium data for PV 1 was 3,140  $\mu\text{g/L}$ . By PV 11 uranium concentrations were below 100  $\mu\text{g/L}$  (Fig. 9). When the influent was switched from BA to AA, at pore volume 13 the uranium concentration went up 45% in the immediate effluent pore volume. The alkalinity in the effluent of P1C3 stayed around 200  $\text{mg/L}$  as  $\text{CaCO}_3$  until alkalinity was added to the influent and the alkalinity went up to 1,400  $\text{mg/L}$  as  $\text{CaCO}_3$ . Sulfate concentrations of the first PV were 900% higher than in subsequent pore volumes. Calcium concentrations were roughly 300% higher in the first PV than in subsequent pore volumes (Appendix B)



**Fig. 9** - P1C3 and P1C4 uranium and alkalinity effluent data. Black dotted line denotes influent switch.

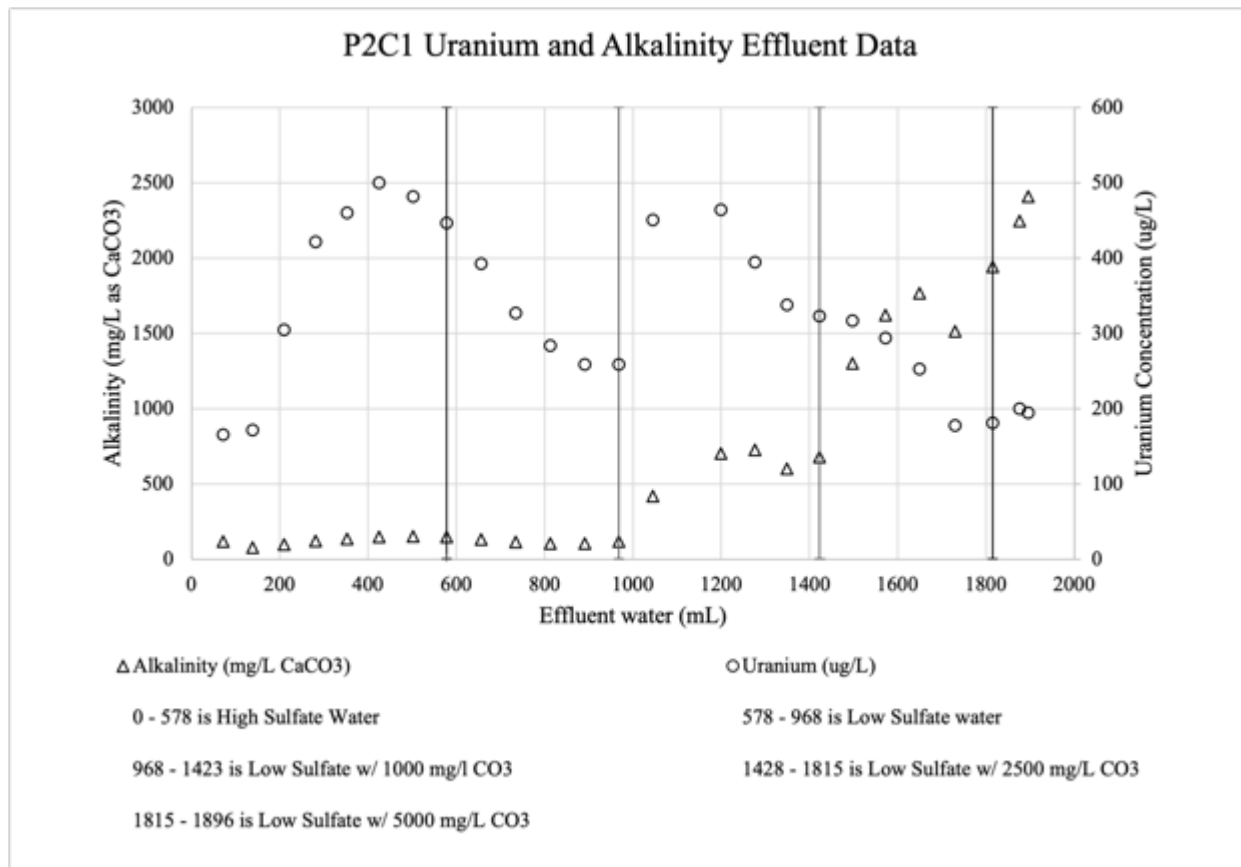
Phase 1 Column 4 (P1C4) uranium and alkalinity effluent concentrations are shown in appendix B. Uranium concentrations for PV 1 of P1C4 was 3,990  $\mu\text{g/L}$ , by PV 11 the concentration had dropped to below 100  $\mu\text{g/L}$ . When the influent was switched at PV 13 from AA to BA there was no measurable increase in effluent uranium concentrations. The alkalinity

of the effluent stayed around 1,500 mg/L as  $\text{CaCO}_3$  during the influent with added alkalinity and fell to around well 710 concentrations when the influent was switched. Sulfate levels were 1000% higher in the first PV of P1C4 than in subsequent PV's. Calcium levels were roughly the same as influent levels.

When the total mass of uranium flushed from each column in phase 1 was examined, columns with sediment 1020 were shown to flush a greater mass of uranium than columns with sediment from well 860 (Fig. 9). In both sets of columns, the net mass of uranium flushed was higher when the alkalinity addition was the first influent.

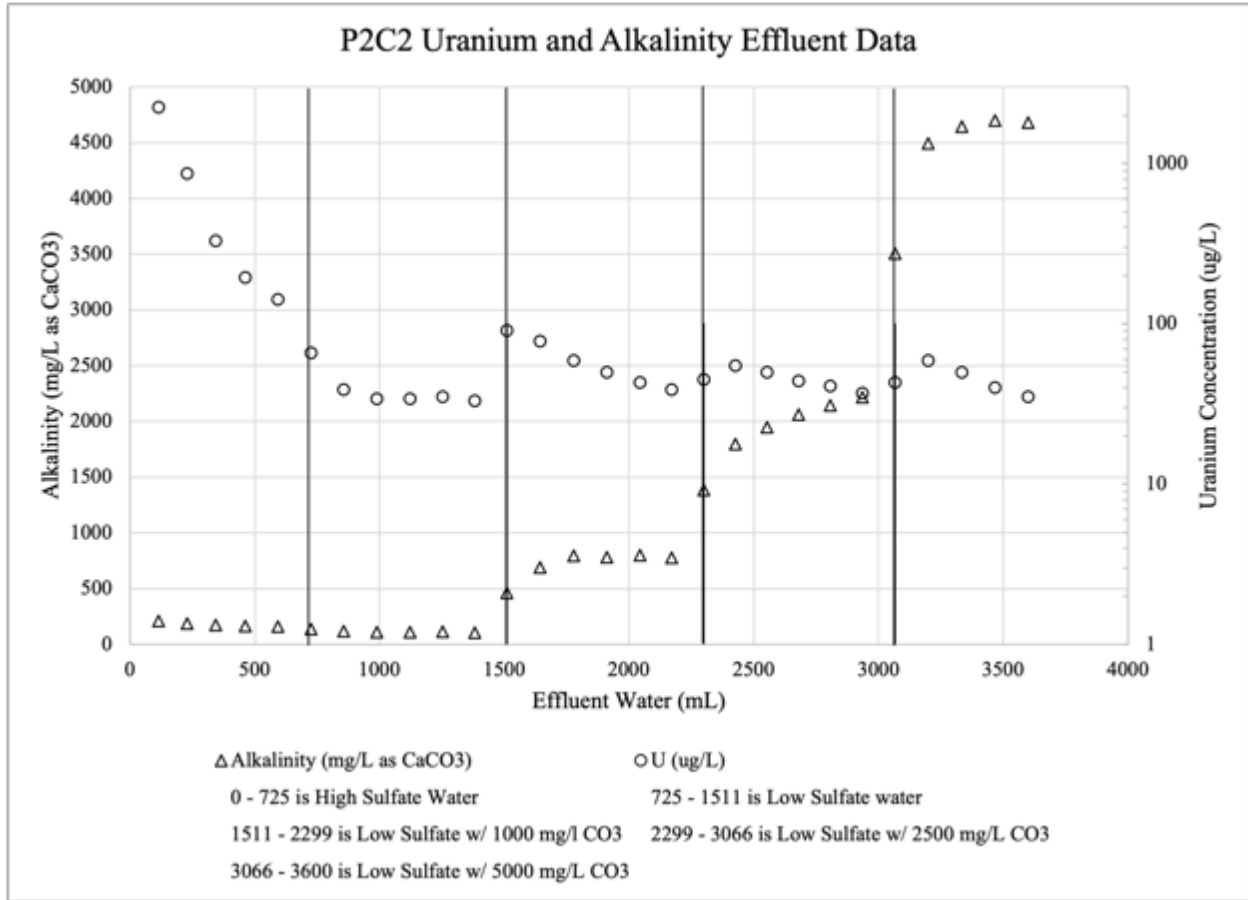
#### *Phase 2 Column 1 and 2*

Both P2C1 and P2C2 used the identical series of five influents (Table 2). Phase 2 Column 1, well 859 sediment, effluent water chemistries are shown in Appendix B. Uranium concentrations for PV 1 of P2C1 were 166 ppb. By PV 6 the concentration was over 500 ppb. When the influent was switched from high sulfate to low sulfate concentrations, the uranium concentrations in the influent began to decrease shown in Fig. 10. At PV 7, right before the influent switch, uranium concentrations were 482 ppb. At PV8 directly after the switch uranium concentrations were 447 ppb, by PV 12 uranium concentrations were 259 ppb. There was an increase in effluent uranium concentrations in the third influent from 259 ppb to 464 ppb. There was no increase in uranium concentrations during influent 4 and 5. Sulfate concentrations were around 10x higher in the effluent than the influent throughout the experiment.



**Fig. 10** - P2C1 uranium and alkalinity effluent data. Lines denote influent switches.

Phase 2 Column 2, well 860 sediment, effluent results are available in Appendix B. Uranium concentrations for PV 1 of P2C2 were 2,250 ug/L, by PV 5 the concentration had fallen to 142 ug/L shown in Figure 11. Concentrations of uranium in the effluent continued to decrease during the second influent, synthetic well 710 water. Uranium concentrations spiked from 33 ppb to 91 ppb during the third influent change when 1,000 mg/L as CaCO<sub>3</sub> was added to the column (Fig. 11). Small spikes in the uranium concentrations were seen in the 4<sup>th</sup> and 5<sup>th</sup> influent changes. Sulfate concentrations in the effluent mirrored the influent concentrations.



**Fig. 11** -P2C2 uranium and alkalinity effluent data. Lines denote influent switches.

### *Mass Balance Analysis*

To calculate the mass of uranium flushed from the column a numerical integration, using the trapezoidal rule, was completed on both influent and effluent waters. The trapezoidal rule is a technique to calculate the area under a curve by approximating the region under the graph of the function as a trapezoid and calculating its area. The simplified equation to calculate the mass flushed from the column using the trapezoidal method is:

$$M = \Sigma \left( (V - V_0) * \left( \frac{C + C_0}{2} \right) \right)$$



Where  $M$  is the mass (mg);  $V$  is the ending volume (L);  $V_0$  is the starting volume (L);  $C$  is the ending concentration (mg/L);  $C_0$  is the starting concentration (mg/L). To calculate the net mass flushed from the column, the mass balance equation is utilized:

$$M_{net} = M_{Ef} - M_{In}$$

Where  $M_{net}$  is the net mass flushed from the column (mg);  $M_{Ef}$  is mass in the effluent of the column (mg);  $M_{In}$  is the mass in the influent of the column (mg).

The mass of uranium flushed from P1C1 influent 1 was 289.07  $\mu\text{g}$  or 22.24  $\mu\text{g/PV}$ . The mass of uranium flushed from P1C1 influent 2 was 36.62  $\mu\text{g}$  or 4.07  $\mu\text{g/PV}$ . The total mass of uranium flushed from P1C1 was 333.16  $\mu\text{g}$  or 15.14  $\mu\text{g/PV}$ .

The mass of uranium flushed from P1C2 influent 1 was 291.5  $\mu\text{g}$  or 24.29  $\mu\text{g/PV}$  (Table 6). The mass of uranium flushed from P1C2 influent 2 was 23.39  $\mu\text{g}$  or 2.34  $\mu\text{g/PV}$ . The total mass of uranium flushed from P1C2 was 314.89  $\mu\text{g}$  or 14.31  $\mu\text{g/PV}$  (Table 6).

During influent 1, P1C2, the column with added alkalinity, flushed 9.3% more uranium per pore volume than the column with no added alkalinity (Table 6). During influent 2, P1C1, the column with added alkalinity, flushed 109% more uranium than the column with no added alkalinity (Table 6). When the total uranium flushed over the whole experiment is compared, P1C1, the column with no added alkalinity in the first influent flushed 5.8% more uranium per pore volume than P1C2 (Table 6).

**Table 6** – Effluent minus influent for each column influent uranium, chloride, sulfate, and calcium mass.

Influent	Net U (ug)	Net Cl (mg)	Net SO <sub>4</sub> (mg)	Net Ca (mg)
P1C1 BA	289.1	1.5	194.2	8.2
P1C1 AA	44.1	-0.8	-5.9	-27.6
P1C1 Net	333.2	0.7	188.3	-19.4
P1C2 AA	291.5	1.8	159.0	-30.7
P1C2 BA	23.4	-0.9	4.4	-60.0
P1C2 Net	314.9	0.8	163.4	-90.7
P1C3 BA	473.8	0.4	105.0	-14.9
P1C3 AA	49.2	-1.0	-6.7	-35.9
P1C3 Net	523.0	-0.5	98.3	-50.9
P1C4 AA	501.1	2.1	113.0	-38.6
P1C4 BA	50.4	-1.2	4.3	-75.3
P1C4 Net	551.5	1.0	117.3	-113.9
P2C1 A	193.5	-1.9	517.6	176.2
P2C1 B	126.1	-8.7	583.7	244.4
P2C1 C	182.1	-9.1	673.85	307.3
P2C1 D	100.4	1.3	793.6	229.4
P2C1 E	15.6	0.4	200.0	38.1
P2C1 Net	617.6	-18.0	2,768.7	995.4
P2C2 A	319.9	-16.7	116.6	33.4
P2C2 B	26.2	-16.5	-14.6	11.5
P2C2 C	44.5	-17.2	-20.1	0.3
P2C2 D	34.6	1.4	2.3	-40.8
P2C2 E	25.1	1.94	-0.9	-28.9
P2C2 Net	450.4	-47.0	83.2	-24.4

The mass of uranium flushed from P1C3 influent 1 was 473.8 ug or 39.48 ug/PV. The mass of uranium flushed from P1C3 influent 2 was 49.29 ug or 5.47 ug/PV. The total mass of uranium flushed from P1C3 was 523 ug or 23.77 ug/PV (Table 6).

The mass of uranium flushed from P1C4 influent 1 was 501.1 ug or 41.8 ug/PV. The mass of uranium flushed from P1C3 influent 2 was 50.4 ug or 3.15 ug/PV. The total mass of uranium flushed from P1C3 was 551.46 ug or 19.7 ug/PV (Table 6).

During influent 1, P1C4, with added alkalinity, flushed 5.8% more uranium from the column than P1C3. During influent 2, P1C3, with added alkalinity, flushed 46.3% more uranium per pore volume than the column with no added alkalinity during influent 2, P1C4. Comparing the total uranium flushed from each column throughout the entire experiment showed that P1C4, the column with added alkalinity in the first influent, flushed 5.4% more uranium per pore volume than the P1C3.

The mass of uranium flushed from P2C1 influent 1 was 193.5 ug or 27.6 ug/PV (Table 6). The mass flushed in influent 2 was 126 ug or 25 ug/PV, in influent 3 uranium mass flushed was 182 ug or 36.4 ug/PV, in influent 4, 100.4 ug of uranium or 20 ug/PV was flushed from the column, and in influent 5, 15.6 ug of uranium or 5.2 ug/PV was flushed. There was 617.6 ug flushed from the total column.

The mass of uranium flushed from P2C2 influent 1 was 320 ug or 53.3 ug/PV (Table 6). The mass flushed in influent 2 was 26.2 ug or 5.2 ug/PV, in influent 3 uranium mass flushed was 44.4 ug or 7.4 ug/PV, in influent 4, 34.6 ug of uranium or 5.8 ug/PV was flushed from the column, and in influent 5, 25.1 ug of uranium or 5 ug/PV was flushed. There was 450.4 ug flushed from the total column.

During influent 1, P2C2, the column with 860 sediment, flushed 93% more uranium per pore volume. During influent 2, 3 and 4, P2C1, the column with 859 sediment flushed more uranium per pore volume than P2C2 (Table 6).

### *2<sup>nd</sup> Order Decay Rates*

Decay rates were calculated for all phase 1 column influents. Effluent uranium concentrations were fit to both 1<sup>st</sup> and 2<sup>nd</sup> order decay rates. The differential equation describing 1<sup>st</sup> order decay is:

$$R = k[C]$$

Where R is the reaction rate (concentration/time); k is the reaction rate coefficient (1/time); C is the concentration at the moment that the rate is measured.

The differential equation describing 2<sup>nd</sup> order decay is:

$$R = k[C]^2$$

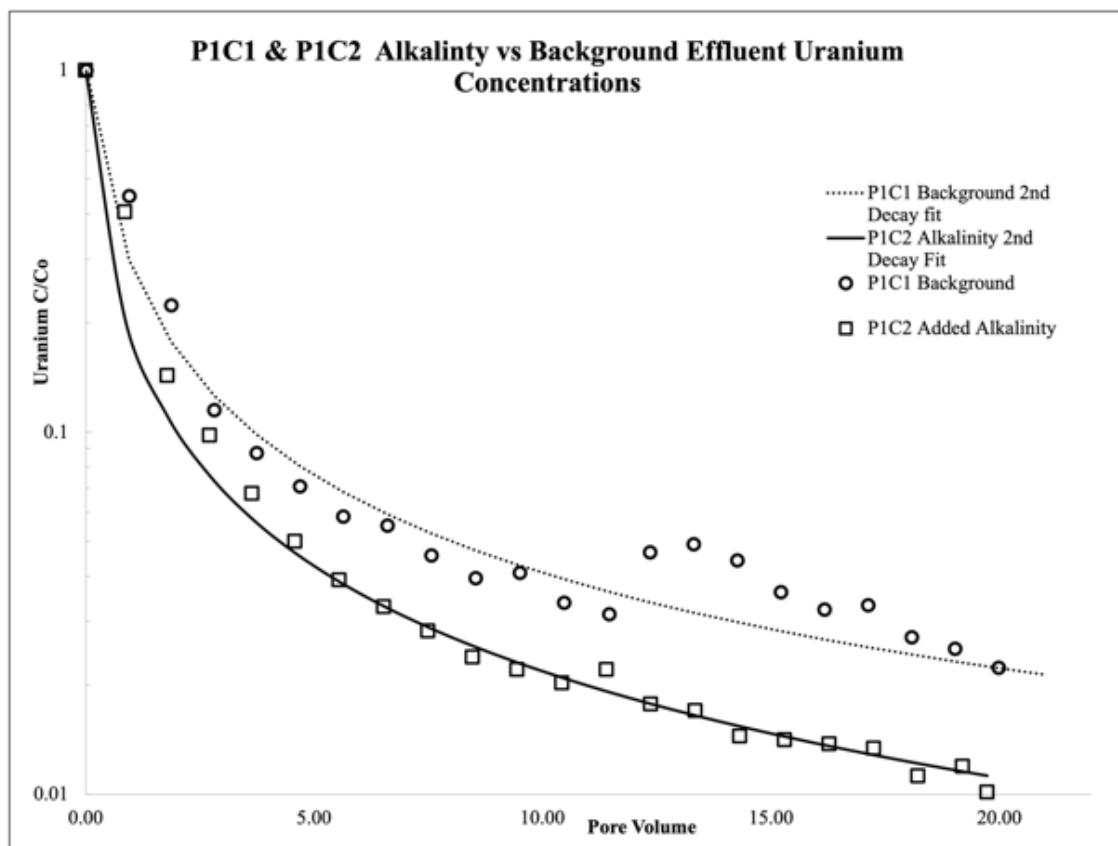
The concentration of uranium in the effluent using 2<sup>nd</sup> order decay can be solved algebraically:

$$C = \frac{1}{\frac{1}{C_0} + kt} + C_{in}$$

Where C is the concentration of uranium in the effluent (mg/L); C<sub>0</sub> is the initial uranium concentration (mg/L); t is the pore volume (L); C<sub>in</sub> is the uranium concentration of the influent water.

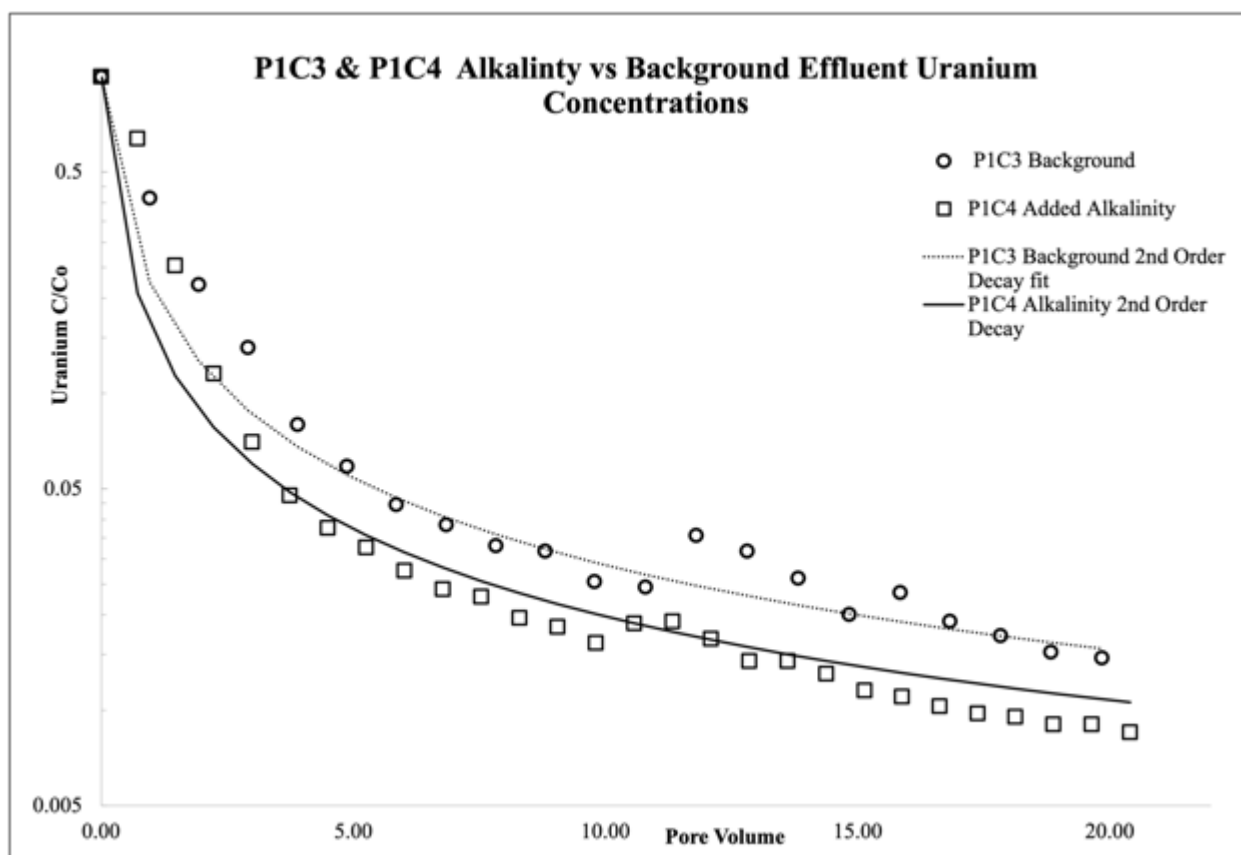
To fit the decay rates to the experimental data the residuals between the calculated experimented and calculated values were minimized using Excel's solver function. The 2<sup>nd</sup> order decay rate produced a better fit than the 1<sup>st</sup> order decay rate.

The first influent of P1C1 and P1C2 decay rates were fit to the uranium effluent concentrations (Fig. 12). P1C1 influent 1 with well 710 groundwater, had a uranium decay rate of 2.54 while with P1C2, well 710 groundwater and added alkalinity had a uranium decay rate of 4.49. The uranium decay rate for influent 2 was 3.65 for P1C1, well 710 with added alkalinity, and 7.58 for P1C2, well 710 groundwater without added alkalinity. When alkalinity is added to the first influent water, the effluent uranium  $C/C_0$  approaches 0 at a faster rate than when alkalinity is not added to the influent.



**Fig. 12** - Phase 1 column 1 (BA) and column 2 (AA) 2<sup>nd</sup> order decay fits. Only the first influents decay rate was used to calculate the 2<sup>nd</sup> order decay fit and calculated concentrations were extrapolated to further pore volumes.

The first influents P1C3 and P1C4 effluent uranium concentrations were fit with a 2<sup>nd</sup> order decay rate (Fig. 13). As with the results from P1C1 and P1C2, when alkalinity is added to the influent solution the effluent  $C/C_0$  approaches 0 at a faster rate than when alkalinity is not added to the influent. P2C3 influent 1 had a uranium decay rate of 3.64 while P2C4 influent 1 had a uranium decay rate of 5.40. P2C3 and P2C4 influent 2 had decay rates of 6.19 and 6.47 respectively.



**Fig. 13** - Phase 1 column 3 (BA) and column 4 (AA) 2nd order decay fits. Only the first influents decay rate was used to calculate the 2nd order decay fit and calculated concentrations were extrapolated to further pore volumes.

### *Flushing Time*

The 2<sup>nd</sup> order decay rates (Fig 12 and 13) that were fit to the experimental column effluent results were used to estimate the field flushing times for uranium at the FTA. Flushing times were calculated using the concentrations of uranium in the effluent that was calculated using the 2<sup>nd</sup> order decay rates. These concentrations, ground water velocity, and the horizontal flow path distance were used to convert the number of PVs needed to flush the column to amount of time required to flush the FTA. Flushing time means the time required for concentrations of uranium to flush below the MCL.

### *Derivation of Sorption Coefficients*

A partition coefficient,  $K_d$ , was calculated for the first PV of each column as well as each influent. The partition coefficient equation is:

$$K_d = \frac{Sed - Sol}{Sol}$$

Where  $K_d$  is the partition coefficient (L/kg); Sed is the uranium mass in the sediment; Sol is the uranium mass in the solution.

The equation can be written as:

$$K_d = \frac{\frac{M_{solid} - M_{solution}}{M_{sediment}}}{C_{solution}}$$

Where  $M_{solid}$  is the mass of uranium on the solid phase (mg);  $M_{solution}$  is the mass of uranium in the solution (mg);  $M_{sediment}$  is the total mass of the sediment (kg);  $C_{solution}$  is the concentration of uranium in the solution (mg/L).

A low  $K_d$  value correlates to a lower mass on the solid phase, and thus, a larger mass of uranium flushed from the column. Table 7 shows every influent's calculated partition coefficient.

In all phase 1 columns, the first PV had  $K_d$  values around 1. When alkalinity was added to the influent, the  $K_d$  values were between 23.75% and 29.63% lower than when alkalinity was not added to the influent. In columns that alkalinity was added to first,  $K_d$  values had a 979% - 1347% increase when switched to no alkalinity. In columns that had no alkalinity added to the first influent,  $K_d$  values had a 381% - 673% increase when alkalinity was added to the influent.

**Table 7** - Calculated  $K_d$ 's for each column's influent. AA = Added Alkalinity. BA = Background Alkalinity

Column	Influent	$K_d$ (L/kg)
P1C1	PV1	0.93
	BA	82.16
	AA	394.36
P1C2	PV1	0.69
	AA	70.47
	BA	760.24
P1C3	PV1	1.79
	BA	118.14
	AA	913.38
P1C4	PV1	1.41
	AA	113.96
	BA	1647.08
P2C1	A-SO4	176.55
	B-Bck	171.95
	C-Low Alk	187.78



	D-Alk	220.18
	E-High Alk	433.90
P2C2	A-SO4	26.09
	B-Bck	442.40
	C-Low Alk	295.18
	D-Alk	402.76
	E-High Alk	385.08

## Discussion

*What effect does increasing alkalinity have on the mass transport of uranium?*

Investigating and quantifying the impact that increasing the influent alkalinity has on the flushing of uranium from a column is an important step in determining the feasibility of alkalinity as a remediation approach. While alkalinity enhanced flushing is a known phenomenon, it is important to examine the impact that alkalinity has on an individual site. This study adds new evidence that alkalinity enhances the mass flushing of uranium and examines its remediation feasibility.

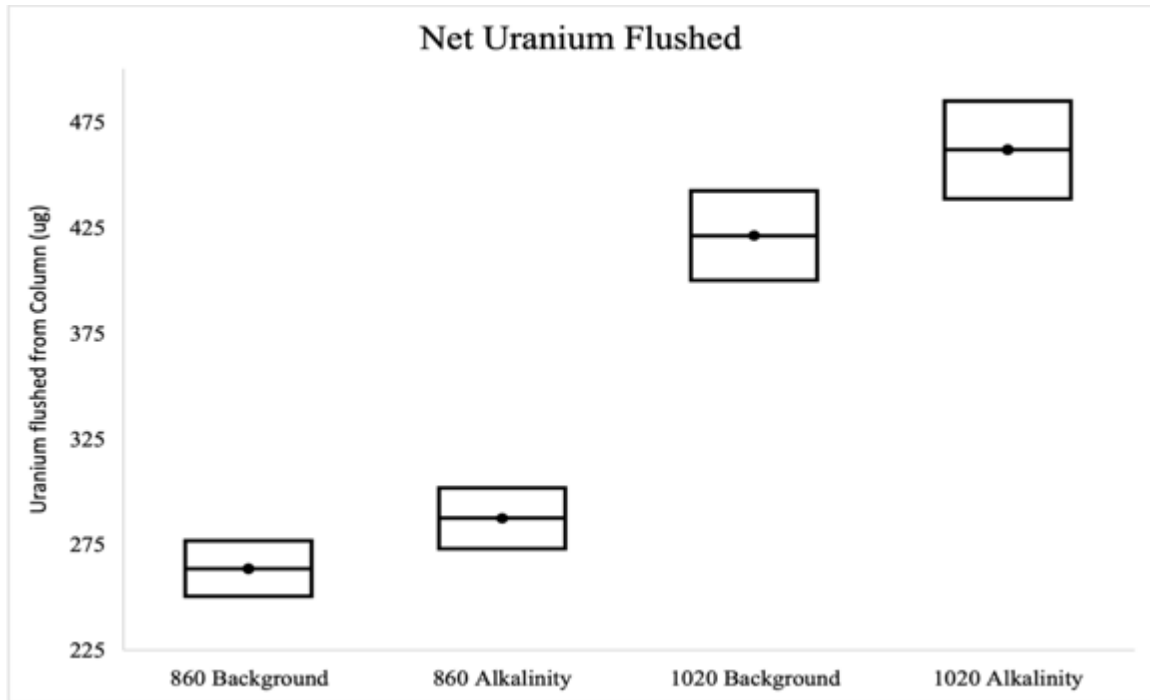
To review, the mobility of U(VI) is significantly enhanced by the addition of high alkaline water. As aqueous calcium and carbonate concentrations increase, uranyl complexes to form calcium-uranyl-carbonate complexes ( $\text{Ca}_2\text{UO}_2(\text{CO}_3)_3^0$  and  $\text{Ca}_2\text{UO}_2(\text{CO}_3)_3^{-2}$ ) (Dong et al. 2006) that are unlikely to adsorb to minerals (Bernhard et al. 2001, Dong et al. 2006). As the concentrations of aqueous uranyl decreases in solution, uranium desorbs from the solid phase until equilibrium is reached (Dangelmayr et al. 2017, Johnson et al. 2022).

If alkalinity additions to the influent is enhancing the desorption of uranium in the column, specific trends will be observed in the effluent data: (1) There will be an increase in uranium mass flushed from the column when alkalinity is added to the influent. Regardless of when alkalinity is added to the influent, either before or after background water, more uranium will be flushed from the column when high alkaline conditions are present. As noted, this occurs from the formation of non-adsorbing calcium-uranyl-carbonate complexes. (2) Alkalinity concentrations will increase in the effluent concentration caused by an increase in the influent alkalinity concentrations. (3) The partition coefficients of AA influents will be lower than the

partition coefficients of BA influents. If alkalinity is increasing desorption of uranium associated with mineral surfaces,, we will see the  $K_d$  value decrease.

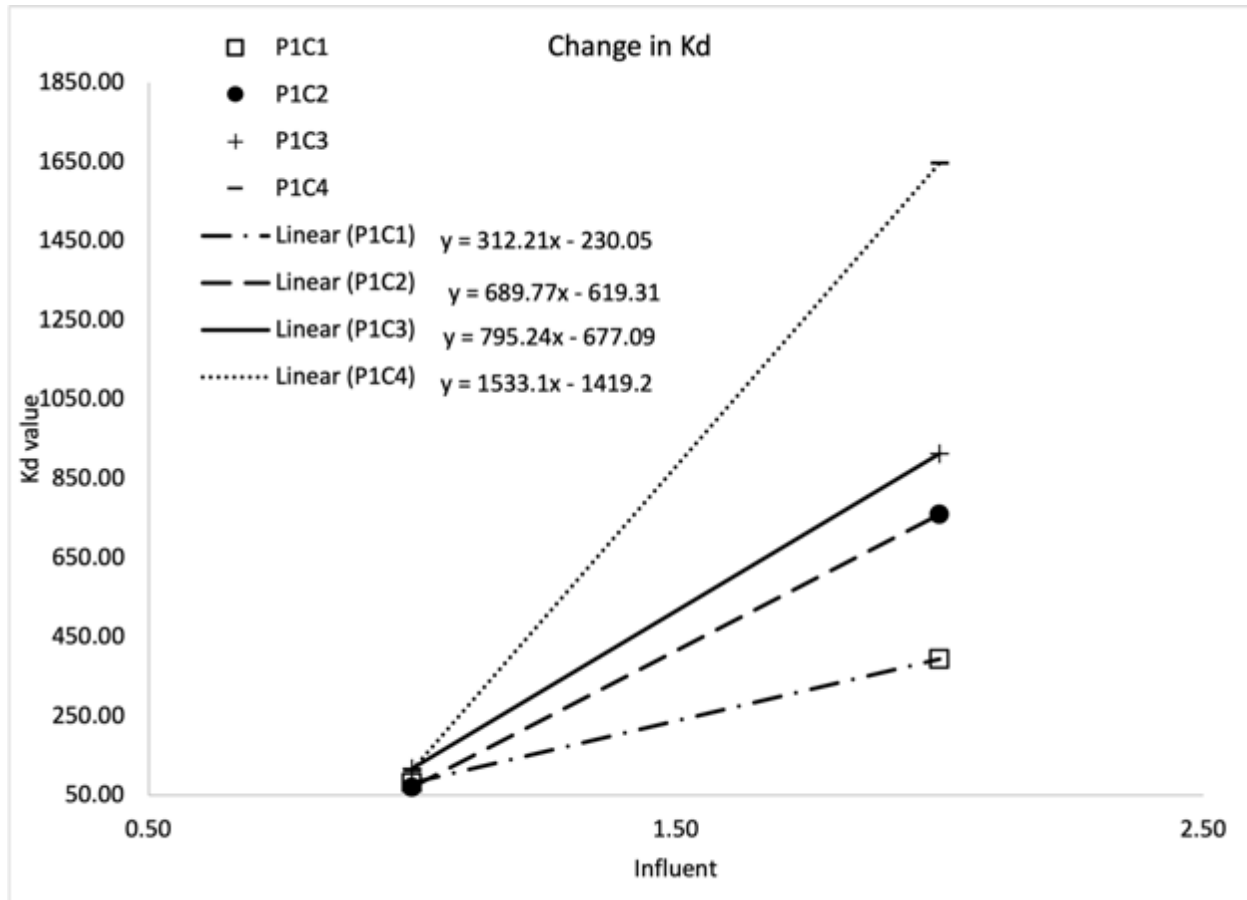
If alkalinity additions to the influent are not enhancing the desorption of uranium in the columns we should not see an increase of mass flushed from the column when alkalinity is added to the influent. Thus, uranium concentrations in the effluent will be similar regardless of in the influent contains added alkalinity (AA) or background alkalinity (BA).

All P1 columns (Table 2) saw an increase in uranium mass flushed (Table 6) when the influent had added alkalinity compared to when the influent had only background levels of alkalinity. Figure 14 compares the amount of mass flushed during each phase 1 columns AA and BA influents. For well 860 sediment, AA influents flushed 9.04% more uranium than the corresponding BA influents. For well 1020 sediment, AA influents flushed 9.64% more uranium than BA influents. Throughout the P1 columns, the AA influent flushed 9.34% more uranium than the BA influent. The addition of alkalinity to the influent of experiment columns increased the flushing of uranium from the columns.



**Fig. 14** - Total uranium mass flushed from each Phase 1 column.

The phase 1 partition coefficient values also indicated that alkalinity enhances desorption of uranium at the FTA. Methods and Results table 7 summarized the  $K_d$  values of each columns AA and BA influents. When uranium is acting most conservatively, the sediment has little or no ability to slow the uranium movement,  $K_d$  values will be lowest. When sediment is retarding the movement of uranium, the  $K_d$  values will be larger (EPA. 1999). When comparing columns using the same sediment, the  $K_d$  values were always lower when the influent was AA compared to BA. This indicates that the sediment is slowing the movement of uranium to a greater extent when there is background alkalinity conditions in the column. When the influent contains added alkalinity, the sediment has less of an ability to slow uranium mobility.



**Fig. 15** - Change in  $K_d$  values from influent 1 to influent 2.

To better quantify the effect that AA has on FTA partition coefficients, every phase 1 influent  $K_d$  value was graphed and the slope between influent 1 and 2 was calculated in figure 15. Examining the  $K_d$  value slopes lead to a better understanding of how influent 1  $K_d$  values influence influent 2  $K_d$  values. If desorption is the dominant mechanism of uranium transport the 1<sup>st</sup> influent partition coefficient will be substantially smaller than the second influent partition coefficient. This occurs because of initial uranium release from the sediment after drying and then coming into equilibrium with the first influent solution (Johnson et al. 2022). All phase 1 columns have a smaller influent 1 partition coefficient than influent 2. Columns P1C2 and P1C4, columns that utilize AA second, have slopes that are roughly half as large as P1C1 and P1C3.

During influent 1, AA columns have a smaller  $K_d$ . During influent 2, AA columns have a smaller  $K_d$  as well.

Interestingly, the mass of uranium flushed from columns containing 1020 sediment, P1C3 and P1C4 was greater than the mass flushed from columns containing 860 sediments, P1C1 and P1C2, regardless of the added alkalinity. The combined uranium mass flushed from 860 sediment was 551.0 ug. The combined uranium mass flushed from 1020 sediment was 882.9 ug. The percent difference in total uranium flushed from the two sediments was 46.3%.

The solid phase data (Appendix B) showed that P1C1 and 2 had 2.4 mg uranium per kg of sediment. P1C3 and 4 had 6.3 mg uranium per kg of sediment. The percent difference of solid phase uranium in the column for the two sediments is 90.7%. Borehole 1020 had 2.6 times more uranium mass in the sediment than borehole 860 but only 1.6 times more uranium mass flushed from the column. When there was more solid-phase uranium, there was more release to the aqueous phase during the column tests/.

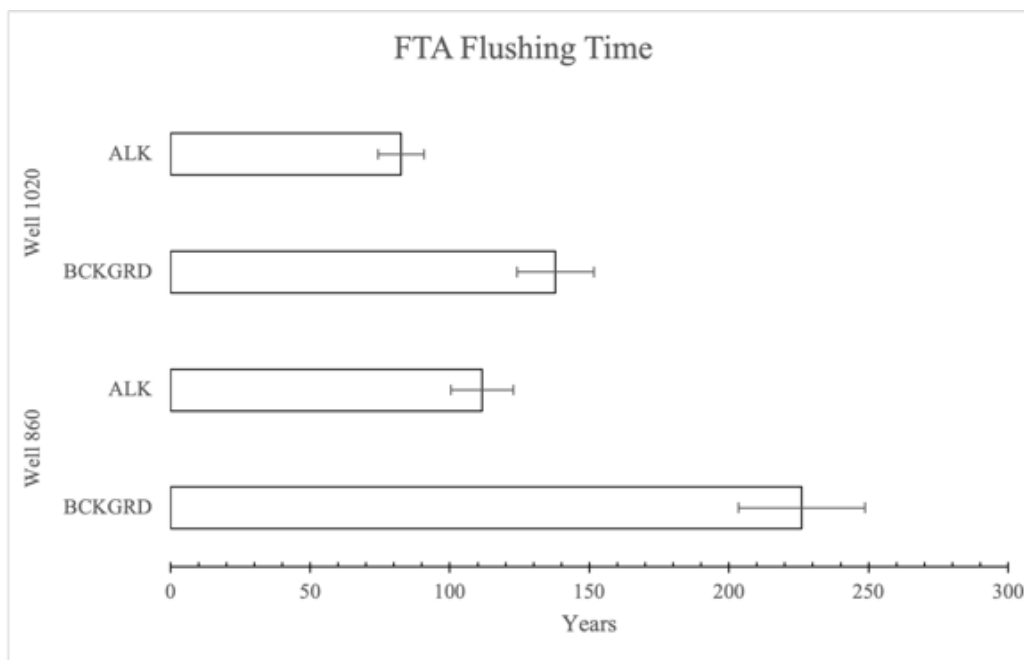
Both sediments are taken from very similar locations around 50 feet apart. Borehole records show that both sediments have similar lithologies, mainly sand and gravel with large clasts. There is a large amount of variability in both the mass of solid uranium and the mass of solid compared to the mass of flushed uranium for the two sediments. Both sediments are from spatially close and similar areas. this shows that heterogeneity in the uranium contamination and  $K_d$  values has a large effect on uranium mass flushed from the column.

Past work at the FTA has shown spatial variability in general water chemistry and sorption partition coefficients throughout the site leads to large source heterogeneities along the flow path (DOE. 2016) (Dam et al. 2015). The spatial variability in both the uranium mass in the

sediment and the sorption partition coefficient as well as the addition of alkalinity are all important factors in the net mass flushed.

*Forward Modeling: Does increasing alkalinity decrease the clean-up time of contaminated aquifers?*

When alkalinity was added to the influent, the average flushing time to below the MCL was 46% faster than when only background water was used (Fig. 16) using column data. Well 860 with background water, P1C1, took 226 years to flush below the MCL. Well 860 with alkalinity, P1C2, took 112 years to flush below the MCL. Adding alkalinity potentially decreases the flushing time by 114 years given well 860 sediment. Well 1020 with background water, P1C3, took 138 years to flush below the MCL. Well 1020 with alkalinity, P1C4, took 83 years to flush below the MCL. Adding alkalinity potentially decreases the flushing time by 55 years.



**Fig. 16** - The amount of time required to flush the FTA when different influents are used. Flushing rates are calculated using 2nd order decay rates.

Regardless of the total uranium mass in the sediment, adding alkalinity to the influent decreased the flushing time to around 100 years from 137 and 226 years. Given the results seen in this experiment, adding alkalinity to the groundwater at the FTA would keep the site on track to complete remediation within the EPA's 40 CFR Part 192, 100-year uranium flushing plan which is not attainable at the current rate of natural attenuation for the site (Dam et al. 2016).

It is important to note that studies on desorption rates calculated in the lab and in the field have shown that lab-based column studies typically overestimate the rate of desorption compared to values calculated in the field (Fox et al. 2011). Therefore, column experiments greatly overpredicted the concentrations of uranium flushed when extrapolated to the field scale (Culver et al. 1997). This is likely caused by lab-based column tests never fully reaching equilibrium during the duration of the experiment. The calculated flushing time of uranium to below the MCL at the FTA should be seen as an upper bound for the time required to flush FTA and not necessarily as the actual flushing time required.

Increasing the alkalinity of influent water into contaminated sediment decreases the flushing time required to bring concentrations to below the MCL. Figure 16 displays that regardless of predicted initial flushing times, once high alkaline water is added to the influent, flushing times decrease to around 100 years. While lab-based column tests can correctly predict that alkalinity will increase the desorption of uranium, the calculated flushing times from this experiment should be used as upper bounds. The required flushing time of uranium contaminated aquifers was at most 46% faster when alkalinity was added to the background water.

Another factor to consider is that as uranium concentrations decrease, higher apparent  $K_d$  values can inhibit uranium flushing and make reaching the clean-up goals difficult (Johnson et



al. 2022). This is typical of the tail end of flushing and is exhibited in these columns (Table 2).

The apparent rise in  $K_d$  values at the end of the flushing experiments reiterates the importance of the calculated flushing times as a bound instead of an actual time required.

*What is the dominant mechanism in the flushing of uranium from the FTA?*

The original Riverton conceptual site model determined that once tailings were removed from the FTA, advection, dispersion, and sorption would dominate the mobility of uranium (Dam et al. 2015). The uranium plume under the FTA would migrate in the direction of groundwater flow and exit the aquifer at the Little Wind River where dilution with river water would occur. Consistently high uranium concentrations have persisted at the FTA where boreholes 859, 860 and 1020 are located (Fig. 4). It is suspected that these consistently elevated contaminant concentrations in the groundwater of the FTA are the result of: (1) spatial heterogeneity in the water chemistry at the FTA (DOE. 2016) and (2) possible dissolution of  $\text{Ca-SO}_4$  minerals (Dam et al. 2015) that might contain trace amounts of uranium. The current conceptual site model that predicts natural attenuation within 100 years does not consider heterogeneity or other transport mechanisms than desorption. It is important to determine if dissolution of  $\text{Ca-SO}_4$  minerals is a mechanism of uranium mobility at the FTA to better characterize the site and determine which, if any, remediation approach is most applicable for the site. To help quantify the dominant mechanisms of mobility at the FTA, phase 2 columns were utilized.

Depending on the mechanism of uranium mobility there will be distinct trends in the columns effluent data from phase 2. Trends that would indicate dissolution as the dominant mechanism of uranium mobility are as follows: (1) The influents alkalinity concentration should

have no or little effect on the amount of uranium flushed from the column. If dissolution is the dominant mechanism of mobility, the effect that the formation of calcium-uranyl-carbonate species has on the desorption equation,  $C_s = K_d C_a$ , will be limited because uranium release from co-dissolution occurs independently of uranium equilibrium conditions. (2) There should be a significant net calcium and sulfate mass flushed from the column. In general, if  $\text{Ca-SO}_4$  minerals are dissolving, then their column effluent concentrations should be very high. (3) The uranium effluent data should follow the same trends that calcium and sulfate do. Basically, flushing of uranium from the column should be proportional to the flushing of calcium and sulfate from the column. With that said, it is suspected that there will be no initial effluent uranium concentration spike during the first PV's effluent data. If dissolution is the dominant mechanism of uranium mobility in a column, uranium mass flushed from the column is limited by the dissolution and flushing of  $\text{Ca-SO}_4$  (Johnson et al. 2022). (4) There should be no change in partition coefficients throughout the column. The dissolution of  $\text{Ca-SO}_4$  minerals occurs at a constant rate, if the flushing of uranium is dominated by dissolution, uranium flushing should also occur at a constant rate.

Trends that would indicate desorption as the dominant mechanism of uranium mobility are as follows: (1) The influent alkalinity will influence the uranium mass flushed from the column. If desorption is the mechanism of desorption, alkalinity will enhance the desorption and increase the uranium mass flushed from the column (Johnson et al. 2022) (Dangelmayr et al. 2017) (Geipel et al. 1998) (Davis et al. 1998). (2) Uranium effluent data should not follow the trends that calcium and sulfate effluent data follow. Even if the dissolution of  $\text{Ca-SO}_4$  minerals and the flushing of calcium and sulfate is occurring in the column, uranium mass flushed will not be correlated to  $\text{Ca-SO}_4$  dissolution. (3) There should be a stark change in influent partition

coefficient values if desorption is the mechanism of uranium mobility. If uranium sorption is limiting uranium mobility,  $K_d$  values will initially be very low as the dried sediment comes into equilibrium with the influent water and effluent uranium concentrations spike in the column (Johnson et al. 2022). As equilibrium is reached in the column,  $K_d$  values should drastically increase, and effluent uranium concentrations will decrease.

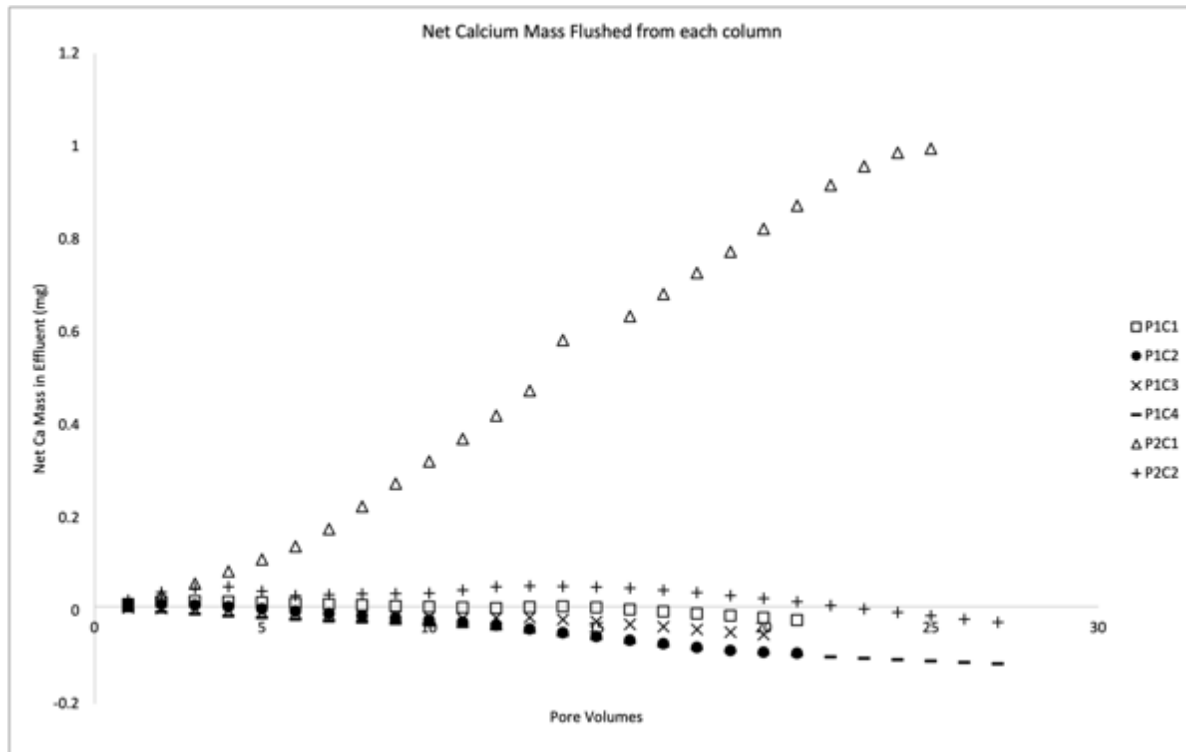
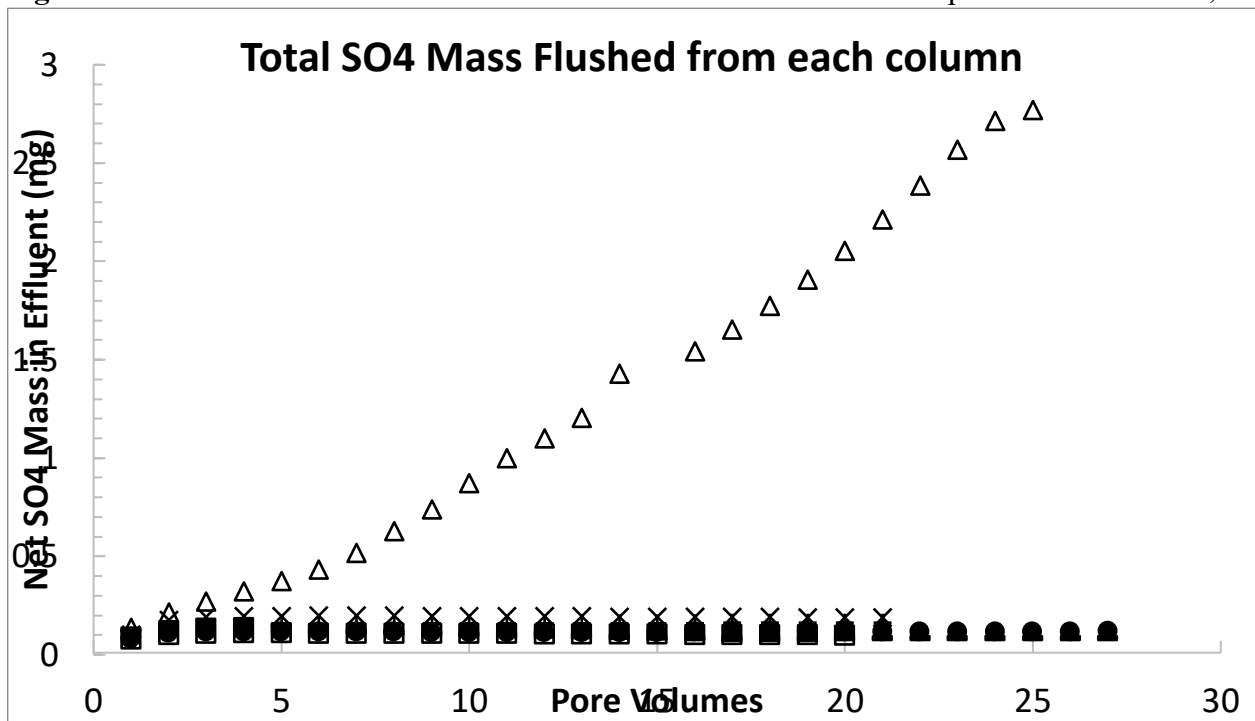
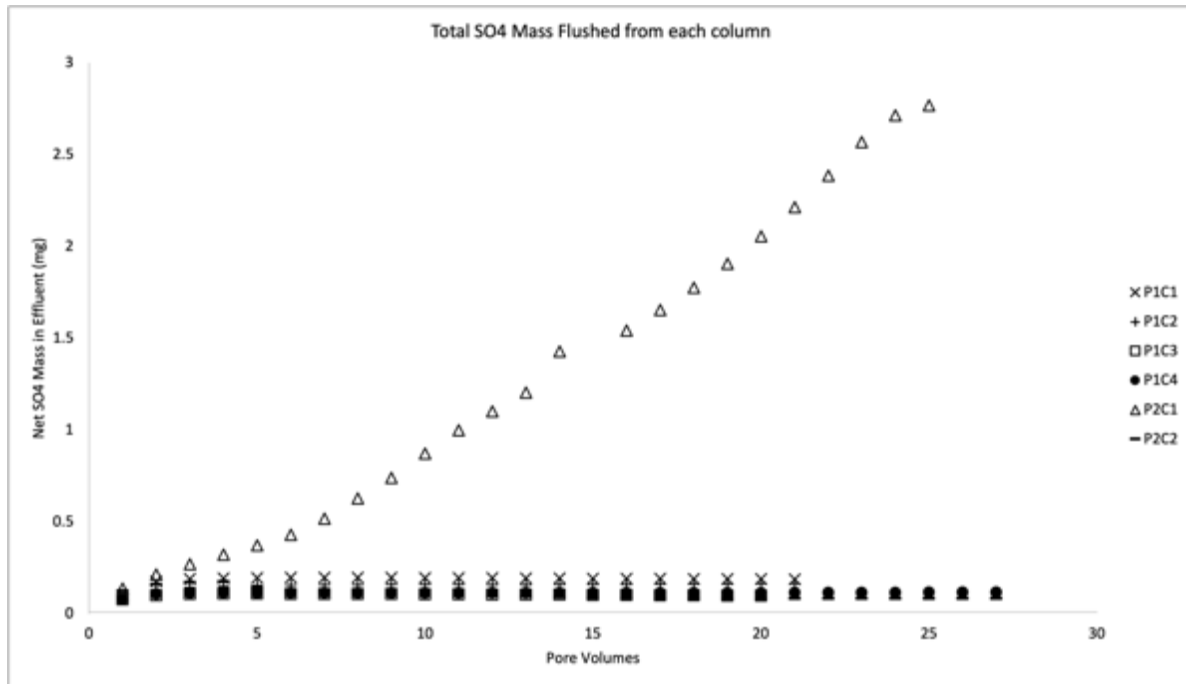


Fig. 17 - Cumulative calcium mass flushed from the columns at different pore volumes. P2C1,



column with borehole 859 sediment.

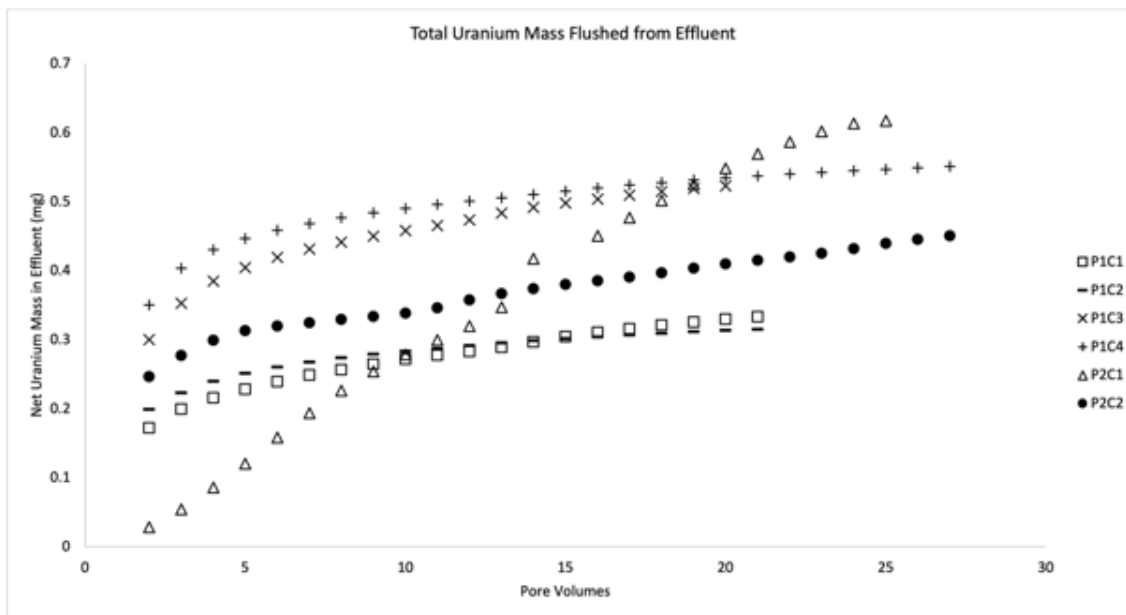


**Fig. 18** - Cumulative Sulfate mass flushed from the column at different pore volumes. P2C1, the column with borehole 859 sediment.

Phase 2 Column 2 was packed with sediment from borehole 860, the same sediment used in P1C1 and P1C2. Phase 2 Column 1 was packed with sediment from borehole 859, ¼ mile upgradient from phase 1 column sediment and near the edge of the uranium plume (Fig. 4, Fig. 5). The solid phase data showed that borehole 859 sediment had large amounts of calcium and sulfate in the sediment (DOE, 2016) as well as elevated sulfate and calcium concentrations in the column effluent. Sustained concentrations of sulfate and calcium in column effluents are indicative of the dissolution of gypsum and other Ca-SO<sub>4</sub> minerals (Dong et al. 2008, Johnson et al. 2022). Solid phase data from borehole 860 and 1020 did not show large amounts of calcium or sulfate. No sustained calcium and sulfate concentrations were observed in the column effluent. Figure 17 and figure 18 visualize the sustained elevated concentrations of calcium and sulfate in the effluent of P2C1. The figures show cumulative mass of calcium and sulfate flushed from the column at each pore volume. If the cumulative mass flushed flattens out and stops increasing,

calcium and sulfate are not being flushed from the column due to  $\text{CaSO}_4$  dissolution. Every column except for P2C1, the column with sediment from borehole 859, shows either a flat or decreasing cumulative calcium and sulfate mass flushed. P2C1 consistently flushes calcium and sulfate from the column throughout the whole experiment. While this alone does not indicate that dissolution is the dominant mechanism of uranium mobility, it shows that  $\text{Ca-SO}_4$  dissolution is occurring in the column.

The same figure was created for uranium mass flushed. The cumulative uranium mass flushed from the column at each pore volume is shown in figure 19. All columns except P2C1 flushed a large initial mass of uranium in the first pore volume, indicative of sorption being the dominant mechanism of uranium mobility, as the dried sediment comes into equilibrium with the influent water (Johnson et al. 2022). P2C1 follows the trends that would be expected from dissolution controlling uranium mobility. There is no large initial uranium spike, instead uranium is steadily flushed from the column around the same rate that calcium and sulfate is.



**Fig. 19** - Cumulative uranium mass flushed from the columns at different pore volumes. P2C1, column with borehole 859 sediment, continuously flushed uranium from the column.

To better quantify the relationship between the Ca-SO<sub>4</sub> mass flushed from the column and the uranium mass flushed, the slope of each pore volumes cumulative mass flushed was calculated for each column. Table 8 summarizes the slope of the cumulative mass of uranium, sulfate and calcium flushed from each column. A larger slope indicates that flushing was sustained throughout the experiment. A smaller or negative slope indicates that most or all the mass was flushed in the first pore volumes. The P2C1 uranium, calcium and sulfate slopes indicate that flushing of uranium, calcium and sulfate occurred throughout the whole experiment.

**Table 8** – Slopes of each Net mass flushed from each column uranium, sulfate and calcium data

Column	Uranium	Sulfate	Calcium
P1C1	0.008	0.000	-0.002
P1C2	0.005	0.001	-0.006
P1C3	0.010	0.000	-0.003
P1C4	0.006	0.000	-0.005
P2C1	0.027	0.116	0.046
P2C2	0.007	-0.003	-0.002

The correlation between the cumulative uranium mass flushed slopes and the cumulative calcium and sulfate mass flushed slopes is summarized in table 9. To calculate the correlation between the slopes, Excels CORREL function was utilized. The CORREL function calculates a correlation coefficient that tells you how strongly two variables are related to each other. The correlation coefficient is a value between -1 and +1. A correlation of +1 indicates a perfect positive correlation. A correlation of -1 indicates a perfect negative correlation.

**Table 9** - The correlation between both SO<sub>4</sub> and Ca to uranium. The K<sub>d</sub> Ratio between Influent 2 and Influent 1 for each column.

Column	U and SO <sub>4</sub>	U and Ca Correlation	K <sub>d</sub> Ratios
	Correlation		INF 2 / INF 1
P1C1	0.10	-0.88	4.8
P1C2	0.93	-0.90	10.8
P1C3	-0.49	-0.88	7.7
P1C4	0.67	-0.89	14.4
P2C1	0.98	0.99	1.0
P2C2	-0.88	-0.69	17.0

Both the U-SO<sub>4</sub> and U-Ca correlation coefficients are nearly perfect positive correlated for P2C1. This is not the case for other columns. The correlation between U-SO<sub>4</sub> and U-Ca is weak for columns with 860 and 1020 sediment. The flushing of uranium in P2C1 is correlated strongly with the flushing of both calcium and sulfate from the column. The flushing of uranium in every other column is not dictated by the flushing of calcium and sulfate. Uranium is flushed from these columns regardless of what happens to calcium and sulfate.

Table 9 also summarizes the partition coefficient ratios between the first and second influents. The partition coefficient, K<sub>d</sub>, is the ratio of the contaminant concentration associated with the solid to the contaminant concentration in the surrounding aqueous solution when the solution is at equilibrium (EPA. 1999). If sediment has little to no ability to slow uranium mobility, uranium would travel conservatively in the direction and at the same velocity as natural groundwater flow. In this case, the partition coefficient would be an extremely low value. A very small amount of uranium would be associated with the solid sediment and the vast majority would be in the surrounding aqueous solution. The ratios between the first influents K<sub>d</sub> value and the second influents K<sub>d</sub> value indicates if desorption or dissolution is the dominant



mechanism of uranium mobility. A ratio larger than 1 indicates that uranium traveled through the column more conservatively during the first influent and the sediment retarded the mobility of uranium to a greater extent during the second influent. In every column except for P2C1 the partition coefficient ratios greatly exceeded 1. This is indicative of desorption dominated uranium mobility because the dried sediment is coming to equilibrium with the first influent water, flushing a larger mass of uranium from the column. Equilibrium has been reached by the second influent and the  $K_d$  value decreases. The partition coefficient ratio of 1.0 for P2C1 is indicative of dissolution as the dominant mechanism of uranium mobility. The desorption of uranium from the solid phase is not occurring in this column to any great extent because most uranium is associated with the precipitated  $\text{Ca-SO}_4$  minerals in the sediment. No sorption equilibration between the dry sediment and water is taking place so there is no large spike of uranium flushed from the column during influent 1. The smaller initial uranium flushing leads a larger influent 1  $K_d$  value. Uranium flushing in P2C1 does not decrease throughout the experiment. As long as there is precipitated  $\text{Ca-SO}_4$  to dissolve, the associated uranium will flush with the calcium and sulfate. This sustained uranium mass flushing leads to no change in  $K_d$  values between influents.

The presence of calcium and sulfate in only 859 sediment, the sustained flushing of calcium and sulfate from the sediment throughout the experiment, the correlation between the uranium and  $\text{Ca-SO}_4$  flushing, and the partition coefficient ratio between influent 1 and influent 2 show that there is more than one mechanism of uranium transport at the FTA. Desorption dominates uranium mobility at the center of the uranium plume in the FTA at both 860 and 1020. At borehole 859, near the head of the plume upgradient of 860 and 1020, the dissolution of  $\text{Ca-SO}_4$  minerals is limiting uranium mobility.

*Applicability of alkalinity enhanced uranium flushing at other contaminated aquifers.*

To fully examine alkalinity enhanced flushing as a remediation approach, the applicability of enhanced uranium flushing at other contaminated aquifers needs to be studied. Points of concern while investigating the applicability include the groundwater velocity of the contaminated aquifer, the dominant mechanism of uranium mobility and the aquifer discharge location.

The groundwater velocity of a contaminated aquifer is the most important factor in determining the time required to flush an aquifer of uranium. The faster groundwater flows through the aquifer, the faster the contaminant will leave the aquifer (Abiye et al. 2017). The groundwater flow at the FTA is relatively fast at around 1 ft/day (Dam et al. 2015). Groundwater flow throughout the site varies from around 0.5 ft/day – 1.0 ft/day and can vary temporally (Dam et al. 2015). Groundwater velocities in surficial alluvial aquifers have a wide range of values. The groundwater gradient and hydraulic conductivity both play important roles that can change flow velocities temporally and spatially (Hall et al. 1991). Common ranges for groundwater velocities in aquifers similar to the Riverton site and many other DOE-LM sites are between 0.1 ft/day – 3.0 ft/day (Walker et al. 2018). In contaminated aquifers that have a lower groundwater velocity than the Riverton site, alkalinity enhanced flushing of uranium will be less effective. Therefore the applicability as a remediation approach is lowered as groundwater velocity decreases.

The dominant mechanism of uranium mobility needs to be established if alkalinity is to be used as a remediation approach. Alkalinity enhances the desorption and mobility of uranium through the formation of dissolved calcium-carbonate-uranyl complexes, which are unlikely to adsorb to minerals (Davis et al. 1998). As concentrations of calcium-carbonate-uranyl species

increase in the water, uranyl concentrations decrease, and uranium desorption occurs. If uranium adsorption is not the dominant mechanism retarding the mobility of uranium, then alkalinity and calcium enhanced flushing is not an applicable remediation strategy.

The location of the contaminated aquifer discharge is an important factor in deciding if alkalinity is a viable remediation approach. The contaminated aquifer at the Riverton site discharges into the Little Wind River. Uranium concentrations immediately above and below gradient show that the discharge from the contaminated aquifer does not increase the amount of uranium in the river (Dam et al. 2015). The Little Wind River dilutes the uranium from the contaminated aquifers to below detectable limits (DOE. 2016). In contaminated aquifers where dilution through the aquifer discharge is not a viable remediation approach, alkalinity enhanced flushing is not applicable.

Alkalinity as a remediation approach is a remediation technique that may be feasible at sites throughout the United States. Defining and understanding the different parameters that effect uranium flushing at specific sites is necessary before the decision to use alkalinity enhanced flushing is made.

## Conclusion

The original Riverton CSM is not completely accurate. The site is not flushing as originally predicted and concentrations are still high at the FTA. Alkalinity enhanced flushing is a relatively novel remediation approach that could potentially decrease the flushing time required for the FTA. In laboratory experiments, increasing the alkalinity of influent water increases the flushing of uranium contaminated sediment at the FTA.

Our column experiments show there is a substantial increase of mass flushed from the columns, 46% more mass flushed, when alkalinity is added to the influent compared to when there is only background concentrations. This increase in uranium mass flushed is caused by higher concentrations of calcium and carbonate in the water. When uranium desorbs from the sediment and forms uranyl the calcium and carbonate complexes to create calcium-carbonate-uranyl species leading to more uranium desorption. This increase in mass flushing from the laboratory column experiments can be extrapolated to the FTA. Increasing alkalinity decreased the time required to flush uranium to below the MCL by 46%. While this decrease in time required to flush is promising, this revised flushing time is more of a lower bound than an actual field flushing time due to inherent difficulties in upscaling results from laboratory experiments to field sites.

If this remediation approach is to be considered at other sites, the dominant mechanism of uranium mobility in the contaminated aquifer needs to be determined. Alkalinity enhances the desorption of uranium from contaminated sediments, if desorption is not the dominant mobilizer of uranium, alkalinity will not enhance uranium flushing. At the FTA the dominant mechanism of uranium mobility is desorption.  $\text{Ca-SO}_4$  minerals have been found in the western part of the FTA, where these minerals are present dissolution of these minerals controls uranium mobility.

This control is likely due to trace amounts of co-precipitated uranium that is released with the mineral dissolution. If the FTA contained a substantial amount of these Ca-SO<sub>4</sub> minerals, dissolution would dominate uranium mobility and alkalinity would not enhance uranium mobility at the site.

While alkalinity enhanced uranium flushing has been shown to be a promising remediation approach in the lab, field scale alkalinity enhanced flushing of uranium contaminated sediments has many limitations and is still relatively untested. Future field scale experiments and complex geochemical modeling need to be completed before alkalinity enhanced flushing could be considered a viable remediation approach.

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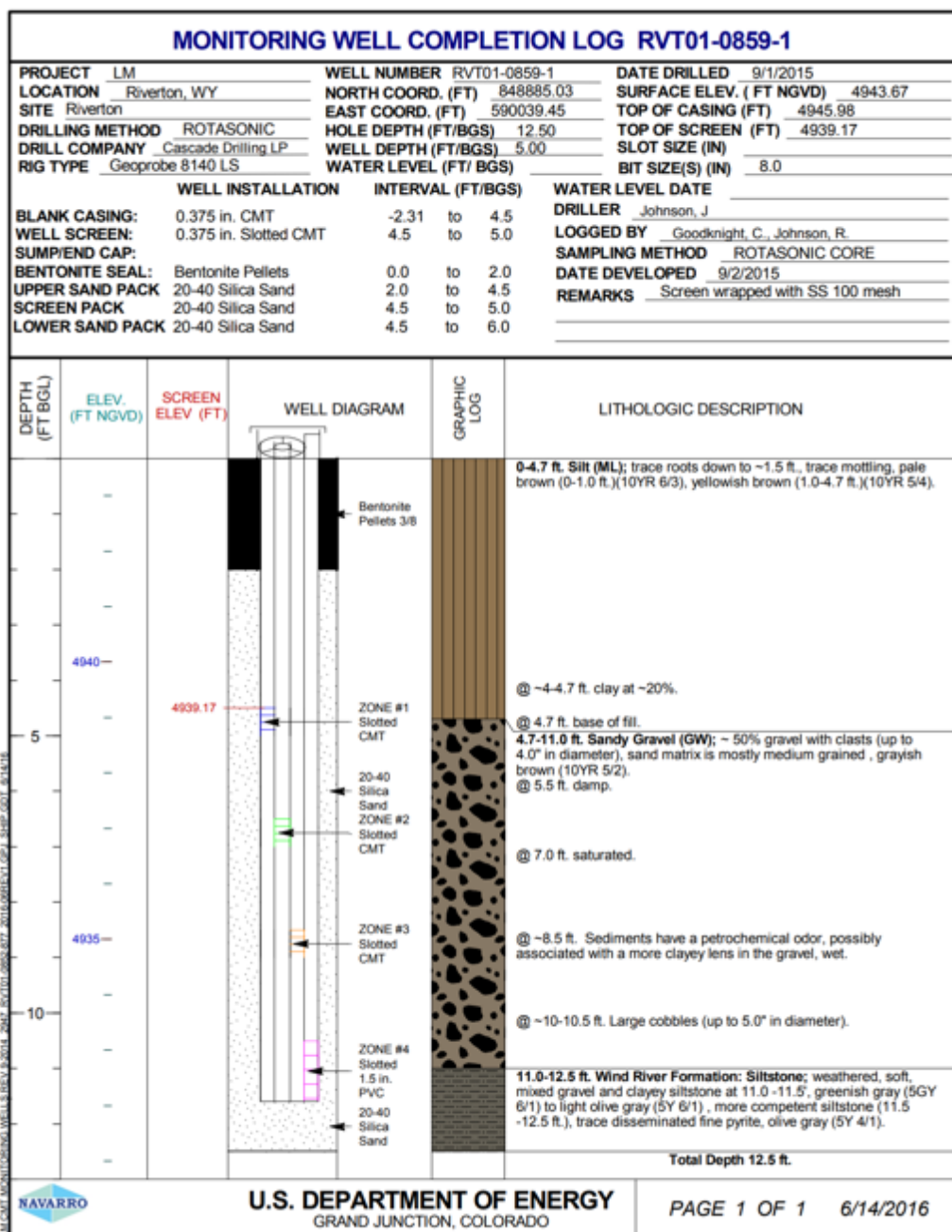
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## Appendix A – Well boring Logs for wells of interest.



Appendix A 1 - Well 859 Bore log. DOE - LM

<b>MONITORING WELL COMPLETION LOG RVT01-0860-4</b>					
<b>PROJECT</b> LM		<b>WELL NUMBER</b> RVT01-0860-4		<b>DATE DRILLED</b> 8/30/2015	
<b>LOCATION</b> Riverton, WY		<b>NORTH COORD. (FT)</b> 848283.00		<b>SURFACE ELEV. ( FT NGVD)</b> 4941.73	
<b>SITE</b> Riverton		<b>EAST COORD. (FT)</b> 590879.17		<b>TOP OF CASING (FT)</b> 4944.38	
<b>DRILLING METHOD</b> ROTASONIC		<b>HOLE DEPTH (FT/BGS)</b> 18.00		<b>TOP OF SCREEN (FT)</b> 4925.73	
<b>DRILL COMPANY</b> Cascade Drilling LP		<b>WELL DEPTH (FT/BGS)</b> 17.00		<b>SLOT SIZE (IN)</b> 0.010	
<b>RIG TYPE</b> Geoprobe 8140 LS		<b>WATER LEVEL (FT/ BGS)</b>		<b>BIT SIZE(S) (IN)</b> 8.0	
<b>WELL INSTALLATION</b>		<b>INTERVAL (FT/BGS)</b>		<b>WATER LEVEL DATE</b>	
<b>BLANK CASING:</b> 1.5 in. PVC Sch 40		-2.65 to 16.0		<b>DRILLER</b> Johnson, J	
<b>WELL SCREEN:</b> 1.5 in. Slotted PVC		16.0 to 17.0		<b>LOGGED BY</b> Goodknight, C., Johnson, R.	
<b>SUMP/END CAP:</b> 1.5 in. PVC Sch 40		17.0 to 17.1		<b>SAMPLING METHOD</b> ROTASONIC CORE	
<b>BENTONITE SEAL:</b> Bentonite Pellets		0.0 to 2.0		<b>DATE DEVELOPED</b> 9/2/2015	
<b>UPPER SAND PACK</b> 20-40 Silica Sand		15.0 to 16.0		<b>REMARKS</b>	
<b>SCREEN PACK</b> 20-40 Silica Sand		16.0 to 17.0			
<b>LOWER SAND PACK</b> 20-40 Silica Sand		17.0 to 18.0			

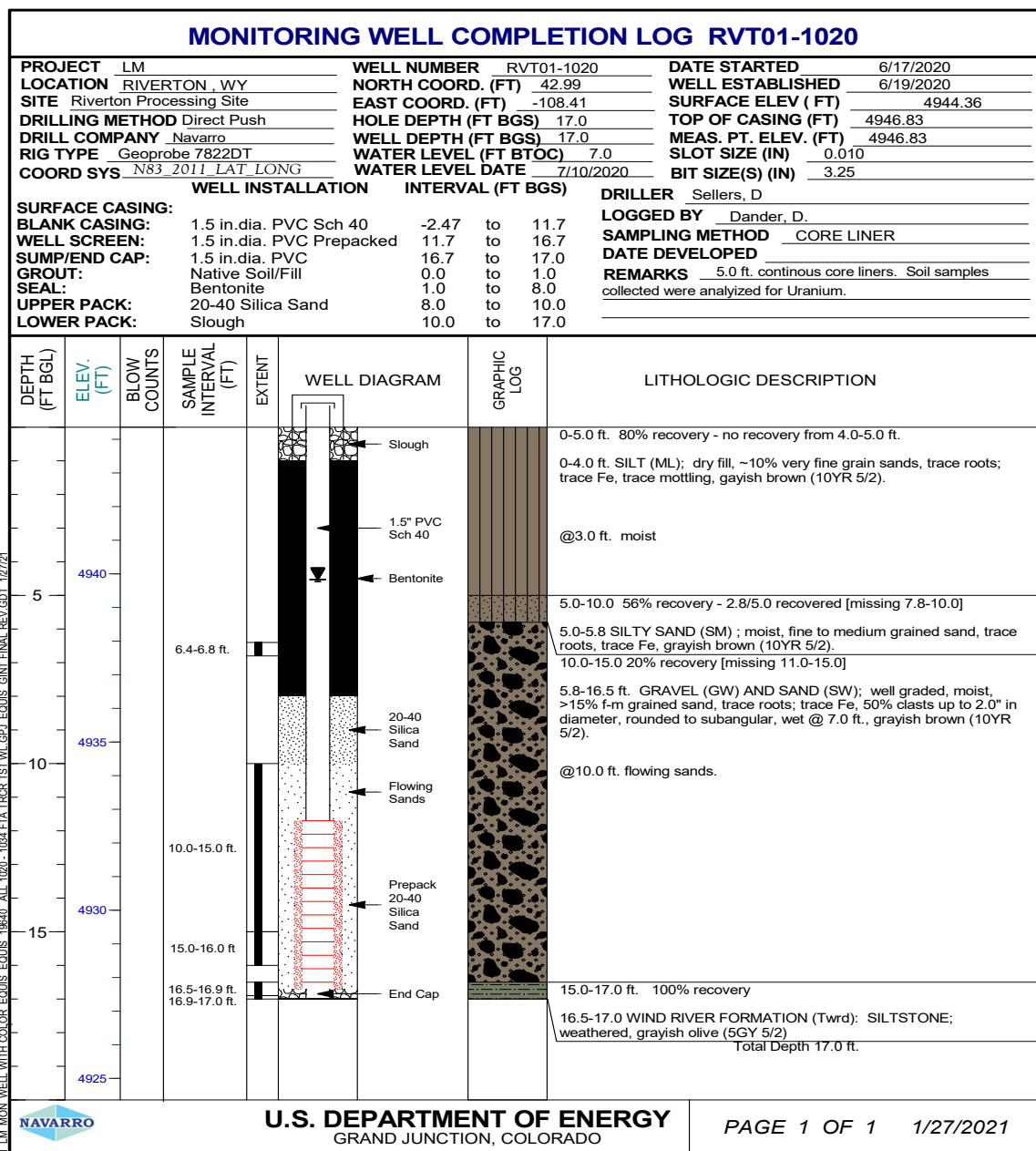
  

DEPTH (FT BGL)	ELEV. (FT NGVD)	SCREEN ELEV (FT)	WELL DIAGRAM	GRAPHIC LOG	LITHOLOGIC DESCRIPTION
					<b>0-4.8 ft. Silt (ML);</b> dry fill, ~10% very fine grained sand, trace roots down to ~1.5 ft., light brownish gray (10YR 6/2).  @ 2.5 ft. sediments are damp, ~3.0 ft. grayish brown (10YR 5/2).  @ 4.8 ft. base of fill. <b>4.8-6.0 ft. Silty Gravel (GM);</b> ~30% gravel with clasts (up to 2.0" in diameter), silt matrix is pale brown (10YR 6/3), dry. <b>6.0-10.2 ft. Sandy Gravel (GW);</b> ~40-50% gravel with clasts (up to 3.0" in diameter), sand matrix is fine to medium grained, grayish brown ( 10YR 5/2).  @ ~8.3 ft. damp. @ ~10.0 ft. saturated. <b>10.2-12.5 ft. Sand (SP);</b> ~90% sand, mostly medium to fine grained, ~10% pebbles (up to 1.0" in diameter), brown (7.5YR 5/2).  <b>12.5-17.0 ft. Sandy Gravel (GW);</b> ~ 50-60% gravel with clasts (up to 4.0" in diameter), sand matrix is fine to medium grained, sand is grayish brown (10YR 5/2).  @ ~15.0-17.0 ft. very coarse cobbles near base of alluvium (up to 5.0- 6.0" in diameter), sand matrix is mostly medium grained , gray (10YR 5/1).  <b>17.0-18.0 ft. Wind River Formation: Siltstone;</b> @ 17.0-17.5 ft. is weathered and greenish gray (5GY 6/1), @ 17.5-18.0' is slightly weathered and medium gray (N5).  <b>Total Depth 18.0 ft.</b>

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Appendix A 2 – 860 Bore Log



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Appendix A 2 - Well 1020 Bore log. DOE - LM

## Appendix B – Column influent, effluent and general chemistry

Appendix B 1 - Overview of each influent water analysis completed at the DOE - LM science lab

Parameter	Units	Influent							
		Phase 1 Well 710	Phase 1 710 w alkalinity	Phase 1 Column 4 710 added Alk	Phase 2 Syn710 High Sulfate	Phase 2 Syn 710	Phase 2 Syn710 low alk	Phase 2 Syn710 Alk	Phase 2 Syn710 High alk
pH		8	8	8.1	7.46	8.14	7.67	7.96	8.24
Sp. Conductance	(uS/cm)	###	###	2780	2070	723	2030	4510	7840
Alkalinity	(mg/L as CaCO3)	###	###	211	165	94	918	2512	5014
U	(ug/L)	7	6	18.4	0.2	0.2	0.2	0.4	0.4
Cl	(mg/L)			1625	120	100	100	77	78
NO3	(mg/L)			5.8	0.5	0.5	0.5	0.5	0.5
SO4	(mg/L)				960	170	170	134	141
Ca	(mg/L)	109.6	67.97		355.6	74.24	41.16	68.95	62.67
Mg	(mg/L)	27	19		89.45	18.67	17.51	16.7	17.56
Na	(mg/L)	75.69	697.0		78.19	42.9	473.2	1229	2315
SiO2	(mg/L)	16.03	15.04		0.18	0.18	0.18	0.18	0.18
K	(mg/L)	2.195	3.476		4.848	2.128	2.468	2.068	2.663
Se	(mg/L)	0	0		0.2	0.2	0.2	0.2	0.2
Mo	(mg/L)	0	0		0.02	0.02	0.02	0.02	0.02
Fe	(mg/L)	0	0		0.02	0.02	0.02	0.02	0.02
Mn	(mg/L)	0	0		0.02	0.02	0.02	0.02	0.02
V	(mg/L)	0	0		0.04	0.04	0.04	0.04	0.04
Sr	(mg/L)	1	0		0.186	0.16	0.16	0.16	0.16

Well	Uranium Solid Phase (mg/kg)
859 Column Sediment	4.6
860 Column Sediment	2.4
1020 Column Sediment	6.3
Sand and Gravel Background	0.5
Silt Background	1.5

Appendix B 2 - Column sediment solid phase data. Completed at the DOE - LM ESL

# Riverton Column Testing

Column conditions:  
Plexiglass 2" by 6" columns filled with soil. Peristaltic pump, with upward flow @ ~0.147 mL/min. Columns filled with 1 PV allowed to sit 24 hrs. Influent water continuously pumped @ 0.147 mL/min. One PV = 83.1

Column 1: RVT 860 15-15.5' and 15.5-17' combined. PV = 83.16 mL. Soil Weight = 432.3 g. Soil Volume = 261.5 mL. Soil height= 12.9 cm. **Soil dry density** = 1.65 g/mL

Test NDate	PV	VolnCum. (mL)	Vol (mL)	ActuaCum. Vol	pH	Sp. ConductuORP (us/cm)	Temperat (°C)	Alkalinity U (mg/L as CaCO3)	Cl (mg/L)	NO3 (mg/L)	SO4 (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	SiO2 (mg/L)	K (mg/L)	Se (mg/L)	Mo (mg/L)	Fe (mg/L)	Mn (mg/L)	V (mg/L)	Sr (mg/L)	CommCharge Balan	AntionCatio %				
Influent water: Well 710 7/2/2020																												
1	7/8/20	1	76	94	0.91	1.01	8.39	3440	136.6	22.4	198.2	2100	34.9	0.5	1033	385.0	73.2	461.3	16.76	17.80	0.22	0.28	0.02	0.16	0.04	1.55	26.5	45.8
1		2	78	172	0.94	1.95	8.38	2350	145.2	22.3	220	944	49	0.5	1887	218.4	38.9	339.1	16.98	13.13	0.2	0.18	0.02	0.09	0.04	0.91	45.1	29.2
1		3	77	249	0.93	2.87	8.38	1383	194.3	22.7	212.6	471	22.5	0.5	441	127.7	20.6	158.8	16.50	9.710	0.2	0.06	0.02	0.05	0.04	0.56	14.1	15.2
1		4	78	327	0.94	3.81	8.33	977	205	22.2	209	242	20.5	0.5	239	112.9	17.4	77.63	17.46	7.846	0.2	0.02	0.02	0.04	0.04	0.51	9.74	10.6
1		5	77	404	0.93	4.74	8	773	207	22.4	188.6	184	16	0.5	202	94.38	16.3	62.82	17.99	7.367	0.2	0.02	0.02	0.02	0.04	0.47	8.44	8.97
1		6	79	483	0.95	5.69	8.18	756	221	22.5	177.8	149	17	0.5	185	84.57	16.2	63.26	18.72	7.198	0.2	0.02	0.02	0.02	0.04	0.46	7.9	8.49
1		7	79	562	0.95	6.64	8.21	757	221	22.6	185.6	135	17	0.5	175	83.60	15.9	62.30	18.26	6.903	0.2	0.02	0.02	0.02	0.04	0.44	7.84	8.36
1		8	80	642	0.96	7.60	8.25	757	223	22.5	189.8	116	17	0.5	170	82.25	16.1	60.87	18.32	6.887	0.2	0.02	0.02	0.02	0.04	0.45	7.82	8.25
1		9	80	722	0.96	8.56	8.31	758	213	22.5	199.8	96	17	0.5	167	86.66	16.2	61.53	18.41	6.716	0.2	0.02	0.02	0.03	0.04	0.45	7.96	8.5
1		10	81	803	0.97	9.54	8.35	767	204	22.6	203.4	110	17	0.5	165	88.69	15.2	61.07	18.41	6.646	0.2	0.02	0.02	0.03	0.04	0.41	7.99	8.5
1		11	80	883	0.96	10.50	8.41	740	197.8	22.6	210.2	86	16	0.5	163	91.62	15.5	61.43	18.76	6.602	0.2	0.02	0.02	0.03	0.04	0.41	8.06	8.68
1		12	81	964	0.97	11.47	8.34	702	220	24.3	211.2	71	17	0.5	161	91.61	15.7	60.79	17.84	6.409	0.2	0.02	0.02	0.03	0.04	0.4	8.06	8.67
1		13	82	1046	0.99	12.46	8.21	772	199.6	23.3	189	66	16	0.5	163	90.71	15.9	62.05	18.87	6.318	0.2	0.02	0.02	0.03	0.04	0.41	7.63	8.69
Influent water: Well 710 7/2/2020 w/ 2500 mg/L CaCO3																												
1		14	82	1128	0.99	13.44	8.04	1195	217	23.2	537	98	16	0.5	160	136.2	29.1	125.3	20.96	7.890	0.2	0.02	0.02	0.04	0.04	0.63	14.5	14.8
1		15	82	1210	0.99	14.43	8.05	622	200	22.5	986	105	16	0.5	161	43.90	30	450.8	20.46	10.42	0.2	0.02	0.02	0.02	0.04	0.51	23.5	24.5
1		16	81	1291	0.97	15.40	8.32	2200	195.4	22.5	1230	93	17	0.5	162	26.51	17.7	597.7	16.98	9.333	0.2	0.02	0.02	0.02	0.04	0.33	28.5	29
1		17	81	1372	0.97	16.38	8.58	2330	208	22.7	1299	76	16	0.5	161	10.12	12.4	654.0	15.65	8.205	0.2	0.02	0.02	0.02	0.04	0.22	29.8	30.2
1		18	79	1451	0.95	17.33	8.57	2530	199.5	22.7	1350	68	18	0.5	162	10.13	9.3	695.8	15.47	7.162	0.2	0.02	0.02	0.02	0.04	0.2	30.9	31.7
1		19	80	1531	0.96	18.29	8.51	2560	194.7	22.7	1373	70	18	0.5	161	15.38	8.26	692.6	14.70	6.557	0.2	0.02	0.02	0.02	0.04	0.21	31.3	31.7
1		20	80	1611	0.96	19.25	8.45	2040	185.4	23.4	1362	57	18	0.5	160	7.713	6.94	715.6	14.84	6.373	0.2	0.02	0.02	0.02	0.04	0.17	31.1	32.2
1		21	80	1691	0.96	20.21	8.49	2580	197.3	23.3	1379	53	18	0.5	160	12.03	6.67	715.6	14.53	6.149	0.2	0.02	0.02	0.02	0.04	0.18	31.4	32.4
1		22	80	1771	0.96	21.18	8.64	2460	267	24.3	1397	47	25	0.5	160	9.315	5.99	727.3	14.87	17.68	0.2	0.02	0.02	0.02	0.04	0.17	32	33

Column conditions:  
Plexiglass 2" by 6" columns filled with soil. Peristaltic pump, with upward flow @ ~0.15 mL/min. Columns filled with 1 PV allowed to sit 24 hrs. Influent water continuously pumped @ 0.147 mL

Column 2: RYT 860 15-15.5 and 15.5-17" combined. PV = 79.8 mL. Soil Weight = 415.3 g. Soil Volume = 261.5 mL. Soil height= 12.9 cm. **Soil dry density** = 1.59 g/mL.

Test ID	Date	PV	VoluCum, ActuCum, pH (mL)	Sp. Cond ORP (uS/cm)	Tempera/AlkalinitU (°C)	Cl NO3 SO4 Ca Mg Na SiO2 K Se Mo Fe Mn V Sr CommChange	Balance																						
Influent water: Well 710 7/2/2020 w/ 2500 mg/L CaCO3																													
2	7/8/20	1	74	0.93	0.93	8.03	5370	217	22.7	832	2760	58	0.5	2098	326.8	79.2	1036	22.59	24.88	0.28	0.3	0.02	0.07	0.04	1.44	62	68.5	5.0	
2		2	74	148	0.93	1.86	8.24	3330	196.7	22.7	1154	1120	27.7	0.5	853	157.7	35.4	760.3	19.88	20.53	0.2	0.11	0.02	0.03	0.04	0.77	41.6	44.4	3.2
2		3	74	222	0.93	2.78	8.2	2800	199.4	22.1	1141	396	22	0.5	411	38.98	19	689.7	18.20	13.34	0.2	0.03	0.04	0.02	0.04	0.4	32	33.9	2.8
2		4	74	296	0.93	3.71	8.36	2720	219	22.2	1242	271	21	0.5	274	30.64	13.6	696.7	16.15	11.57	0.2	0.02	0.03	0.02	0.04	0.32	31.1	33.2	3.3
2		5	74	370	0.93	4.64	8.56	2500	194.9	22.9	1334	187	18	0.5	237	6.900	10.3	704.5	15.76	10.57	0.2	0.02	0.02	0.02	0.04	0.22	32.1	32.1	0.0
2		6	75	445	0.94	5.58	8.89	2640	178.6	22.9	1372	138	18	0.5	213	4.814	8.43	738.4	16.07	10.13	0.2	0.02	0.02	0.02	0.04	0.18	32.4	33.3	1.4
2		7	77	522	0.96	6.54	8.88	2670	171.7	23	1390	108	18	0.5	196	3.565	7.18	702.4	14.85	8.469	0.2	0.02	0.02	0.02	0.04	0.17	32.4	31.5	1.4
2		8	78	600	0.98	7.52	8.86	2650	174.6	23	1420	91	18	0.5	183	3.723	6.29	707.1	14.73	8.047	0.2	0.02	0.02	0.02	0.04	0.17	32.7	31.7	1.6
2		9	77	677	0.96	8.49	8.77	2610	172	23	1416	78	18	0.5	178	5.401	5.62	691.6	15.04	7.299	0.2	0.02	0.02	0.02	0.04	0.17	32.5	31	2.4
2		10	78	755	0.98	9.46	8.74	2680	170.8	23.1	1440	66	18	0.5	174	6.776	5.18	697.6	14.77	6.841	0.2	0.02	0.02	0.02	0.04	0.17	32.9	31.3	2.6
2		11	78	833	0.98	#####	8.67	2640	172.1	23.1	1442	61	18	0.5	169	8.864	4.84	688.7	14.58	6.812	0.2	0.02	0.02	0.02	0.04	0.17	32.9	31	3.0
2		12	78	911	0.98	#####	8.58	2630	180.6	23.1	1430	56	18	0.5	168	11.45	4.62	704.8	14.28	6.389	0.2	0.02	0.02	0.02	0.04	0.17	32.6	31.8	1.3
Influent water: Well 710 7/2/2020																													
2		13	78	989	0.98	#####	8.69	2550	193.7	23.1	1380	61	17	0.5	159	7.183	4.19	672.5	14.09	6.091	0.2	0.02	0.02	0.02	0.04	0.16	31.4	30.1	2.1
2		14	77	1066	0.96	#####	8.61	1924	182.4	23.3	864	49	16	0.5	177	7.499	1.92	469.4	13.04	4.151	0.2	0.02	0.02	0.02	0.04	0.16	21.4	21.1	0.9
2		15	78	1144	0.98	#####	8.75	1161	172.4	22.7	464	47	17	0.5	179	5.033	0.77	284.5	14.12	6.14	0.2	0.02	0.19	0.02	0.04	0.16	13.5	12.8	2.8
2		16	78	1222	0.98	#####	8.82	1031	162.7	22.8	331	40	18	0.5	179	2.940					0.2	0.02	0.02	0.02	0.04	0.16	10.9	10.8	0.5
2		17	78	1300	0.98	#####	8.86	962	160.4	22.9	284	39	18	0.5	178	2.223					0.2	0.02	0.02	0.02	0.04	0.16	9.9	9.67	1.2
2		18	78	1378	0.98	#####	8.66	922	179.6	22.7	272	38	18	0.5	177	2.245					0.2	0.02	0.02	0.02	0.04	0.16	9.64	8.92	3.9
2		19	78	1456	0.98	#####	8.86	959	161.4	22.7	272	37	18	0.5	178	3.437					0.2	0.02	0.02	0.02	0.04	0.16	9.66	9.29	2.0
2		20	77	1533	0.96	#####	8.14	585	231	23.3	215	41	13	0.5	177	46.00					0.2	0.02	0.02	0.02	0.04	0.16	8.5	7.1	9.0
2		21	78	1611	0.98	#####	8.28	797	224	23.3	216	33	18	0.5	177	66.61					0.2	0.02	0.02	0.02	0.04	0.16	8.52	6.65	12.3
2		22	43	1654	0.54	#####	8.16	749	227	23.3	228	46	28	0.5	177	74.12					0.2	0.02	0.02	0.02	0.04	0.16	8.76	6.69	13.4

# Riverton Column Testing

Column conditions:  
Plexiglass 2" by 6" columns filled with soil. Peristaltic pump, with upward flow @ ~0.15 mL/min. Columns filled with 1 PV allowed to sit 24 hrs. Influent water continuously pumped @ 0.155 mL/min

Column 3: RVT 1020 15-15.5' and 15.5-16' and 16-16.5' combined. PV = 95.93 mL. Soil Weight = 436.2 g. Soil Volume = 261.5 mL. Soil height= 12.9 cm. **Soil dry density = 1.67 g/mL**

Test N	Date	PV	VoluCum. (mL)	ActuaCum. (mL)	pH	Sp. ConduORP (uS/cm)	Temp (°C)	Alkalinity U (mg/L as CaCO3)	Cl (mg/L)	NO3 (mg/L)	SO4 (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	SiO2 (mg/L)	K (mg/L)	Se (mg/L)	Mo (mg/L)	Fe (mg/L)	Mn (mg/L)	V (mg/L)	Sr (mg/L)		
Influent water: Well 710 7/2/2020																								
3	7/8/21	94	94	0.98	0.98	8.45	2960	174.1	23.1	226.8	3140	42	0.5	1485	273	32.49	468.6	10.27	9.552					
3	2	94	188	0.98	1.96	8.53	1530	1715	23.2	220.4	1300	27.8	0.5	520	91.4	10.29	250.8	9.507	5.311	0.04	0.1	0.02	0.04	0.16
3	3	93	281	0.97	2.93	8.23	1120	196.6	22.5	210	693	23	0.5	293	93.8	11.45	140.4	11.27	5.221	0.03	0.03	0.02	0.04	0.16
3	4	94	375	0.98	3.91	8.31	915	178.2	22.3	210.4	439	21	0.5	203	88.61	11.01	85.84	11.54	4.238	0.02	0.02	0.02	0.04	0.16
3	5	94	469	0.98	4.89	8.28	731	215	23.2	188.4	251	17	0.5	171	76	11.76	65.61	13.49	4.266	0.02	0.02	0.02	0.04	0.16
3	6	94	563	0.98	5.87	8.31	750	202	23.2	194.2	220	17	0.5	167	81.67	12.30	60.67	13.71	3.926	0.02	0.02	0.02	0.04	0.16
3	7	94	657	0.98	6.85	8.34	743	201	23.3	197.6	140	17	0.5	166	82.58	12.64	57.90	14.06	3.707	0.02	0.02	0.02	0.04	0.16
3	8	95	752	0.99	7.84	8.39	756	203	23.3	204.8	121	17	0.5	165	85.87	13.15	59.18	14.75	3.762	0.02	0.02	0.02	0.04	0.16
3	9	94	846	0.98	8.82	8.42	767	183.9	23.3	208	104	16	0.5	164	86.6	13.17	57.23	14.52	3.511	0.02	0.02	0.02	0.04	0.16
3	10	94	940	0.98	9.80	8.43	755	190.1	23.4	211.6	100	16	0.5	163	88.61	13.68	57.38	15.05	3.499	0.02	0.02	0.02	0.04	0.16
3	11	94	1034	0.98	10.8	8.4	766	186.5	23.4	216	80	16	0.5	163	85.57	14.38	57.09	14.88	3.367	0.02	0.02	0.02	0.04	0.16
3	12	97	1131	1.01	11.31	8.41	778	219	23.2	217.6	77	16	0.5	163	75.4	11.51	53.58	14.85	3.502	0.02	0.02	0.02	0.04	0.16
Influent water: Well 710 7/2/2020 w/ 2500 mg/L CaCO3																								
3	13	96	1227	1.00	12.27	8.02	1412	240	23.3	691	112	16	0.5	159	127.5	31.57	183.1	18.67	5.146	0.02	0.02	0.02	0.04	0.16
3	14	97	1324	1.01	13.24	8.23	2130	190.5	22.9	1150	100	16	0.5	163	26.71	21.71	513.4	15.64	6.568	0.02	0.02	0.02	0.04	0.16
3	15	97	1421	1.01	14.21	8.44	1120	183.8	23.1	1310	82	18	0.5	162	24.03	12.51	559.7	13.62	6.197	0.02	0.02	0.02	0.04	0.16
3	16	97	1518	1.01	15.18	8.6	2560	173.4	22.8	1384	60	18	0.5	162	12.31	6.148	644.3	12.68	5.011	0.02	0.02	0.02	0.04	0.16
3	17	97	1615	1.01	16.15	8.64	2530	172.5	22.8	1353	74	18	0.5	162	10.46	8.436	644.5	13.05	5.519	0.02	0.02	0.02	0.04	0.16
3	18	95	1710	0.99	17.10	8.6	2380	238	24.2	1409	60	19	0.5	161	8.178	5.253	672.7	12.83	6.213	0.02	0.02	0.02	0.04	0.16
3	19	96	1806	1.00	18.06	8.65	2560	215	24.1	1410	54	18	0.5	161	9.432	4.342	673.8	12.66	4.622	0.02	0.02	0.02	0.04	0.16
3	20	96	1902	1.00	19.02	8.56	2630	221	24.1	1437	48	18	0.5	160	11.63	3.916	679.0	12.42	4.285	0.02	0.02	0.02	0.04	0.16
3	21	97	1999	1.01	19.99	8.52	2620	223	24.6	1433	46	18	0.5	160	10.72	3.439	670.2	11.99	4.042	0.02	0.02	0.02	0.04	0.16



# Riverton Column Testing

Column conditions:

Pieleglas 2" by 6' columns filled with soil. Peristaltic pump, with upward flow @ ~0.15 mL/min. Columns filled with 1 PV allowed to sit 24 hrs. Influent water continuously pumped @ 0.151 mL/min. One PV = 73.5 mL.

Column 4: RVT 102015-15.5' and 15.5-16' and 16-16.5' combined. PV = 73.5 mL. Soil Weight = 424.8 g. Soil Volume = 261.5 mL. Soil height= 12.9 cm. Soil dry density = 1.62 g/mL.

Test N Date	PV	Volume Cum. V/Actual Cum. (mL)	pH	Sp. Conductivity (uS/cm)	ORP (mV)	Temperature (°C)	Alkalinity as CaCO <sub>3</sub> (mg/L)	Cl (mg/L)	NO <sub>3</sub> (mg/L)	SO <sub>4</sub> (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	SiO <sub>2</sub> (mg/L)	K (mg/L)	Se (mg/L)	Mo (mg/L)	Fe (mg/L)	Mn (mg/L)	V (mg/L)	Sr (mg/L)	CombiCharge Balance %							
Influent water- Well 710 7/2/2020 w/ 2500mg/L CaCO <sub>3</sub>	4	731/20	71	74	0.74	0.98	7.73	4750	202	22.8	835	3990	50	0.5	1743	81.81	36.26	877.95	21.15	11.36	249.46	1722.40	29.06	13.29	8.86	899.33	54.41	45.54	8.9
	1	71	142	0.74	1.72	7.92	3880	206	22.8	1089	2540	35	0.5	882	59.12	22.64	745.58	21.19	8.81	151.78	1053.17	4.64	3.56	8.52	494.67	41.14	37.47	4.7	
	2	72	214	0.75	2.47	8.54	2690	179.2	22.9	1294	1010	35	0.5	307	9.51	11.28	606.92	20.35	6.92	96.71	263.15	4.05	0.10	8.52	162.50	32.99	28.07	8.1	
	3	72	287	0.76	3.23	8.56	2570	177	22.9	1368	460	23	0.5	186	8.19	8.39	616.99	20.16	6.97	64.28	114.83	6.95	0.18	9.72	156.52	31.89	28.1	6.9	
	4	73	360	0.76	3.99	8.48	2580	185.5	22.9	1405	280	23	0.5	166	10.40	7.68	618.61	19.96	5.94	61.91	47.94	4.83	21.09	10.72	165.94	34.12	29.93	6.4	
	5	72	432	0.75	4.74	8.59	2630	192.8	23.9	1424	190	22	0.5	163	14.58	7.14	620.05	19.91	5.89	70.76	57.50	4.89	3.01	9.75	136.60	34.5	28.43	6.7	
	6	72	504	0.75	4.99	8.31	2630	192.8	23.9	1469	150	16	0.5	163	14.58	6.60	640.78	19.65	5.64	67.51	50.34	3.35	7.88	10.68	146.78	33.58	29.94	6.1	
	7	73	577	0.76	5.25	8.25	2660	200	22.9	1499	110	16	0.5	168	30.51	6.41	650.31	19.97	5.94	61.91	47.94	4.83	21.09	10.72	165.94	34.12	30.07	5.4	
	8	73	650	0.76	6.02	8.16	2660	205	23.2	1508	110	17	0.5	167	33.15	6.17	653.32	19.04	5.93	54.89	38.63	3.19	26.17	10.67	165.94	34.12	29.93	6.4	
	9	73	723	0.76	7.78	8.29	2670	211	22.6	1508	110	17	0.5	167	33.15	6.17	653.32	19.04	5.93	54.89	38.63	3.19	26.17	10.67	165.94	34.12	29.93	6.4	
	10	73	796	0.76	8.54	8.21	2680	203	22.7	1504	91	16	0.5	167	27.40	5.79	660.14	19.01	4.96	46.67	39.48	11.27	7.64	12.09	128.68	34.12	29.93	6.4	
	11	73	869	0.76	9.30	8.31	2680	197.3	23.2	1496	78	17	0.5	167	28.48	5.94	661.13	19.12	4.99	38.97	31.87	1.90	23.80	12.21	151.60	34.88	30.78	4.8	
Influent Water- Well 710 7/2/2020							7.66	853	185	9.6	212	6.40	22.67	0.50	152.67	88.00	22.77	61.73	16.13	2.23	0.02	0.02	0.02	0.04	0.04	0.53			
	13	72	941	0.75	10.05	8.32	2670	193.1	24.2	1499	73	16	0.5	167	12.92	5.65	656.56	20.11	4.97	37.38	32.04	16.19	4.34	12.72	117.76	33.72	29.78	4.7	
	14	73	1014	0.76	10.81	8.25	2160	190.3	24.2	1095	64	17	0.5	172	13.45	3.73	598.55	17.85	3.15	36.89	36.54	2.75	7.06	11.15	98.36	35.07	33.18	5.7	
	15	73	1087	0.76	11.57	8.49	1269	124.9	24.4	489	72	18	0.5	175	17.34	0.70	303.40	13.65	1.87	55.39	41.65	23.65	8.29	10.91	37.10	13.94	53.17	7.0	
	16	73	1160	0.76	12.33	8.51	999	100.8	24.1	313	76	18	0.5	174	43.3	0.70	199.09	14.46	1.88	63.10	44.85	48.55	4.30	14.47	21.10	10.94	53.63	7.4	
	17	73	1233	0.76	13.09	8.64	903	172	24.1	271	67	18	0.5	173	41.6	0.75	179.11	13.95	0.97	52.12	39.43	79.72	3.15	13.62	21.27	9.35	53.63	7.4	
	18	73	1306	0.76	13.85	8.55	876	185.6	24.1	271	57	18	0.5	171	11.46	2.96	163.27	16.93	1.16	37.75	31.24	13.88	3.35	13.56	63.91	9.059	52.86	6.2	
	19	73	1399	0.76	14.61	8.43	795	186.5	23.8	239	57	18	0.5	172	27.23	7.40	130.64	18.92	1.64	29.36	31.50	62.44	17.97	12.58	143.68	8.859	52.86	6.2	
	20	73	1452	0.76	15.38	8.56	820	191.1	23.7	232	52	18	0.5	172	11.03	11.15	113.45	20.08	1.91	17.80	29.10	7.52	30.34	8.69	218.74	8.859	52.86	6.2	
	21	73	1525	0.76	16.14	8.59	791	196.1	23.6	232	46	18	0.5	173	63.01	21.56	79.32	20.68	1.91	17.80	29.10	7.52	30.34	8.69	218.74	8.859	52.86	6.2	
	22	71	1596	0.74	16.88	8.17	576	186.4	23.9	100	44	18	0.5	177	57.62	21.42	63.14	20.68	1.91	17.80	29.10	7.52	30.34	8.69	218.74	8.859	52.86	6.2	
	23	71	1668	0.75	17.63	8.37	576	186.4	23.9	185	41	18	0.5	176	62.92	22.09	56.39	22.68	2.26	10.45	22.48	4.75	20.93	2.75	340.02	8.17	7.502	2.9	
	24	72	1740	0.75	18.38	8.37	793	192.4	23.6	181	39	18	0.5	178	62.92	24.17	55.35	22.68	2.05	10.89	24.68	4.75	20.93	2.75	341.02	8.17	7.502	2.9	
	25	72	1812	0.75	19.13	8.43	718	184.9	23.8	201	38	18	0.5	176	67.89	24.17	57.42	22.70	1.95	11.62	24.90	4.75	20.93	2.75	341.02	8.17	7.502	2.9	
	26	72	1884	0.75	19.88	8.48	716	176.4	23.7	205	36	18	0.5	176	68.42	26.16	55.62	22.31	1.57	10.52	23.96	2.21	34.44	2.78	342.32	8.78	6.036	1.5	
	27	73	1957	0.76	20.64	8.51	761	166.7	23.7	211	36	18	0.5	175	70.51	25.76	56.62	22.60	1.54	10.08	22.66	3.05	42.51	2.82	354.24	8.379	6.139	1.5	
	28	73	2030	0.76	21.40	8.51	762	168.4	23.7	215	34	18	0.5	174	70.66	26.59	50.22	22.63	1.54	8.87	22.80	70.55	46.74	2.91	359.67	8.439	7.937	3.1	

## Grand Junction Office Site Column Testing

**Column conditions:**

Plexiglass 2" by 6" columns filled with soil. Peristaltic pump, with upward flow @ ~0.144 mL/min. Columns filled with 1 PV allowed to sit 24 hrs. Influent water continuously pumped @ 0.0

Column 1: RVT Well 859 8.4-10 ft. PV=76 mL. Soil Weight = 474.0 g. Soil Volume = 261.5 mL. Soil height= 12.9 cm (6.0 in). **Soil dry density = 1.81 g/mL**

Test NDate	PV	Volurum Cur.	Actua Cum.	1 pH	Alkalinity U	Cl	NO3	SO4	Ca	Mg	Na	SiO2	K	Mo	Fe	Mn	V	Sr	CommCharge	Balance		
		(ml)			(mg/L as C (ug/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)		Anions	Cations %	
Influent water: 0.710 SPF High Sulfate																						
1	11/7/19	1	72	0.95	0.95	7.51	119	166	135	0.5	3763	522	34.9	1624	11.2	18.2	1.24	0.02	0.16	0.20	1.25	
1		2	67	139	0.88	1.83	7.33	80.2	172	117	0.5	2248	610	30.3	627	11	12.1	0.68	0.02	0.15	0.16	1.24
1		3	71	210	0.93	2.76	7.51	98.4	305	104	0.5	1808	681	43.8	235	12.7	9.36	0.53	0.02	0.17	0.15	1.34
1		4	71	281	0.93	3.70	7.72	123.8	422	103	0.5	1662	720	56.2	126	13.2	7.85	0.47	0.02	0.19	0.16	1.39
1		5	72	353	0.95	4.64	7.63	137.2	460	102	0.5	1693	720	67.3	99.8	13.2	7.2	0.42	0.02	0.20	0.16	1.35
1		6	72	425	0.95	5.59	7.2	151	500	102	0.5	1621	710	75.7	90.6	13.6	7.12	0.36	0.02	0.22	0.17	1.38
1		7	77	502	1.01	6.61	8.11	152	482	100	0.5	1786	715	80.3	91	14.6	7.4	0.31	0.02	0.23	0.18	1.37
Influent water: 0.710 SPF Low Sulfate																						
1		8	76	578	1.00	7.61	8.03	149.6	447	91	0.5	1606	701	83.1	87.4	14.1	6.96	0.23	0.02	0.24	0.17	1.32
1		9	78	656	1.03	8.63	7.98	134	393	79	0.5	1596	706	82	74	13.7	6.57	0.20	0.02	0.25	0.17	1.30
1		10	78	734	1.04	9.66	7.82	116	327	75	0.5	1585	696	78.4	59.8	13.5	5.98	0.15	0.02	0.24	0.16	1.15
1		11	79	813	1.03	10.70	7.7	106.2	284	74	0.5	2124	674	69.8	53.5	12.9	5.68	0.12	0.02	0.23	0.15	1.17
1		12	78	891	1.03	11.72	7.95	104.8	259	77	0.5	1481	704	53.9	49.3	13.9	5.71	0.09	0.02	0.22	0.16	1.13
Influent water: 0.710 SPF Low Sulfate with 1000mg/L CO3																						
1		13	77	968	1.01	12.74	7.9	118.5	259	77	0.5	1478	717	47.3	52.4	13.6	5.65	0.08	0.02	0.21	0.15	1.10
1		14	77	1045	1.01	13.75	7.89	420	451	77	0.5	1569	765	38.4	196	16.3	8.11	0.08	0.02	0.20	0.27	1.10
1		15	77	1122	1.01	14.76																
1		16	77	1199	1.01	15.78	7.69	704	464	77	0.5	1662	726	21.9	459	16.8	11.9	0.05	0.02	0.17	0.38	0.98
1		17	77	1296	1.01	16.79	7.76	727	395	83	0.5	1653	708	18.5	467	16.8	12.1	0.04	0.02	0.16	0.39	0.91
1		18	73	1349	0.96	17.75	7.85	604	338	78	0.5	1762	672	16.1	492	17.1	13.5	0.04	0.02	0.09	0.39	0.86
Influent water: 0.710 SPF Low Sulfate with 2500mg/L CO3																						
1		19	74	1423	0.97	18.72	7.83	681	323	77	0.5	1792	671	13.9	511	17.5	13.3	0.03	0.02	0.1	0.42	0.86
1		20	74	1497	0.97	19.70	7.71	1300	317	80	0.5	1986	712	12.6	836	19.6	15.1	0.02	0.02	0.1	0.69	0.91
1		21	75	1572	0.99	20.68	7.64	1623	294	79	0.5	2171	725	10.4	933	21.8	16	0.02	0.02	0.13	0.79	0.88
1		22	77	1649	1.01	21.70	7.62	1768	253	83	0.5	2157	714	8.78	976	21.8	15.3	0.02	0.02	0.16	0.82	0.86
1		23	81	1730	1.07	22.76	7.82	1514	178	80	0.5	2267	516	7.45	980	22.9	15.4	0.02	0.02	0.02	0.80	0.71
Influent water: 0.710 SPF Low Sulfate with 5000mg/L CO3																						
1		24	85	1815	1.12	23.88	7.66	1942	181	81	0.5	2305	566	6.33	1119	23.3	15.3	0.02	0.02	0.03	0.95	0.74
1		25	61	1876	0.86	24.68	7.6	2248	200	82	0.5	2748	521	6.21	1652	27.5	16.5	0.02	0.02	0.02	1.48	0.74
1		26	20	1896	0.26	24.95	7.8	2408	195	82	0.5	2981	488	5.54	1622	29.8	16.6	0.02	0.02	0.04	1.60	0.71

Grand Junction Office Site Column Testing

Column conditions:

Plexiglass 2" by 8" columns filled with soil. Peristaltic pump, with upward flow @ ~0.15 mL/min. Columns filled with 1 PV allowed to sit 24 hrs. Influent water continuously pumped @ 0.015 mL

Column 2: RVT Well 860 12.5-17 ft. PV =129 mL Soil Weight = 575.0 g. Soil Volume = 362.8 mL. Soil height= 17.9 cm (8.0 in). **Soil dry density** = 1.58 g/mL

Test	Date	PV	VolunCum. (mL)	ActuaCum. (mL)	pH	Sp. Conductivity (uS/cm)	U	Cl	NO3	SO4	Ca	Mg	Na	SiO2	K	Se	Mo	Fe	Mn	V	Sr	Comn	Charge Balance	
							(ug/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)		Anion Cations%	
Influent water: 0710 SPF High Sulfate																								
2	11/7/19	1	115	115	0.89	0.89	7.80	5120	210.4	2250	142	0.5	2661	565	98.1	778	20.6	27.2	0.2	0.66	0.02	0.42	0.04	1.98
2		2	114	229	0.88	1.78	7.93	2800	187.8	866	86	0.5	1439	558	75.7	161	20.7	18.6	0.2	0.12	0.02	0.35	0.04	1.74
2		3	115	344	0.89	2.67	7.79	2290	171.8	330	83	0.5	1079	452	60.5	85.4	19.4	14.9	0.2	0.02	0.02	0.29	0.04	1.39
2		4	118	462	0.91	3.58	7.62	2150	165.4	194	84	0.5	1000	396	63.9	80.3	18.6	14.1	0.2	0.02	0.02	0.29	0.04	1.21
2		5	131	593	1.02	4.60	8.05	2080	161.9	142	83	0.5	963	374	70	78	18.1	13.1	0.2	0.02	0.02	0.29	0.04	1.06
Influent water: 0710 SPF Low Sulfate																								
2		6	132	725	1.02	5.62	7.97	1315	138.8	66	78	0.5	490	191	39.7	56	15.9	9.03	0.2	0.02	0.02	0.15	0.04	0.54
2		7	132	857	1.02	6.64	8.15	817	117.4	39	76	0.5	182	96	21.3	44.8	14.8	6.85	0.2	0.02	0.02	0.08	0.04	0.28
2		8	132	989	1.02	7.67	8.07	783	111.6	34	75	0.5	150	85	18.7	44.1	13.9	6.5	0.2	0.02	0.02	0.07	0.04	0.24
2		9	132	1121	1.02	8.69	7.98	762	108.8	34	74	0.5	142	80.9	18.5	43.9	13	6.11	0.2	0.02	0.02	0.07	0.04	0.23
2		10	132	1253	1.02	9.71	8.1	754	114.8	35	74	0.5	141	78.5	18.2	43.9	12.5	5.75	0.2	0.02	0.02	0.07	0.04	0.22
2		11	129	1382	1.00	10.71	8.28	736	107.2	33	75	0.5	143	82.6	20.3	48.6	12.5	8.3	0.2	0.02	0.02	0.06	0.04	0.22
Influent water: 0710 SPF Low Sulfate with 1000mg/L CO3																								
2		12	129	1511	1.00	11.71	8.03	1311	460	91	75	0.5	142	136	37.9	131	14.6	11.9	0.2	0.02	0.02	0.08	0.04	0.38
2		13	133	1644	1.03	12.74	8.08	1710	691.5	78	78	0.5	144	60.1	27.6	353	13.1	8.98	0.2	0.02	0.02	0.01	0.04	0.23
2		14	135	1779	1.05	13.79	8.25	1860	796.5	59	75	0.5	141	46.7	16.3	438	10.7	8.01	0.2	0.02	0.02	0.02	0.04	0.16
2		15	132	1911	1.02	14.81	8.35	1860	780.5	50	78	0.5	144	23.6	11.8	462	10.3	7.04	0.2	0.02	0.02	0.02	0.04	0.16
2		16	133	2044	1.03	15.84	8.34	1899	801	43	75	0.5	140	31.4	9.76	459	9.23	6.39	0.2	0.02	0.02	0.02	0.04	0.16
2		17	127	2171	0.98	16.83	8.48	1879	775	39	75	0.5	141	14.2	8.59	490	9.22	6.65	0.2	0.02	0.02	0.02	0.04	0.16
Influent water: 0710 SPF Low Sulfate with 2500mg/L CO3																								
2		18	128	2299	0.99	17.82	8.11	2740	1383	45	79	0.5	137	34.1	18.4	733	10.4	8.61	0.2	0.02	0.02	0.02	0.04	0.16
2		19	128	2427	0.99	18.81	8.29	3620	1796	55	80	0.5	138	14.5	21.1	774	10.2	9.24	0.2	0.02	0.02	0.02	0.04	0.16
2		20	127	2554	0.98	19.80	8.16	3870	1949	50	80	0.5	138	28.5	16	848	8.94	8.2	0.2	0.02	0.02	0.02	0.04	0.16
2		21	126	2680	0.98	20.78	8.47	4070	2064	44	78	0.5	138	11.17	11.28	1068	6.854	6.967	0.2	0.02	0.02	0.02	0.04	0.16
2		22	127	2807	0.98	21.76	8.32	4230	2144	41	78	0.5	137	8.93	9.042	1131	6.066	6.141	0.2	0.02	0.02	0.02	0.04	0.16
2		23	129	2936	1.00	22.76	8.71	4220	2216	37	78	0.5	138	5.673	7.264	1169	6.055	5.620	0.2	0.02	0.02	0.02	0.04	0.16
Influent water: 0710 SPF Low Sulfate with 5000mg/L CO3																								
2		24	130	3066	1.01	23.77	8.45	6250	3508	43	79	0.5	136	12.43	13.92	1799	6.608	7.807	0.2	0.02	0.02	0.02	0.04	0.16
2		25	134	3200	1.04	24.81	8.97	7070	4494	59	81	0.5	142	5.399	16.57	2236	6.319	8.939	0.2	0.02	0.02	0.02	0.04	0.16
2		26	134	3334	1.04	25.84	8.93	7990	4646	50	81	0.5	139	8.957	18.60	2355	5.158	7.714	0.2	0.02	0.02	0.02	0.04	0.16
2		27	133	3467	1.03	26.88	8.89	7920	4700	40	81	0.5	139	9.751	26.37	2302	5.398	8.103	0.2	0.02	0.02	0.02	0.04	0.16
2		28	133	3600	1.03	27.91	8.82	7940	4682	35	80	0.5	138	8.473	28.79	2382	5.256	7.702	0.2	0.02	0.02	0.02	0.04	0.16

## Appendix C – Column Experiment Methodology

22-210

Riverton CO<sub>2</sub> Column tests Column #1 Sediment 859 8.4-10'

11/4/19

Using 6" column (12.9cm)

Empty column = 984.3g

Full column = 1458.3g

Soil mass = 474g

Soil density 1.81 g/mL

Pump test @ 0.15 mL/min

Pump set @ 0.15 mL/min delivered 0.11 mL/min

Pump set @ 0.19 mL/min delivered 0.14 mL/min

Pump set @ 0.20 mL/min delivered 0.144 mL/min

Pump set @ 3.00 mL/min delivered ~~2.2 mL/min~~ 2.18 mL/min

pump set @ 3.75 mL/min delivered 2.72 mL/min

Prepared 2L of SPR 0710 high sulfate. Added CO<sub>2</sub> to get pH to  $7.6 \pm 0.2$

pH 7.46

Pump started @ 10:25 2.72 mL/min

Water to fill column = 28 min

PV = 76.2 mL

NFI



10/7/2019 PVI = 72ml  
PV2 = 67ml

11/8/2019 PV3 = 48ml + 23ml = 71ml  
PV4 = 48ml + 23ml = 71ml  
PV5 = 49ml + 23ml = 72ml

Prepared next series of water "low sulfate"  $\neq$  INF3

pH adjust - goal is  $7.4 \pm 0.2$   $\text{pH} = 7.43$

Prepared next water "low sulfate" ~~with~~ w/ 1000mg/L  $\text{CO}_3$   $\neq$  INF4

added 1.5g/L  $\text{NaHCO}_3$  to low sulfate water

16:17

Switch to "low sulfate" water reset fraction collector and increase time/tube to 186 min.

PV6 = 49ml + 23ml = 72ml PV7 will still be  $\uparrow \text{SO}_4$  PV8 will be  $\downarrow \text{SO}_4$

11/10/19 PV7 = 51 + 26 = 77

PV8 = 51 + 25 = 76

PV9 = 52 + 26 = 78

PV10 = 52 + 26 = 78

PV11 = 53 + 26 = 79

14:50 switch to "low sulfate" water w/ 1000mg/L  $\text{CO}_3$ . Reset fraction collector and ~~time to~~ time to 182 min

PV12 will still be  $\downarrow \text{SO}_4$  PV13 will be  $\downarrow \text{SO}_4 + \text{CO}_3$

FINISHED

PV 23 will be low SO<sub>4</sub> w/ 2500 CO<sub>3</sub>

11/15/19 1 Volume increasing in tubes. Decrease flow on pump from 0.20  $\rightarrow$  0.19 mL/min.  
 2 This occurred when fraction collector switched from tube 2  $\rightarrow$  3 on PV 24  
 3

11/15/19 4 PV 23 = 81 mL  
 5 PV 24 = 85 mL  
 6  
 7  
 8  
 9  
 10  
 11  
 12  
 13  
 14  
 15  
 16  
 17  
 18  
 19  
 20  
 21  
 22  
 23  
 24  
 25  
 26  
 27  
 28  
 29  
 30  
 31

Stoller

11/15

22:57

flow was diminished increased pump  
back to 0.22 mL/min looks like  
tubing into column plugging. Quickly took  
it apart to clear the small barb fitting  
that looked plugged.

PV25 tube #3 is short on volume  
PV26 tube #1 is short on volume.

yellow/brown color is back

11/16/19 19:10 arrive column flowing  
very slow ~ 8 mL in 3 hrs and  
slowing.

Stoller

11/16/19 19:10 stop flow to  
column, cut the end of tube #1  
of PV 28. 19:49

Combine tubes as normal.  
may combine PV's to get enough  
volume.

Tube #1 will go w/ PV 27.

$$PV=25 = 50 + 11 = 61 \text{ mL}$$

↳ ppt in collector tubes

$$PV26 = 20 \text{ mL}$$

↳ ppt in tubes

$$PV 27 = 12 \text{ mL} + 1 (PV 28)$$

↳ ppt in tubes

Combined to  
have enough  
volume.



Riverton CO<sub>3</sub> Column Tests      Column #2      Sediment 860 12.5-17'

11/4/19

Using 8" column (17.9 cm)

Empty column = 1055.6g

Full column = 1630.6g

Soil mass = 575.0g

Soil density = 1.58 g/dL

Pump test @ 0.15 mL/min

Pump set @ 0.15 mL/min delivered 0.12 mL/min

Pump set @ 0.18 mL/min delivered 0.15 mL/min

Pump set @ 3.00 mL/min delivered 2.5 mL/min

Pump set @ 3.6 mL/min delivered 2.99 mL/min

Starting pH 7.38 (7.6  $\pm$  0.2 is target)  $\approx$  INF2

Pump start @ 16:00 2.99 mL/min

Water to ~~start~~ fill column = 43 min

PV = 128.6 mL

17/19 PV1 = 47 mL + 46 mL + 22 mL = 115 mL

1/8/2019

PV2 =

46 mL + 16 mL + 22 mL = 114 mL

PV3 =

46 mL + 47 mL + 22 mL = 115 mL

Prepared next series of water "low sulfate" = INF3

pH adjusted to  $7.4 \pm 0.2$

pH = 7.48

Prepared next water "low sulfate" w/ 1000  $\mu\text{g/L}$   $\text{CO}_3$  INF4

added 1.5 grams/L  $\text{NaHCO}_3$  to low sulfate water

20:50 Switch to "low sulfate" water reset fraction collector

change time to 15a min/tube and 6 tubes/PV

PV5 will still be  $\uparrow$  say PV6 will be  $\downarrow$  say

PV4 =  $42 + 48 + 23 = 113$

PV5 =  $43 + 44 + 44 = 131$

PV6 =  $44 + 44 + 44 = 132$

11/2/17

Didn't have enough tubes loaded in frac. collector missed 1 full tube and 1 partial tube from PV10. Assume full volume.

PV7 =  $44 + 44 + 44 = 132$

PV8 =  $44 + 44 + 44 = 132$

PV9 =  $44 + 44 + 44 = 132$

[illegible]

1	2	3	4	5	6	7	8	9	10	11	12	13
11/20/19	PV 21 =	42 + 42 + 42 =	126 mL									
2	PV 22 =	59 + 48 + 20 =	127 mL									
3												
17:07	Influent switched to low sulfate			+ low sulfate	+ 5000 mg/L CO <sub>3</sub>							
4												
5												
6												
7												
8												
9												
10												
11												
12/2/19	PV 23 =	41 + 44 + 44 =	129 mL									
13	PV 24 =	44 + 43 + 43 =	130 mL									
14												
15												
16												
17												
18												
19												
20												
21												
22												
23												
24												
25												
26												
27												
28												
29												
30												
31												



# Riverton CO<sub>2</sub> Column Tests Column #3 Sediment 858 0-25'

11/4/19 1 Using 8" column (17.9cm)

2 Using 50/50 wt/wt glass beads. Soil is fine grained

3 Empty column = 1048.7g

4 Full column = 1652.2g

5 Soil mass = 603.5g

6 Soil density = 1.66g

7 Pump test @ 0.1 mL/min

8 Pump set @ 0.1 mL/min delivered 0.07 mL/min

9 Pump set @ 0.13 mL/min delivered 0.088

10 Pump set @ 0.15 mL/min delivered 0.10 mL/min

11 Pump set @ 3.00 mL/min 2.05 mL/min

12 Pump set @ 4.00 mL/min delivered 2.75 mL/min

13 Pump start @ 16:00 2.75 mL/min

14 Water to fill column = 43 mL

15  $PV = 118.2 \text{ mL}$

16  $PV = 44 \text{ mL} + 43 \text{ mL} + 21 \text{ mL} = 108 \text{ mL}$

Soil = 356.7g  
Glass = 357.1g

Didn't want to be here at midnight.

PV12	will still be 1000mg/L $\text{CO}_2$
PV13	will be 2500mg/L $\text{CO}_2$ .

[illegible]

## Fin Columns

Column 1 Riv 860 15-15.5' and 15.5'-17' Combined with alk influent is 6" Column  
 Empty Column = 985.4g  
 Full Column = 1418.2g  
 Soil Volume =  $77 \text{ cm}^3$   
 Soil Density =  $9/\text{vol} =$

without ALK  
 Net Soil Mass =  
 Height of soil =  $5 \frac{1}{16}$ "  $5.0625$ "

Column 2 Riv 860 15-15.5' + 15.5'-17' Combined with ALK in 6" column  
 Empty Column = ~~985.4g~~ 992.7g  
 Full Column = ~~1418.2g~~ 1408.0g

Column 3 Riverton 1020 15-15.5' and 15.5-16' and 16-16.5' w/out ALK influent in 6" column  
 Empty Column = 984.6g  
 Full Column = ~~1420.8g~~ 1420.8g

Column 4 Riverton 1020 15-15.5' + 15.5-16' + 16-16.5' w/ ALK influent in 6" column  
 Empty Column = 994.2g : 424.8g  
 Full Column = 1419.0g  
 Soil Volume  
 Soil Density

Column 4 influent = 5.014g Sodium Bicarbonate / 2 Liters 710 water



3.16 ml 0.147 ml/min = 565 min

Column #1 PV 10 = 94.3 hrs = 3.93 Days 3 Days 22 hrs = Sunday Around 1pm

Column #2 PV 10 = 90.3 hrs = 3.76 Days 3 Days 18 hrs = Sunday Around 12am

Column #3 PV 10 = 103.2 hrs = 4.3 Days 7 hrs = Sunday 10pm

Script PH well 710 field

1 7.77  
2 7.61  
3 7.61  
3

Pump #1 Pump Test

Column #1

Flow Rate

Set at  $0.15 \text{ ml/min}$  Actual:  $0.147 \text{ ml/min}$

Pump #2 Pump Test

Column #2

Flow Rate

Set at  $0.150 \text{ ml/min}$   
 $0.170$

Pump #3 Pump Test

Column #3

Flow Rate

Set at  $0.150 \text{ ml/min}$   
 $0.210$

Pump #4 Pump Test Empty weight =  $2.104 \text{ g}$ , Full =  $5.576 \text{ g}$ , Full =  $5.314$

Flow Rate  $0.15 \text{ ml/min}$  =  $0.151 \text{ ml/min}$

7/7/2020

Column #1

Priming Column  
 Flow rate =  $0.42 \text{ mL/min} \times 198 \text{ minutes} = 83.16 \text{ mL}$

$$83.16 \div 4 = 20.79 \text{ mL/Tube}$$

$$20.79 \text{ mL} / 0.147 \text{ mL} \text{ per } \underline{141.43 \text{ min}} \text{ / Tube}$$

Column #2

Priming Column  
 Flow rate =  $0.42 \text{ mL/min} \times 190 \text{ min} = 79.8 \text{ mL}$

$$79.8 \div 4 = 19.95 \text{ mL/Tube}$$

$$19.95 \text{ mL} / 0.147 \text{ mL} \text{ per } \underline{135.71 \text{ min}} \text{ / Tube}$$

Column #3

Priming Column  
 Flow rate =  $0.459 \text{ mL/min} \times 209 \text{ min} = 95.93 \text{ mL}$

$$95.93 \text{ mL} / 4 \text{ Tubes} = 23.98 \text{ mL/Tube}$$

$$23.98 \text{ mL/Tube} / 0.155 \text{ mL} \text{ per } \underline{154.73 \text{ min}} \text{ / Tube}$$

Column #4 Priming Column

Empty weigh boat = 2.106 g

## River for Column #1 F60 sediment

7/8/2020

PH Influent 7.50

Influent H<sub>2</sub>O well 710 water  
 flow Rate 0.147 ml/min  
 Column Fill time 198 @ 0.42 ml/min  
 PV = 83.16 ml 1 PV = 9.43 hrs

Start Fraction collector: 15:55

PV1 = 76 ml

PV2 = 78 ml

PV3 = 77 ml

PV4 = 78 ml

PV13 = 82 ml  
 PV14 = 82 ml

7/13/20

PV5 = 77 ml

PV6 = 79 ml

PV7 = 74 ml

PV8 = 80 ml

PV9 = 80 ml

PV10 = 81 ml

PV11 = 80 ml

PV12 = 91 ml

7/19/2020

H<sub>2</sub>O Influent change to River for 710 well w/ 2500 w/L @ CaO<sub>3</sub>  
 Pump started: 11:15

7/19/20

PV13 = 82 ml

PV14 = 82 ml

7/15/20

PV15 = 82 ml

PV16 = 81 ml

89



## Riverston Column #2 860 Sediment

7/8/2020

pH Influent 7.80

Influent H<sub>2</sub>O: well 710 w/ 2500 mg/L as CaCO<sub>3</sub>  
 Flow Rate 0.147 mL/min  
 Column fill time 10 min @ 0.142 mL/min  
 PV = 79.8 mL 1 PV = 9.05 hours

Start fraction collector 16:44

PV1 = 74 mL - Precipitate at bottom of collection tubes.

PV2 = 74 mL - Precipitate at bottom of collection tubes

PV3 = 74 mL - Precip @ bottom of tube

PV4 = 74 mL - Small amount of precip @ bottom "

PV5 = 74 mL - Small amount of precip

PV6 = 75 mL - NO precip

PV7 = 77 mL

PV8 = 78 mL

PV9 = 77 mL

PV10 = 78 mL

PV11 = 78 mL

PV12 = 78 mL

7/13/2020

H<sub>2</sub>O Influent Change to Riverston 710 well

pH Influent 7.55

pump started @ 8:20.

7/14/20

PV13 = 78 mL

PV14 = 77 mL

## Riverston Column #2

7/15/20: PV158 ~~78 mL~~ 78 mL

PV16 78 mL

PV17 78 mL

7/16/20: PV18 = 78 mL

PV19 = 78 mL

7/17/20: Pump off @ 0630. One tube post 10 PV was ran through column but not collected.

PV20 = 78 mL

PV21 = 77 mL

PV22 = 78 mL

PV23 = 43 mL

Column plugged, Ran ~ 4 hours longer than calculated  
Pump off @ 1630

# Riverston Column #3 <sup>1020</sup> ~~560~~ Sediment

7/8/2020

pH Influent: 7.60

Influent 1+20: well 710 water  
 Flow Rate 0.155 ml/min  
 Column fill time 209 min @ 0.459 ml/min  
 PV = 95.93 ml (PV = 10.32 hours)

Shunt Fraction Collector: 15:41

PV1 = 94 ml

PV2 = 94 ml

PV3 = 95 ml

PV4 = 94 ml

PV5 = 94 ml

PV6 = 94 ml

PV7 = 94 ml

PV8 = 95 ml

PV9 = 94 ml

PV10 = 94 ml

PV11 = 94 ml

7/13/2020 Influent changed to Riverston 710 w/ 2500 ug/L as CaCO<sub>3</sub>  
 Pump started @ 9:30

7/14/2020 PV12 = 97 ml  
 PV13 = 96 ml

7/15/2020 PV14 = 97 ml  
 PV15 = 97 ml



7/16/20	1	2	3	4	5	6	7	8	9	10	11	12	13
PV16		97 mL											
PV17		97 mL											
7/17/20	3												
PV18 =	4	95 mL											
PV19 =	5	96 mL											
PV20 =	6	96 mL											
PV21 =	7	97 mL											
	8												
Pump & Fraction Collector OFF @ 1635													
	9												
	10												
	11												
	12												
	13												
	14												
	15												
	16												
	17												
	18												
	19												
	20												
	21												
	22												
	23												
	24												
	25												
	26												
	27												
	28												
	29												
	30												
	31												

Influent H<sub>2</sub>O well 710  
flow rate 0.151 m<sup>3</sup>/min  
Column fill time = 147

Pump on @ 0923

Fraction collected started @ 1324

$PV = 7 \text{ mL}$

71 ml

PV3 = 72 mL

page	77
77	

PVS = 13 mL  
DMSO = 22 mL

PVB-	1 cmL
PVB-	77 cmL

401 -	15 ml
0.18 -	73 ml

100	1.5ml
0.04%	73ml

for ...

0.01073 m/s

$$\phi \vee H = 73 \text{ mL}$$

pv12: 75ml

U

$PV = 7 \text{ cm}$

$$P_{V14} = 75 \text{ m}$$
$$P_{V15} = 7 \text{ m}^2$$
$$0.16 \div 73 \text{ mL}$$
$$b_v | 7 = 73m$$

$P_{V18} = 73 \text{ mmHg}$

1.00	1.00
------	------

8770 p19 ~ 73 ml

$$20 \approx 73 \text{ mol}$$
$$21 = 73 \text{ ml}$$

8/11/20 PV 22:71 ml

$$23 \div 72 \text{ m}$$
$$24 = 72n$$
$$25 \div 72 \text{ mL} \quad 28 \div 73 \text{ mL}$$
 $26 \sim 72 \text{ mil}$ 

27~ 73 mL