

Effects of Irrigating with Treated Oil and Gas Product Water on Crop Biomass and Soil Permeability

FINAL TECHNICAL REPORT

Prepared By

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ABSTRACT

Demonstrating effective treatment technologies and beneficial uses for oil and gas produced water is essential for producers who must meet environmental standards and deal with high costs associated with produced water management. Proven, effective produced-water treatment technologies coupled with comprehensive data regarding blending ratios for productive long-term irrigation will improve the state-of-knowledge surrounding produced-water management. Effective produced-water management scenarios such as cost-effective treatment and irrigation will discourage discharge practices that result in legal battles between stakeholder entities. The goal of this work is to determine the optimal blending ratio required for irrigating crops with CBNG and conventional oil and gas produced water treated by ion exchange (IX), reverse osmosis (RO), or electro-dialysis reversal (EDR) in order to maintain the long term physical integrity of soils and to achieve normal crop production.

The soils treated with CBNG produced water were characterized with significantly lower SAR values compared to those impacted with conventional oil and gas produced water. The CBNG produced water treated with RO at the 100% treatment level was significantly different from the untreated produced water, while the 25%, 50% and 75% water treatment levels were not significantly different from the untreated water. Conventional oil and gas produced water treated with EDR and RO showed comparable SAR results for the water treatment technologies. There was no significant difference between the 100% treated produced water and the control (river water). The EDR water treatment resulted with differences at each level of treatment, which were similar to RO treated conventional oil and gas water. The 100% treated water had SAR values significantly lower than the 75% and 50% treatments, which were similar (not significantly different).

The results of the greenhouse irrigation study found the differences in biomass production between each soil were significant for Western Wheatgrass and Alfalfa. The Sheridan sandy loam soil resulted in the highest production for western wheatgrass and alfalfa while the X-ranch sandy loam had the lowest production rate for both plants. Plant production levels resulting from untreated CBNG produced water were significantly higher compared to untreated conventional oil and gas produced water. However, few differences were found between water treatments.

The biomass produced from the greenhouse study was analyzed for elemental composition and for forage value. Elemental composition identified several interesting findings. Some of the biomass was characterized with seemingly high boron and sodium levels. High levels of boron found in some of the biomass was unexpected and may indicate that alfalfa and western wheatgrass plants may have been impacted by either soil or irrigation water containing high boron levels. Plants irrigated with water treated using EDR technology appeared to contain higher levels of boron with increased levels of treatment. Forage evaluations were conducted using near infrared reflectance spectroscopy. The data collected show small differences, generally less than 10%, between produced water treatments including the no treatment and 100% treatment conditions for each plant species.

studied. The forage value of alfalfa and western wheatgrass did not show significant tendencies dependent on soil, the amount of produced water treatment, or treatment technology.

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EXECUTIVE SUMMARY

Demonstrating effective treatment technologies and beneficial uses for oil and gas produced water is essential for producers who must meet environmental standards and high costs associated with produced water management, and thus, maintain safe and efficient oil and gas production in the US. Proven, effective produced-water treatment technologies coupled with comprehensive data regarding blending ratios for productive long-term irrigation will improve the state-of-knowledge surrounding produced-water management in the west and other regions. This newly gained knowledge will help managers find beneficial uses of the produced water that will provide an economic return in the form of crop production that uses a windfall water source that would otherwise be managed as a contaminant stream at an additional cost to the producer. Irrigating with treated produced water will also ensure that the cropland remains viable and productive once extraction projects have ended and irrigation resumes using traditional irrigation sources or a dry-land ecosystem relying on natural precipitation. Irrigating with produced water will also relieve some of the water-volume strains on natural streams and rivers in areas like the PRB where water quantity sometimes causes more problems than poor water quality. Furthermore, effective produced-water management scenarios such as cost-effective treatment and irrigation will discourage discharge practices that result in legal battles between stakeholder entities.

The goal of this work is to determine the optimal blending ratio required for irrigating crops with produced water treated with various pretreatment methods followed by ion exchange (IX) reverse osmosis (RO) or electro-dialysis reversal (EDR) in order to maintain the long term physical integrity of representative soils from the Powder River Basin (PRB) and achieve normal crop production.

This project will use two (2) treatment trains to clean oil and gas produced water: (1) physiochemical pretreatment (DAF + organo-clay) followed by DT RO or (2) physiochemical pretreatment (DAF + organo-clay) followed by EDR to reduce organic and inorganic constituent loads in oil and gas produced water. The treatment of CBNG produced water will be evaluated using DT RO and IX (EMIT Technology) without a pretreatment to remove oil and other hydrocarbons. The potential benefit of these treatments will be the ability to process high volumes of poor quality water with limited membrane fouling, thus, reducing O&M costs of treating produced water using processes already established for other water treatment applications. Potential inadequacies of using IX, RO and EDR technologies for treating produced water are the lack of robust data describing the performance of such treatments under demanding on site water quality and climactic conditions.

Hydraulic conductivity (HC) values for the X-Ranch soil irrigated with various combinations of treated CBNG produced water and conventional oil and gas produced water treated with various technologies were determined using flexible-walled permeameters.

Limited differences exist in the HC of soils impacted with treated and untreated CBNG produced water. Produced water treated using the IX and RO technologies at the 100% level was found to be similar to the control (river water), while the treatment levels of 25%, 50% and 75% resulted in significantly lower HC values that compared well to the values associated with untreated produced water.

The HC data collected for conventional oil and gas produced water showed no improvement in HC over untreated produced water for all levels of treatment. Water treatment did not appear to improve HC for oil and gas produced water.

Soils used in the hydraulic conductivity study were evaluated at the conclusion of the study to determine how the irrigation water impacted the chemistry of the material. The primary parameters of concern were EC and SAR. In general, the soils impacted by the CBNG produced water and the conventional oil and gas produced waters did not have a significant impact on the EC values of the soils. The resulting EC values from all treatments would not be expected to significantly impact plant growth. The only concern would be whether or not the EC values were high enough to prevent dispersion of clays due to the corresponding high SAR values. However, the SAR values associated with the treated produced waters were relatively low in all cases and would not be expected to cause dispersion.

The soils treated with CBNG produced water were characterized with significantly lower SAR values compared to the conventional oil and gas water. The CBNG produced water treated with RO at the 100% treatment level was significantly different from the untreated produced water while the 25%, 50% and 75% water treatment levels were not significantly different from the untreated water. Conventional oil and gas produced water treated with EDR and RO showed comparable SAR results for the water treatment technologies. There was no significant difference between the 100% treated produced water and the control (river water) with the use of EDR and RO. The EDR water treatment resulted with differences at each level of treatment as the SAR of the 25% treatment was significantly higher than the 50% treatment, the 50% treatment was significantly higher compared to the 75% treatment and the 75% treatment was higher compared to the 100% treatment. Similar results characterized the RO treated conventional oil and gas water. The 100% treated water had SAR values significantly lower than the 75% and 50% treatments, which were similar (not significantly different). The 25% treatment resulted in SAR values significantly higher than the 50% and 75% water treatments.

Germination results show that produced water from both CBNG and conventional oil and gas production did not significantly impact germination rate. In fact germination rate appeared to be somewhat less in the control (river water) compared to that determined for raw produced

waters. Differences are apparent between several of the treatments for alfalfa and western wheatgrass germination. However, variation between replicates was found to be rather high resulting in no significant differences in germination of alfalfa and western wheatgrass seeds when watered with the 19 water treatments.

The results of the greenhouse irrigation study found the differences in biomass production between each soil were significant for Western Wheatgrass and Alfalfa. The Sheridan sandy loam soil resulted in the highest production for western wheatgrass and alfalfa while the X-ranch sandy loam had the lowest production rate for both plants. Plant production levels resulting from untreated CBNG produced water were significantly higher compared to untreated conventional oil and gas produced water. However, few differences were found between water treatments. For example, CBNG produced water treated with ion exchange resulted in no significant difference in western wheatgrass production for the 25%, 50%, 75% and 100% treatment blends. The use of RO treated CBNG produced water for irrigation resulted in a significantly lower level for the 100% treated produced water compared to the 25% blend. The lower production level associated with the 100% treated water is likely associated with either a plant toxicity or nutritional imbalance caused by the treatment. The produced water treated using EDR technology generated high western wheatgrass production compared to that resulting from the RO technology. However, the plant production levels associated with EDR did not differ significantly based on the level of treatment.

The biomass produced during the greenhouse study was analyzed for elemental composition and for forage value. Samples from each replication were composited to acquire enough sample for analysis, as a result, treatment replications were not established and a statistical evaluation was not completed. Elemental composition identified several interesting findings. Some of the biomass was characterized with seemingly high boron and sodium levels. High levels of boron found in some of the biomass was unexpected and may indicate that alfalfa and western wheatgrass plants may have been impacted by either soil or irrigation water containing high boron levels. It appeared that water treatment technology had an impact on the amount of boron that plants accumulated in their biomass. Plants irrigated with water treated using EDR technology appeared to contain higher levels of boron with increased levels of treatment. This finding was the opposite effect found for sodium levels.

Forage evaluations were conducted using near infrared reflectance spectroscopy. The data collected show small differences, generally less than 10%, between produced water treatments including the no treatment and 100% treatment conditions for each plant species studied. The forage value of alfalfa and western wheatgrass did not show significant tendencies dependent on either soil, the amount of produced water treatment, or treatment technology.

Some differences in crude protein content of biomass may exist for the Sheridan soil dependent on the percentage of water treatment.

INTRODUCTION

With the current price of natural gas and its strong demand, the continued development of the coalbed methane (CBM) industry in the PRB is a certainty. Coalbed methane reserves in the PRB represent a major recent play for the industry and are of great importance to the region and the nation. CBM reserves are estimated at over 25 trillion cubic feet in the PRB of Wyoming and Montana alone. This is equivalent to the gas reserves of the Gulf Coast. However, according to the Final Environmental Impact Statement (January, 2003), an anticipated 51,000 wells are expected to be in service within ten years.

There are a number of issues that face the CBM industry, foremost of which is associated with the vast water quantities associated with CBM production. Large quantities of CBM produced water are being discharged as part of the process of releasing gas from coal seams. The excess produced water is causing concerns from several points of view. The drawdown of water in the coal aquifers is causing concerns from landowners and others, who are worried about the availability of water for future generations. In addition, there is concern as to how to use the water in worthwhile, environmentally sound applications. Significant quantities of produced water are anticipated with estimates of over three million acre feet being produced over the next ten years and an estimated 4-8 trillion gallons over the potential 30-35 years of the PRB CBM play (FEIS, 2003). The number of producing wells and the volume of produced water has increased in recent years in the PRB while total gas production has remained relatively constant (Figure 1).

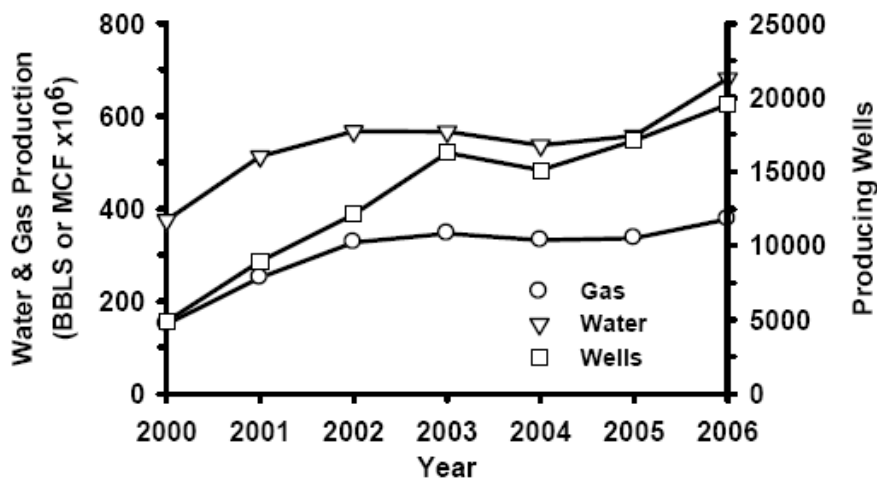


Figure 1 Gas and Produced Water Production and Producing Wells in the Powder River Basin, Wyoming. Figure Made using Data from the Wyoming Oil and Gas Commission Statistics (<http://wogcc.state.wy.us>).

The practice of discharging large volumes of water into drainage channels or using it to irrigate rangeland areas has the potential to cause problems with regard to salinity and sodicity of

soils. The primary problems associated with salinity are related to the ability of plants to take up water to facilitate the biochemical processes of photosynthesis and plant growth. As the solution electrolyte concentrations of soil increase, plants will become less able to absorb sufficient volumes of water. As a result, the plants are not able to function at high levels and will grow at slow rates or die. The major impact of sodicity on soils is associated with soil structure. Soil structure is important to maintain the flow of gases (oxygen) and solution (water plus nutrients) to the plant roots. Poor soil structure can cause severe erosion of once-productive soils. High levels of sodium can cause the structure of a soil to completely disperse.

An important aspect of the sodicity and salinity chemistry of soils is that the two are closely related. For example, a highly sodic (high sodium adsorption ratio (SAR)) soil can maintain its soil structure if the salinity level (electrical conductivity (EC)) of the soil is high. However, if the salinity level is low, a highly sodic soil will slake and disperse and the structure will be lost. If a soil is characterized by a low SAR, the application of clean water or water characterized by low EC can cause degradation of soil structure. If the electrolyte concentration of the water applied to the soil is high, the soils will maintain their structure.

Some waters currently being disposed of in the PRB are of such quality that land application should not cause any significant problems. However, there is evidence that some of the CBM-produced waters will cause problems with salinity and sodicity in soils. The geographical distribution of SAR values for the CBM waters within the PRB are shown in Figure 2. The SAR values increase to the north and west. In fact, the Big George coal seam, the next big play, is expected to produce higher water discharge/quantity of gas and very poor quality (very high SAR) water.

One dilemma with produced water management is to make sure that water applied to soils meets the favorable combination of salinity and sodicity that will allow plants to grow at good production levels and maintain the structure of soils. Each soil will react differently to the chemistry of the water applied and the method of application. Therefore, research is necessary to (1) understand these interactions in order to develop improved irrigation practices and (2) assess long-term consequences of irrigation on salt movement, loading and plant productivity in order to assess CBM producer liabilities.

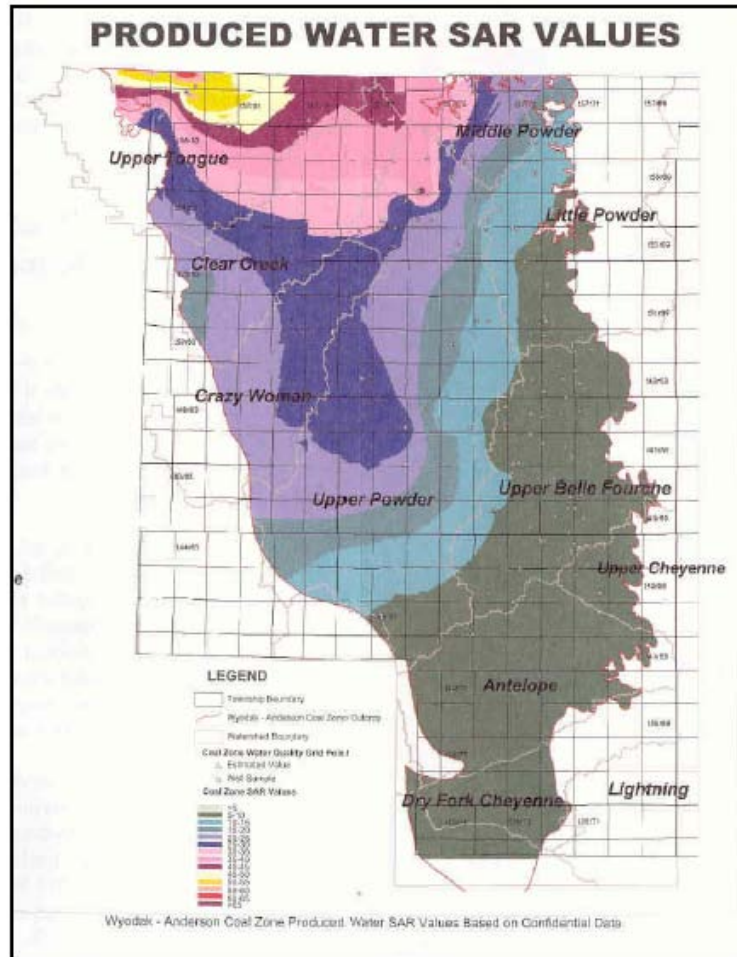


Figure 2 Distribution of Produced Water SAR Values in the PRB. (FEIS Jan. 2003)

Potential Impacts

Demonstrating effective treatment technologies and beneficial uses for oil and gas produced water is essential for producers who must meet environmental standards and high costs associated with produced water management, and thus, maintain safe and efficient oil and gas production in the US. Proven, effective produced-water treatment technologies coupled with comprehensive data regarding blending ratios for productive long-term irrigation will improve the state-of-knowledge surrounding produced-water management in the west and other regions. This newly gained knowledge will help managers find beneficial uses of the produced water that will provide an economic return in the form of crop production that utilizes a windfall water source that would otherwise be managed as a contaminant stream at an additional cost to the producer. Irrigating with treated produced water will also ensure that the cropland remains viable and productive once extraction projects have ended and irrigation resumes using traditional irrigation sources or a dry-land ecosystem relying on natural precipitation. Irrigating with produced water will also relieve some of the water-volume strains on natural streams and rivers in areas like the PRB where water quantity sometimes causes more problems than poor

water quality. Furthermore, effective produced-water management scenarios such as cost-effective treatment and irrigation will discourage discharge practices that result in legal battles between stakeholder entities.

Summary of Existing Treatment Technologies

Produced water is a byproduct from oil or gas producing wells. Every year, about 14 to 18 billion barrels of produced water is generated from on-shore oil and gas production in the U.S. alone (Veil et al. 2004). The volume of produced water from oil and gas wells changes over time and the water:oil/gas ratio usually increases over the lifetime of a well.

Produced water generally contains free phase oil (droplets), suspended solids, and dissolved organics and inorganics (e.g., total petroleum hydrocarbons, BTEX, fatty acids, salts, sodium chloride, and metals). Some of these constituents are toxic, and improper disposal of produced water can result in soil, water, and air contamination.

Common disposal practices for produced water management include surface impoundment, use for dust suppression on roads, reuse for production processes, surface/subsurface irrigation, surface discharge, and subsurface injection. For example, in the gas industry, typically 60 to 90% of produced water is injected into the subsurface during well drilling, fracturing, or disposal (Hayes and Arthur 2004), while the rest is evaporated or land applied on-site, or transported and disposed of off-site.

Comprehensive treatments are usually needed to remove suspended solids, free oil, and volatile organics compounds (VOCs) before the produced water is discharged, injected, or consumed. For example, for underground injection, scaling from calcium carbonate and barium sulfate, excessive solids, corrosion and biomass need to be controlled to prevent plugging of subsurface formations. Conventional treatment technologies for oil removal include oil water separators, corrugated plate separators, centrifugation, hydrocyclone separation, and gas floatation with or without chemical addition. Corrugated plate separators, centrifugation, hydrocyclone separation and gas floatation are also widely used for solids separation with chemical enhanced treatment (Interstate Oil and Gas Compact Commission and ALL Consulting 2006). These technologies have been applied by the oil and gas industry with relatively low capital investment. Effluents from these treatments usually meet water quality requirements for surface impoundment and subsurface injection.

Other technologies that have been utilized to treat produced water include filtration, constructed wetlands, freeze and thaw separation, and ion exchange. These methods are usually limited to relatively low flow rates and can be influenced by the local climate. For example, filtration methods such as packed bed adsorption, which use activated carbon, organo clay and other sorbents, are usually limited by flow rate and pressure drop (<10 gpm and 10 psi pressure drop) through the bed.

Solvent extraction, sorbent adsorption and membrane separation are recently developed technologies for produced water treatment (Interstate Oil and Gas Compact Commission and ALL Consulting 2006). Due to high operation and maintenance (O&M) costs, the use of solvent

extraction and sorbent adsorption are limited. Micro or ultra-filtration (MF or UF) membrane technologies can effectively remove dispersed and emulsified oil, as well as suspended solids from produced water, however, the conventional membranes used are susceptible to fouling by suspended solids and organics in the produced water. Cleaning of such fouling is difficult and costly.

Enhanced biological treatment technologies such as fluidized bed bioreactors and membrane bioreactors have been successfully used in refinery industries to eliminate organic compounds in process wastewater to meet effluent discharge limits (Hayes and Arthur 2004). However, biological treatment processes are susceptible to large flow fluctuations and variations in organic contents. Factors such as temperature and metals in the produced water may also limit the performance of biological treatment technologies.

Ceramic ultrafiltration is a newly emerging technique that can remove large organic molecules such as oil and grease, dissolved hydrocarbons, proteins, large colloidal particles, and some microorganisms. It can tolerate high variations in concentrations of suspended solids and oil and grease in the produced water. Ceramic UF can also be cleaned with chemicals that do not compromise membrane performance, which is critical for waste streams with variable quality or a high propensity for membrane fouling (Ashaghi et al. 2007).

Electrodialysis (ED) relies on cationic (positive) and anionic (negative) movements of ions that are induced by an electrical field generated by cathode and anode electrodes. In ED, ion selective membranes are placed between a pair of electrodes. A spacer sheet that permits feed water to flow along the face of the membrane is placed between each pair of membranes. Positively charged ions migrate toward the cathode and negatively charged ions migrate toward the anode. During migration the charged ions are rejected by similarly charged ion exchange membranes. As a result, water within the alternate compartment becomes concentrated, leaving desalinated water within the effluent compartment of the ED unit. The concentrate and desalinated water are continuously removed from the unit in a flow-through system. Pilot studies of electrodialysis of produced water (Miller et al. 1997) demonstrated that electrodialysis may be cost effective for reducing TDS when it is less than 10,000 mg/L, achieving an effluent TDS of < 2,500 mg/L. The process of electrodialysis reversal (EDR) operates on the same principle as ED except that the polarity of the electrodes is periodically reversed to push anions and cations back through the ion exchange membranes into the main channel to back flush and extend the life of the membranes.

Reverse osmosis (RO) technology has been successfully used for sea water desalination for more than 30 years. Bench and pilot studies using the RO process for produced water treatment have produced mixed results due to the high organic content of the produced water, scaling constituents, and fine particles present in the produced water that tend to foul RO membranes within a short time. Therefore, a well designed pretreatment process is critical for RO treatment of produced water. Cakmakci et al. (2008) concluded that a combination of sedimentation, oil-water separation, dissolved air floatation (DAF), and ceramic MF are among common pretreatment options. Bench and pilot scale packages including pretreatment and RO

have been tested for treating oil produced water (Burnett and Siddiqui 2006). These packages include centrifugation, organo-clay adsorption, MF, and UF membrane separation followed by RO. The system showed >50% water recovery and the effluent was used for agricultural irrigation. The RO membrane used in those studies was of conventional spiral wound configuration, which contains spaces that tend to host biological growth and trigger membrane fouling, adversely affecting the system flow and performance (Siler 1993). Consequently, spiral wound membranes need extensive cleaning and regeneration maintenance restore and maintain high performance.

Recently, a new disk tube (DT) module membrane for RO separation was developed in Switzerland and Germany. Siler (1993) compared the DT module with a conventional spiral wound module in a controlled study and results indicate that the DT module achieved a 30% higher in flux than the spiral wound module. Furthermore, the DT module can be cleaned and restored with a single flush of 1% sodium hydroxide, while the spiral wound module needs two flushes of special chemicals, resulting in higher O&M costs.

This DT RO technology has been used to treat landfill leachate containing elevated TDS, organics and trace metals. The U.S. Environmental Protection Agency evaluated this technology in landfill leachate treatment applications and reported that "...the DT module technology was very effective in removing contaminants from the landfill leachate" (EPA 1998). The removal rate for total organic carbon (TOC), TDS, total metals, and VOCs were 97, 99, 99, and 90%, respectively. The water recovery rate from DT RO was 73% and membrane cleaning was easily achieved.

A DT RO system for landfill treatment was installed in Japan in 1999 and it maintained the expected performance during a 2.5-year test treating high salinity water containing highly-scaling ions (Ushikoshi et al. 2002). Additionally, a full scale DT RO was installed in China for treating landfill leachate and was determined to perform well (Liu et al. 2008).

Technologies to be Tested

This project will utilize two treatment trains to clean oil and gas produced water: (1) physiochemical pretreatment (DAF + organo-clay) followed by DT RO or (2) physiochemical pretreatment (DAF + organo-clay) followed by EDR to reduce organic and inorganic constituent loads in oil and gas produced water. The potential benefit of either treatment train will be the ability to process high volumes of poor quality water with limited membrane fouling, thus, reducing O&M costs of treating produced water using processes already established for other water treatment applications. Potential inadequacies of using RO and EDR technologies for treating produced water are the propensity for membrane fouling and the lack of robust data describing the performance of such treatment trains under demanding on site water quality and climactic conditions.

Development Strategies

Large volumes of produced water, lack of injection sites, and complicated regulatory permitting processes warrant the use of alternative produced water treatment technologies that

can treat produced water and meet requirements for surface discharge or beneficial uses such as irrigation and livestock consumption. Although produced water from the oil and gas industry is similar to landfill leachate in terms of TDS and a high scaling potential, technologies such as DT RO and EDR have yet to be thoroughly evaluated for produced water treatment. Therefore, a determination of how these technologies perform in conjunction with pretreatment technologies for treatment of oil and gas produced water is necessary. The potential for high volume throughput using these treatment systems make them attractive for produced water management if membrane fouling can be mitigated. This research project will address pretreatment options for limiting membrane fouling as well as optimal blends of treated and untreated water for irrigation.

Successful applications of new technologies such as DT RO and EDR in produced water treatment will help the oil and gas industry reduce environmental impacts during production, realizing beneficial use of produced water in areas where the water supply is limited, such as in the western US. It will also sustain expanded exploration and production of oil and gas from existing operations. This project will provide insight on the logistics and economics of treating produced water with the aforementioned treatment trains as well as optimal blending ratios of treated water with untreated water for irrigation. Additionally, we expect the data obtained regarding optimal water blends to maintain high crop quality/yields as well as good soil permeability will be readily extrapolated to other water treatment methods currently in use such as ion exchange.

OBJECTIVES

The goal of this work is to determine the optimal blending ratio required for irrigating crops with produced water treated with various pretreatment methods followed by reverse osmosis (RO) or electro-dialysis reversal (EDR) in order to maintain the long term physical integrity of representative soils from the Powder River Basin (PRB) and achieve normal crop production.

Experimental Methods

Soil Collection

Three soil types were collected at various sites in Wyoming for use in the research project. Two (2) soil types were sampled at sites in the Powder River Basin that have not previously been irrigated with produced water, the X-ranch site and the Sheridan site. One soil type was collected from the Wind River Basin that has not previously been irrigated with produced water. The soil material collected from the X-ranch site located north of Sheridan Wyoming was used for the hydraulic conductivity portion of the study, while soils collected from all three (3) sites were used in the plant productivity portion of the study. Soil samples were collected from the upper soil horizons (i.e., A and B horizons) associated with forage crop root zones, transported to laboratory, homogenized, and used to make 4 inch diameter soil columns for the hydraulic conductivity study and to fill 6 inch diameter pots for the greenhouse study.

Collection of Produced Water

Produced water was collected from a conventional oil and gas site in the Wind River Basin, WY and from a CBM site in the Powder River Basin, WY. Conventional oil and gas produced water required pretreatment to remove oil and grease that could potentially foul membranes while CBM produced did not require pretreatment. The pretreatment train included DAF, organoclay filtration, and ultra-filtration.

Pilot Testing

Pilot tests will be conducted using a wide range of treated and raw water blends to determine pertinent water blending ratios and soil types to be tested during full-scale experimentation. These pilot tests will include Petri-dish germination experiments and single replicate soil permeability tests.

Soil Column Study

Soil columns (3 inches diameter; 4 inches long) were constructed and placed in flexible-walled permeameters (Trautwein Apparatus). The soil column was placed in a flexible sleeve that is under pressure to prevent any leakage of permeant along the edges of the column. The respective water blends were applied to the soil columns at a constant head pressure (Figure 1). Leachate was collected for chemical analysis (when sufficient volume was present) and the soil columns were analyzed for hydraulic conductivity and chemical composition at the end of each experiment as detailed in Analytical Methods. The soil column test matrix included: 1 soil types \times 2 produced water sources \times 2 water treatment technologies (for each water source) \times 5 water blending ratios (including controls - 100% treated and raw water) \times 3 replicates. The nominal blending mixtures for the greenhouse and soil column experiments will include 0, 25, 50, 75, and 100% treated water. Statistical evaluations were conducted using ANOVA with the Minitab Software Package.

Germination Study

Petri-dish seed germination experiments were completed as part of the preliminary testing conducted in support of the greenhouse portion of this project. The germination study was done using using a thin layer of soil in each Petri-dish. Treatments were evaluated in triplicate using ten (10) seeds in each Petri-dish. Nineteen (19) treatments were evaluated consisting of 1) river water; 2) CBM produced water (raw); 3) Oil and Gas (O&G) produced water (raw); 4) 25% CBM Reverse Osmosis (RO); 5) 50% CBM RO; 6) 75% CBM RO; 7) 100% CBM RO; 8) 25% CBM Ion Exchange (IX); 9) 50% CBM IX; 10) 75% CBM IX; 11) 100% CBM IX; 12) 25% O&G RO; 13) 50% O&G RO; 14) 75% O&G RO; 15) 100% O&G RO; 16) 25% O&G EDR (electrodialysis reversal); 17) 50% O&G EDR; 18) 75% O&G EDR; and 19) 100% O&G EDR. Initially each Petri-dish was evaluated daily for germination followed

by weekly evaluations. Statistical evaluations were conducted using ANOVA with the Minitab Software Package.

Greenhouse Study

The irrigation experiment was initiated using two (2) plant species, alfalfa and western wheatgrass, and nineteen (19) treatments. The experiment was setup using two (2) blocks (one for each plant species) with four (4) replicates for each treatment. The pots were completely randomized within each block. Six-inch diameter plastic pots were filled with each soil type and planted with either western wheat grass (*Pascopyrum smithii*) or alfalfa (*Medicago sativa*; 10 seeds each). The green house test matrix included: 3 soil types \times 2 produced water sources \times 2 water treatment technologies (for each water source) \times 2 forage crop species \times 5 water blending ratios \times 4 replicates \approx 456 pots (considering controls and various water blends including 100% treated or raw water). Each pot was watered liberally with its respective water blend to maintain optimal conditions for germination during the first 1 to 2 weeks of the experiment. Once the 10 seeds in each pot germinated (or not) and had emerged, plants were randomly removed from each pot so a maximum of 4 separate plants existed in each pot. Sufficient water was used to maintain moist soil conditions throughout the study. Two (2) cuttings from the pots were completed during the growing period. Biomass was collected from the above-ground portion of each plant, dried and analyzed as detailed in Analytical Methods. Plant materials collected during the greenhouse study were dried in forced air ovens set at temperatures of 105° C for 24 hours. Dry weights were determined and the plant materials were stored until the study was terminated. Samples were composited by treatment and sent to the laboratory for analysis. Data collected were evaluated using ANOVA with the Minitab Software Package.

Analytical Methods

Water and Soil Analysis

Water and soil samples were collected, preserved and analyzed for all constituents using standard methods (Table 1). Soil hydraulic conductivity (coefficient of permeability) was determined for the soil treated with each water treatment combination using flexible wall permeameters (described in ASTM method D5084). The treated soil from each column was homogenized and sampled for chemical analyses using the saturated paste method. Standard methods were used to analyze the samples.

Plant Tissue Analysis

Plant materials analysis was conducted by Energy Laboratories Helena Montana. Total dry biomass was determined by drying plant materials to constant weight at 55°C. Plant materials were digested using the standard ASTM wet-ashing procedure (acid digestion of ash in 70% trace-metal grade nitric acid at 75°C for 24h). Samples were analyzed for metals by

ICP/ICPMS. Other analysis including boron, molybdenum, chloride, sulfur and nitrate were conducted using standard methods.

- *Forage Quality Analysis*
- Forage quality was determined using near infrared spectroscopy (NIRS; e.g, Stuth et al. 2003). Protein, fiber content, and digestibility were the primary parameters of interest in this study.

RESULTS

Produced Water Treatment for the Irrigation Study

Conventional produced water received further treatment by RO or EDR and CBM produced water was treated by RO or IX. All treated and raw water was collected at one time and used throughout the experiment. These large volumes of treated water (~600 gallons for each treatment/water source) and raw water (~1000 gallons from each source) were transported to WRI and stored under constant, cool conditions until blended for use in irrigation studies. The chemical composition of the stored treated and raw waters was analyzed on a regular basis (at least weekly) to determine if any changes in water quality occur over time. No significant changes in water quality were found.

EMIT Water Discharge Technology an Exterran Water Management Services Company provided WRI with CBM produced water treated using ion exchange (EMIT Higgins LoopTM system), and conventional source produced water treated with an electro-dialysis based treatment system. One of EMIT's existing clients located in the Powder River Basin (PRB) agreed to provide WRI with raw and treated CBM produced water from one of its existing treatment locations operated by EMIT. The treated water was ion exchange product water (before addition of blend water or soil amendments) from an EMIT Higgins LoopTM system.

In addition, EMIT desalinated approximately 1000 gallons conventional source produced water using EMIT's Electrodialysis Reversal (EDR) and Cation (CIX)/Anion (AIX) fixed bed pilot systems. The source of the conventional well produced water was a gas producing well located in the Wind River Basin near Riverton, WY.

MWH treated the CBNG produced water and conventional oil and gas produced water treated using reverse osmosis RO technology. This water was transported to WRI for use in the laboratory and greenhouse studies.

Description of Water Treatment Systems

EMIT Higgins LoopTM Process- Ion Exchange (EMIT Water Discharge Technology an Exterran Company)

EMIT's Higgins LoopTM Process utilizes Severn Trent Services HigginsTM Loop Continuous Countercurrent Ion Exchange (CCIX) technology to remove sodium and other cations from CBM produced waters. A general Process Flow Diagram of the EMIT Higgins LoopTM Process used to treat CBM Produced Water is shown below. Untreated CBM produced water is pumped from the feed tank to the Higgins LoopTM adsorption section where sodium and other cations are removed via ion exchange. Loop product water is then routed through an air stripper and blend tank as needed to adjust pH and sodium adsorption ratio (SAR). The drawing shows the location of connection points used by WRI for the un-treated and product water sources. Note that the source for product water delivered to WRI is pre blend and soil amendment addition.

CBM Produced Water Process Flow Diagram

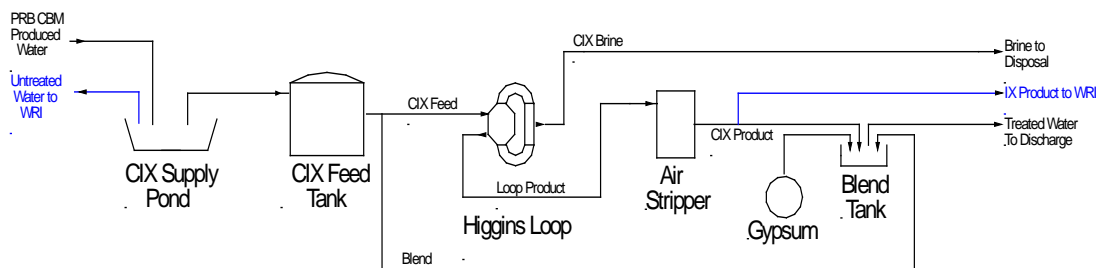


Figure 3 CBNG Produced Water Process Flow Diagram

EDR/CIX/AIX Pilot System

The pilot system selected to treat conventional source produced water was two-stage EDR for primary desalination, followed by a cation/anion ion exchange polish. Pre-treated and filtered (1um) conventional source produced water was desalinated in the primary step using two EDR modules connected in series. EDR product water was then routed to and polished using a cation/anion fixed bed ion exchange pilot system. The Conventional Produced Water Process Flow Diagram shown below shows major components and general flow direction of the treatment system used for this pilot test. System flow capacity for this pilot system was approximately 1.5 L/m.

WRI fluid source locations are identified in the drawing. Note that the IX product water delivered to WRI was not pH adjusted, or amended with SAR enhancing minerals.

Conventional Produced Water Process Flow Diagram

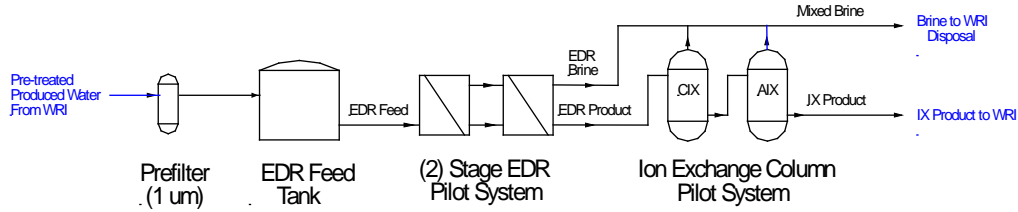


Figure 4 Conventional Oil and Gas Produced Water Process Flow Diagram

Treatment Results

CBM Source Produced Water

Approximately 4000 gallons of un-treated produced water was acquired from an existing EMIT CBM water treatment site in the Powder River Basin (PRB), and transported it to an undisclosed location for alternate treatment. WRI returned to the same EMIT CBM location and acquired approximately 600 gallons of Higgins Loop™ CCIX Product Water to the laboratory for use as irrigation water in the study.

The lab results of samples taken by WRI of the raw and ion exchange product water collected from CBM Produced Water are shown in Table 1.

Table 1 Laboratory Results for CBNG Produced Water Treated with IX

| Parameter | Raw Produced Water | IX Treated Produced Water |
|---------------------------------------|--------------------|---------------------------|
| pH | 8.2 | 5.5 |
| EC(μ S/cm) | 2640 | 380 |
| SAR | 51.3 | 14.7 |
| Alkalinity (mg/L as CaCO_3) | 1533 | 16.7 |
| Sodium (mg/L) | 1100 | 86.2 |
| Potassium (mg/L) | 26.2 | 1.7 |
| Calcium (mg/L) | 15.9 | <1.0 |
| Magnesium (mg/L) | 11.5 | <1.0 |
| Chloride (mg/L) | 34.4 | 63.5 |
| Sulfate (mg/L) | 16.7 | 15.3 |

The same raw CBNG produced water was transported to an undisclosed location and treated using a RO unit that was operated by MWH. The laboratory results of the raw and RO treated water are presented in Table 2.

Table 2 Laboratory Results for CBNG Produced Water Treated with RO

| Parameter | Raw Produced Water | RO Treated Produced Water |
|---|--------------------|---------------------------|
| pH | 8.2 | 6.5 |
| EC(μ S/cm) | 2640 | 106 |
| SAR | 51.3 | 0.2 |
| Alkalinity (mg/L as CaCO ₃) | 1533 | 34.5 |
| Sodium (mg/L) | 1100 | 13.3 |
| Potassium (mg/L) | 26.3 | <1.0 |
| Calcium (mg/L) | 15.9 | <1.0 |
| Magnesium (mg/L) | 11.5 | <1.0 |
| Chloride (mg/L) | 34.4 | 5.6 |
| Sulfate (mg/L) | 16.7 | 2.0 |

Conventional Source Produced Water

Approximately 800 gallons of produced water was obtained from a conventional gas well operated near Riverton, WY. Lab results showed the water initially had about 86.8 mg/L oil and grease and 66 mg/L GRO. The water was treated on location using dissolved air filtration and organo-clay treatment systems to reduce oil and grease to 65.2 mg/L and GRO to 57 mg/L. The water was further treated with DAF and Organo-clay system at the WRI laboratory to reduce TPH and GRO to <0.01 mg/L. After treatment the water was shipped to EMIT in 16 x 55 gallon drums for EDR treatment.

Combined in one tank, the measured pH was 8.38 and measured EC was 9.39 mS/cm. The water was then filtered for several days through Mycelx HRM and EB organic removal cartridges, 10 micron cartridge filters, and 1 micron bag filters. Analysis of the filtered water with a Turner Design TD-500D Handheld Oil in Water Meter, was 1.3 mg/L TPH before filtration and 0.6 mg/L TPH after filtration.

Filtered feed water was dosed with hydrochloric acid (to pH 6.5) and sodium hexametaphosphate (to 5 ppm) as needed for scale control prior to treatment with EDR. EMIT processed the water from 6-29-2009 through 7-2-2009, producing 14 drums of product water. The actual Feed water flow rate was 1.548 LPM, Diluate (product) rate was 1.333 LPM and Concentrate overflow rate was 0.215 LPM (13.9% brine generation rate) for a total online processing time of about 33 hours.

After 2-stage EDR, the 14 drums of Product water were processed using the CIX/AIX Ion Exchange pilot system to further reduce sodium and chloride levels as needed for WRI's soil irrigation study. Feed water flow rate through the IX system ranged between 0.75 and 1.8 LPM.

Brine generation was measured to be 2.7% of feed flow. Combined system (EDR + IX) fluid balance for processing 800 gallons of produced water was 650 gallons product water, 120 gallons of concentrate/brine, and 30 gallons wasted as tank and vessel residual.

A summary of the lab analytical results for treatment of Conventional Source Produced Waters using the EDR/IX system is shown below in Table 3.

Table 3 Laboratory Results for EDR Treatment of Conventional Source Produced Water

| Parameter | Raw Conventional Oil and Gas Produced Water | EDR Treated Water |
|--|--|--------------------------|
| pH | 8.3 | 4.4 |
| EC(μ S/cm) | 9720 | 193 |
| SAR | 341.8 | 2.5 |
| Alkalinity(total) (mg/L as CaCO ₃) | 2584 | 0 |
| Sodium (mg/L) | 4135 | 26.9 |
| Potassium (mg/L) | 21.9 | <1.0 |
| Calcium (mg/L) | 7.7 | 7.3 |
| Magnesium (mg/L) | 1.3 | <1.0 |
| Chloride (mg/L) | 1800 | 8 |
| Sulfate (mg/L) | 5.9 | 2.2 |

For CBM produced water, the CCIX system removed 93.7% of the TDS. The EDR/IX system used for treatment of Conventional Source produced water had TDS and chloride reductions of 97.7% and >99%, respectively. As noted previously, the product water from both systems delivered to WRI was not pH adjusted, or amended with SAR enhancing minerals. SAR and pH are easily adjusted to the desired levels by addition of hydrated lime and/or gypsum.

The same raw conventional oil and gas produced water was transported to an undisclosed location and treated using an RO unit that was operated by MWH. The laboratory results of the raw and RO treated water are presented in Table 4.

Table 4 Laboratory Results for Conventional Oil and Gas Produced Water Treated with RO

| Parameter | Raw Conventional Oil and Gas Produced Water | RO Treated Water |
|--|---|------------------|
| pH | 8.3 | 9.2 |
| EC(μ S/cm) | 9720 | 157 |
| SAR | 341.8 | 3.8 |
| Alkalinity(total) (mg/L as CaCO ₃) | 2584 | 50.2 |
| Sodium (mg/L) | 4135 | 22.5 |
| Potassium (mg/L) | 21.9 | <1.0 |
| Calcium (mg/L) | 7.7 | <1.0 |
| Magnesium (mg/L) | 1.3 | <1.0 |
| Chloride (mg/L) | 1800 | 9.7 |
| Sulfate (mg/L) | 5.9 | 1.6 |

One of the problems associated with treated produced water was trying to maintain the stability of the water chemistry. Some small changes were observed from the time the samples were collected and treated to the time that the hydraulic conductivity measurements were made. Every attempt was made to prevent changes by keeping water in cold storage and reducing the time the water was exposed to air prior to use in the laboratory. Any impact is expected to be minimal. The tables provided above show the water quality at the time that hydraulic conductivity measurements were initiated.

Hydraulic Conductivity Measurements using Flexible-walled Permeameters

Hydraulic conductivity (HC) values for the X-Ranch soil irrigated with various combinations of treated CBNG produced water and conventional oil and gas produced water treated with various technologies were determined using flexible-walled permeameters (Figure 5).

Data collected from the hydraulic conductivity study are presented in Table 3 (laboratory test run data and statistical evaluations are presented in Appendix A and B, respectively). For the CBNG produced water portion of the study, results tended to follow expectations with the hydraulic conductivity of soil impacted with the 100% reverse osmosis treated water comparing well with the HC of soil treated with river water (no significant difference). The river water contained relative high EC (0.8 dS/m) and low SAR (0.8), while the 100% treated CBNG produced water was characterized by very low EC (0.1 dS/m) and a SAR of 2.0. Apparently, the very low salt content of the water treated by reverse osmosis was not an apparent factor impacting soil structure. It should be noted that irrigation water characterized with very low salt content has

been shown to decrease the hydraulic conductivity of irrigated soils (reference) but was a limited factor in this study. An important finding of this research effort is that soils treated with blended waters appeared to cause similar impacts to soil structure. The HC values of soil materials irrigated with 25%, 50% and 75% treated water (the other percentage of the blend is untreated CBNG produced water) significantly lower compared to the control (river water) and 100% treated water. The HC values associated with these treatments were found similar to the untreated produced water.



Figure 5 Flexible-walled Permeameter Apparatus.

Data collected show that the relatively high SAR values of the 75% treatment (SAR = 14), the 50% blend (SAR = 24.3), the 25% blend (SAR = 31.7) and the no treatment water (SAR = 38.2) significantly impacted the HC values to lower levels compared to the control and 100% treatment. The relatively low EC values associated with these treatments apparently did not compensate for the tendency for dispersion.

The CBNG produced water treated by ion exchange (EMIT Process) resulted in similar outcomes as noted for the reverse osmosis treated water. The soil treated with 100% (no blending) ion exchange treated water was characterized with a high hydraulic conductivity compared to the blended waters and very similar to that determined for the 100% treated reverse osmosis treated water (no significant differences). This was true even though the 100% ion exchange treated water was characterized with a higher SAR value (SAR = 5.8) and a very low

EC value (0.3 dS/m) compared to the 100% reverse osmosis and river water. The hydraulic conductivities of soils treated with the 75%, 50% and 25% blends were very similar (no significant differences) and were found to be very similar (no significant difference) to the results from untreated water treatment.

Table 5 Hydraulic Conductivity of Soil Treated with Treated Water.

| Water Type | Treatment | Hydraulic Conductivity (HC) (cm/s) | Statistical Difference HC | EC (dS/m) | SAR |
|---|--|---|---------------------------|-----------|------|
| Coalbed Natural Gas Produced Water | | | | | |
| River Water | No Treatment | Rep1: 2.7×10^{-3} Rep2: 1.7×10^{-3} Rep3: 2.8×10^{-3} Avg: 2.4×10^{-3} SD: 6.1×10^{-4} | a | 0.8 | 0.8 |
| CBNG Produced Water | 100% - Reverse Osmosis | Rep1: 2.4×10^{-3} Rep2: 1.9×10^{-3} Rep3: 2.6×10^{-3} Avg: 2.3×10^{-3} SD: 3.6×10^{-4} | a | 0.1 | 2.0 |
| CBNG Produced Water | Blend: 75% - Reverse Osmosis; 25% Untreated | Rep1: 5.2×10^{-4} Rep2: 1.1×10^{-3} Rep3: 4.9×10^{-4} Avg: 7.0×10^{-4} SD: 3.4×10^{-4} | b | 0.8 | 14.0 |
| CBNG Produced Water | Blend: 50% - Reverse Osmosis; 50% Untreated | Rep1: 5.0×10^{-5} Rep2: 2.2×10^{-4} Rep3: 3.4×10^{-4} Avg: 2.0×10^{-4} SD: 1.5×10^{-4} | b | 1.4 | 24.3 |
| CBNG Produced Water | Blend: 25% - Reverse Osmosis; 75% Untreated | Rep1: 1.4×10^{-4} Rep2: 3.8×10^{-5} Rep3: 6.7×10^{-5} Avg: 8.2×10^{-5} SD: 5.3×10^{-5} | b | 2.1 | 31.7 |
| CBNG Produced Water | No Treatment | Rep1: 1.7×10^{-5} Rep2: 1.5×10^{-4} Rep3: 1.5×10^{-4} Avg: 1.1×10^{-4} SD: 7.7×10^{-5} | b | 3.0 | 38.2 |
| CBNG | 100% - Ion | Rep1: 2.2×10^{-3} | a | 0.3 | 5.8 |

| | | | | | |
|-----------------------------------|--|---|---|-----|------|
| Produced Water | Exchange | Rep2: 1.7×10^{-3} Rep3: 1.9×10^{-3} Avg: 1.9×10^{-3} SD: 2.5×10^{-4} | | | |
| CBNG Produced Water | Blend: 75% - Ion Exchange; 25% Untreated | Rep1: 1.6×10^{-4} Rep2: 1.6×10^{-4} Rep3: 5.0×10^{-4} Avg: 2.7×10^{-4} SD: 2.0×10^{-4} | b | 1.0 | 17.8 |
| CBNG Produced Water | Blend: 50% - Ion Exchange; 50% - Untreated. | Rep1: 2.1×10^{-5} Rep2: 4.0×10^{-4} Rep3: 4.5×10^{-4} Avg: 2.9×10^{-4} SD: 2.4×10^{-4} | b | 1.6 | 24.7 |
| CBNG Produced Water | Blend: 25% - Ion Exchange; 75% - Untreated. | Rep1: 9.4×10^{-5} Rep2: 3.1×10^{-4} Rep3: 8.2×10^{-5} Avg: 1.6×10^{-4} SD: 1.3×10^{-4} | b | 2.1 | 32.2 |
| Oil and Gas Produced Water | | | | | |
| River Water | No Treatment | Rep1: 2.7×10^{-3} Rep2: 1.7×10^{-3} Rep3: 2.8×10^{-3} Avg: 2.4×10^{-3} SD: 6.1×10^{-4} | c | 0.8 | 0.8 |
| Oil & Gas Produced Water | 100% - Reverse Osmosis | Rep1: 1.1×10^{-4} Rep2: 3.2×10^{-4} Rep3: 9.6×10^{-5} Avg: 1.7×10^{-4} SD: 1.2×10^{-4} | d | 0.1 | 5.7 |
| Oil & Gas Produced Water | Blend: 75% - Reverse Osmosis; 25% Untreated | Rep1: 8.1×10^{-7} Rep2: 3.9×10^{-6} Rep3: 3.5×10^{-6} Avg: 2.7×10^{-6} SD: 1.7×10^{-6} | d | 2.8 | 116 |
| Oil & Gas Produced Water | Blend: 50% - Reverse Osmosis; 50% Untreated | Rep1: 4.7×10^{-6} Rep2: 6.4×10^{-6} Rep3: 5.7×10^{-6} Avg: 5.6×10^{-6} SD: 8.9×10^{-7} | d | 4.9 | 167 |
| Oil & Gas | Blend: 25% - | Rep1: 3.4×10^{-6} | d | 7.6 | 228 |

| | | | | | |
|--------------------------|---------------------------------------|---|---|-----|------|
| Produced Water | Reverse Osmosis; 75% Untreated | Rep2: 3.1×10^{-6} Rep 3: 4.3×10^{-6} Avg: 3.6×10^{-6} SD: 6.2×10^{-7} | | | |
| Oil & Gas Produced Water | No Treatment | Rep1: 4.8×10^{-6} Rep2: 3.9×10^{-6} Rep3: 2.5×10^{-6} Avg: 3.7×10^{-6} SD: 1.2×10^{-6} | d | 8.8 | 272 |
| Oil & Gas Produced Water | 100% - EDR | Rep1: 1.5×10^{-4} Rep2: 2.9×10^{-4} Rep3: 1.5×10^{-3} Avg: 6.3×10^{-4} SD: 7.2×10^{-4} | d | 1.5 | 34.6 |
| Oil & Gas Produced Water | Blend: 75% - EDR; 25% Untreated | Rep1: 3.9×10^{-6} Rep2: 3.9×10^{-6} Rep3: 3.9×10^{-6} Avg: 3.9×10^{-6} SD: 0 | d | | 103 |
| Oil & Gas Produced Water | Blend: 50% - EDR; 50% - Untreated. | Rep1: 4.9×10^{-6} Rep2: 6.3×10^{-6} Rep3: 8.1×10^{-6} Avg: 6.4×10^{-6} SD: 1.6×10^{-6} | d | | 225 |
| Oil & Gas Produced Water | Blend: 25% - EDR; 75% - Untreated. | Rep1: 5.5×10^{-6} Rep2: 7.8×10^{-6} Rep3: 5.0×10^{-6} Avg: 6.1×10^{-6} SD: 1.5×10^{-6} | d | | 241 |

On a comparative basis, soils treated with the conventional oil and gas produced water (produced water generated from traditional oil and gas production) treated with RO were more adversely impacted compared to soils treated with CBNG produced water treated with RO. The HC of soils impacted with 100% treated (reverse osmosis) oil and gas produced water (average - 1.7×10^{-4} cm/s) was about a factor of 10 lower compared to the hydraulic conductivity of soils treated with 100% RO treated CBNG produced water. Another interesting fact was that water treatment did not significantly improve HC to higher levels compared to the untreated produced water. No significant differences in HC were found for X-Ranch soil impacted with conventional oil and gas produced water treated by RO at the 25%, 50%, 75% and 100%

treatment levels. Similar results were found for the EDR treated produced water. As shown in Table 5, soil HC values associated with the 100% EDR treated water are not significantly different from the 25%, 50%, 75%, 100% treated water, and the untreated water. The HC values associated with the control (river water) were significantly higher.

The soil HC values associated with the conventional oil and gas produced water appear to be directly related to the high SAR makeup of each water used to impact the soil columns. The conventional oil and gas water is characterized with high salt content (high EC values) and very high SAR values. The SAR of the untreated produced water is 272 with the blends resulting from RO treatment ranging from 116 for the 75% blend to 228 for the 25% blend. The 100% treated water was characterized with a low SAR of 5.7 but a corresponding low EC of 0.1 dS/m. Similar findings resulted for the EDR treated produced water as the 75%, 50% and 25% blends were characterized with very high SAR values that tended to result in relatively low HC. It should also be noted that the 100% treated produced water was characterized with a high SAR value of 34.6 and an EC of 1.5 dS/m. The relatively low HC associated with the 100% treated is likely due to the high SAR and low EC, which does not compensate for the high dispersion tendency resulting from the SAR .

Summary

Limited differences exist in the HC of soils impacted with treated and untreated CBNG produced water. Produced water treated using the IX and RO technologies at the 100% level was found to be similar to the control (river water), while the treatment levels of 25%, 50% and 75% resulted in significantly lower HC values that compared well to the values associated with untreated produced water.

The HC data collected for conventional oil and gas produced water showed no improvement in HC over the untreated produced water for all levels of treatment. Water treatment did not appear to improve HC for oil and gas produced water.

Characterization of Soils Used in the Hydraulic Conductivity Study

Soils used in the hydraulic conductivity study were evaluated at the conclusion of the study to determine how the irrigation water impacted the chemistry of the material. The primary parameters of concern were EC and SAR, which will be discussed in the following paragraphs. The data are presented in Tables 4 and 5 and the statistical evaluations are provided in Appendix C.

SAR

The soils treated with CBNG produced water were characterized with significantly lower SAR values compared to the conventional oil and gas water. The CBNG produced water treated with RO at the 100% treatment level was significantly different from the untreated produced

water while the 25%, 50% and 75% water treatment levels were not significantly different from the untreated water. The SAR values associated with RO treated CBNG produced water was similar to the untreated water characterized with SAR values significantly higher compared to the treated water and the 25%, 50% and 75% water treatments being significantly higher compared to the 100% treated water. SAR values associated with IX treated water appeared to be somewhat mixed as the 100% treatment was similar to the 25% and 75% treatments while the 50% treatment was significantly higher. The 25%, 50% and 75% treatments resulted in SAR values that were not significantly different.

Conventional oil and gas produced water treated with EDR and RO showed comparable SAR results for the water treatment technologies. There was no significant difference between the 100% treated produced water and the control (river water) with the use of EDR and RO. The EDR water treatment resulted with differences at each level of treatment as the SAR of the 25% treatment was significantly higher than the 50% treatment, the 50% treatment was significantly higher compared to the 75% treatment and the 75% treatment was higher compared to the 100% treatment. Similar results characterized the RO treated conventional oil and gas water. The 100% treated water had SAR values significantly lower than the 75% and 50% treatments, which were similar (not significantly different). The 25% treatment resulted in SAR values significantly higher than the 50% and 75% water treatments.

EC

The EC values for the CBNG produced water treated with RO and ion exchange didn't vary much from the control (river water) but did show some significant differences compared to the untreated produced water. The 100% RO treated water was the only water treatment significantly different compared to the untreated produced water. The ion exchange treated produced water did not show any differences in EC values between treatments but did result in significant differences between the untreated water compared to the 25%, 75% and 100% treatment.

The results of the EDR treated conventional oil and gas water seemed to mimic the trends found for the SAR data. The treatment levels appeared to decrease EC levels with the amount of treatment from untreated to 100% treatment. These data are shown in Table 6 and 7. Similar findings were shown for the RO treated water with the 50% treatment falling out of sequence for some unknown reason.

Table 6 Coalbed Natural Gas (CBNG) Produced Water Treated with RO and IX at Various Levels of Treatment.

| Treatment | Replicate | pH units | EC dS/m | Ca meq/L | Mg meq/L | K meq/L | Na meq/L | SAR |
|-----------|-----------|-------------|------------|-------------|-------------|------------|-------------|-------|
| Control | 1 | 7.3 | 0.6 | 2.66 | 1.47 | 0.12 | 1.82 | 1.27 |
| Control | 2 | 7.2 | 0.61 | 2.82 | 1.64 | 0.15 | 1.75 | 1.17 |
| Control | 3 | 7.2 | 0.6 | 2.98 | 1.58 | 0.23 | 2.12 | 1.40 |
| No Trt | 1 | 7.6 | 1.26 | 1.02 | 0.55 | 0.19 | 11.9 | 13.43 |
| No Trt | 2 | 7.5 | 1.13 | 1.06 | 0.54 | 0.19 | 11 | 12.30 |
| No Trt | 3 | 7.7 | 1.16 | 0.99 | 0.5 | 0.18 | 11.6 | 13.44 |
| 25% RO | 1 | 8 | 0.66 | 0.86 | 0.42 | 0.17 | 5.85 | 7.31 |
| 25% RO | 2 | 7.8 | 0.76 | 1.35 | 0.59 | 0.15 | 6.79 | 6.89 |
| 25% RO | 3 | 7.7 | 0.69 | 0.89 | 0.45 | 0.1 | 6.2 | 7.57 |
| 50% RO | 1 | 7.1 | 0.9 | 1.27 | 0.63 | 0.12 | 7.45 | 7.64 |
| 50% RO | 2 | 7.5 | 0.52 | 0.64 | 0.32 | 0.07 | 4.03 | 5.82 |
| 50% RO | 3 | 7.9 | 0.67 | 0.66 | 0.32 | 0.1 | 5.85 | 8.36 |
| 75% RO | 1 | 7.4 | 0.67 | 1.12 | 0.54 | 0.12 | 5.56 | 6.10 |
| 75% RO | 2 | 7.4 | 0.7 | 1 | 0.49 | 0.12 | 5.62 | 6.51 |
| 75% RO | 3 | 7.4 | 0.6 | 1.15 | 0.54 | 0.12 | 5.05 | 5.49 |
| 100% RO | 1 | 7.1 | 0.47 | 2.26 | 1.08 | 0.13 | 1.5 | 1.16 |
| 100% RO | 2 | 7.1 | 0.51 | 2.34 | 1.15 | 0.14 | 1.61 | 1.22 |
| 100% RO | 3 | 7.1 | 0.53 | 2.71 | 1.27 | 0.15 | 1.51 | 1.07 |
| 25% IX | 1 | 8 | 0.6 | 0.92 | 0.4 | 0.08 | 5.23 | 6.44 |
| 25% IX | 2 | 8 | 0.52 | 0.77 | 0.35 | 0.1 | 4.91 | 6.56 |
| 25% IX | 3 | 8 | 0.52 | 0.86 | 0.4 | 0.11 | 4.71 | 5.93 |
| 50% IX | 1 | 7.4 | 0.71 | 0.96 | 0.44 | 0.12 | 6.08 | 7.27 |
| 50% IX | 2 | 7.8 | 0.69 | 0.82 | 0.38 | 0.11 | 5.88 | 7.59 |
| 50% IX | 3 | 7.6 | 0.81 | 0.94 | 0.43 | 0.11 | 6.57 | 7.94 |
| 75% IX | 1 | 7.6 | 0.59 | 0.74 | 0.35 | 0.09 | 5.04 | 6.83 |
| 75% IX | 2 | 7.5 | 0.62 | 0.97 | 0.44 | 0.1 | 5.13 | 6.11 |
| 75% IX | 3 | 7.6 | 0.56 | 0.97 | 0.43 | 0.09 | 4.86 | 5.81 |
| 100% IX | 1 | 7.1 | 0.61 | 2.2 | 0.99 | 0.14 | 3.39 | 2.68 |
| 100% IX | 2 | 7.2 | 0.66 | 2.18 | 0.97 | 0.13 | 3.69 | 2.94 |
| 100% IX | 3 | 7.1 | 0.66 | 2.34 | 1.08 | 0.14 | 3.43 | 2.62 |

Table 7 Conventional Oil and Gas Produced Water Treated with EDR and RO at Various Levels of Treatment.

| Treatment | Replicate | pH units | EC dS/m | Ca meq/L | Mg meq/L | K meq/L | Na meq/L | SAR |
|-------------|-----------|-------------|------------|-------------|-------------|------------|-------------|-------|
| Control | 1 | 7.3 | 0.6 | 2.66 | 1.47 | 0.12 | 1.82 | 1.27 |
| Control | 2 | 7.2 | 0.61 | 2.82 | 1.64 | 0.15 | 1.75 | 1.17 |
| Control | 3 | 7.2 | 0.6 | 2.98 | 1.58 | 0.23 | 2.12 | 1.40 |
| No Trt | 1 | 7.8 | 2.66 | 1.01 | 0.48 | 0.14 | 23.6 | 27.34 |
| No Trt | 2 | 8.2 | 2.26 | 0.76 | 0.36 | 0.12 | 21 | 28.06 |
| No Trt | 3 | 7.5 | 3.51 | 1.14 | 0.6 | 0.17 | 29.7 | 31.84 |
| 25% EDR | 1 | 8.2 | 1.3 | 0.7 | 0.31 | 0.14 | 11.1 | 15.62 |
| 25% EDR | 2 | 8.2 | 2.03 | 0.88 | 0.38 | 0.16 | 16.4 | 20.66 |
| 25% EDR | 3 | 8.2 | 2.01 | 0.83 | 0.36 | 0.11 | 18.1 | 23.46 |
| 50% EDR | 1 | 7.8 | 1.46 | 0.88 | 0.41 | 0.1 | 12.5 | 15.56 |
| 50% EDR | 2 | 7.7 | 1.42 | 1.09 | 0.51 | 0.1 | 11.7 | 13.08 |
| 50% EDR | 3 | 7.6 | 1.76 | 0.95 | 0.43 | 0.1 | 13.9 | 16.73 |
| 75% EDR | 1 | 7.5 | 1.1 | 0.84 | 0.38 | 0.09 | 8.31 | 10.64 |
| 75% EDR | 2 | 7.3 | 1.12 | 1.29 | 0.6 | 0.11 | 8.77 | 9.02 |
| 75% EDR | 3 | 7.5 | 1.4 | 1.48 | 0.69 | 0.14 | 10.8 | 10.37 |
| 100% EDR | 1 | 7.3 | 0.61 | 3.34 | 1.53 | 0.14 | 1.48 | 0.95 |
| 100% EDR | 2 | 7.3 | 0.5 | 3.01 | 1.23 | 0.12 | 1.54 | 1.06 |
| 100% EDR | 3 | 7.2 | 0.49 | 2.58 | 1.07 | 0.12 | 1.51 | 1.12 |
| 25% RO | 1 | 8 | 2.18 | 0.96 | 0.41 | 0.14 | 17.7 | 21.39 |
| 25% RO | 2 | 7.6 | 1.44 | 1.14 | 0.52 | 0.09 | 11 | 12.07 |
| 25% RO | 3 | 7.5 | 1.49 | 0.8 | 0.36 | 0.08 | 11.8 | 15.49 |
| 50% RO | 1 | 7.8 | 1.04 | 0.64 | 0.28 | 0.07 | 7.8 | 11.50 |
| 50% RO | 2 | 7.8 | 1.07 | 0.77 | 0.33 | 0.08 | 8.52 | 11.49 |
| 50% RO | 3 | 7.8 | 1.48 | 0.91 | 0.41 | 0.1 | 11.7 | 14.40 |
| 75% RO | 1 | 7.4 | 1.52 | 2.09 | 1.1 | 0.16 | 10.8 | 8.55 |
| 75% RO | 2 | 7.4 | 1.32 | 1.23 | 0.57 | 0.11 | 10.3 | 10.86 |
| 75% RO | 3 | 7.4 | 1.85 | 1.88 | 0.91 | 0.15 | 13.6 | 11.51 |
| 100% RO | 1 | 7.3 | 0.47 | 2.07 | 0.99 | 0.13 | 1.88 | 1.52 |
| 100% RO | 2 | 7.4 | 0.45 | 1.89 | 0.88 | 0.11 | 1.66 | 1.41 |
| 100% RO | 3 | 7.4 | 0.52 | 2.22 | 1.06 | 0.12 | 1.93 | 1.51 |

SUMMARY

In general, the soils impacted by the CBNG produced water and the conventional oil and gas produced waters did not have a significant impact on the EC values of the soils. The resulting EC values resulting from all treatments would not be expected to significantly impact plant growth. The only concern would be whether or not the EC values were high enough to prevent dispersion of clays due to the corresponding SAR values.

The soils treated with CBNG produced water were characterized with significantly lower SAR values compared to the conventional oil and gas water. The CBNG produced water treated with RO at the 100% treatment level was significantly different from the untreated produced water while the 25%, 50% and 75% water treatment levels were not significantly different from the untreated water. The SAR values associated with RO treated CBNG produced water was similar to the untreated water. Conventional oil and gas produced water treated with EDR and RO showed comparable SAR results for the water treatment technologies. There was no significant difference between the 100% treated produced water and the control (river water) with the use of EDR and RO.

One issue that needs to be evaluated in a future study is associated with the chemical nature of the produced water treatments and the resulting chemistry of the impacted soils. Some questions as to the validity of the data are apparent. For example, the conventional oil and gas produced water treated with EDC at the 25% level was characterized with an EC of 7.6 dS/m and a SAR of 228. After treatment, the impacted soil was characterized with a mean SAR of 19.9 and a mean EC of 1.8 dS/m. The level of impact found appears to be much less than expected.

Germination Studies

Germination results are shown in Figures 1 and 2. It appears that produced water from both CBNG and conventional oil and gas production did not significantly impact germination rate. In fact germination rate appeared to be somewhat less in Treatment 1, which is river water compared to that determined for raw produced waters. Differences are apparent between several of the treatments for alfalfa and western wheatgrass germination. However, variation between replicates was found to be rather high resulting in no significant differences in germination of alfalfa and western wheatgrass seeds when watered with the 19 water treatments.

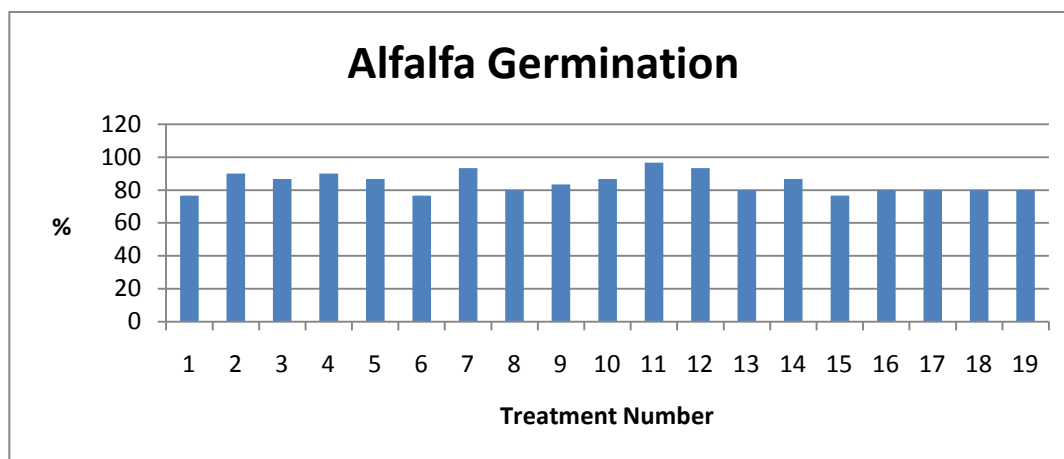


Figure 6 Percent Germination for Alfalfa for the Nineteen (19) Treatments. Treatment Number is Defined Previously in this Report.

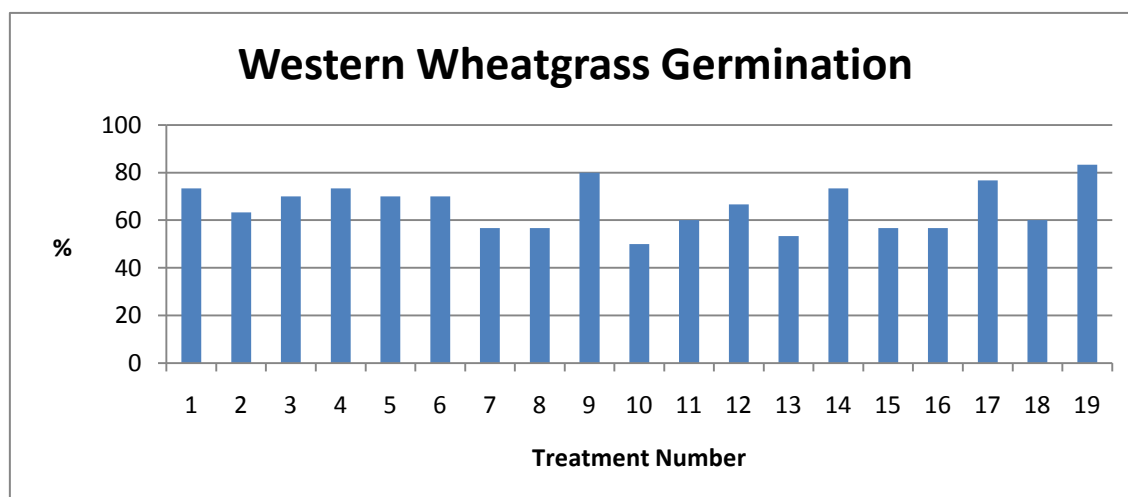


Figure 7 Percent Germination for Western Wheatgrass for the Nineteen (19) Treatments. Treatment Numbers are Defined Previously in this Report.

Greenhouse Irrigation Experiment

The results of the greenhouse irrigation study are provided in Table 8 and 9 (Laboratory data is presented in Appendix E). The differences found between each soil were significant for Western Wheatgrass and Alfalfa. The Sheridan sandy loam soil resulted in the highest production for western wheatgrass and alfalfa while the X-ranch sandy loam had the lowest production rate for both plants. The soils reacted to the various water treatment combinations (blends) likely due to the interactions between the soils and the chemical makeup of the treated water. A discussion will be provided in the next section of the report with regard to the potential plant toxicities resulting from elements found in the plant tissue that were likely concentrated by the various water treatment technologies.

Table 8 Alfalfa Biomass Production Using Treated Produced Water from CBNG and Oil and Gas Wells for Irrigation. Average Biomass Weights of Four (4) Replicates from Two (2) Cuttings.

| | | Riverton Clay Loam | | Sheridan Sandy | | X-Ranch Sandy | |
|----------------------------|---------|--------------------|------------------------|-----------------|------------------------|-----------------|------------------------|
| | | Soil | | Loam Soil | | Loam Soil | |
| | | % Treated Water | Avg Biomass Weight (g) | % Treated Water | Avg Biomass Weight (g) | % Treated Water | Avg Biomass Weight (g) |
| CBNG Produced Water | Raw | 0 | 0.51 | 0 | 1.66 | 0 | 0.36 |
| | RO | 25 | 1.90 | 25 | 1.38 | 25 | 1.54 |
| | | 50 | 1.68 | 50 | 1.75 | 50 | 1.40 |
| | | 75 | 1.62 | 75 | 1.75 | 75 | 1.23 |
| | | 100 | 1.58 | 100 | 2.30 | 100 | 1.81 |
| | IE | 25 | 1.56 | 25 | 1.50 | 25 | 0.55 |
| | | 50 | 1.33 | 50 | 1.86 | 50 | 1.70 |
| | | 75 | 1.36 | 75 | 1.91 | 75 | 1.21 |
| | | 100 | 1.65 | 100 | 2.70 | 100 | 1.29 |
| | Control | River Water | 1.92 | River Water | 2.42 | River Water | 0.84 |
| Oil and Gas Produced Water | Raw | 0 | 0.32 | 0 | 0.00 | 0 | 0.32 |
| | EDR | 25 | 0.46 | 25 | 0.60 | 25 | 0.00 |
| | | 50 | 0.00 | 50 | 0.96 | 50 | 0.00 |
| | | 75 | 0.91 | 75 | 1.70 | 75 | 0.55 |
| | | 100 | 1.37 | 100 | 1.85 | 100 | 0.66 |
| | RO | 25 | 0.16 | 25 | 0.15 | 25 | 0.27 |
| | | 50 | 0.39 | 50 | 1.62 | 50 | 0.13 |
| | | 75 | 1.44 | 75 | 1.52 | 75 | 1.57 |
| | | 100 | 1.56 | 100 | 2.41 | 100 | 0.95 |
| | Control | River Water | 1.92 | River Water | 1.65 | River Water | 0.84 |

| | | % Treated Water | Avg Biomass Weight (g) | % Treated Water | Avg Biomass Weight (g) | % Treated Water | Avg Biomass Weight (g) |
|----------------------------|---------|-----------------|------------------------|-----------------|------------------------|-----------------|------------------------|
| CBNG Produced Water | Raw | 0 | 1.39 | 0 | 2.64 | 0 | 0.89 |
| | RO | 25 | 1.57 | 25 | 2.81 | 25 | 1.21 |
| | | 50 | 1.95 | 50 | 2.03 | 50 | 0.97 |
| | | 75 | 1.50 | 75 | 1.50 | 75 | 0.93 |
| | | 100 | 1.28 | 100 | 1.02 | 100 | 0.78 |
| | IE | 25 | 1.19 | 25 | 2.45 | 25 | 0.81 |
| | | 50 | 1.18 | 50 | 2.06 | 50 | 0.81 |
| | | 75 | 1.28 | 75 | 1.51 | 75 | 0.98 |
| | | 100 | 1.19 | 100 | 1.18 | 100 | 0.66 |
| | Control | River Water | 0.95 | River Water | 1.13 | River Water | 0.76 |
| Oil and Gas Produced Water | Raw | 0 | 0.41 | 0 | 1.07 | 0 | 0.27 |
| | EDR | 25 | 0.70 | 25 | 1.28 | 25 | 0.32 |
| | | 50 | 0.99 | 50 | 1.37 | 50 | 0.53 |
| | | 75 | 0.76 | 75 | 1.83 | 75 | 0.39 |
| | | 100 | 1.07 | 100 | 1.35 | 100 | 0.44 |
| | RO | 25 | 0.37 | 25 | 1.46 | 25 | 0.33 |
| | | 50 | 0.59 | 50 | 1.58 | 50 | 0.79 |
| | | 75 | 0.68 | 75 | 1.72 | 75 | 0.51 |
| | | 100 | 0.98 | 100 | 1.19 | 100 | 0.62 |
| | Control | River Water | 0.95 | River Water | 1.13 | River Water | 0.76 |

Table 9 Western Wheatgrass Biomass Production Using Treated Produced Water from CBNG and Oil and Gas Wells for Irrigation. Average Biomass Weights of Four(4) Replicates from Two (2) Cuttings.

Biomass Production of the Soils Evaluated

The potential productivity of each soil was significantly different based on plant production from western wheatgrass with the highest plant production rate associated with the Sheridan sandy loam soil and the lowest production rate associated with the X-Ranch sandy loam soil (ANOVA statistics are provided in the Appendix F). Plant production levels resulting from untreated CBNG produced water were significantly higher compared to untreated conventional oil and gas produced water. However, few differences were found between water treatments. For example, CBNG produced water treated with ion exchange resulted in no significant difference in western wheatgrass production for the 25%, 50%, 75% and 100% treatment blends. The use of RO treated CBNG produced water for irrigation resulted in a significantly lower level for the 100% treated produced water compared to the 25% blend while the results for the 50% and 75% blends were not significantly different from the 100% treated and the 25% blend. The lower production level associated with the 100% treated water is likely associated with either a plant toxicity or nutritional imbalance caused by the treatment. The treatments used for the conventional oil and gas produced water seemed to vary. The produced water treated using EDR technology generated high western wheatgrass production compared to that resulting from the RO technology. However, the plant production levels associated with EDR did not differ significantly based on the amount of treatment. For example, 100% treated water resulted in production values not significantly different from the 25%, 50% and 75% blends. The same results were found for the RO treated water.

As noted for western wheatgrass, the potential productivity of each soil was significantly different based on plant production from alfalfa with the highest biomass production associated with the Sheridan sandy loam soil and the lowest production rate associated with the X-Ranch sandy loam soil (ANOVA statistics are provided in the Appendix B). Plant production levels of alfalfa resulting from untreated CBNG produced water appeared to be higher compared to untreated conventional oil and gas produced water. However, the variability of the data set showed overlap in the 95% confidence interval, which indicates no significant difference. Few differences were also found between water treatments. For example, CBNG produced water treated with ion exchange resulted in no significant difference in alfalfa biomass production for the 25%, 50%, 75% and 100% treatment blends. The use of RO treated CBNG produced water for irrigation resulted in a no significant difference between the 25% treatment, 50% treatment and the 75% treatment.

The treatments used for the conventional oil and gas produced water resulted in some significant differences in biomass generation. The produced water treated using EDR technology generated high alfalfa production compared to that resulting from the RO technology. The biomass production associated with conventional oil and gas produced water treated with EDR seemed to match the level of treatment with the 100% treated water resulting in the highest biomass production and the 25% blend resulting in the lowest. There were no significant

differences in the production levels characterizing the 100% treatment and the 75% treatment, which were both significantly higher compared to the 25% and 50% treatments. The results for the 25% and 50% treatments were not significantly different.

Alfalfa

Alfalfa biomass production levels resulting from irrigating with CBNG and conventional oil and gas produced waters treated using various technologies and blending rates are presented in Figures 8 and 9. The results are discussed in the following sections of the report.

Riverton Clay Loam Soil

Biomass resulting from the Riverton clay loam soil irrigated with conventional oil and gas produced water treated with IX (EMIT technology) was significantly different from the untreated water for the 50% blend, the 75% blend and the 100% treatment. However, the blends and 100% treated water were found to generate biomass at levels not significantly different than the control (river water). In addition, the 25% blend was not significantly different from the untreated (raw) water. Similar results were found for the CBNG produced water treated with RO. Significant differences were found between the raw water (untreated) and the 25% blend, 50% blend, the 75% blend, and the 100% treated water, while no significant differences were found between these treatment levels and the control (river water).

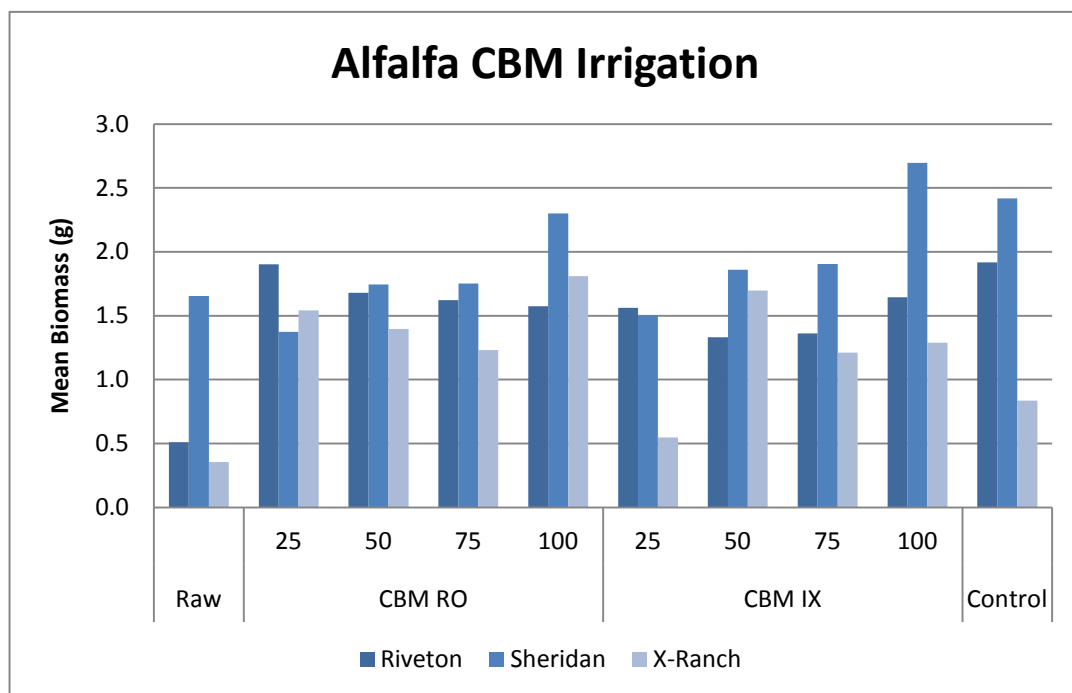


Figure 8 Alfalfa Production Using Treated CBM Produced Water for Irrigating Three (3) Soils – Riverton, Sheridan and X-Ranch Sampling Sites

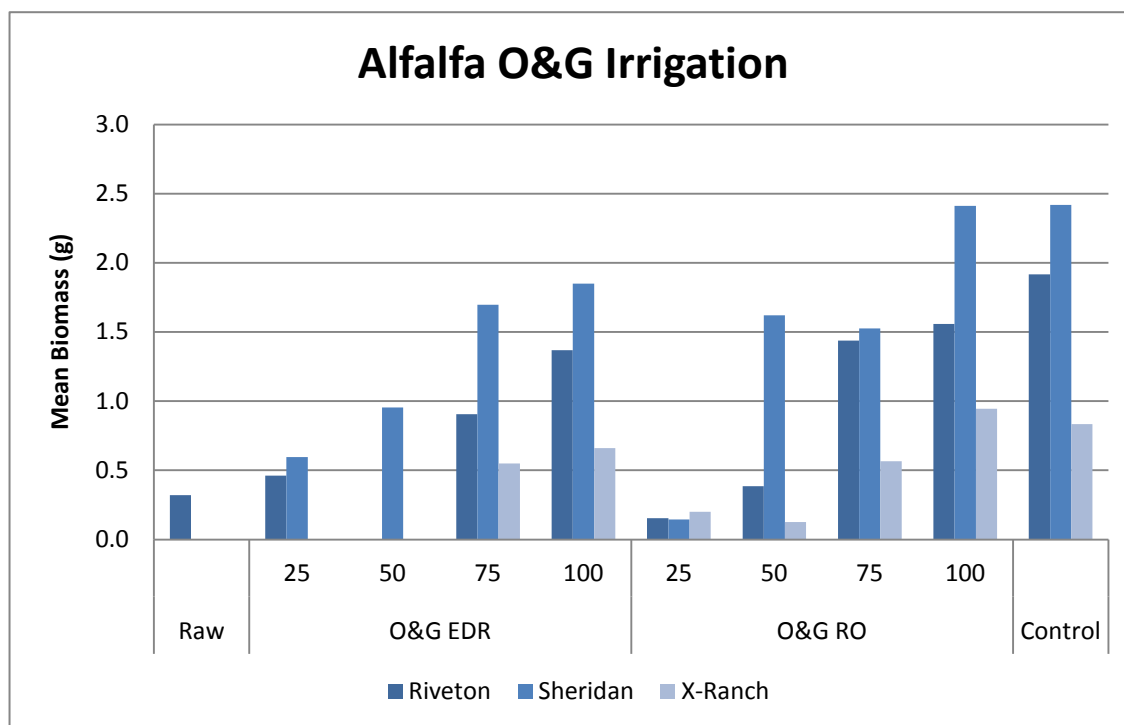


Figure 9 Alfalfa Production Using Treated Oil and Gas Produced Water for Irrigating Three (3) Soils – Riverton, Sheridan and X-Ranch Sampling Sites

The Riverton clay loam soil irrigated with produced water generated from conventional oil and gas wells resulted in plant biomass levels lower compared to the CBNG produced water irrigated plants. The EDR 75% blend and the 100% treatments were characterized with significantly higher production compared to the raw water irrigated soil, while the 50% and 75% blends resulted in alfalfa biomass production not significantly different from the raw water. There was no significant difference between the Control (river water) and the 100% treated water and borderline significance between the control and the 75% blended treatment.

Sheridan Sandy Loam Soil

As noted previously, the Sheridan sandy loam soil was the most productive soil used in the greenhouse study. The alfalfa biomass production levels resulting from irrigating with IX treated CBNG produced water appeared to be highest for the control (river water) and the 100% treated water, which were not significant different. The 25%, 50% and 75% blends were associated with significantly lower biomass production and were characterized with biomass production similar to the untreated water (raw). The biomass resulting from irrigation with RO treated CBNG produced water provided similar trends but with slightly different results. The 100% treated water compared well to the control but was also not significantly different from the production levels resulting from untreated water and the 50% and 75% treatments.

Biomass production levels associated with EDR water treatment of conventional oil and gas produced water varied significantly using the various blends of treated water for irrigation. The produced water treated at the 100% level using EDR was not significantly different compared to the 75% blend and the control (river water), while the biomass generated from irrigating with the 25% and 50% blends was significantly lower. The production associated with the 25% blend was found to be comparable to that produced by the raw water and was found not to be significantly different than the biomass production from the 50% blend. RO treated water provided similar results to the EDR treated water with the 100% treated water resulting in the highest biomass production rate comparing well to the control (river water). The production associated with the 100% treated water was significantly higher compared to the 25%, 50% and 75% blends while the 50% and 75% blends was not significantly higher than the control. The 25% blend resulted in much lower biomass production and was found to have very similar results compared to the untreated produced water.

Differences in biomass production were noticeably higher for untreated CBNG produced water compared to conventional oil and gas produced water. In general terms, the conventional oil and gas produced water treated at the 50%, 75% and 100% levels resulted in biomass levels not significantly different from corresponding treatment levels for CBNG produced water.

X-Ranch Sandy Loam Soil

The X-Ranch sandy loam soil was found to generate lower production of alfalfa compared to the Sheridan sandy loam soil but similar biomass production levels compared to the Riverton clay loam soil. Biomass production rates for all treatment levels using produced water treated with the IX (EMIT's technology) for irrigation showed significantly higher levels compared to the untreated water. The treated water at the various blending levels was not significantly different than production rates associated with the river water (control). The use of RO to treat the CBNG produced water resulted in similar results.

The conventional oil and gas produced water treated with EDR and RO resulted in very similar plant production levels. Biomass production from the 100% treatment was not significantly different from the control, while the biomass production associated with the 75% blend was significantly lower compared to the control but not significantly different than the 100% treated produced water. The 25%, 50% and 75% blends were not significantly different compared to the untreated conventional oil and gas produced water. As noted previously, the RO treated water resulted in very similar relationships between the level of biomass production and the level of treatment. It appears that biomass production resulting from irrigating with conventional oil and gas produced water treated with EDR and RO can be considered equivalent.

Photographs taken about 70% through the time period prior to the first cutting are provided to demonstrate differences in biomass production between treatments. Plants shown in

Figure 10 show differences in alfalfa growth in the Sheridan soil irrigated with conventional oil and gas produced water treated with EDR. In this study, the alfalfa plants responded well to the EDR treatment of conventional oil and gas produced water. As the amount of water treated increases, plant production appears to increase.



Figure 10 Alfalfa Growing in Sheridan Soil Irrigated with O&G Produced Water Treated with EDR at Various Combinations. Left to right are O&G raw, 25% O&G EDR, 50% O&G EDR, 75% O&G EDR, 100% O&G EDR, and River Water (Control).

The alfalfa biomass production associated with using CBNG produced water treated using RO with various blend rates is shown in Figure 11. This photo was taken about 70% through the time period prior to the first cutting. The photograph shows limited differences in the growth of alfalfa in the range of water quality conditions from river water (control) to the raw CBNG produced water.



Figure 11 Alfalfa Growing in Sheridan Soil Irrigated With CBM Produced Water Treated with RO at Various Combinations. Left to right are CBM raw, 25% CBM RO, 50% CBM RO, 75% CBM RO, 100% CBM RO, and River Water (Control).

Western Wheatgrass

The biomass production results using the three (3) soils to grow western wheatgrass irrigated with a variety of water treatments are presented in Figure 1 and 12.

Riverton Clay Loam Soil

The Riverton clay loam soil irrigated with coalbed natural gas produced water treated with IX (EMIT technology) was not significantly different from the untreated water this included plant production resulting from the 25%, 50%, and 75% blends. Similar results were found for the CBNG produced water treated with RO. No significant differences were found between the raw water (untreated) and the 100% treated water and the blends. However, differences were found between the 25% blend and the river water (control), between the 50% blend and the 100% treated water, and the 50% blend and the control. The cause of the significant differences will be discussed in the section of the report contemplating potential plant toxicities.

The Riverton clay loam soil irrigated with produced water generated from conventional oil and gas wells resulted in similar plant production rates as described for the CBNG produced water. The EDR 100% treatment was characterized with significantly higher biomass production compared to the raw water irrigated soil. However, the 25%, 50% and 75% blends resulted in western wheatgrass weights in the middle range between the raw water and the 100% treated water with no significantly difference from the raw water and the 100% treated water. Results for the RO treated conventional oil and gas water demonstrated a significant difference in plant

production between the 100% treated water and the 25% blend while no differences were found between the other treatment combinations.

Sheridan Sandy Loam Soil

As noted previously, the Sheridan sandy loam soil was the most productive soil used in the greenhouse study. However, the treatment of CBNG produced water using IX (EMIT technology) and RO provided some interesting results. The plant production levels resulting from irrigating with IX treated water appeared to be highest for the untreated CBNG produced water (raw) followed in order by the 25%, 50%, 75% and 100 treated blends. An important note is that the control (river water) was not significantly different from the 100% treated water. Plant productivity levels using the 100% treated water were significantly lower compared to the raw water (untreated), the 50% blend and the 25% blend. No significant difference in biomass production was observed between the 100% treated water and the 75% blend. The point is that the lower percentage treated water improved plant productivity. Similar results were shown using CBNG produced water treated with RO technology for irrigation. The use of untreated water for irrigation resulted in high plant production rates compared to the control (river water). The blended water RO treatments resulted in the same conclusions shown for the IX treatment with the 25% blend resulting in the highest plant production and decreased biomass production with additional treatment from 25% to 100%.

Biomass production levels associated with EDR and RO water treatment of conventional oil and gas produced water did not vary significantly using the various blends of treated water with one exception. The produced water treated with EDR at the 75% treatment level resulted in biomass production that was significantly higher compared to irrigating with raw water, the river water and the various treated water blends.

The reasons for the differences found for the Sheridan sandy loam soil are not readily apparent. However, the plant materials analysis may provide some suggestions for the results. This will be reviewed in the following section.

X-Ranch Sandy Loam Soil

The X-Ranch sandy loam soil was found to generate the lowest biomass production of western wheatgrass of the three (3) soils studied. Biomass production results using produced water treated with the IX (EMIT's technology) for irrigation showed no significant difference between untreated water, treated water at the various blending levels, and river water (control). The use of RO to treat the CBNG produced water resulted in only one difference, which was the difference between the 25% blend compared to 100% treated water and the river water (control). The conventional oil and gas produced water treated with EDR and RO resulted in very similar biomass production levels. The production levels associated with EDR treated water for all

blends from 100% treated to raw water (no treatment) were not significant different. However, the river water (control) was associated with significantly higher levels of productivity compared to EDR treated water for the 25% blend. For the conventional oil and gas produced water, only the 50% blend resulted in higher biomass production levels compared to the untreated produced water. The biomass production associated with the river water (control) was similar to the 50% and 100% treated water and significantly higher compared to biomass generated with the 25% and 75% blends. The reason for the apparent discrepancy in the data is not known at this time.

The growth status for western wheatgrass prior to the first cutting is shown in Figure 14 for the conventional oil and gas produced water treated with EDR and in Figure 15 for CBNG produced water treated with RO. The photos show very limited differences between treatments for both produced waters.

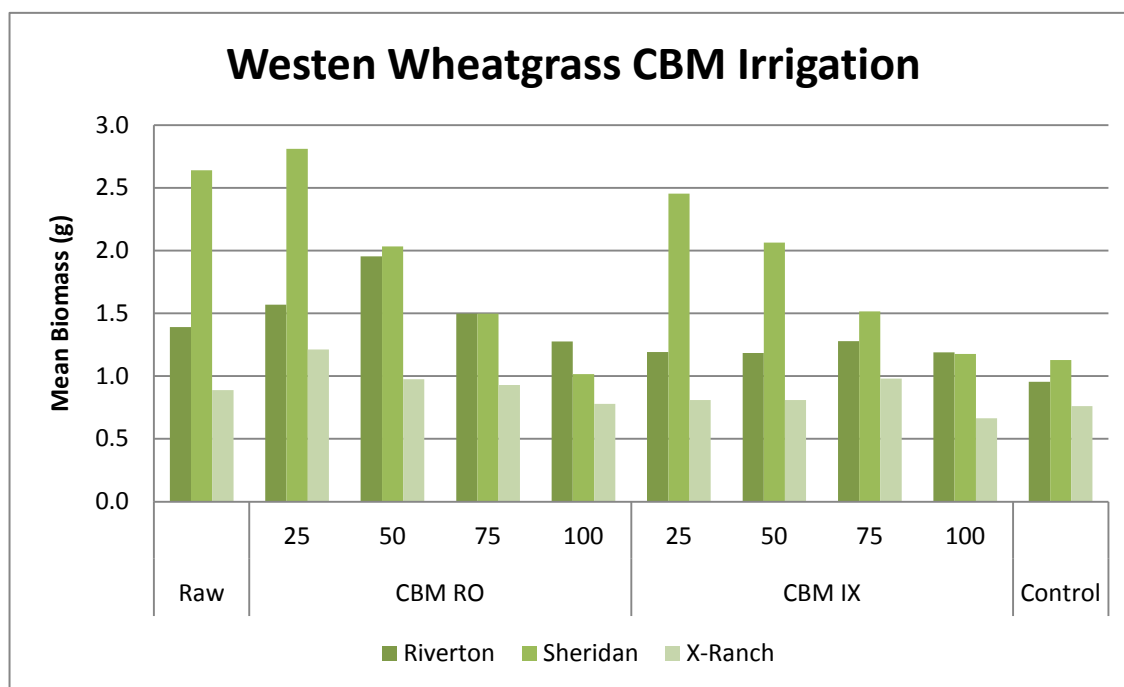


Figure 12 Western Wheatgrass Production Using Treated CBM Produced Water for Irrigating Three (3) Soils – Riverton, Sheridan and X-Ranch Soils

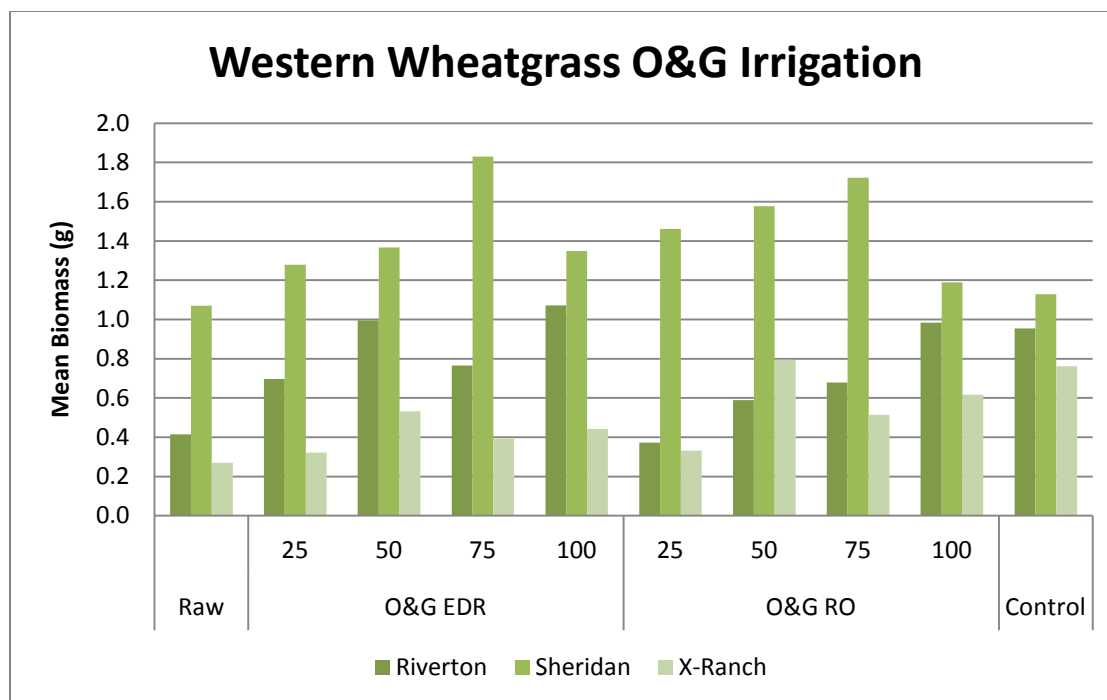


Figure 13 Western Wheatgrass Production Using Treated Conventional Oil and Gas Produced Water for Irrigating Three (3) Soils – Riverton, Sheridan and X-Ranch Sampling Sites



Figure 14 Western Wheatgrass Growing in Sheridan Soil Irrigated with O&G Produced Water Treated with EDR at Various Combinations. Left to right are O&G raw, 25% O&G EDR, 50% O&G EDR, 75% O&G EDR, 100% O&G EDR, and River Water (Control).



Figure 15 **Western Wheatgrass Growing in Sheridan Soil Irrigated with CBM Produced Water Treated with RO at Various Combinations. Left to right are CBM raw, 25% CBM RO, 50% CBM RO, 75% CBM RO, 100% CBM RO, and River Water (Control).**

Elemental Constituents of Biomass

The biomass produced during the greenhouse study was analyzed for elemental composition and for forage value (Sample analyses presented in Appendix E). Samples from each replication were composited to acquire enough samples for analysis, as a result, treatment replications were not established and a statistical evaluation was not completed. Elemental composition identified several interesting findings. Some of the biomass was characterized with seemingly high boron and sodium levels.

High sodium levels were expected due to the amount of sodium found in the produced water used for irrigation. The impact of sodium on biomass production was not apparent and likely didn't occur except through its impact on soil structure, which would tend to reduce production. Produced water treated with the three (3) technologies studied (RO, IX, and EDR) using 0 to 100 treatment blends resulted in correspondingly decreasing levels of sodium.

High levels of boron found in some of the biomass was unexpected and may indicate that alfalfa and western wheatgrass plants may have been impacted by either soil or irrigation water containing high boron levels. It appeared that water treatment technology had an impact on the amount

of boron that plants accumulated in their biomass. Plants irrigated with water treated using EDR technology appeared to contain higher levels of boron with increased levels of treatment. This finding was the opposite effect found for sodium levels. For example, total boron levels found in western wheatgrass plants grown in Riverton soil treated with 25%, 50%, 75% and 100% blends of EDR treated conventional oil and gas produced water, contained boron levels of 302 mg/kg, 528 mg/kg, 610 mg/kg and 642 mg/kg, respectively. Another example using the EDR treatment technology was with western wheatgrass growing on the Sheridan soil irrigated with conventional oil and gas produced water. The results of this treatment were 201 mg/kg, 332 mg/kg, 541 mg/kg and 2120 mg/kg for 25%, 50%, 75% and 100% blends, respectively. The same results were found for each treatment that used EDR water treatment technology. Irrigating plants using produced water treated with the RO and IX treatment technologies appeared to result in biomass that was characterized with both increased, no change and decreased boron levels with increased treatment. This finding may have important implications for the use of EDR technology to treat certain types of water. However, the test conducted in this study should not be considered a significant finding because of the problem associated with treatment duplication. A replicated test will be required to determine whether or not these water treatment technologies have an boron accumulation affect on biomass.

Forage Quality of Biomass Produced on Three (3) Soils Irrigated with Treated CBNG Produced Water or Conventional Oil and Gas Produced Water

Forage evaluations were conducted using near infrared reflectance spectroscopy. Data associated with the Riverton soil for a selected list of parameters are presented in Table 10. The data collected show small differences, generally less than 10%, between produced water treatments including the no treatment and 100% treatment conditions for each plant species studied.

Similar results were found for the forages grown using the Sheridan soil with RFV (Table 11). No apparent tendencies were noted for the alfalfa forage evaluations. However, some tendencies were shown for western wheatgrass due to treatment. For example, crude protein (CP) values tended to increase with less treated water for both produced waters and treatment technology. The other parameters presented did not clearly demonstrate any tendencies.

Forage quality data for the X-Ranch soil are presented in Table 12. Many samples are not included in the data set because of the lack of biomass generated during the greenhouse study. A minimum amount of sample was required to perform the NIRS analysis. The data shown for the X-Ranch soil do not show any apparent tendencies.

The forage value of alfalfa and western wheatgrass grown in the greenhouse study did not show significant tendencies dependent on either soil, the amount of produced water treatment, or treatment technology. Some differences in crude protein content of biomass may exist for the Sheridan soil dependent on the percentage of water treatment. Without a statistical evaluation, no determinations can be made.

Table 10 Forage Quality for Alfalfa and Western Wheatgrass Grown on the Riverton Soil Irrigated with Conventional Oil and Gas Produced Water Treated with EDR and RO; and CBNG Produced Water treated with IX and RO. (COG – conventional oil and gas; RO – reverse osmosis; IX – ion exchange (EMIT Technology); EDR – electrodialysis reversal; CP – crude protein; SP – soluble protein; ADF – acid detergent fiber; NDF – neutral detergent fiber; P – phosphorous; TDN – total digestible nutrients; RFV – relative feed value)

| Sample | Type | Trt Tech | CP (%DM) | SP (%DM) | ADF (%DM) | NDF (%DM) | P (%DM) | TDN (%DM) | RFV |
|---------------------------|---------|----------|----------|----------|-----------|-----------|---------|-----------|-----|
| <u>Alfalfa</u> | | | | | | | | | |
| 100% Treated | COG | RO | 26.3 | 10.6 | 21.3 | 25.4 | 0.3 | 67.2 | 265 |
| 75% Treated | COG | RO | 28.1 | 10.5 | 18.6 | 22.8 | 0.4 | 67.9 | 304 |
| 100% Treated | COG | EDR | 27.1 | 9.8 | 20.5 | 25.5 | 0.3 | 66.5 | 266 |
| Control | River | No Trt | 27.7 | 10.6 | 20.7 | 24.6 | 0.4 | 67.8 | 275 |
| 100% Treated | CBNG | IX | 27.4 | 11.0 | 20.5 | 25.2 | 0.3 | 66.6 | 270 |
| 75% Treated | CBNG | IX | 27.4 | 10.8 | 21.3 | 25.3 | 0.4 | 67.1 | 265 |
| 50% Treated | CBNG | IX | 26.7 | 10.0 | 22.5 | 26.5 | 0.4 | 65.0 | 250 |
| 25% Treated | CBNG | IX | 28.4 | 10.9 | 19.1 | 23.8 | 0.3 | 68.0 | 290 |
| 100% Treated | CBNG | RO | 28.5 | 10.8 | 18.0 | 23.2 | 0.4 | 69.3 | 301 |
| 75% Treated | CBNG | RO | 25.6 | 10.4 | 21.7 | 26.8 | 0.3 | 67.3 | 250 |
| 50% Treated | CBNG | RO | 27.5 | 10.4 | 19.5 | 24.5 | 0.3 | 68.9 | 280 |
| 25% Treated | CBNG | RO | 27.3 | 10.0 | 20.2 | 25.0 | 0.3 | 67.3 | 273 |
| <u>Western Wheatgrass</u> | | | | | | | | | |
| 100% Treated | COG | RO | 11.1 | 4.2 | 39.5 | 58.6 | 0.3 | 56.2 | 92 |
| 100% Treated | COG | EDR | 8.6 | 4.0 | 39.9 | 56.3 | 0.3 | 56.2 | 96 |
| 50% Treated | COG | EDR | 10.1 | 4.2 | 39.9 | 54.8 | 0.3 | 54.3 | 98 |
| 100% Treated | CBNG | IX | 9.3 | 3.8 | 39.7 | 57.5 | 0.3 | 55.9 | 94 |
| 75% Treated | CBNG | IX | 10.2 | 3.9 | 40.5 | 57.3 | 0.3 | 55.0 | 93 |
| 50% treated | CBNG | IX | 11.8 | 4.3 | 39.0 | 56.1 | 0.3 | 56.3 | 97 |
| 25% Treated | CBNG | IX | 13.9 | 5.0 | 37.3 | 55.5 | 0.3 | 57.4 | 100 |
| 100% Treated | CBNG | RO | 10.1 | 3.8 | 39.9 | 58.0 | 0.3 | 57.4 | 93 |
| 75% Treated | CBNG | RO | 10.1 | 3.8 | 39.8 | 56.7 | 0.3 | 57.1 | 95 |
| 50% Treated | CBNG | RO | 10.9 | 4.0 | 37.2 | 58.4 | 0.3 | 59.5 | 96 |
| 25% Treated | CBNG | RO | 11.0 | 4.3 | 37.2 | 56.2 | 0.3 | 58.6 | 99 |
| Untreated | No Trt. | No Trt | 14.3 | 5.1 | 36.4 | 56.1 | 0.3 | 57.9 | 101 |

Table 11 Forage Quality for Alfalfa and Western Wheatgrass Grown on the Sheridan Soil Irrigated with Conventional Oil and Gas Produced Water Treated with EDR and RO; and CBNG Produced Water treated with IX and RO. (COG – conventional oil and gas; RO – reverse osmosis; IX – ion exchange (EMIT Technology); EDR – electrodialysis reversal; CP – crude protein; SP – soluble protein; ADF – acid detergent fiber; NDF – neutral detergent fiber; P – phosphorous; TDN – total digestible nutrients; RFV – relative feed value)

| Treatment | Water | Trt Tech. | CP (%DM) | SP (%DM) | ADF (%DM) | NDF (%DM) | P (%DM) | TDN (%DM) | RFV |
|---------------------------|-------|-----------|----------|----------|-----------|-----------|---------|-----------|-----|
| <u>Alfalfa</u> | | | | | | | | | |
| 100% Treated | COG | RO | 25.2 | 10.0 | 21.5 | 27.1 | 0.3 | 67.0 | 248 |
| 75% Treated | COG | RO | 27.2 | 9.8 | 18.9 | 23.9 | 0.3 | 68.4 | 289 |
| 50% Treated | COG | RO | 26.5 | 9.7 | 21.0 | 25.1 | 0.4 | 66.8 | 269 |
| 100% treated | COG | EDR | 25.4 | 9.1 | 20.9 | 27.5 | 0.3 | 67.3 | 245 |
| 75% Treated | COG | EDR | 26.5 | 9.5 | 20.1 | 24.5 | 0.3 | 67.3 | 278 |
| Control | River | No Trt | 26.3 | 10.7 | 21.8 | 26.6 | 0.3 | 66.2 | 251 |
| 100% Treated | CBNG | IX | 26.1 | 10.6 | 20.2 | 25.5 | 0.3 | 67.1 | 267 |
| 75% Treated | CBNG | IX | 25.1 | 10.4 | 22.4 | 27.7 | 0.3 | 65.6 | 240 |
| 50% Treated | CBNG | IX | 24.2 | 9.6 | 23.2 | 28.8 | 0.3 | 65.7 | 229 |
| 25% Treated | CBNG | IX | 26.8 | 10.5 | 20.9 | 26.2 | 0.3 | 67.4 | 258 |
| 100% Treated | CBNG | RO | 26.8 | 10.1 | 19.1 | 25.1 | 0.3 | 68.1 | 274 |
| 75% Treated | CBNG | RO | 25.4 | 10.0 | 21.0 | 26.3 | 0.3 | 67.2 | 256 |
| 50% Treated | CBNG | RO | 26.2 | 11.0 | 21.5 | 26.3 | 0.3 | 66.3 | 255 |
| 25% Treated | CBNG | RO | 25.6 | 10.2 | 21.5 | 27.3 | 0.3 | 66.5 | 246 |
| No Treatment | CBNG | No Trt | 26.1 | 10.1 | 20.4 | 25.4 | 0.3 | 67.6 | 267 |
| <u>Western Wheatgrass</u> | | | | | | | | | |
| 100% Treated | COG | RO | 10.1 | 4.0 | 39.0 | 59.5 | 0.3 | 57.0 | 91 |
| 75% Treated | COG | RO | 13.5 | 5.7 | 33.7 | 57.2 | 0.3 | 60.0 | 102 |
| 50% Treated | COG | RO | 20.4 | 7.5 | 28.6 | 53.5 | 0.3 | 61.6 | 116 |
| 25% Treated | COG | RO | 21.8 | 8.7 | 27.1 | 51.7 | 0.3 | 62.3 | 122 |
| 100% Treated | COG | EDR | 10.5 | 4.4 | 41.6 | 56.2 | 0.3 | 53.6 | 94 |
| 75% Treated | COG | EDR | 16.3 | 5.9 | 33.3 | 57.2 | 0.3 | 59.9 | 102 |
| 50% Treated | COG | EDR | 17.1 | 6.9 | 30.2 | 55.3 | 0.3 | 61.6 | 110 |
| 25% Treated | COG | EDR | 21.5 | 8.4 | 26.9 | 51.3 | 0.3 | 62.4 | 123 |
| No Treatment | COG | No Trt | 20.2 | 8.9 | 25.3 | 46.7 | 0.3 | 63.3 | 138 |
| Control | River | No Trt | 9.8 | 3.9 | 39.2 | 59.5 | 0.3 | 57.0 | 91 |
| 100% Treated | CBNG | IX | 8.0 | 3.9 | 39.8 | 60.2 | 0.3 | 56.6 | 90 |
| 75% Treated | CBNG | IX | 11.2 | 4.6 | 37.9 | 61.7 | 0.3 | 59.1 | 90 |
| 50% Treated | CBNG | IX | 12.5 | 5.4 | 36.4 | 61.9 | 0.3 | 59.9 | 91 |
| 25% Treated | CBNG | IX | 13.7 | 5.9 | 35.0 | 61.5 | 0.3 | 60.4 | 93 |
| 75% Treated | CBNG | RO | 10.1 | 4.5 | 37.2 | 60.5 | 0.3 | 60.1 | 92 |
| 50% Treated | CBNG | RO | 13.1 | 5.2 | 36.3 | 61.6 | 0.3 | 59.4 | 92 |
| 25% Treated | CBNG | RO | 15.3 | 6.1 | 32.7 | 60.1 | 0.3 | 61.7 | 98 |
| No Treatment | CBNG | No Trt | 16.2 | 6.5 | 31.5 | 57.9 | 0.3 | 62.4 | 103 |

Table 12 Forage Quality for Alfalfa and Western Wheatgrass Grown on the X-Ranch Soil Irrigated with CBNG Produced Water Treated with IX and RO. (COG – conventional oil and gas; RO – reverse osmosis; IX – ion exchange (EMIT Technology); EDR – electrodialysis reversal; CP – crude protein; SP – soluble protein; ADF – acid detergent fiber; NDF – neutral detergent fiber; P – phosphorous; TDN – total digestible nutrients; RFV – relative feed value)

| Treatment | Water | Trt. Tech | CP (%DM) | SP (%DM) | ADF (%DM) | NDF (%DM) | P (%DM) | TDN (%DM) | RFV |
|---------------------------|-------|-----------|----------|----------|-----------|-----------|---------|-----------|-----|
| <u>Alfalfa</u> | | | | | | | | | |
| 75% Trt | CBNG | IX | 26.7 | 10.4 | 19.2 | 24.1 | 0.3 | 68.1 | 286 |
| 50% Trt | CBNG | IX | 25.7 | 10.3 | 21.7 | 25.8 | 0.3 | 65.9 | 259 |
| 100% Trt | CBNG | RO | 23.4 | 9.6 | 24.4 | 28.8 | 0.3 | 64.1 | 225 |
| 75% Trt | CBNG | RO | 24.9 | 9.9 | 21.4 | 25.9 | 0.3 | 66.5 | 259 |
| 50% Trt | CBNG | RO | 26.2 | 10.3 | 21.5 | 26.1 | 0.4 | 65.5 | 257 |
| 25% Trt | CBNG | RO | 24.9 | 9.7 | 23.0 | 27.6 | 0.3 | 64.8 | 239 |
| <u>Western Wheatgrass</u> | | | | | | | | | |
| 25% Trt | CBNG | RO | 17.8 | 6.5 | 32.3 | 55.7 | 0.4 | 61.1 | 107 |

CONCLUSIONS

1. Limited differences were found in HC values for soils impacted with treated and untreated CBNG produced water. Produced water treated using the IX and RO technologies at the 100% level was found to be similar to the control (river water) while the HC of soil associated with treatment levels of 25%, 50% and 75% were significantly lower than the control. The HC values associated with the 25%, 50%, and 75% treatments compared well to the HC of soils irrigated with untreated produced water.
2. The HC data collected for conventional oil and gas produced water showed no improvement in HC over untreated produced water for all levels of treatment. Water treatment at any level did not appear to improve HC for conventional oil and gas produced water.
3. Soils impacted by the CBNG produced water and the conventional oil and gas produced water did not have a significant impact on the EC values of the soils. The EC values resulting from all treatments would not be expected to significantly impact biomass production. The only concern would be whether or not the EC values were high enough to prevent dispersion of clays resulting from corresponding high SAR values. However, the SAR values associated with the treated CBNG produced waters were relatively low in all cases and would not be expected to cause dispersion.
4. Some questions as to the validity of the data set with regards to the impact of produced water on soils are apparent. For example, the conventional oil and gas produced water treated with EDC at the 25% treatment level was characterized with an EC of 7.6 dS/m and a SAR of 228. After treatment, the impacted soil was characterized with a mean SAR of 19.9 and a mean EC of 1.8 dS/m. Irrigating a soil with such characteristics would be expected to have a greater impact on the chemistry of the receiving soil.
5. In the germination study, variation between replicates was found to be high resulting in no significant differences in germination for the alfalfa and for the western wheatgrass seeds when watered with the 19 water treatments.
6. The differences in biomass production found between each soil in the Greenhouse irrigation study were significant for Western Wheatgrass and Alfalfa. The Sheridan sandy loam soil resulted in the highest biomass production for western wheatgrass and alfalfa, while the X-ranch sandy loam had the lowest production rate for both plants. The soils reacted to the various water treatment combinations (blends) likely due to the interactions between the soils and the chemical makeup of the treated water.
7. Elemental composition identified several interesting findings. Some of the biomass was characterized with seemingly high boron and sodium levels.
8. High levels of boron found in some of the biomass was unexpected and may indicate that such plants were impacted by either soil or irrigation water containing high boron levels. It appeared that water treatment technology had an impact on the amount of boron that plants accumulated in their biomass. Plants irrigated with water treated using EDR technology

appeared to contain higher levels of boron with increased levels of treatment. The opposite effect was found for biomass sodium levels.

9. The forage value of alfalfa and western wheatgrass grown in the greenhouse study did not show tendencies dependent on either soil, the amount of produced water treatment, or treatment technology. Some differences in crude protein content of biomass may exist for the Sheridan soil dependent on the percentage of water treatment. However, no meaningful determinations can be made without a statistical evaluation.

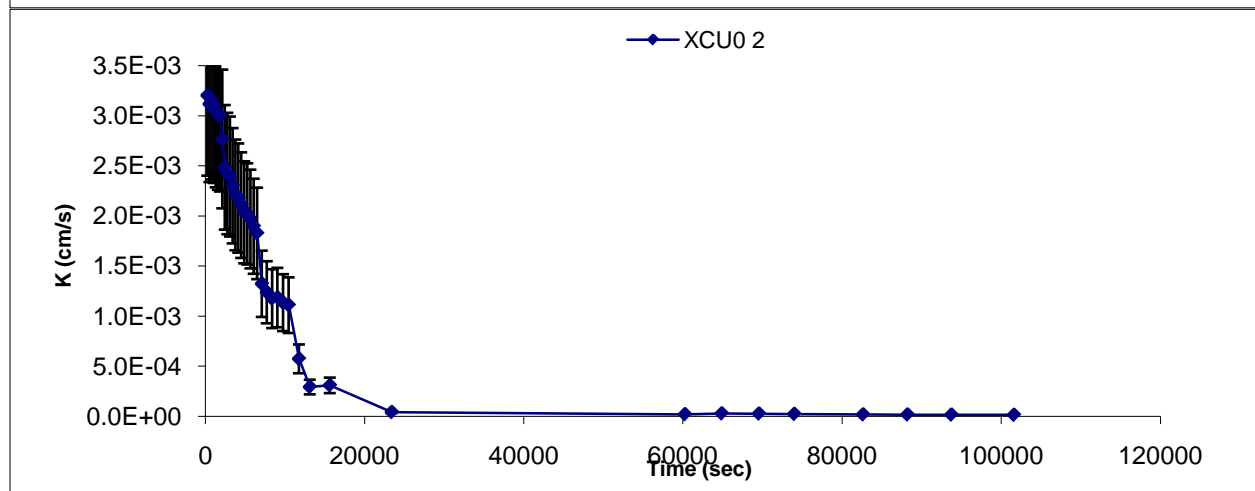
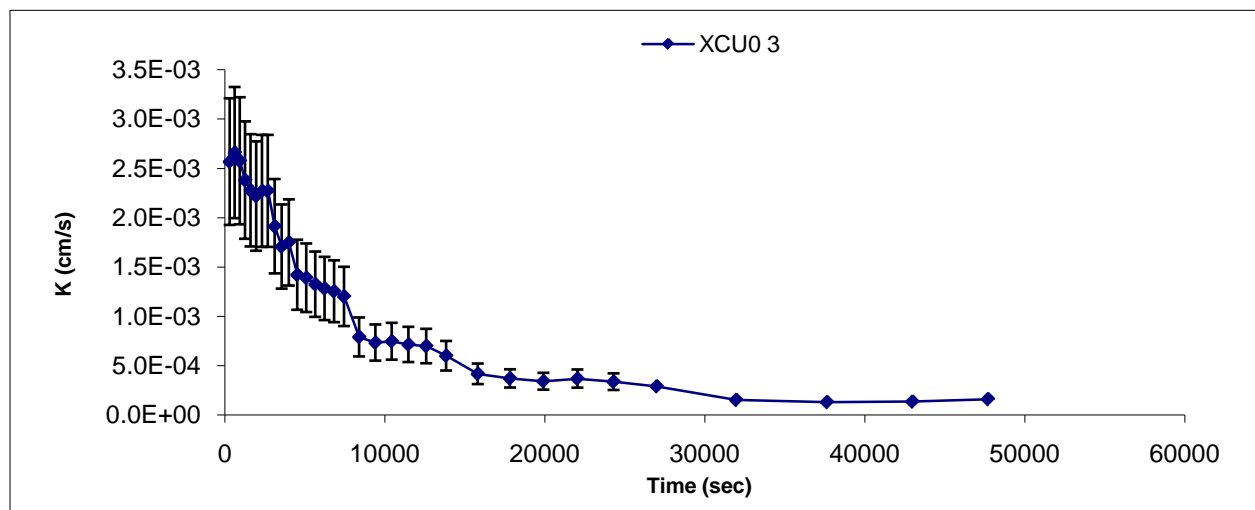
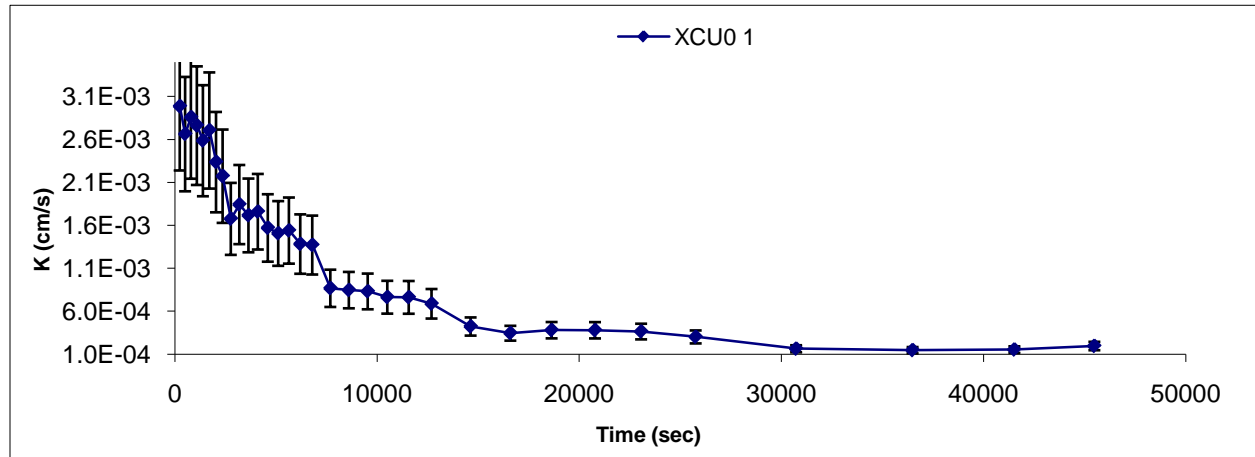
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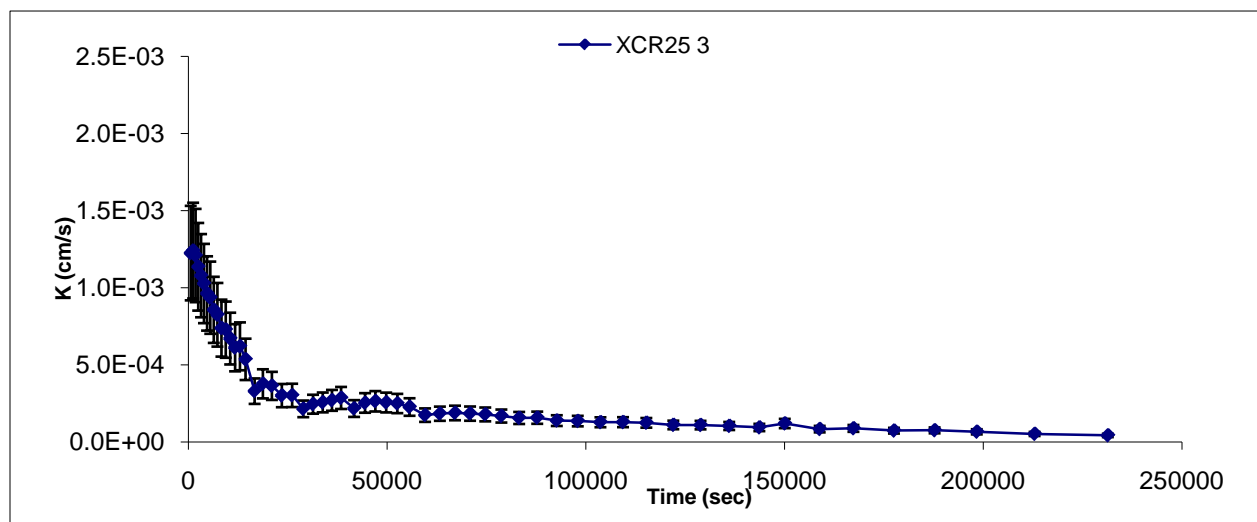
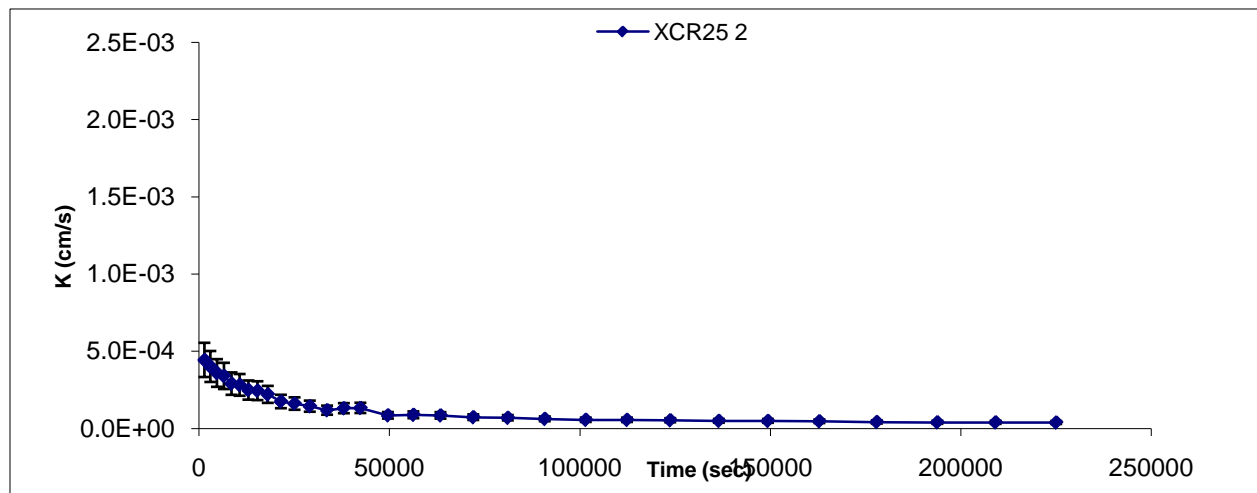
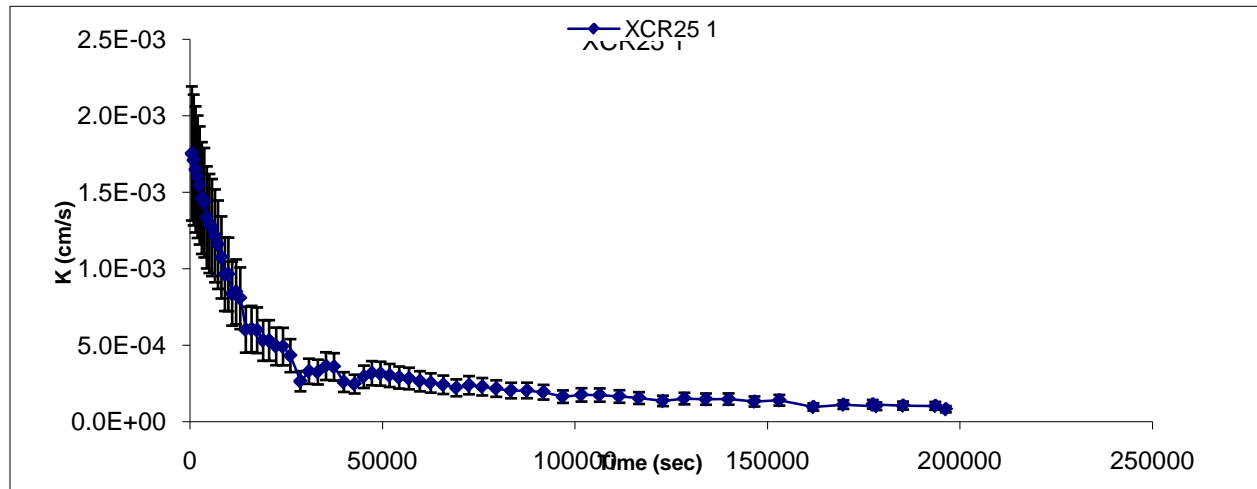
APPENDICES

APPENDIX A. Laboratory Data Generated During Hydraulic Conductivity Determination

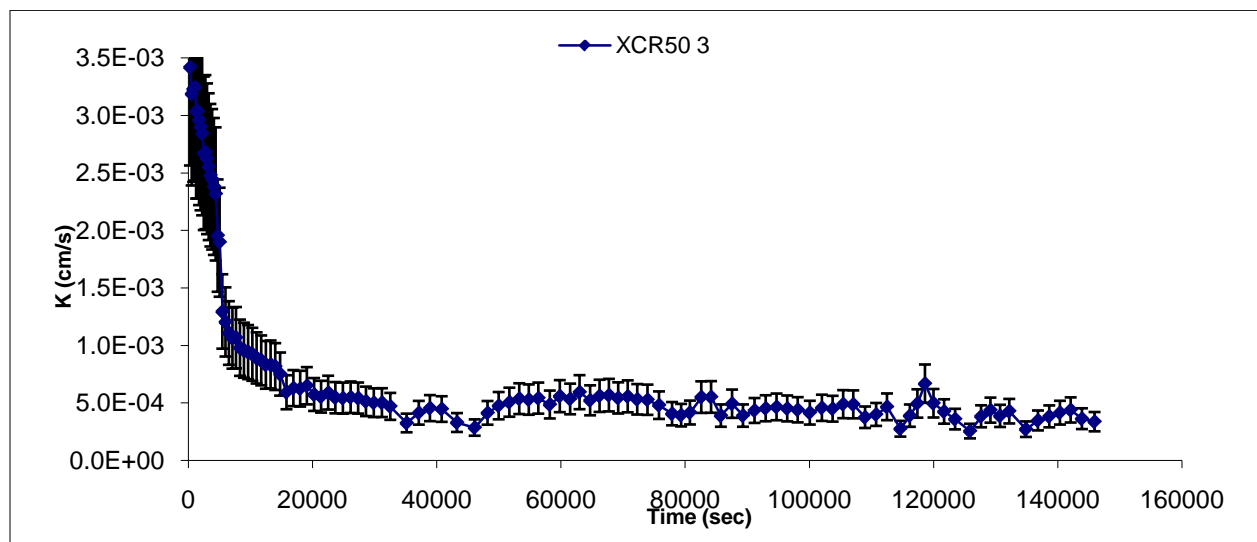
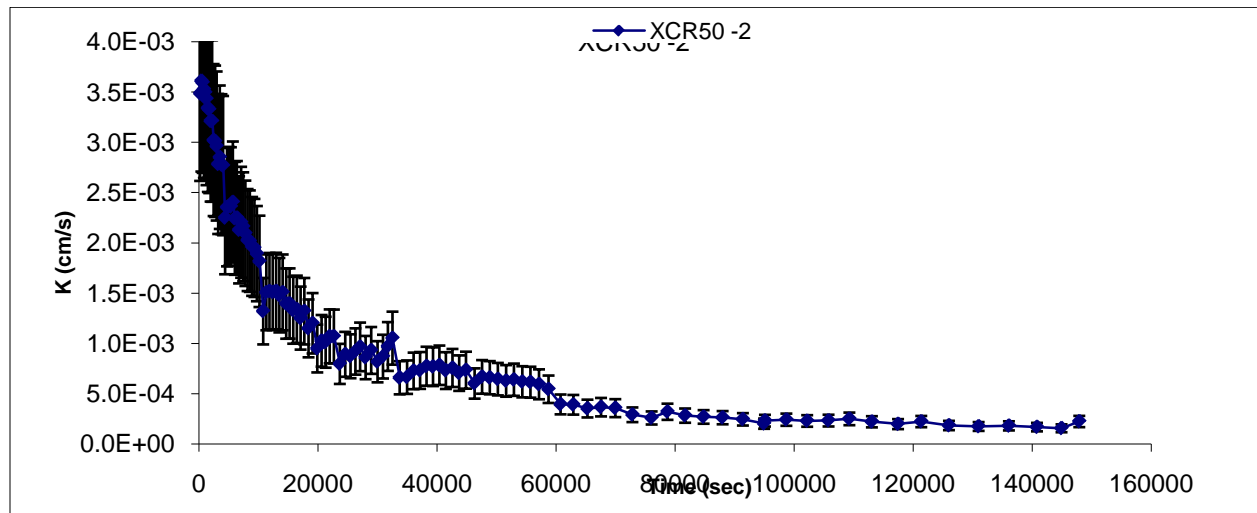
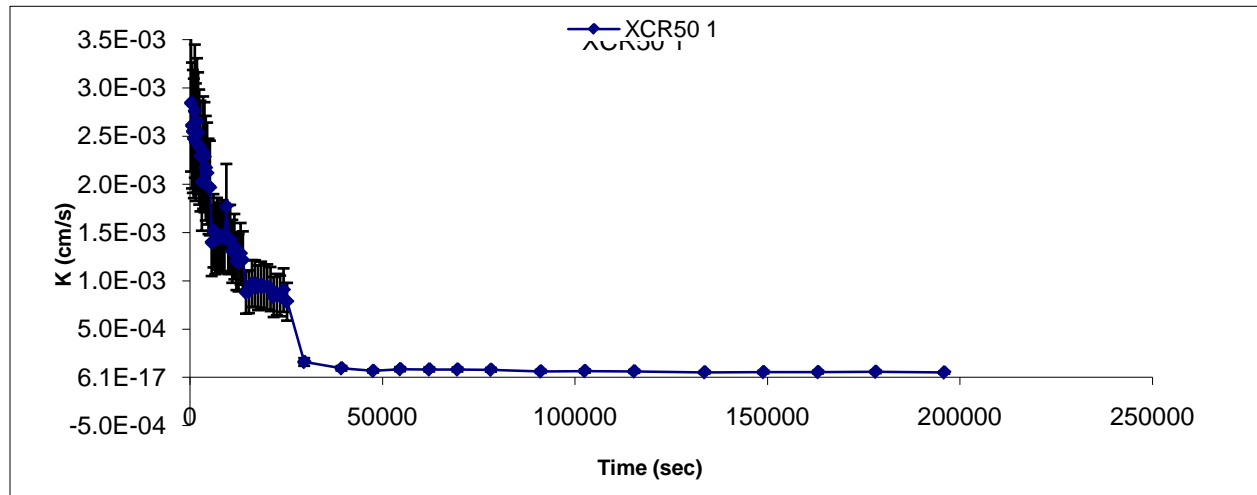
Hydraulic conductivity determination using X-Ranch soil and untreated CBNG Produced water (3 replications).



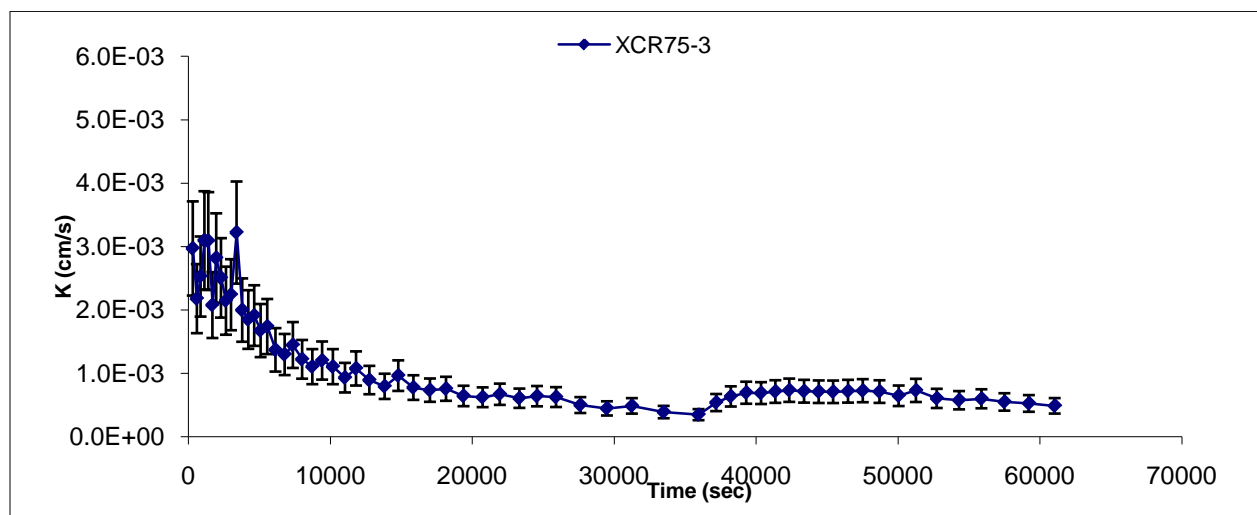
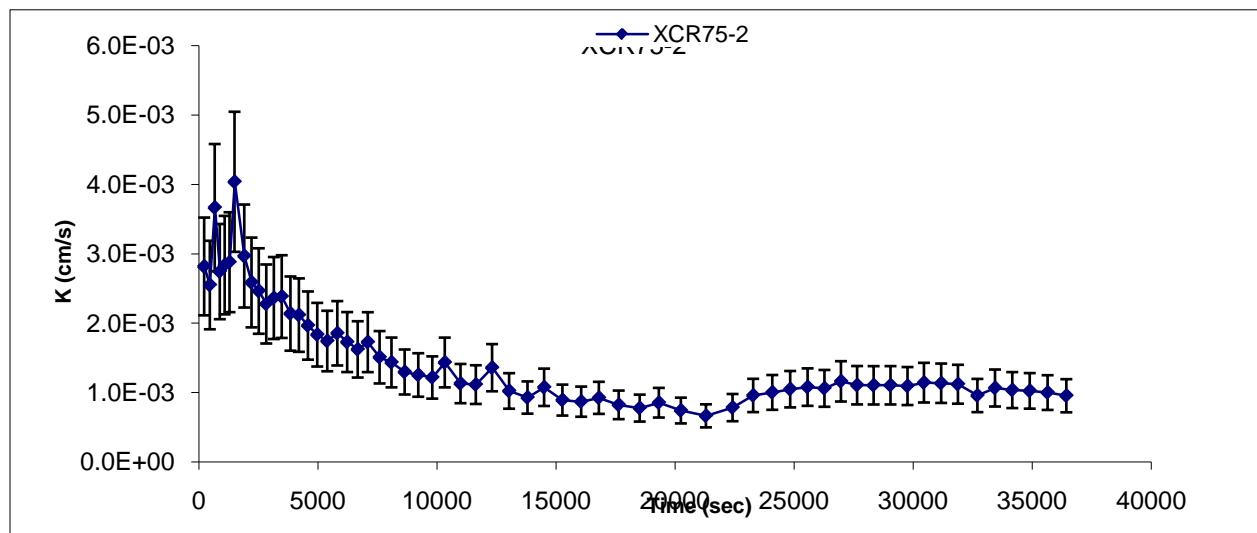
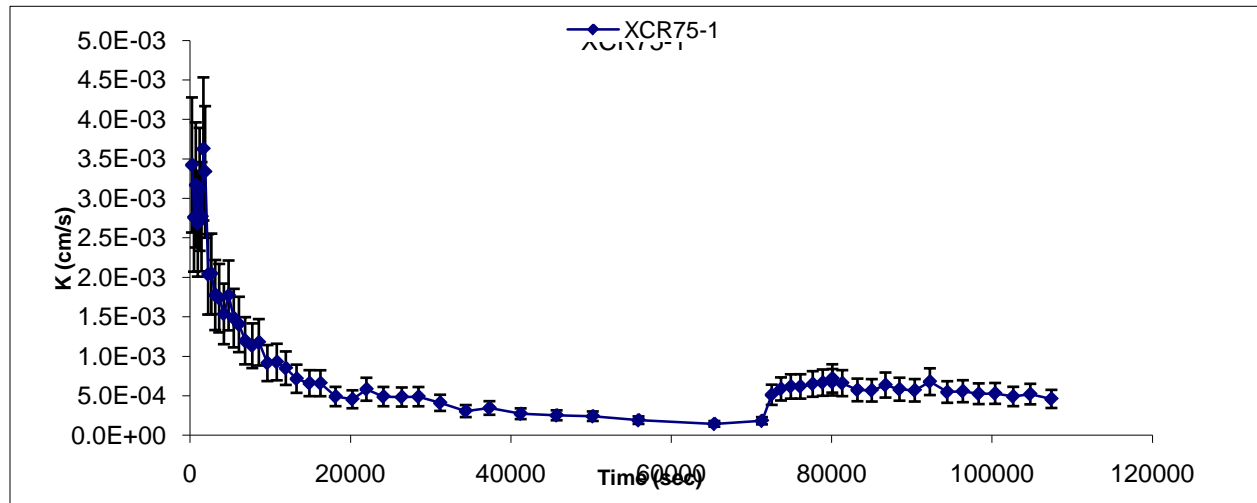
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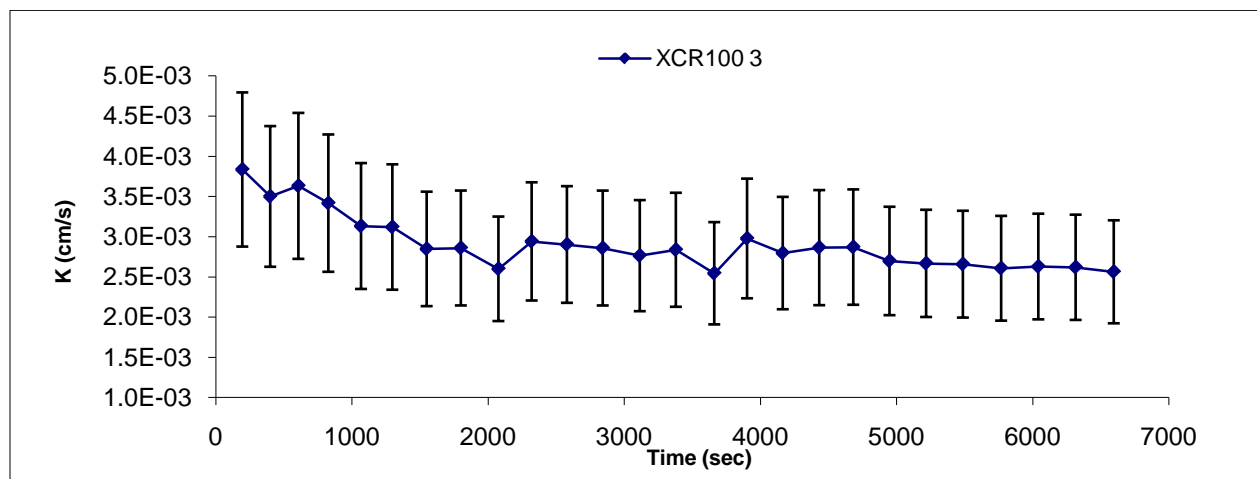
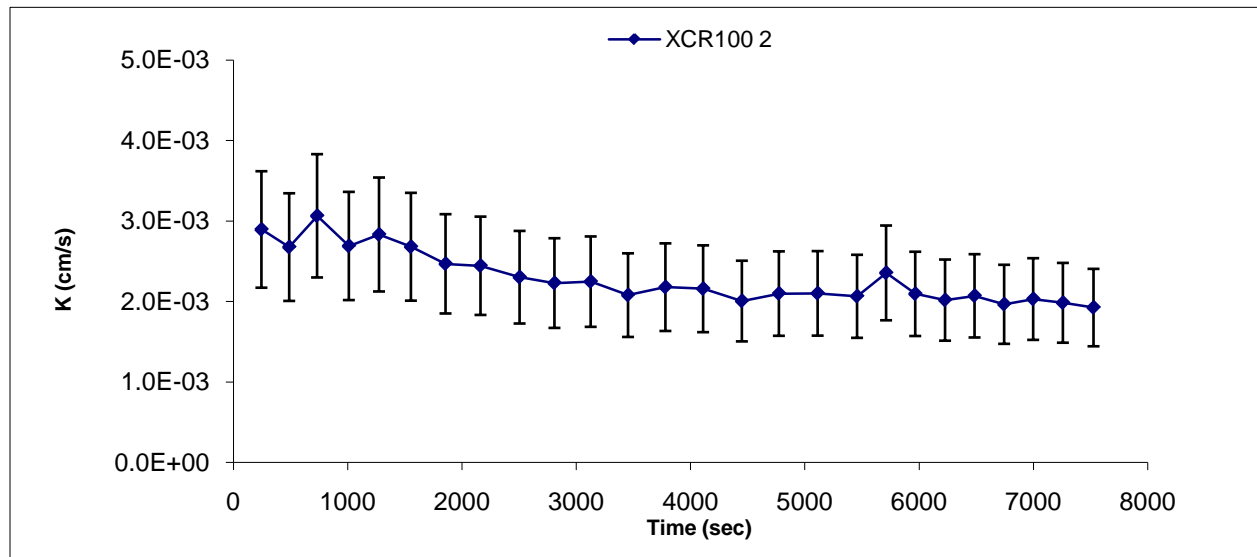
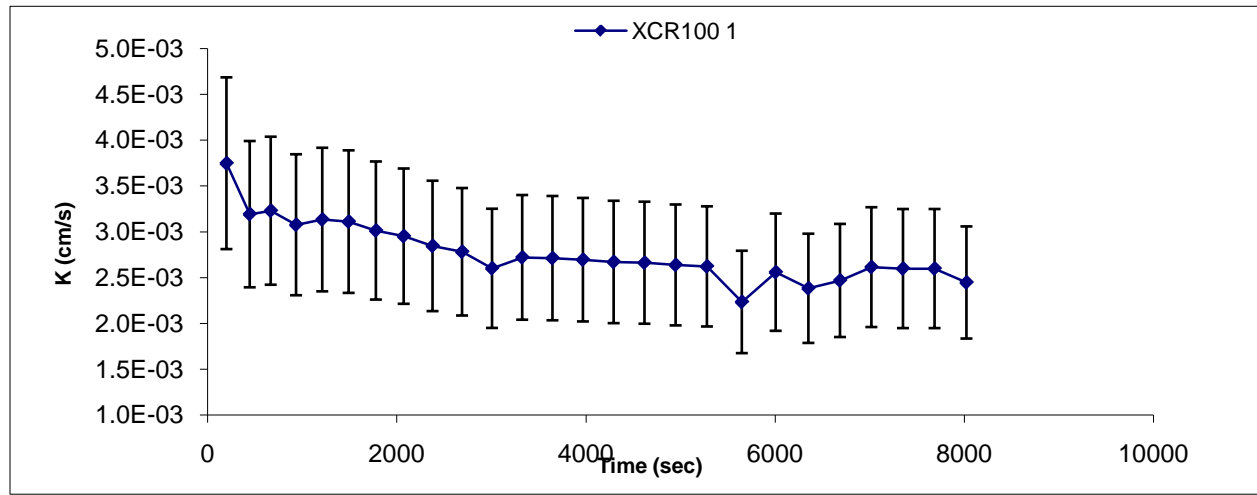
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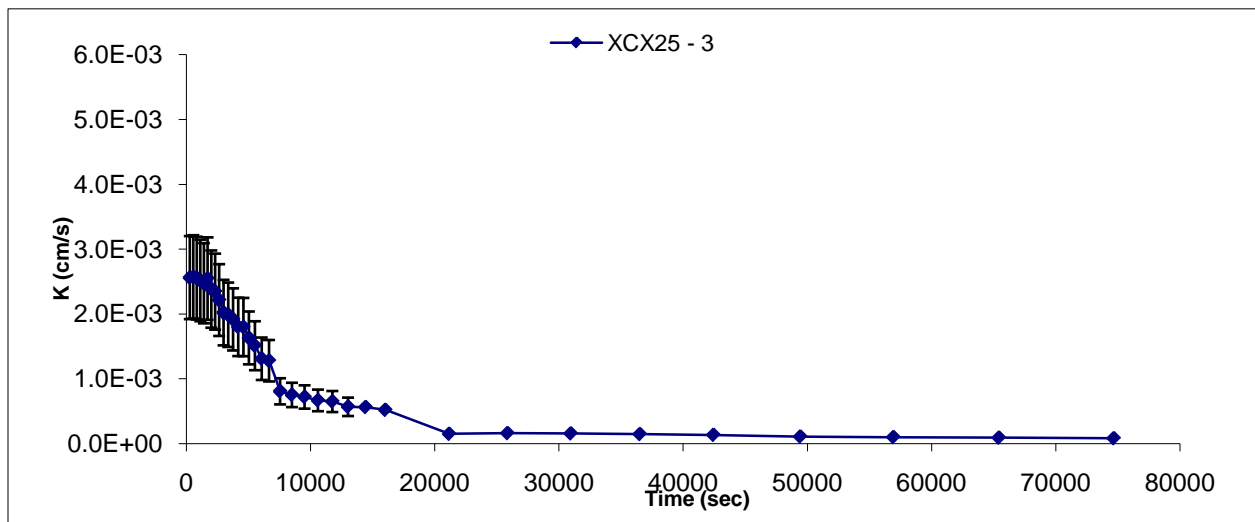
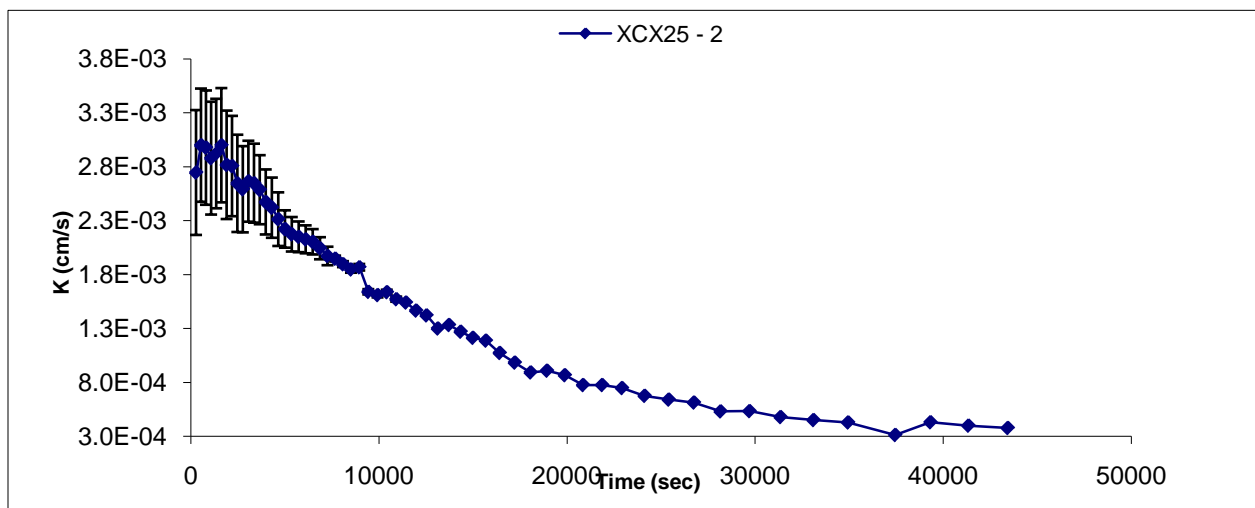
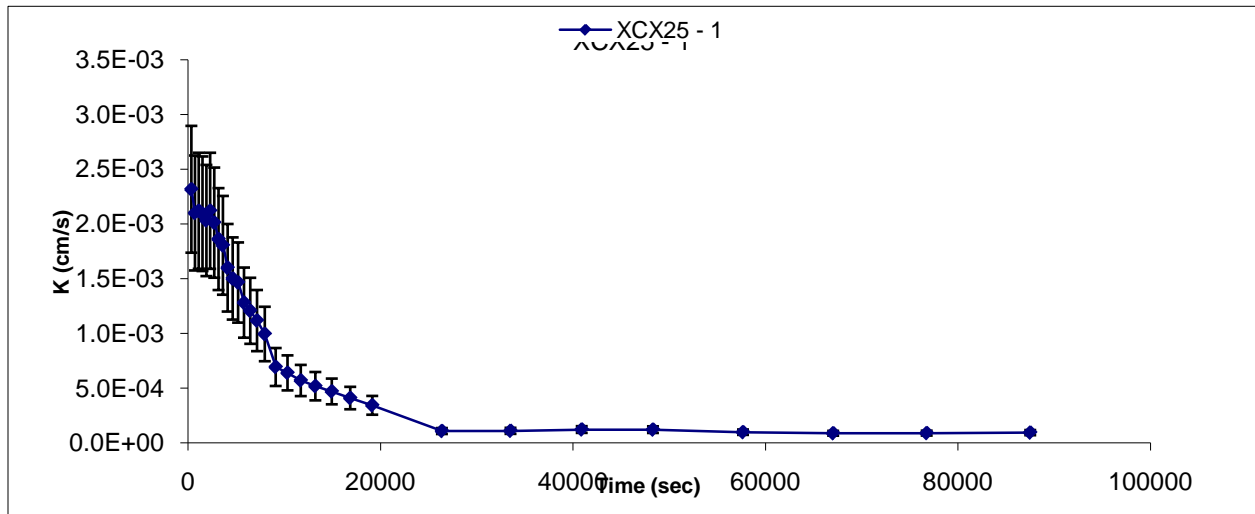
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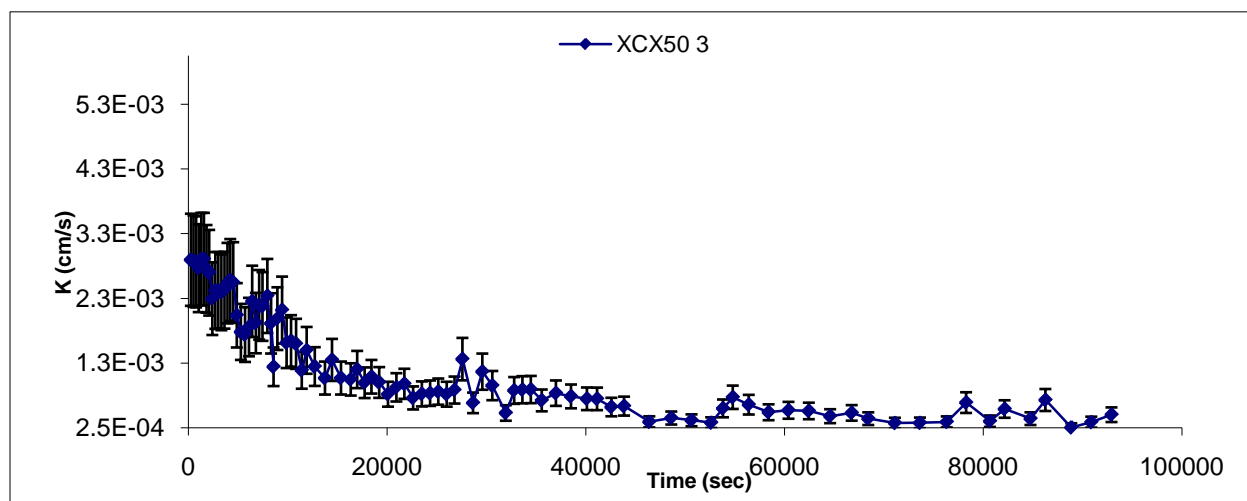
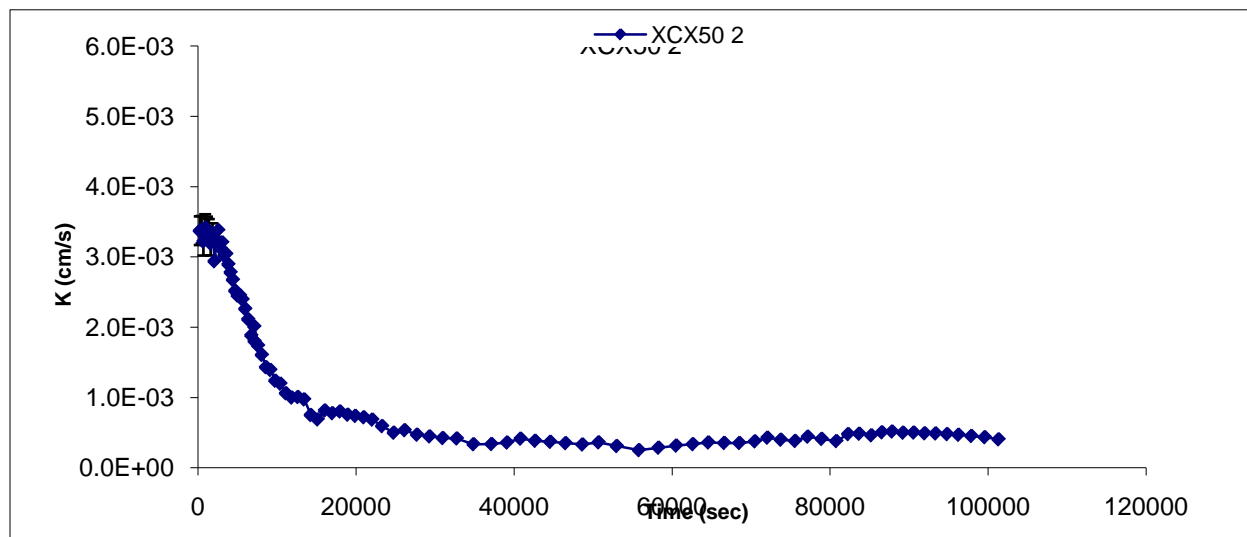
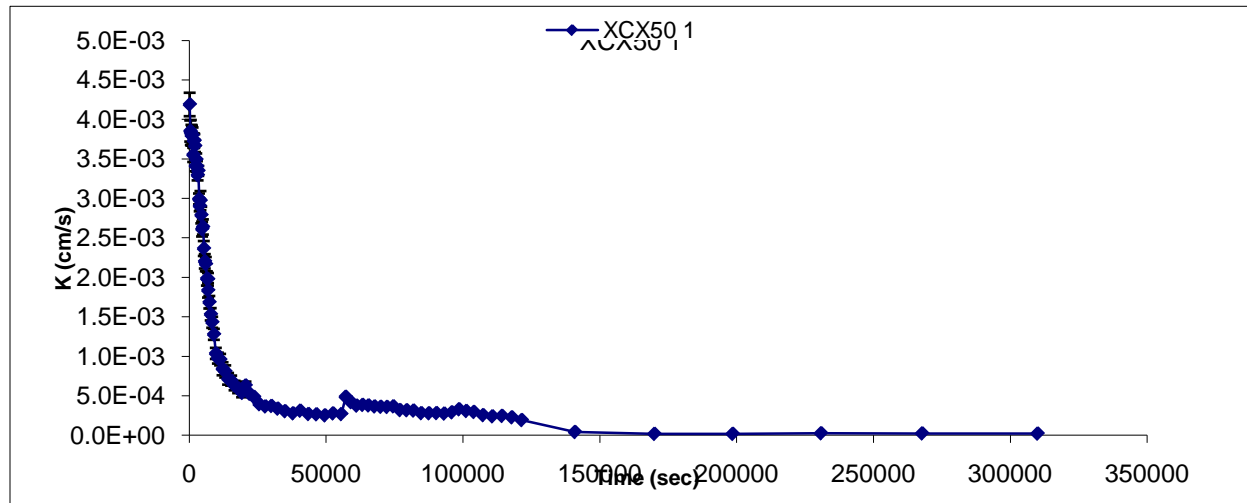
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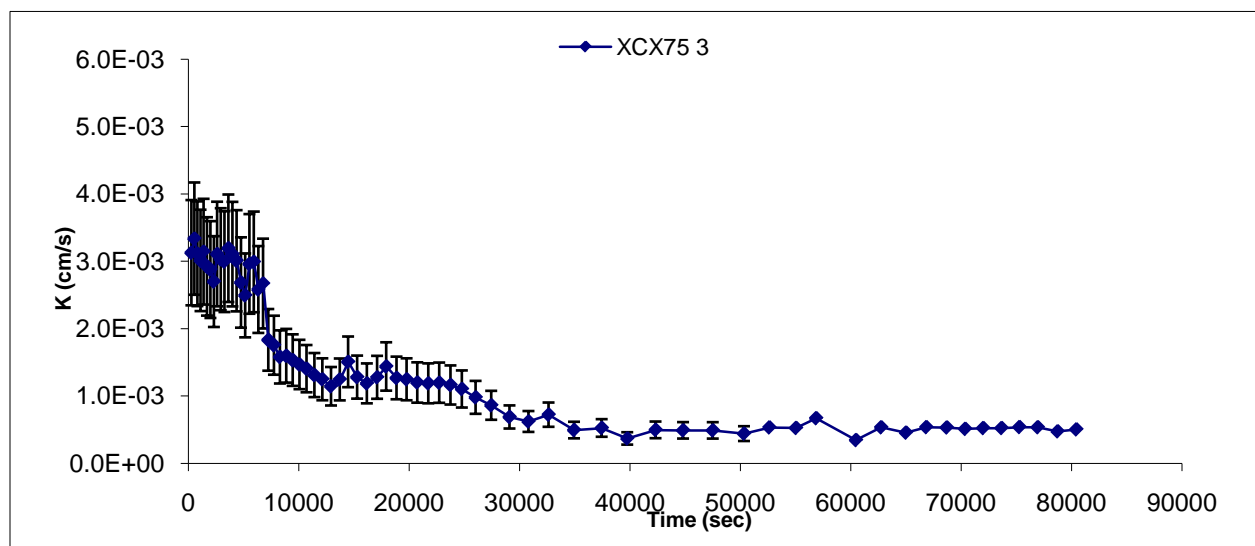
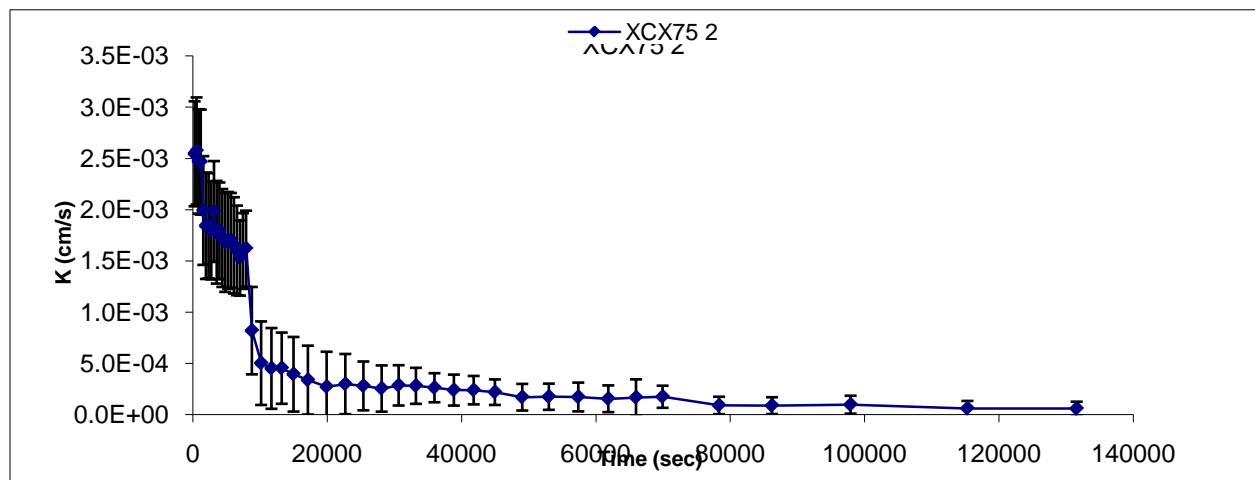
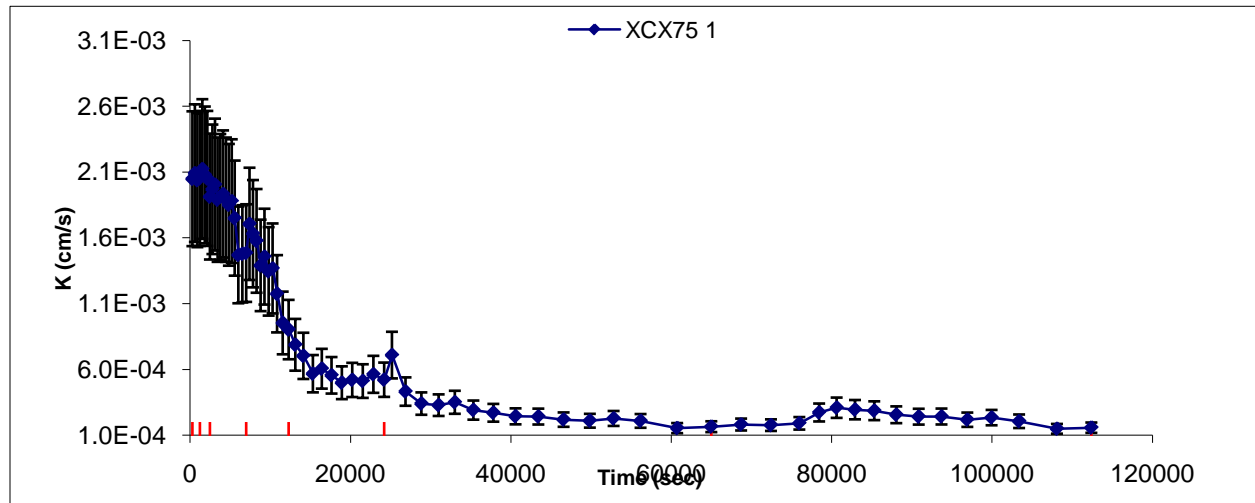
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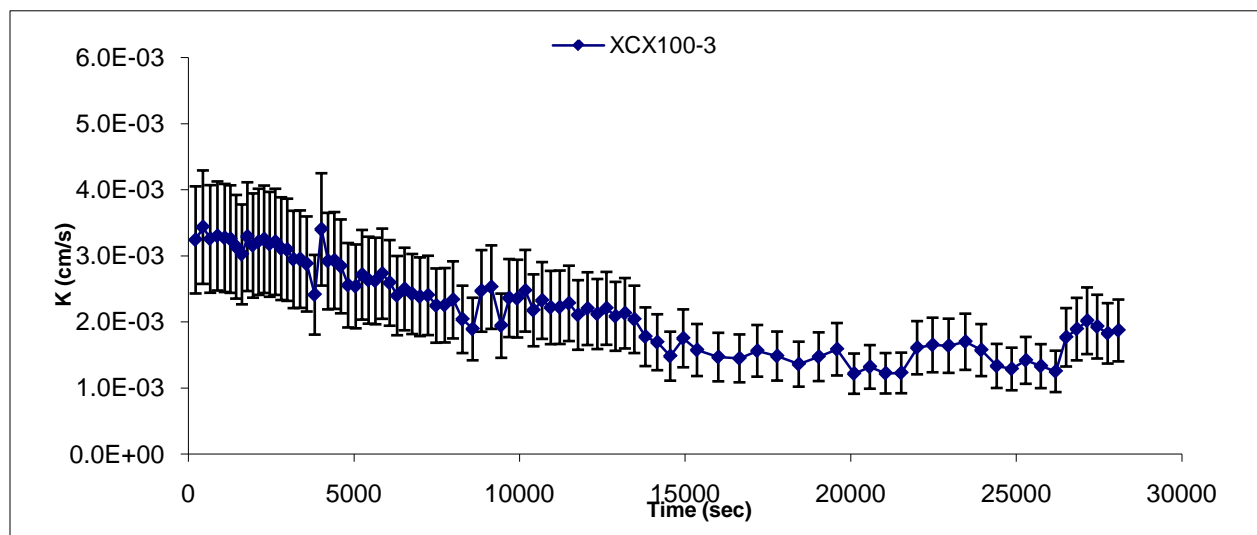
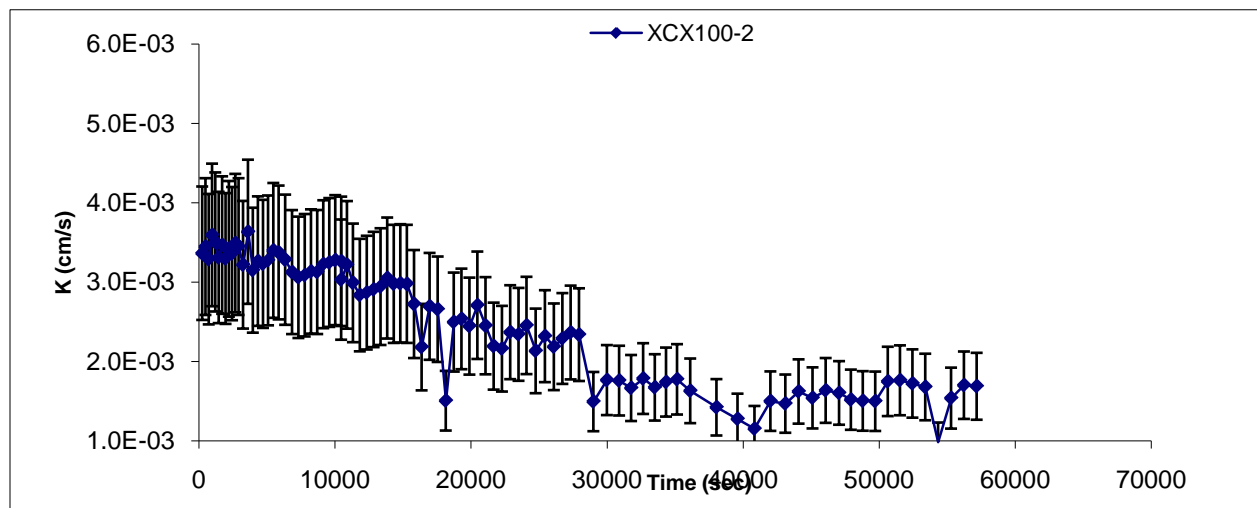
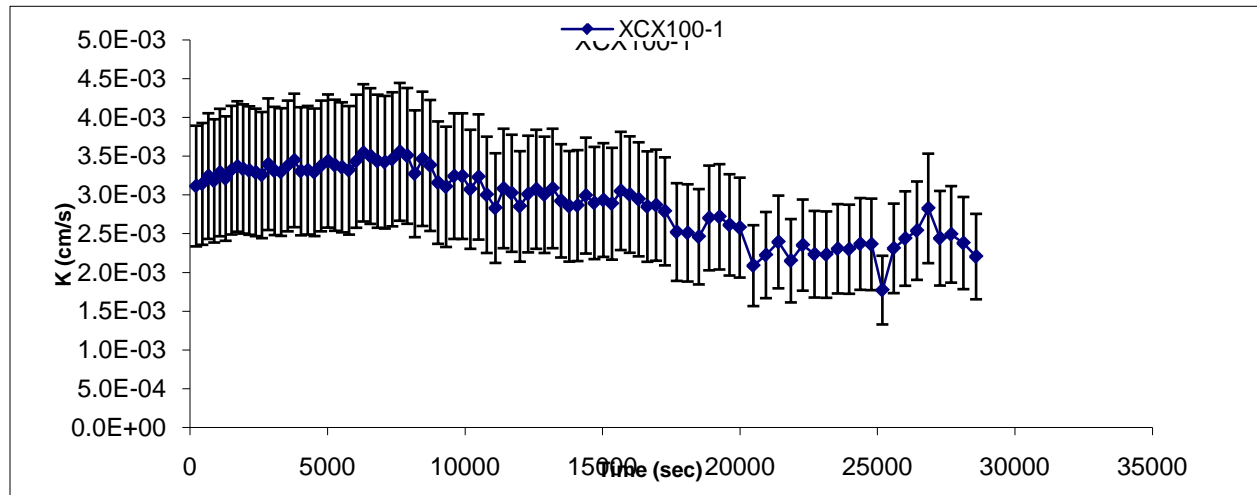
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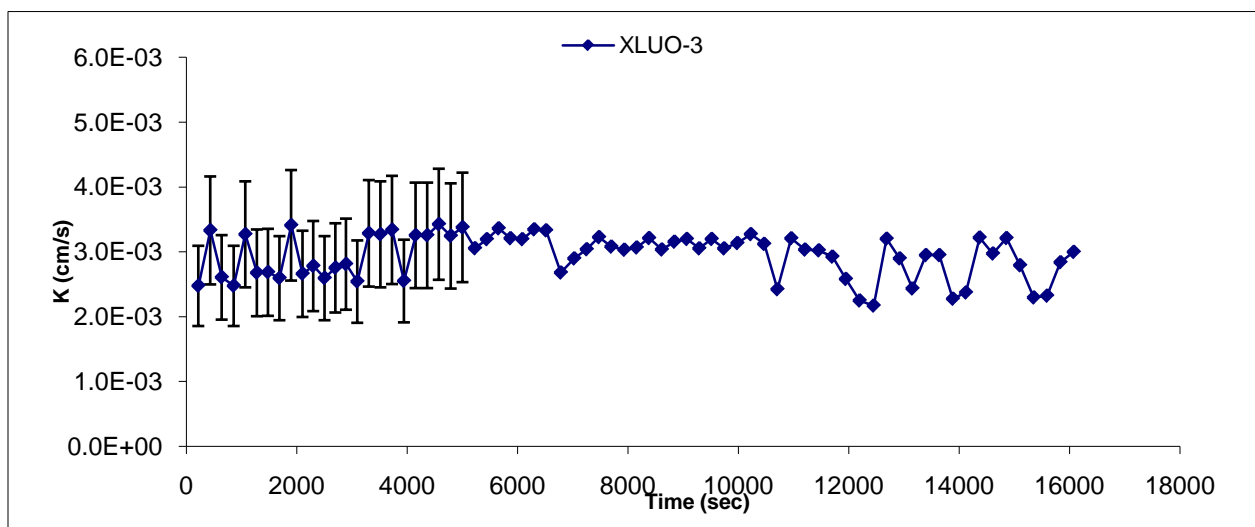
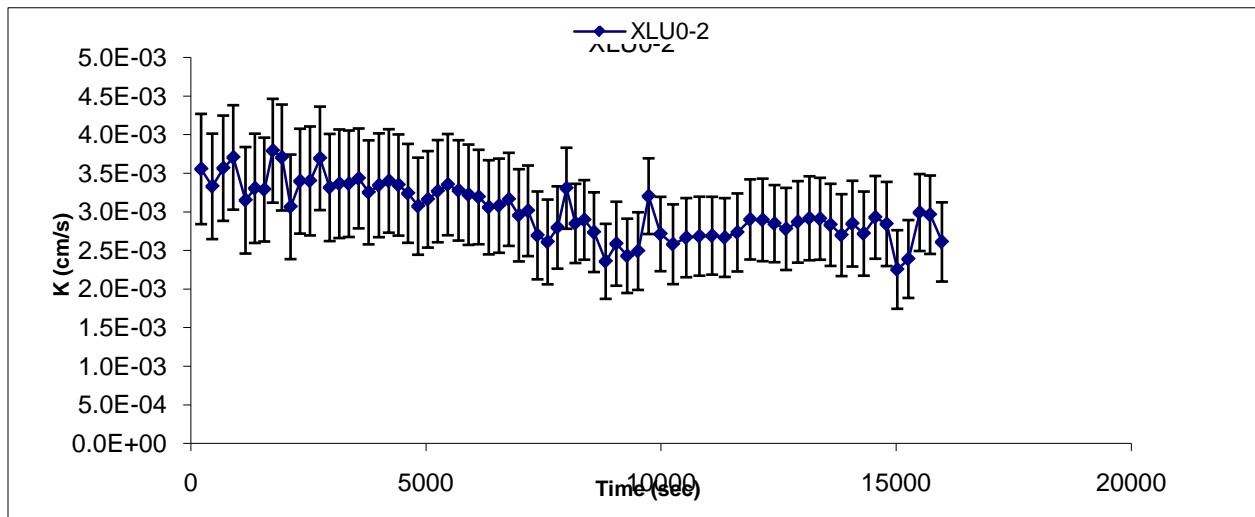
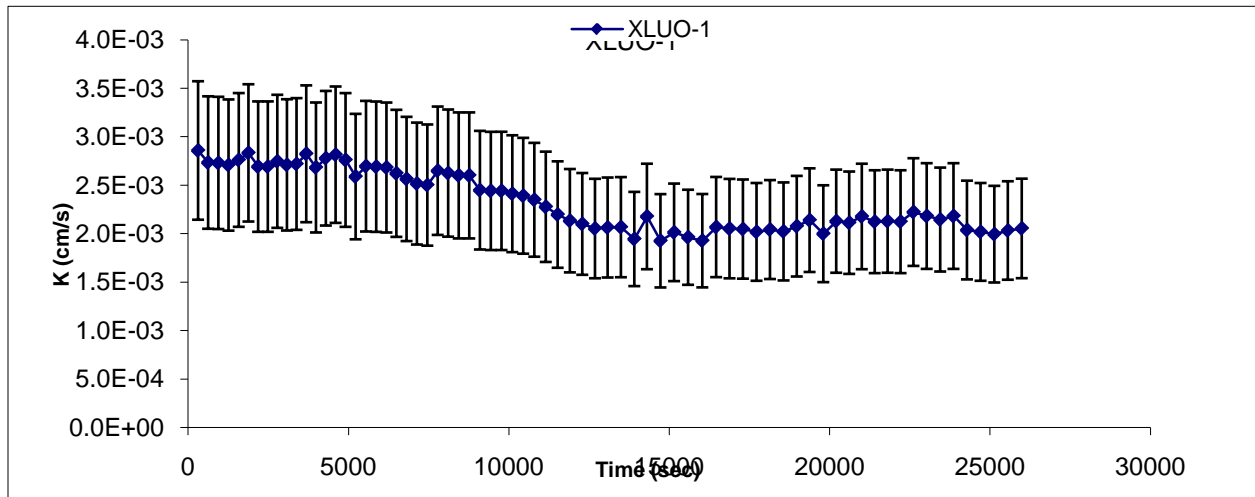
Hydraulic conductivity determination using X-Ranch soil and 75% IX treated CBNG Produced water (3 replications).



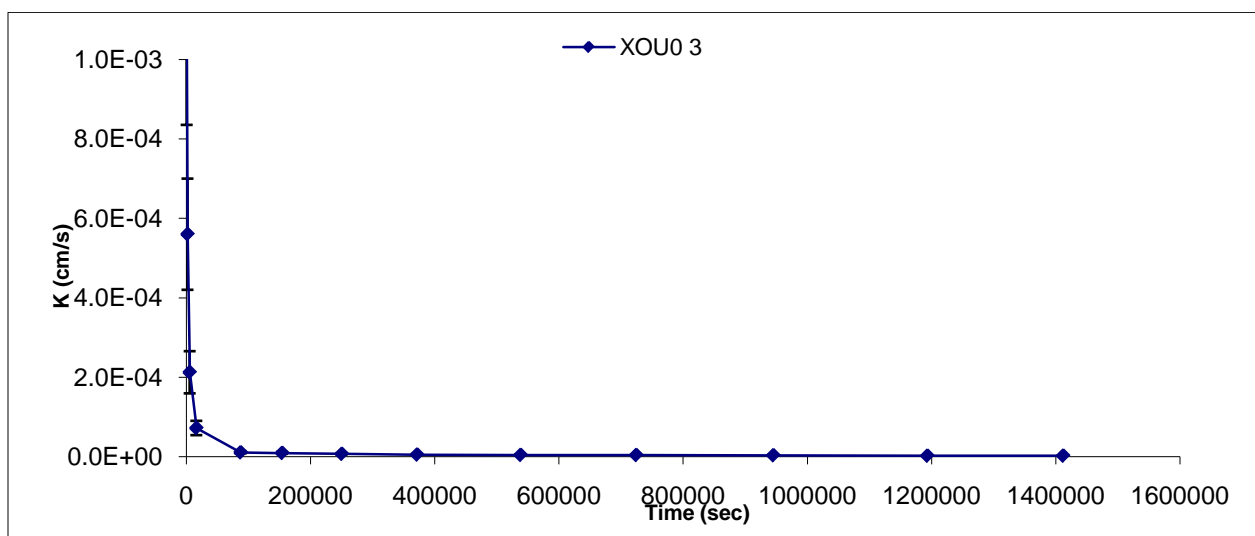
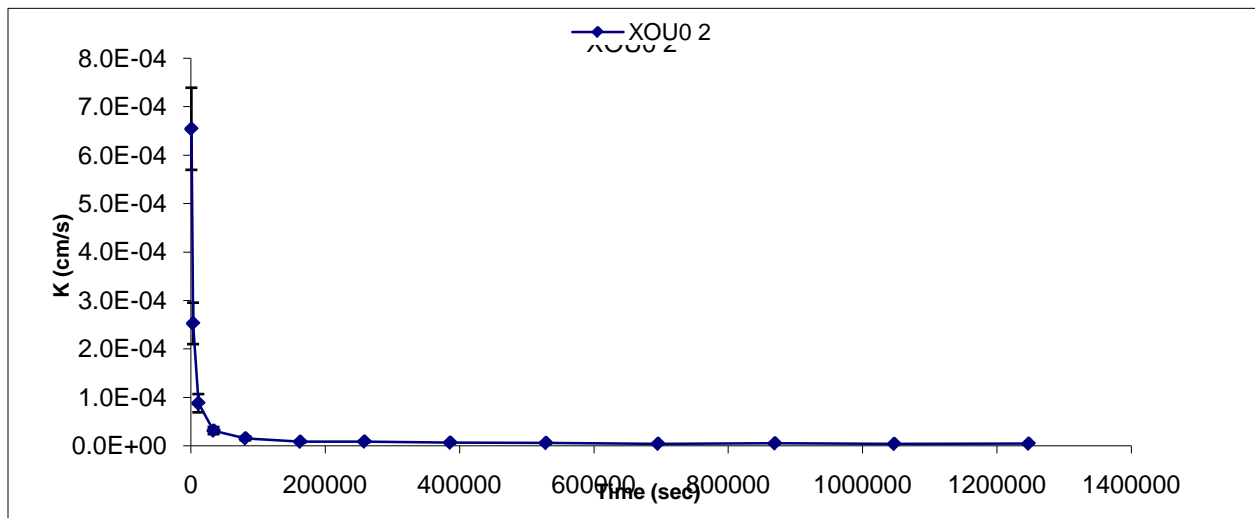
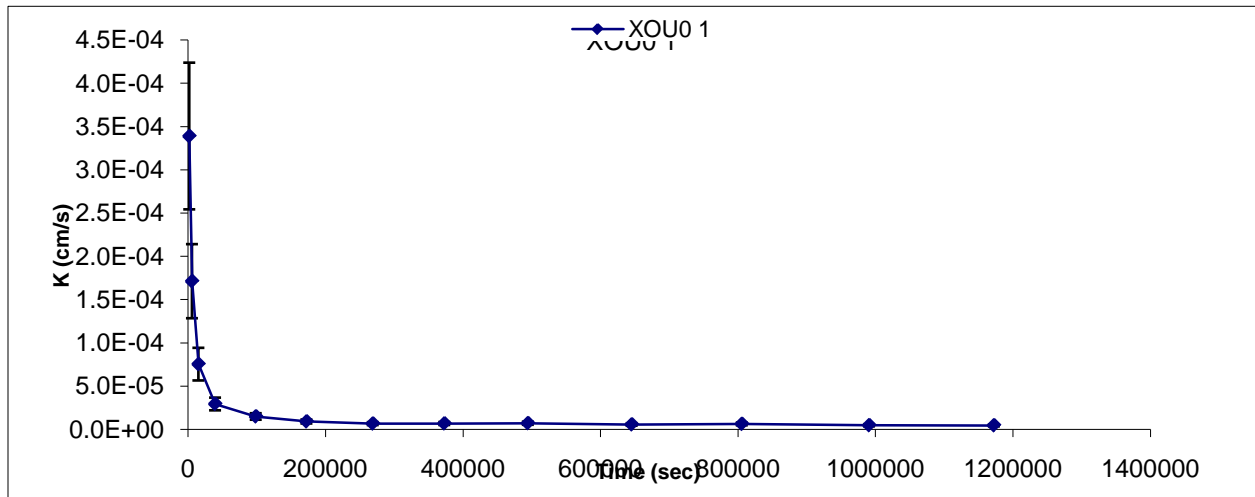
Hydraulic conductivity determination using X-Ranch soil and 75% IX treated CBNG Produced water (3 replications).



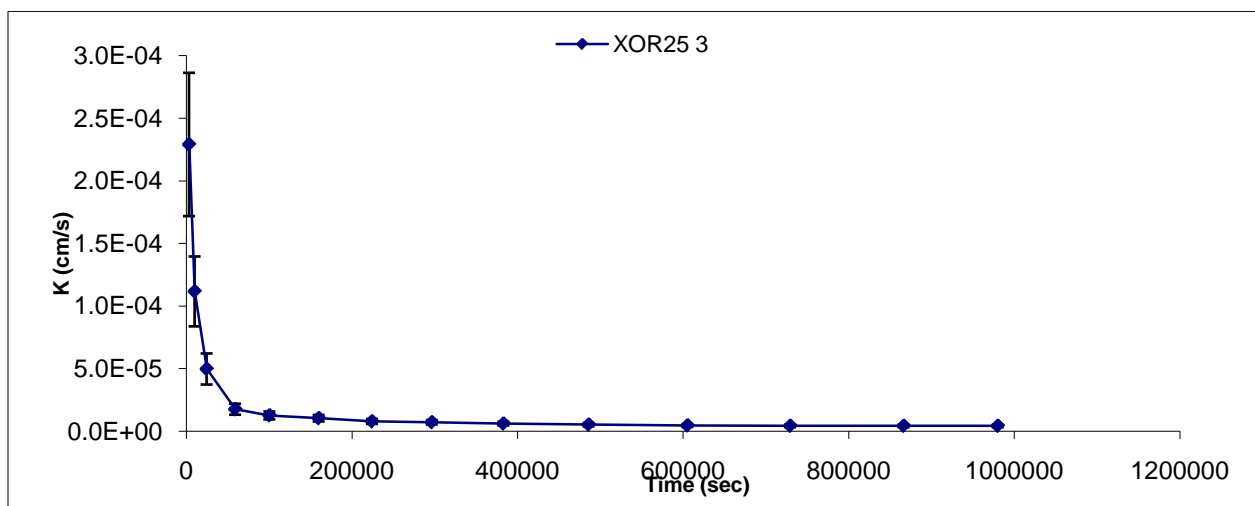
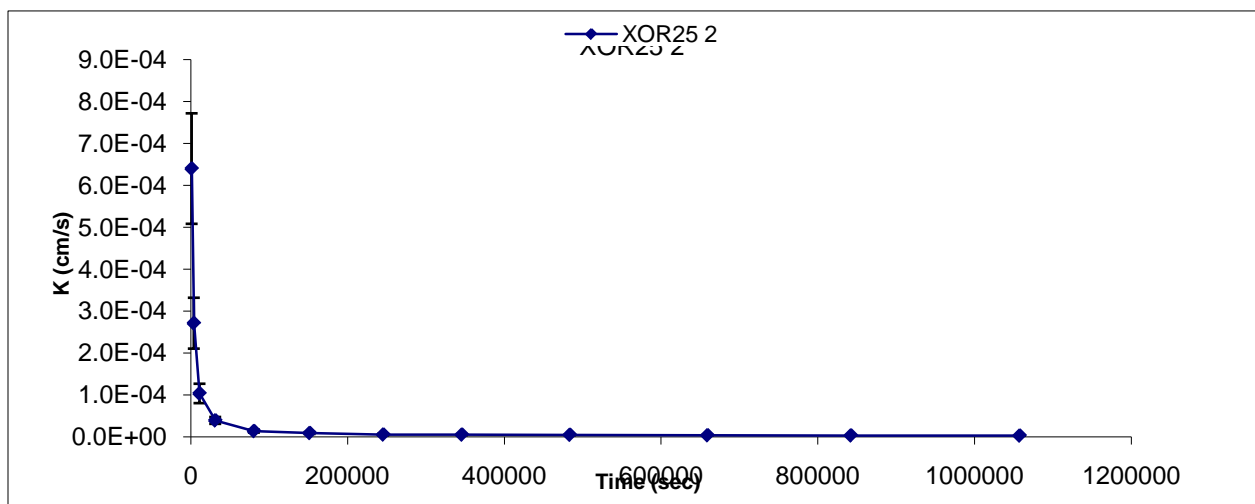
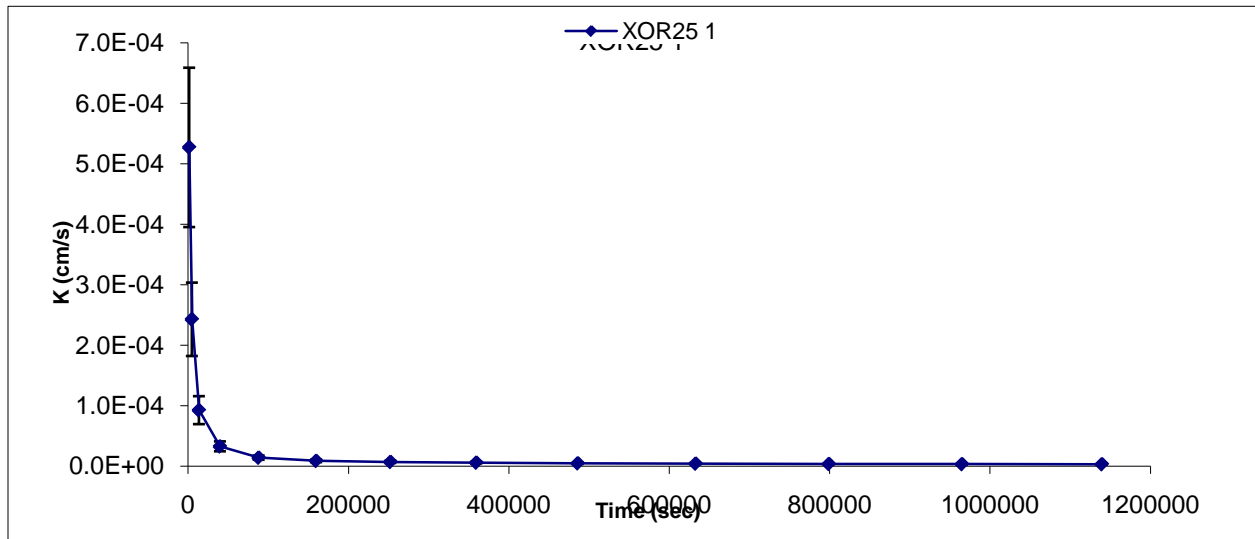
Hydraulic conductivity determination using X-Ranch soil and River Water (control) (3 replications).



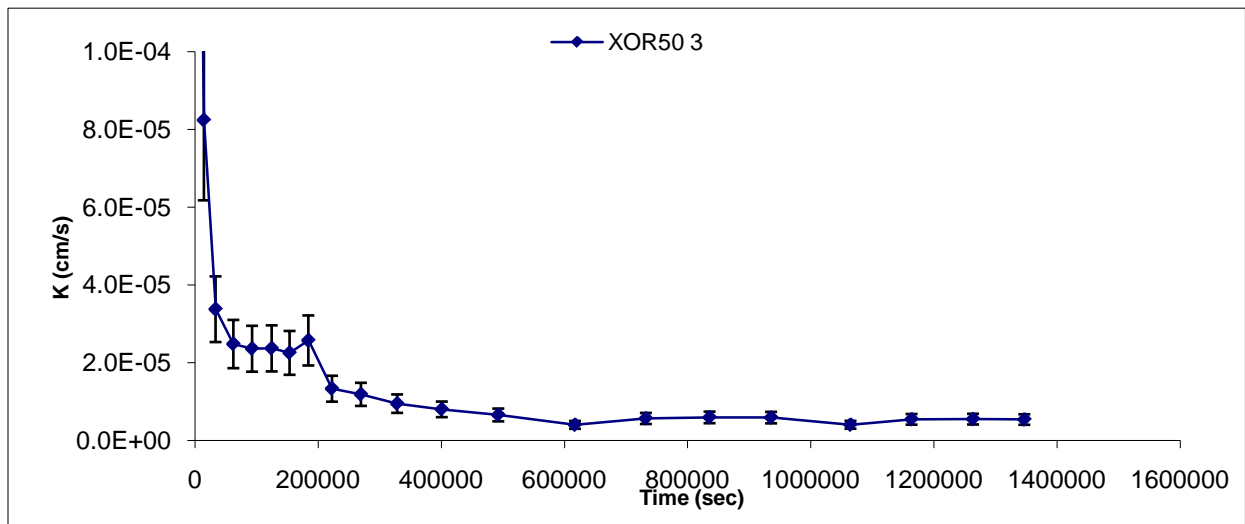
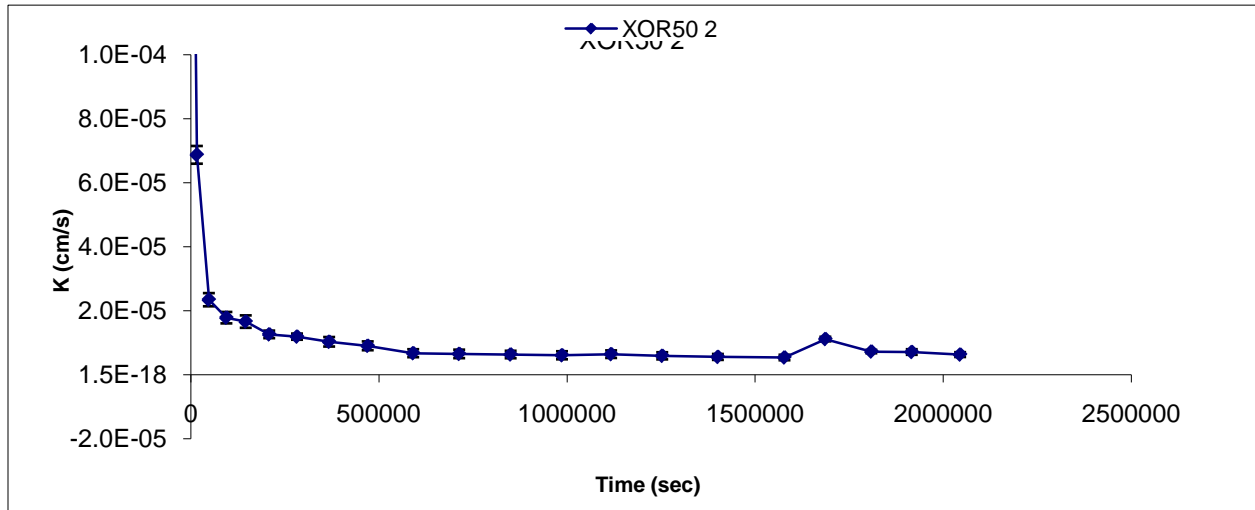
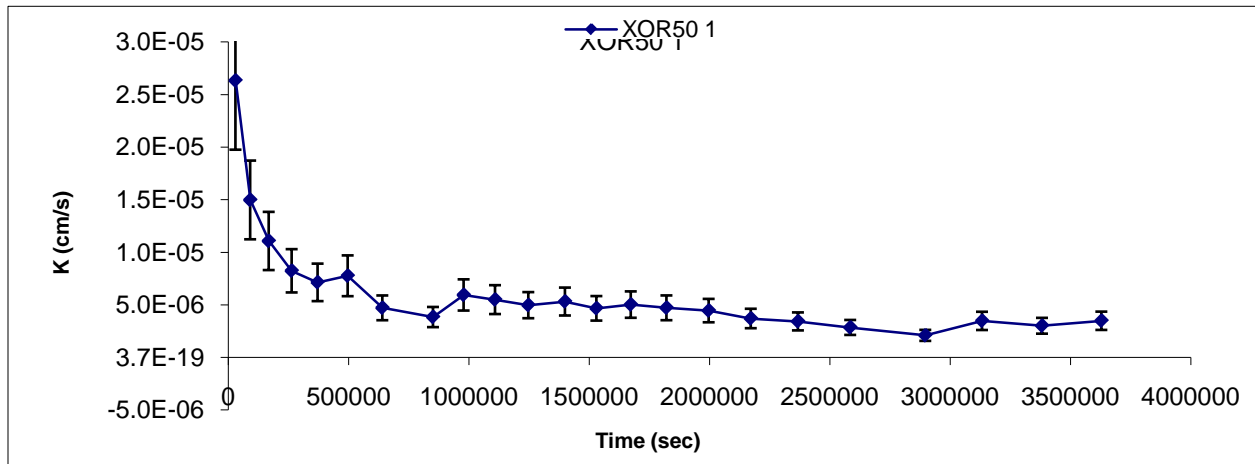
Hydraulic conductivity determination using X-Ranch soil and raw conventional oil and gas produced water (3 replications).



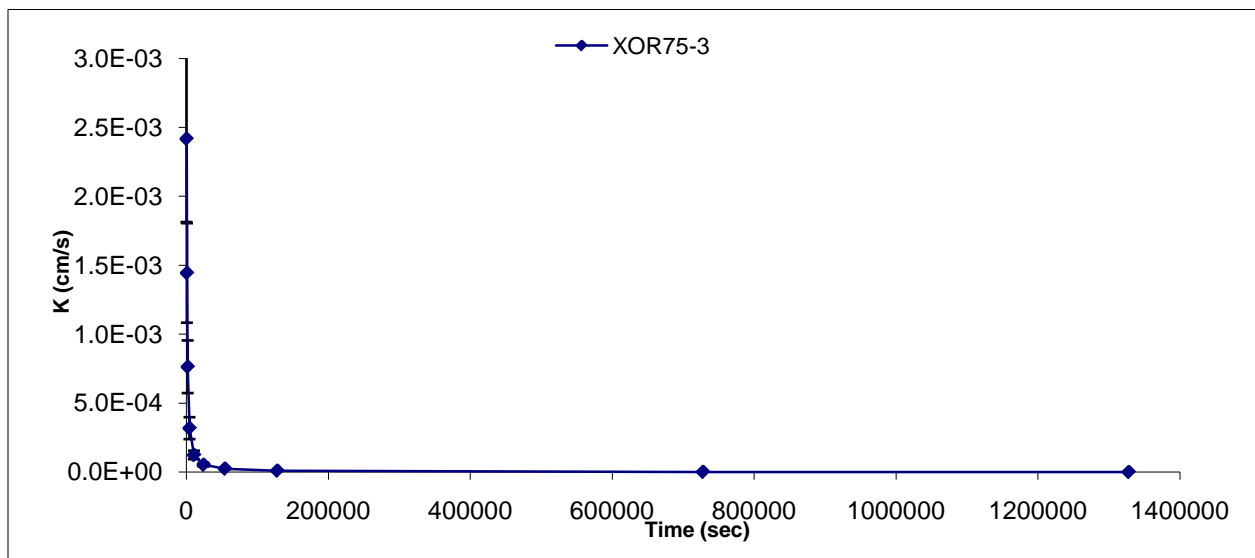
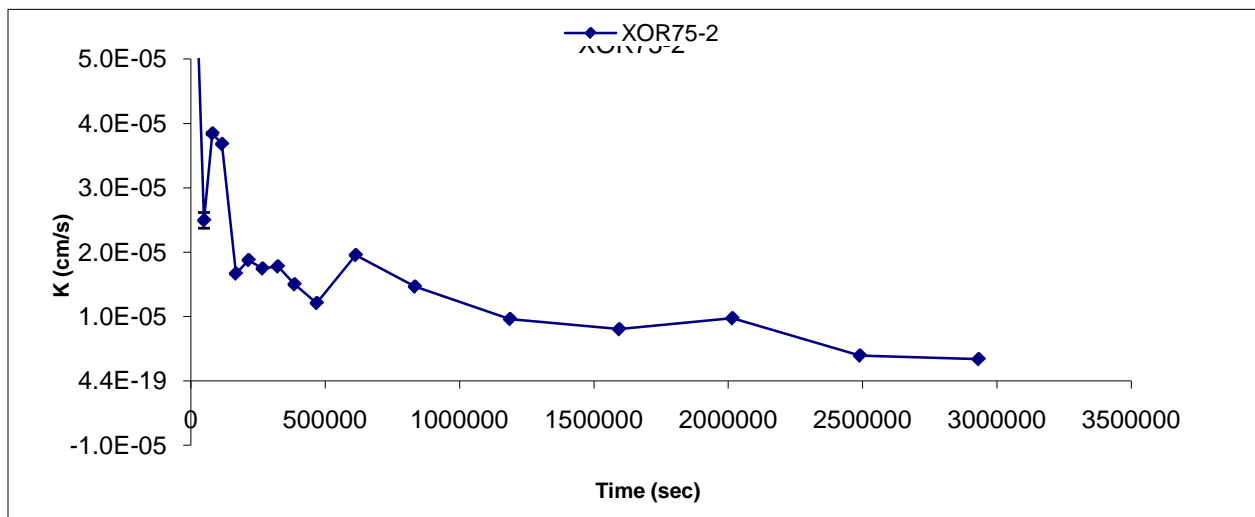
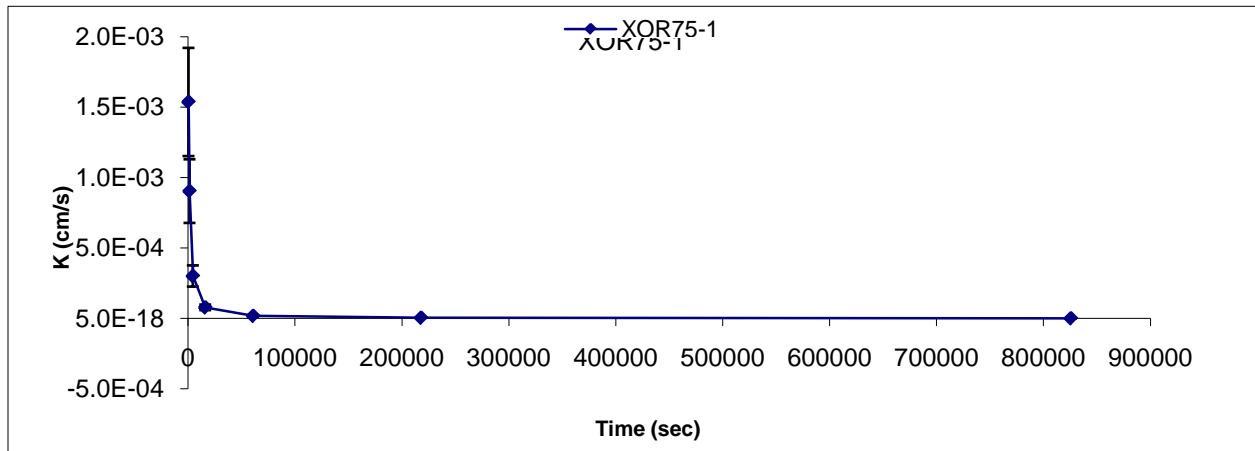
Hydraulic conductivity determination using X-Ranch soil and 25% RO treated conventional oil and gas produced water (3 replications).



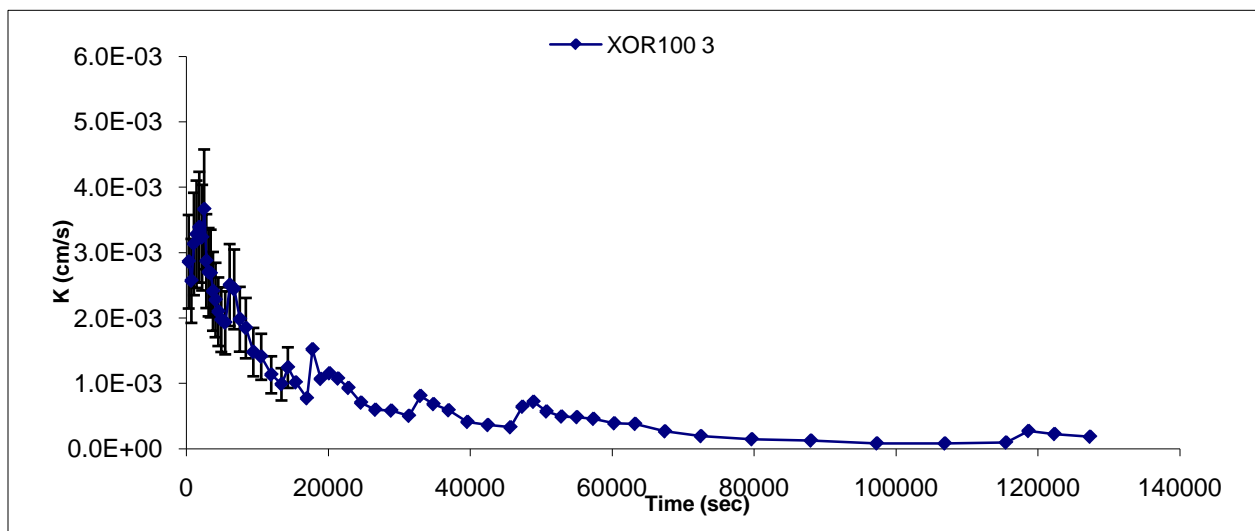
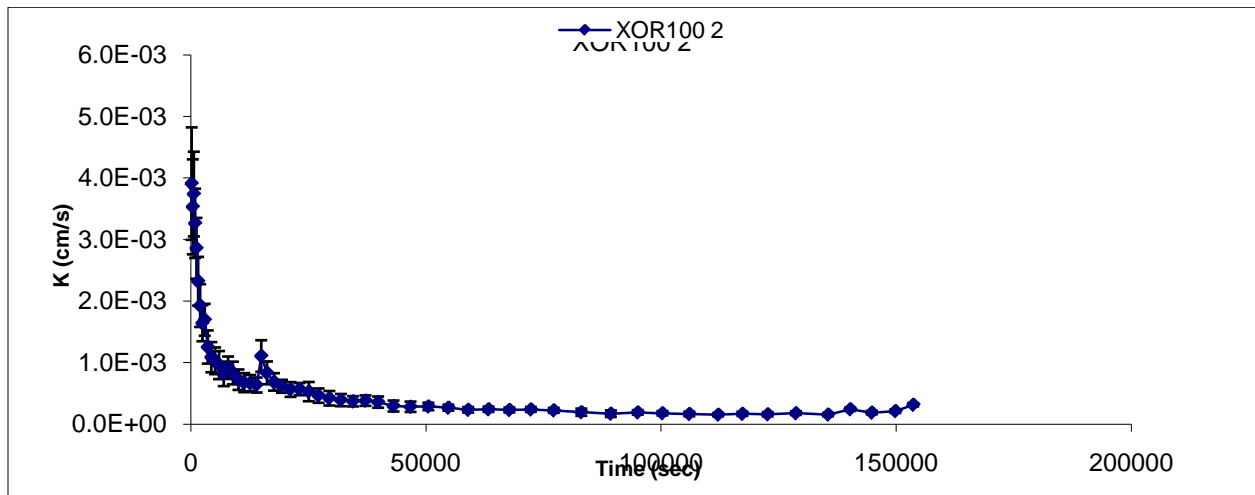
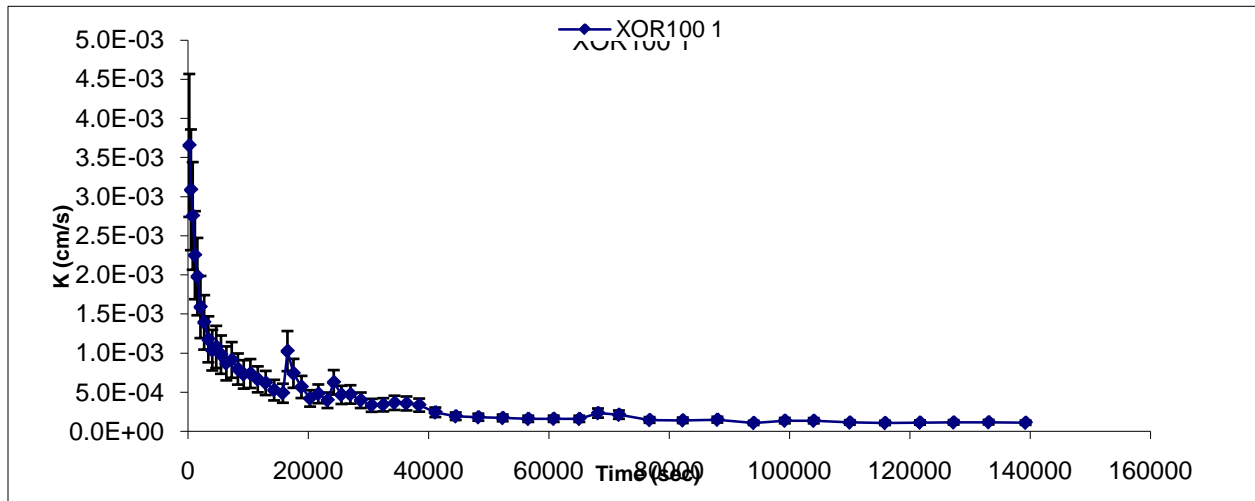
Hydraulic conductivity determination using X-Ranch soil and 50% RO treated conventional oil and gas produced water (3 replications).



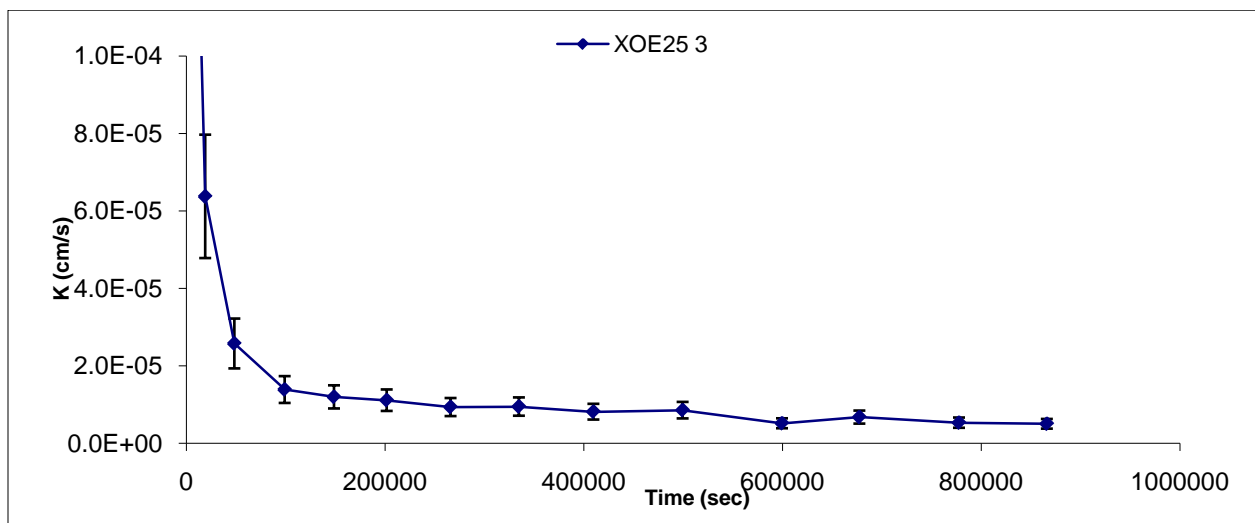
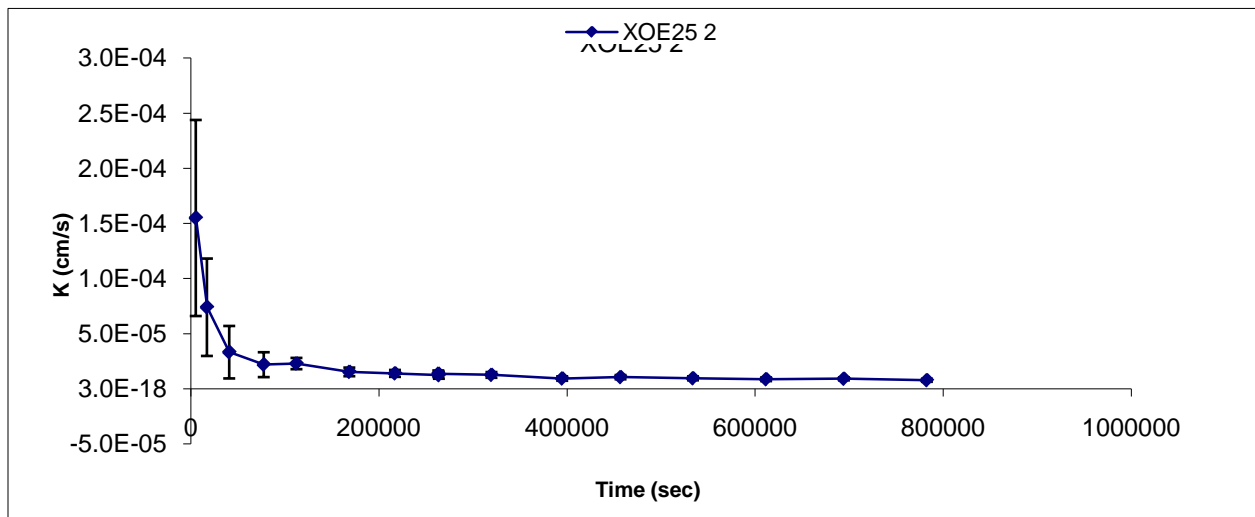
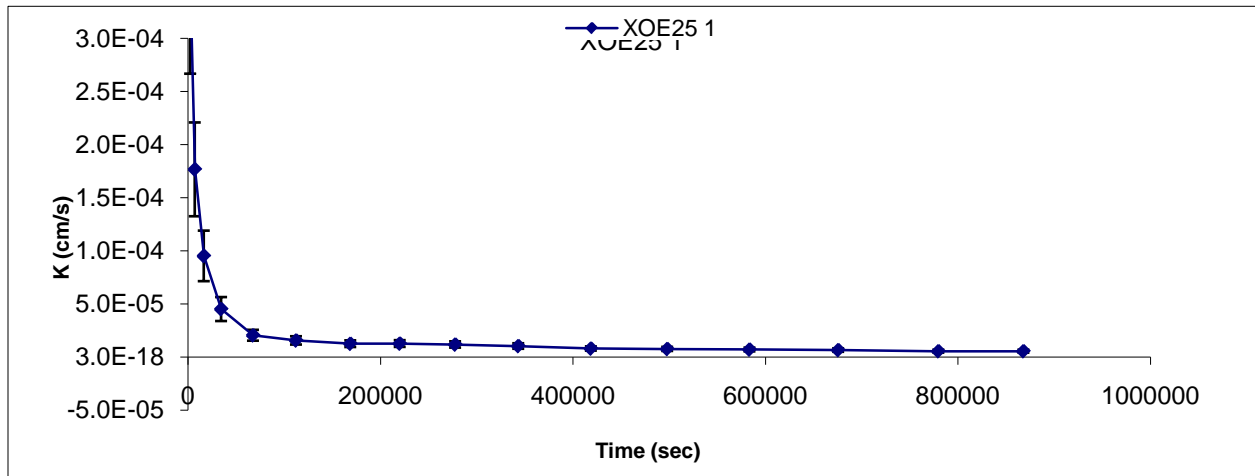
Hydraulic conductivity determination using X-Ranch soil and 75% RO treated conventional oil and gas produced water (3 replications).



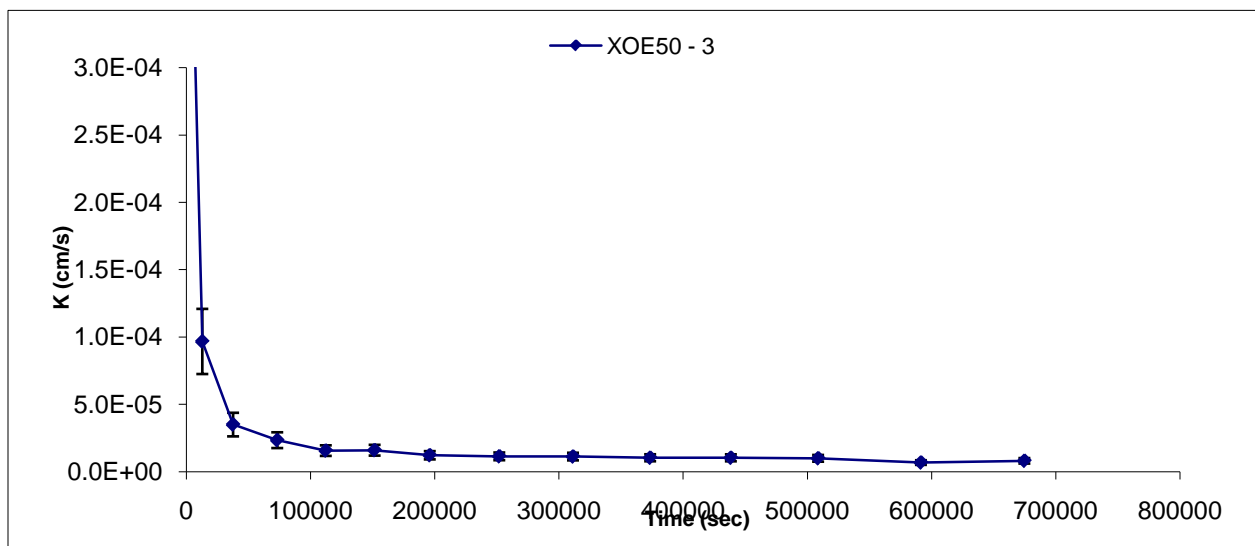
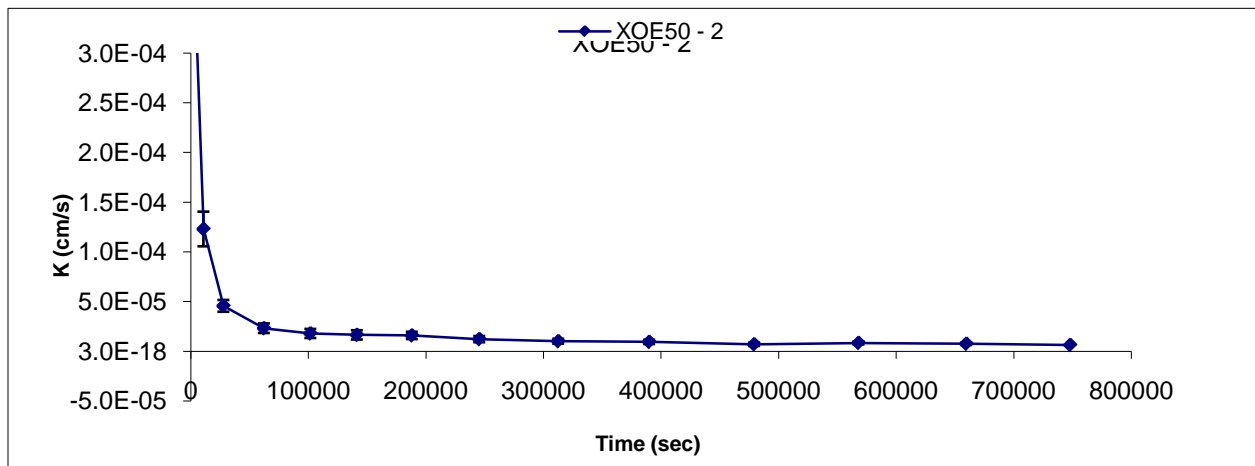
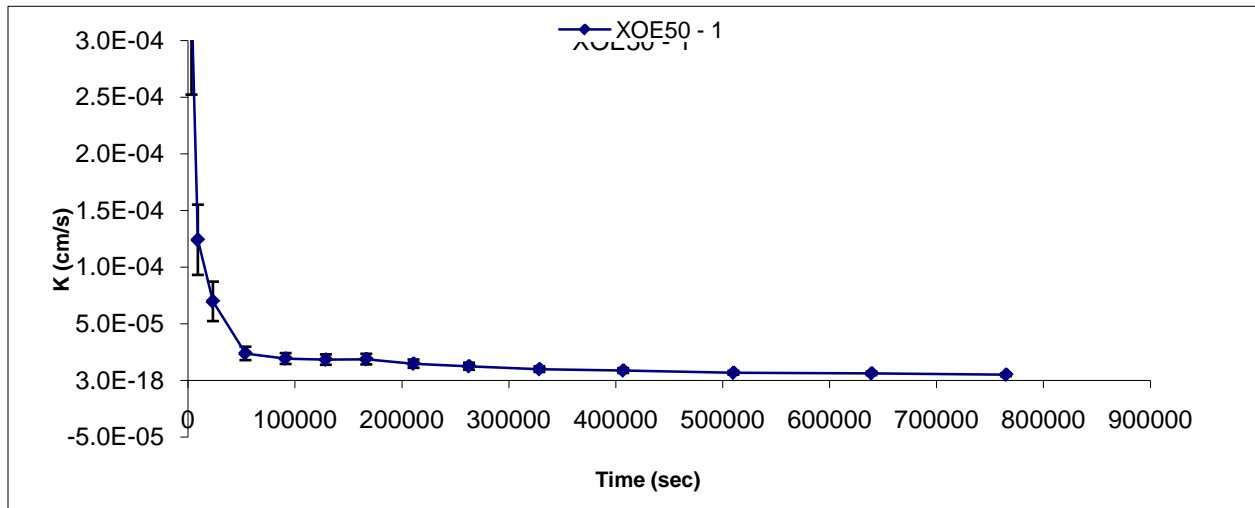
Hydraulic conductivity determination using X-Ranch soil and 100% RO treated conventional oil and gas produced water (3 replications).



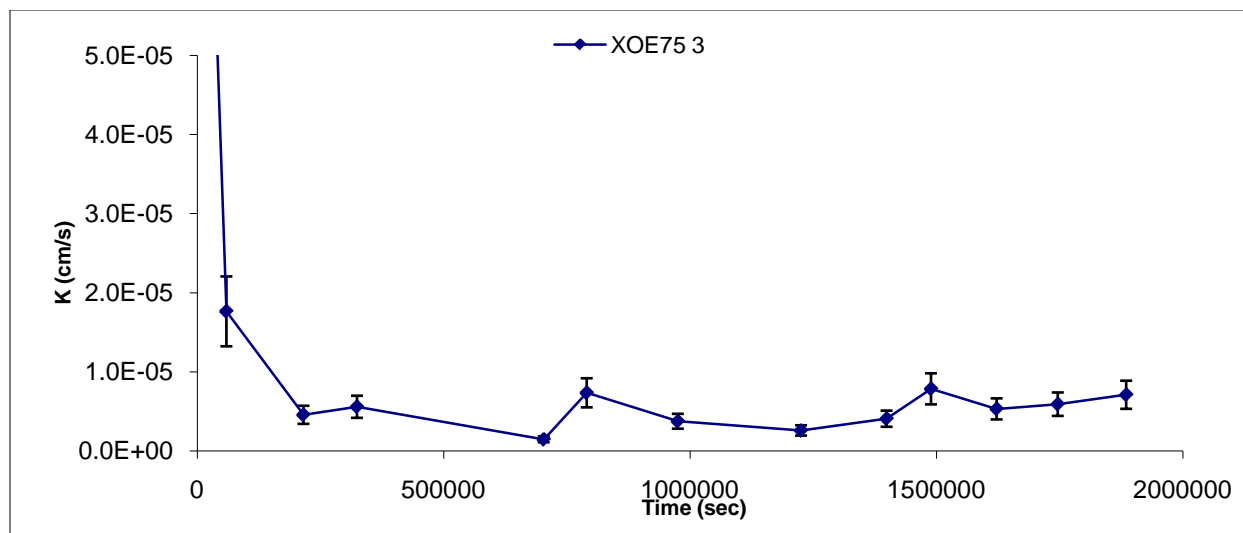
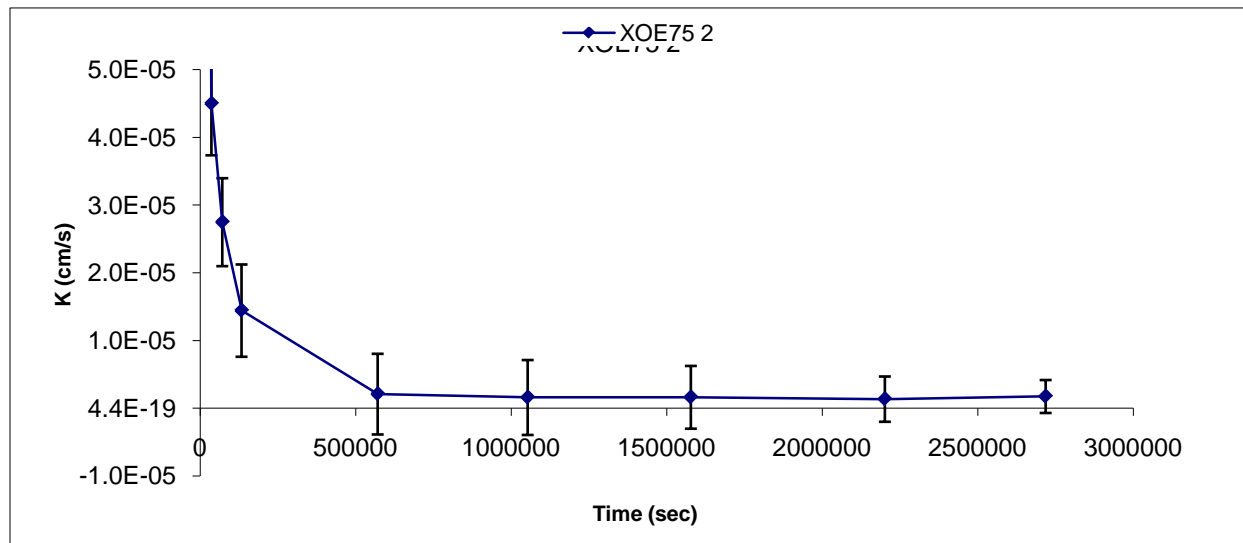
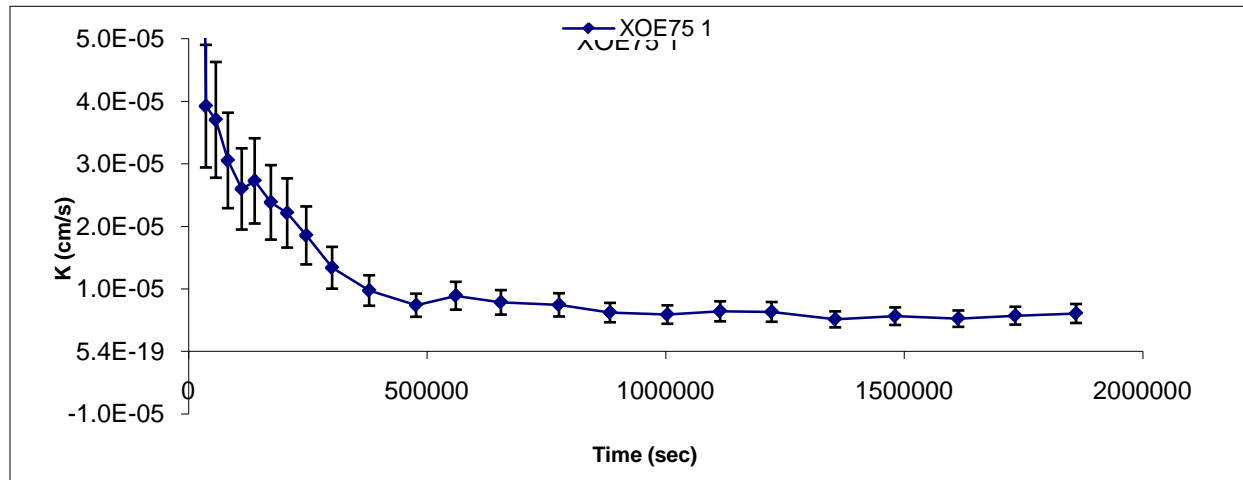
Hydraulic conductivity determination using X-Ranch soil and 25% EDR treated conventional oil and gas produced water (3 replications).



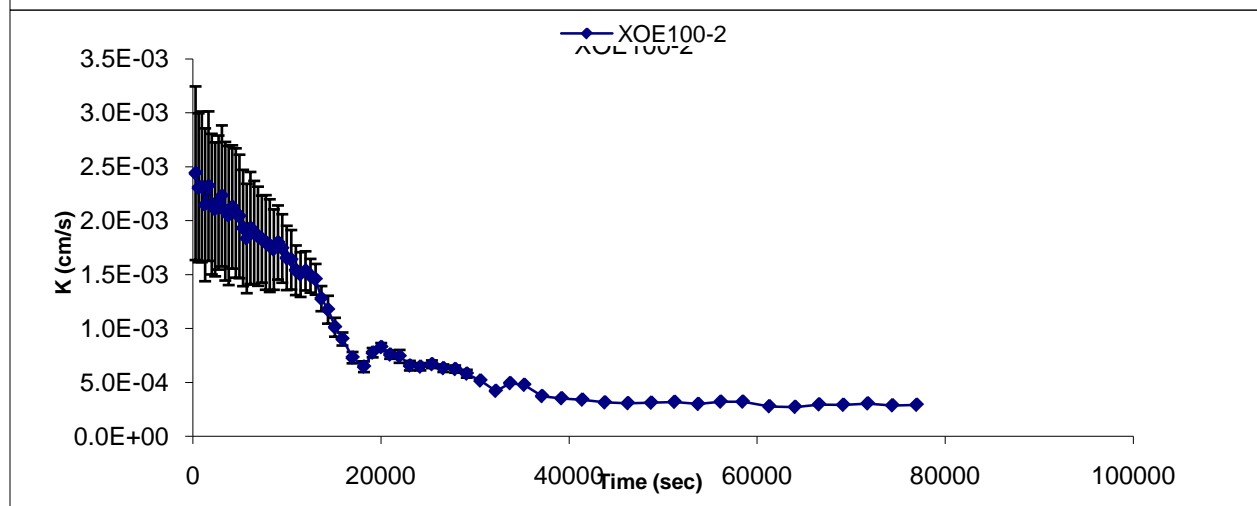
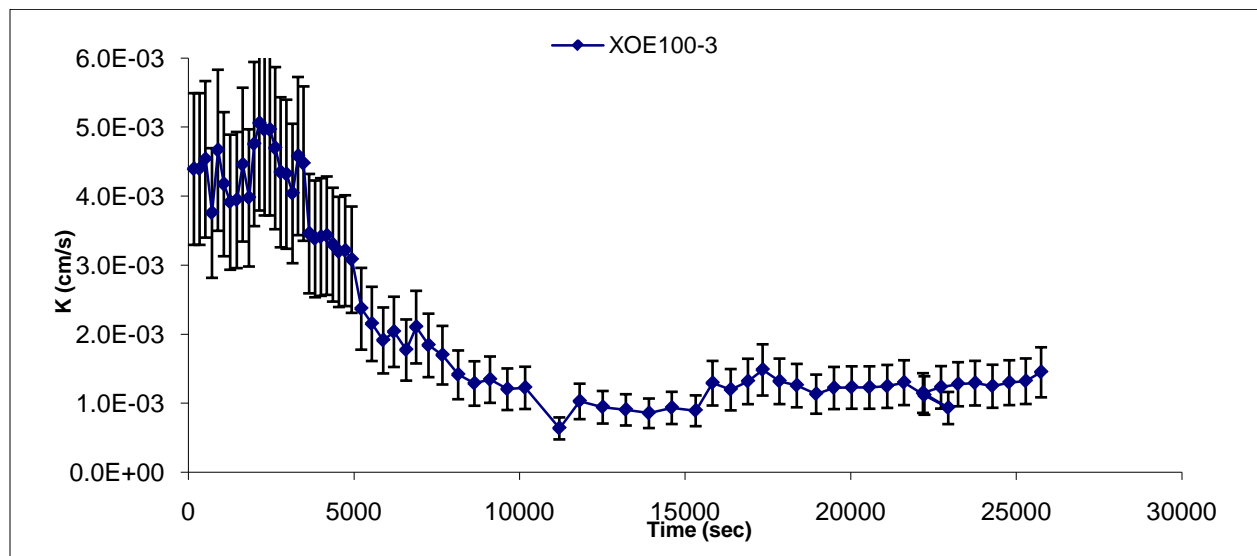
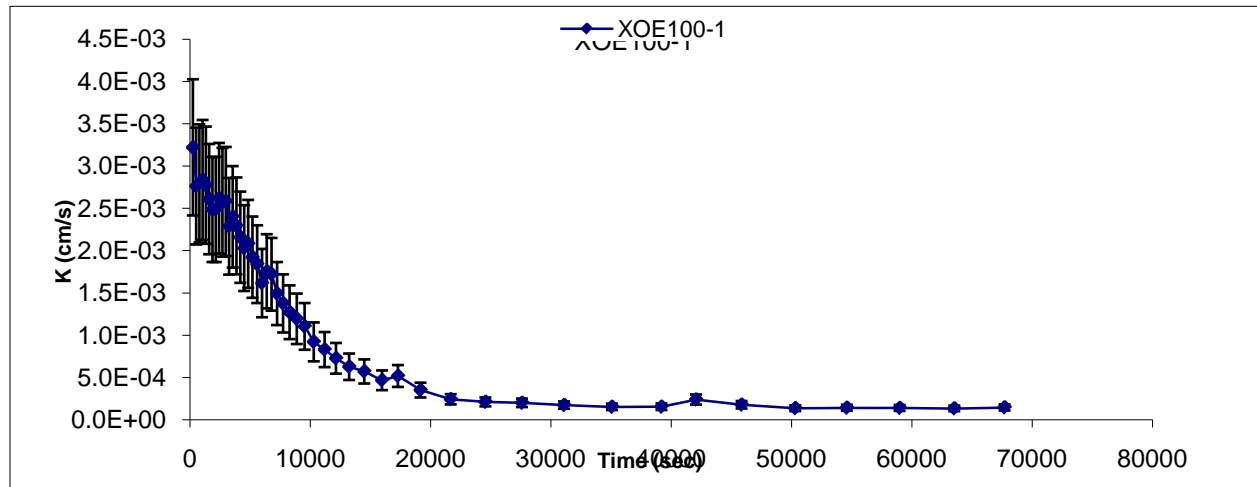
Hydraulic conductivity determination using X-Ranch soil and 50% EDR treated conventional oil and gas produced water (3 replications).



Hydraulic conductivity determination using X-Ranch soil and 75% EDR treated conventional oil and gas produced water (3 replications).



Hydraulic conductivity determination using X-Ranch soil and 100% EDR treated conventional oil and gas produced water (3 replications).



APPENDIX B. Statistic Evaluation of the Hydraulic Conductivity Data

CBNG Produced Water - One-way ANOVA: HC versus Water Treatment

| Source | DF | SS | MS | F | P |
|-----------------|----|-----------|-----------|-------|-------|
| Water Treatment | 9 | 0.0000251 | 0.0000028 | 34.01 | 0.000 |
| Error | 20 | 0.0000016 | 0.0000001 | | |
| Total | 29 | 0.0000268 | | | |

S = 0.0002866 R-Sq = 93.87% R-Sq(adj) = 91.11%

| Level | N | Mean | StDev |
|----------------|---|-----------|-----------|
| CBNG - 100% IX | 3 | 0.0019333 | 0.0002517 |
| CBNG - 25% IX | 3 | 0.0001620 | 0.0001283 |
| CBNG - 50% IX | 3 | 0.0002903 | 0.0002346 |
| CBNG - 75% IX | 3 | 0.0002733 | 0.0001963 |
| CBNG - No Trt | 3 | 0.0001057 | 0.0000768 |
| CBNG 100% RO | 3 | 0.0023000 | 0.0003606 |
| CBNG 25% RO | 3 | 0.0000817 | 0.0000526 |
| CBNG 50% RO | 3 | 0.0002033 | 0.0001457 |
| CBNG 75% RO | 3 | 0.0007033 | 0.0003439 |
| River Water | 3 | 0.0024000 | 0.0006083 |

Individual 95% CIs For Mean Based on
Pooled StDev

| Level | ---+-----+-----+-----+----- |
|----------------|---------------------------------|
| CBNG - 100% IX | (---*---) |
| CBNG - 25% IX | (---*---) |
| CBNG - 50% IX | (---*---) |
| CBNG - 75% IX | (---*---) |
| CBNG - No Trt | (---*---) |
| CBNG 100% RO | (---*---) |
| CBNG 25% RO | (---*---) |
| CBNG 50% RO | (---*---) |
| CBNG 75% RO | (---*---) |
| River Water | (---*---) |
| | ---+-----+-----+-----+----- |
| | 0.00000 0.00080 0.00160 0.00240 |

Pooled StDev = 0.0002866

Conventional Oil and Gas Produced Water - One-way ANOVA: HC versus Water Treatment

| Source | DF | SS | MS | F | P |
|-----------------|----|-----------|-----------|-------|-------|
| Water Treatment | 9 | 0.0000155 | 0.0000017 | 18.33 | 0.000 |
| Error | 20 | 0.0000019 | 0.0000001 | | |
| Total | 29 | 0.0000173 | | | |

S = 0.0003061 R-Sq = 89.19% R-Sq(adj) = 84.32%

| Level | N | Mean | StDev |
|----------------|---|-----------|-----------|
| O&G - 100% EDR | 3 | 0.0006467 | 0.0007423 |
| O&G - 100% RO | 3 | 0.0001753 | 0.0001255 |
| O&G - 25% EDR | 3 | 0.0000061 | 0.0000015 |
| O&G - 25% RO | 3 | 0.0000036 | 0.0000006 |
| O&G - 50% EDR | 3 | 0.0000064 | 0.0000016 |
| O&G - 50% RO | 3 | 0.0000056 | 0.0000009 |
| O&G - 75% EDR | 3 | 0.0000039 | 0.0000000 |
| O&G - 75% RO | 3 | 0.0000027 | 0.0000017 |
| O&G No Trt | 3 | 0.0000037 | 0.0000012 |
| River Water | 3 | 0.0024000 | 0.0006083 |

Individual 95% CIs For Mean Based on Pooled StDev

| Level | -----+-----+-----+-----+----- |
|----------------|---------------------------------|
| O&G - 100% EDR | (----*----) |
| O&G - 100% RO | (---*---) |
| O&G - 25% EDR | (----*----) |
| O&G - 25% RO | (----*----) |
| O&G - 50% EDR | (----*----) |
| O&G - 50% RO | (----*----) |
| O&G - 75% EDR | (----*----) |
| O&G - 75% RO | (----*----) |
| O&G No Trt | (----*----) |
| River Water | (----*----) |
| | -----+-----+-----+-----+----- |
| | 0.00000 0.00080 0.00160 0.00240 |

Pooled StDev = 0.0003061

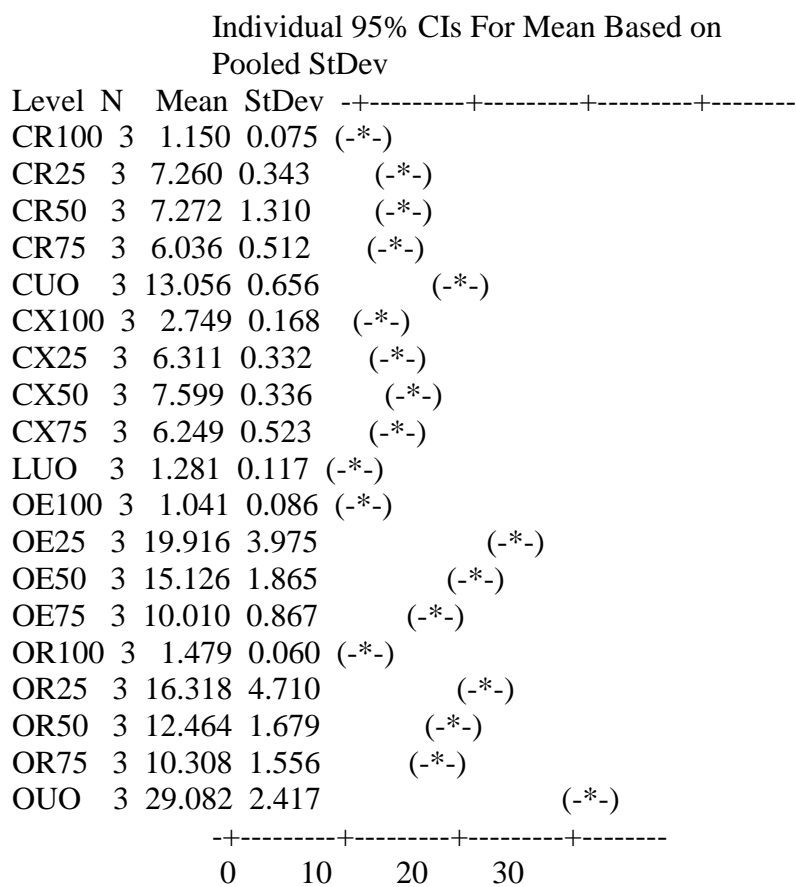
APPENDIX C. Statistical Evaluations of the SAR and EC of Samples Used in the Hydraulic Conductivity Evaluations

Alfalfa

One-way ANOVA: SAR versus Treatment

| Source | DF | SS | MS | F | P |
|-----------|----|---------|--------|-------|-------|
| Treatment | 18 | 2867.20 | 159.29 | 53.68 | 0.000 |
| Error | 38 | 112.77 | 2.97 | | |
| Total | 56 | 2979.96 | | | |

S = 1.723 R-Sq = 96.22% R-Sq(adj) = 94.42%



Pooled StDev = 1.723

Western Wheatgrass

One-way ANOVA: Biomass (g) versus Soil

| Source | DF | SS | MS | F | P |
|--------|-----|--------|--------|-------|-------|
| Soil | 2 | 35.284 | 17.642 | 75.84 | 0.000 |
| Error | 225 | 52.342 | 0.233 | | |
| Total | 227 | 87.626 | | | |

S = 0.4823 R-Sq = 40.27% R-Sq(adj) = 39.74%

Individual 95% CIs For Mean Based on
Pooled StDev

| Level | N | Mean | StDev | -+-----+-----+-----+----- |
|----------|----|--------|--------|---------------------------|
| Riverton | 76 | 1.0556 | 0.4847 | (--*---) |
| Sheridan | 76 | 1.6411 | 0.6084 | (---*--) |
| X Ranch | 76 | 0.6856 | 0.3047 | (---*--) |

-+-----+-----+-----+-----
0.60 0.90 1.20 1.50

Pooled StDev = 0.4823

Riverton Soil - One-way ANOVA: Biomass (g)_1 versus Water Type_1

| Source | DF | SS | MS | F | P |
|--------------|----|---------|--------|------|-------|
| Water Type_1 | 18 | 12.0015 | 0.6667 | 6.76 | 0.000 |
| Error | 57 | 5.6185 | 0.0986 | | |
| Total | 75 | 17.6199 | | | |

S = 0.3140 R-Sq = 68.11% R-Sq(adj) = 58.04%

| Individual 95% CIs For Mean Based on Pooled StDev | | | | | |
|---|---|--------|--------|--------------------------|----------------|
| Level | N | Mean | StDev | -----+-----+-----+-----+ | |
| CBM IX 100 | 4 | 1.1895 | 0.1603 | (---*---) | |
| CBM IX 25 | 4 | 1.1920 | 0.1350 | (---*---) | |
| CBM IX 50 | 4 | 1.1845 | 0.2663 | (---*---) | |
| CBM IX 75 | 4 | 1.2795 | 0.2388 | (---*---) | |
| CBM RAW | 4 | 1.3895 | 0.2058 | (---*---) | |
| CBM RO 100 | 4 | 1.2770 | 0.4032 | (---*---) | |
| CBM RO 25 | 4 | 1.5695 | 0.7019 | (---*---) | |
| CBM RO 50 | 4 | 1.9545 | 0.1903 | (---*---) | |
| CBM RO 75 | 4 | 1.4970 | 0.2421 | (---*---) | |
| Control | 4 | 0.9545 | 0.3058 | (---*---) | |
| O&G EDR 100 | 4 | 1.0720 | 0.6146 | (---*---) | |
| O&G EDR 25 | 4 | 0.6970 | 0.2143 | (---*---) | |
| O&G EDR 50 | 4 | 0.9945 | 0.1964 | (---*---) | |
| O&G EDR 75 | 4 | 0.7645 | 0.1759 | (---*---) | |
| O&G Raw | 4 | 0.4145 | 0.2014 | (---*---) | |
| O&G RO 100 | 4 | 0.9845 | 0.4313 | (---*---) | |
| O&G RO 25 | 4 | 0.3720 | 0.1190 | (---*---) | |
| O&G RO 50 | 4 | 0.5895 | 0.1539 | (---*---) | |
| O&G RO 75 | 4 | 0.6795 | 0.2396 | (---*---) | |
| | | | | -----+-----+-----+-----+ | |
| | | | | 0.60 | 1.20 1.80 2.40 |

Pooled StDev = 0.3140

Sheridan Soil - One-way ANOVA: Biomass (g)_2 versus Water Type_2

| | | | | | |
|--------------|----|--------|-------|------|-------|
| Source | DF | SS | MS | F | P |
| Water Type_2 | 18 | 20.636 | 1.146 | 9.17 | 0.000 |
| Error | 57 | 7.123 | 0.125 | | |
| Total | 75 | 27.759 | | | |

S = 0.3535 R-Sq = 74.34% R-Sq(adj) = 66.24%

Individual 95% CIs For Mean Based on
Pooled StDev

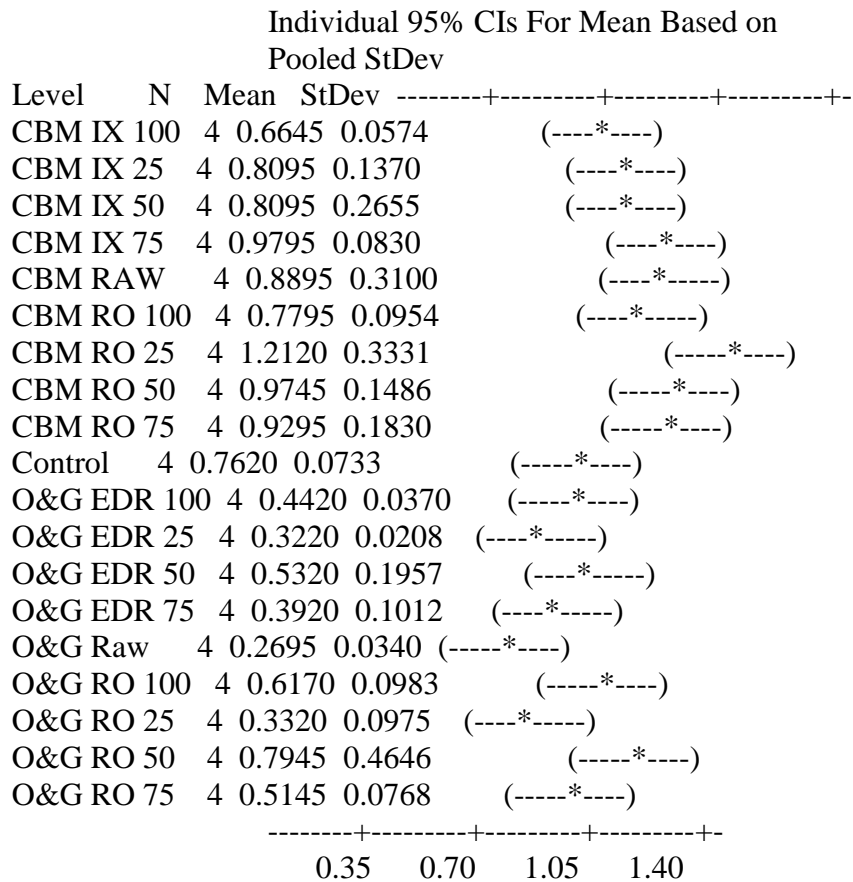
| Level | N | Mean | StDev | -+-----+-----+-----+----- | |
|-------------|---|--------|--------|---------------------------|------|
| CBM IX 100 | 4 | 1.1770 | 0.0589 | (----*----) | |
| CBM IX 25 | 4 | 2.4545 | 0.5564 | (----*----) | |
| CBM IX 50 | 4 | 2.0645 | 0.6261 | (----*----) | |
| CBM IX 75 | 4 | 1.5145 | 0.2809 | (----*----) | |
| CBM RAW | 4 | 2.6395 | 0.3157 | (----*----) | |
| CBM RO 100 | 4 | 1.0170 | 0.2394 | (----*----) | |
| CBM RO 25 | 4 | 2.8095 | 0.4336 | (----*----) | |
| CBM RO 50 | 4 | 2.0320 | 0.3841 | (----*----) | |
| CBM RO 75 | 4 | 1.4970 | 0.1291 | (----*----) | |
| Control | 4 | 1.1295 | 0.3508 | (----*----) | |
| O&G EDR 100 | 4 | 1.3495 | 0.1328 | (----*----) | |
| O&G EDR 25 | 4 | 1.2795 | 0.2595 | (----*----) | |
| O&G EDR 50 | 4 | 1.3670 | 0.3047 | (----*----) | |
| O&G EDR 75 | 4 | 1.8295 | 0.3062 | (----*----) | |
| O&G Raw | 4 | 1.0695 | 0.4463 | (----*----) | |
| O&G RO 100 | 4 | 1.1895 | 0.2906 | (----*----) | |
| O&G RO 25 | 4 | 1.4620 | 0.1047 | (----*----) | |
| O&G RO 50 | 4 | 1.5770 | 0.5234 | (----*----) | |
| O&G RO 75 | 4 | 1.7220 | 0.3436 | (----*----) | |
| | | | | -+-----+-----+-----+----- | |
| | | 0.70 | 1.40 | 2.10 | 2.80 |

Pooled StDev = 0.3535

X-Ranch Soil - One-way ANOVA: Biomass (g)_3 versus Water Type_3

| | | | | | |
|--------------|----|--------|--------|------|-------|
| Source | DF | SS | MS | F | P |
| Water Type_3 | 18 | 4.9566 | 0.2754 | 7.82 | 0.000 |
| Error | 57 | 2.0069 | 0.0352 | | |
| Total | 75 | 6.9635 | | | |

S = 0.1876 R-Sq = 71.18% R-Sq(adj) = 62.08%



Pooled StDev = 0.1876

Appendix D. Biomass Production Data by Irrigation Treatment

Alfalfa

| Sample I | | Soil | Water Type | Replicate | Biomass (g) |
|---------------|---------|----------|------------|-------------|-------------|
| A-R-C-R-100-1 | Alfalfa | Riverton | CBM RO 100 | Replicate 1 | 1.52 |
| A-R-C-R-100-2 | Alfalfa | Riverton | CBM RO 100 | Replicate 2 | 1.79 |
| A-R-C-R-100-3 | Alfalfa | Riverton | CBM RO 100 | Replicate 3 | 1.74 |
| A-R-C-R-100-4 | Alfalfa | Riverton | CBM RO 100 | Replicate 4 | 1.25 |
| A-R-C-R-25-1 | Alfalfa | Riverton | CBM RO 25 | Replicate 1 | 1.93 |
| A-R-C-R-25-2 | Alfalfa | Riverton | CBM RO 25 | Replicate 2 | 1.62 |
| A-R-C-R-25-3 | Alfalfa | Riverton | CBM RO 25 | Replicate 3 | 2.21 |
| A-R-C-R-25-4 | Alfalfa | Riverton | CBM RO 25 | Replicate 4 | 1.85 |
| A-R-C-R-50-1 | Alfalfa | Riverton | CBM RO 50 | Replicate 1 | 1.46 |
| A-R-C-R-50-2 | Alfalfa | Riverton | CBM RO 50 | Replicate 2 | 1.64 |
| A-R-C-R-50-3 | Alfalfa | Riverton | CBM RO 50 | Replicate 3 | 1.86 |
| A-R-C-R-50-4 | Alfalfa | Riverton | CBM RO 50 | Replicate 4 | 1.76 |
| A-R-C-R-75-1 | Alfalfa | Riverton | CBM RO 75 | Replicate 1 | 1.47 |
| A-R-C-R-75-2 | Alfalfa | Riverton | CBM RO 75 | Replicate 2 | 1.64 |
| A-R-C-R-75-3 | Alfalfa | Riverton | CBM RO 75 | Replicate 3 | 1.55 |
| A-R-C-R-75-4 | Alfalfa | Riverton | CBM RO 75 | Replicate 4 | 1.83 |
| A-R-C-U-0-1 | Alfalfa | Riverton | CBM RAW | Replicate 1 | 0.00 |
| A-R-C-U-0-2 | Alfalfa | Riverton | CBM RAW | Replicate 2 | 0.00 |
| A-R-C-U-0-3 | Alfalfa | Riverton | CBM RAW | Replicate 3 | 2.04 |
| A-R-C-U-0-4 | Alfalfa | Riverton | CBM RAW | Replicate 4 | 0.00 |
| A-R-C-X-100-1 | Alfalfa | Riverton | CBM IX 100 | Replicate 1 | 2.02 |
| A-R-C-X-100-2 | Alfalfa | Riverton | CBM IX 100 | Replicate 2 | 1.72 |
| A-R-C-X-100-3 | Alfalfa | Riverton | CBM IX 100 | Replicate 3 | 1.89 |
| A-R-C-X-100-4 | Alfalfa | Riverton | CBM IX 100 | Replicate 4 | 0.95 |
| A-R-C-X-25-1 | Alfalfa | Riverton | CBM IX 25 | Replicate 1 | 1.10 |
| A-R-C-X-25-2 | Alfalfa | Riverton | CBM IX 25 | Replicate 2 | 1.85 |
| A-R-C-X-25-3 | Alfalfa | Riverton | CBM IX 25 | Replicate 3 | 1.64 |
| A-R-C-X-25-4 | Alfalfa | Riverton | CBM IX 25 | Replicate 4 | 1.66 |
| A-R-C-X-50-1 | Alfalfa | Riverton | CBM IX 50 | Replicate 1 | 1.12 |
| A-R-C-X-50-2 | Alfalfa | Riverton | CBM IX 50 | Replicate 2 | 1.77 |
| A-R-C-X-50-3 | Alfalfa | Riverton | CBM IX 50 | Replicate 3 | 1.18 |
| A-R-C-X-50-4 | Alfalfa | Riverton | CBM IX 50 | Replicate 4 | 1.26 |
| A-R-C-X-75-1 | Alfalfa | Riverton | CBM IX 75 | Replicate 1 | 1.46 |
| A-R-C-X-75-2 | Alfalfa | Riverton | CBM IX 75 | Replicate 2 | 0.95 |
| A-R-C-X-75-3 | Alfalfa | Riverton | CBM IX 75 | Replicate 3 | 1.42 |
| A-R-C-X-75-4 | Alfalfa | Riverton | CBM IX 75 | Replicate 4 | 1.62 |

| | | | | | |
|---------------|---------|----------|-------------|-------------|------|
| A-R-L-U-0-1 | Alfalfa | Riverton | Control | Replicate 1 | 1.53 |
| A-R-L-U-0-2 | Alfalfa | Riverton | Control | Replicate 2 | 2.72 |
| A-R-L-U-0-3 | Alfalfa | Riverton | Control | Replicate 3 | 1.96 |
| A-R-L-U-0-4 | Alfalfa | Riverton | Control | Replicate 4 | 1.46 |
| A-R-O-E-100-1 | Alfalfa | Riverton | O&G EDR 100 | Replicate 1 | 1.44 |
| A-R-O-E-100-2 | Alfalfa | Riverton | O&G EDR 100 | Replicate 2 | 1.07 |
| A-R-O-E-100-3 | Alfalfa | Riverton | O&G EDR 100 | Replicate 3 | 1.18 |
| A-R-O-E-100-4 | Alfalfa | Riverton | O&G EDR 100 | Replicate 4 | 1.78 |
| A-R-O-E-25-1 | Alfalfa | Riverton | O&G EDR 25 | Replicate 1 | 1.21 |
| A-R-O-E-25-2 | Alfalfa | Riverton | O&G EDR 25 | Replicate 2 | 0.00 |
| A-R-O-E-25-3 | Alfalfa | Riverton | O&G EDR 25 | Replicate 3 | 0.64 |
| A-R-O-E-25-4 | Alfalfa | Riverton | O&G EDR 25 | Replicate 4 | 0.00 |
| A-R-O-E-50-1 | Alfalfa | Riverton | O&G EDR 50 | Replicate 1 | 0.00 |
| A-R-O-E-50-2 | Alfalfa | Riverton | O&G EDR 50 | Replicate 2 | 0.00 |
| A-R-O-E-50-3 | Alfalfa | Riverton | O&G EDR 50 | Replicate 3 | 0.00 |
| A-R-O-E-50-4 | Alfalfa | Riverton | O&G EDR 50 | Replicate 4 | 0.00 |
| A-R-O-E-75-1 | Alfalfa | Riverton | O&G EDR 75 | Replicate 1 | 1.23 |
| A-R-O-E-75-2 | Alfalfa | Riverton | O&G EDR 75 | Replicate 2 | 1.12 |
| A-R-O-E-75-3 | Alfalfa | Riverton | O&G EDR 75 | Replicate 3 | 0.53 |
| A-R-O-E-75-4 | Alfalfa | Riverton | O&G EDR 75 | Replicate 4 | 0.74 |
| A-R-O-R-100-1 | Alfalfa | Riverton | O&G RO 100 | Replicate 1 | 1.41 |
| A-R-O-R-100-2 | Alfalfa | Riverton | O&G RO 100 | Replicate 2 | 1.82 |
| A-R-O-R-100-3 | Alfalfa | Riverton | O&G RO 100 | Replicate 3 | 1.09 |
| A-R-O-R-100-4 | Alfalfa | Riverton | O&G RO 100 | Replicate 4 | 1.91 |
| A-R-O-R-25-1 | Alfalfa | Riverton | O&G RO 25 | Replicate 1 | 0.00 |
| A-R-O-R-25-2 | Alfalfa | Riverton | O&G RO 25 | Replicate 2 | 0.00 |
| A-R-O-R-25-3 | Alfalfa | Riverton | O&G RO 25 | Replicate 3 | 0.62 |
| A-R-O-R-25-4 | Alfalfa | Riverton | O&G RO 25 | Replicate 4 | 0.00 |
| A-R-O-R-50-1 | Alfalfa | Riverton | O&G RO 50 | Replicate 1 | 0.00 |
| A-R-O-R-50-2 | Alfalfa | Riverton | O&G RO 50 | Replicate 2 | 0.62 |
| A-R-O-R-50-3 | Alfalfa | Riverton | O&G RO 50 | Replicate 3 | 0.00 |
| A-R-O-R-50-4 | Alfalfa | Riverton | O&G RO 50 | Replicate 4 | 0.92 |
| A-R-O-R-75-1 | Alfalfa | Riverton | O&G RO 75 | Replicate 1 | 1.24 |
| A-R-O-R-75-2 | Alfalfa | Riverton | O&G RO 75 | Replicate 2 | 0.79 |
| A-R-O-R-75-3 | Alfalfa | Riverton | O&G RO 75 | Replicate 3 | 1.70 |
| A-R-O-R-75-4 | Alfalfa | Riverton | O&G RO 75 | Replicate 4 | 2.02 |
| A-R-O-U-0-1 | Alfalfa | Riverton | O&G Raw | Replicate 1 | 0.64 |
| A-R-O-U-0-2 | Alfalfa | Riverton | O&G Raw | Replicate 2 | 0.00 |
| A-R-O-U-0-3 | Alfalfa | Riverton | O&G Raw | Replicate 3 | 0.00 |
| A-R-O-U-0-4 | Alfalfa | Riverton | O&G Raw | Replicate 4 | 0.64 |

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|---------------|---------|----------|------------|-------------|------|
| A-S-C-R-100-1 | Alfalfa | Sheridan | CBM RO 100 | Replicate 1 | 3.00 |
| A-S-C-R-100-2 | Alfalfa | Sheridan | CBM RO 100 | Replicate 2 | 1.83 |
| A-S-C-R-100-3 | Alfalfa | Sheridan | CBM RO 100 | Replicate 3 | 1.86 |
| A-S-C-R-100-4 | Alfalfa | Sheridan | CBM RO 100 | Replicate 4 | 2.51 |
| A-S-C-R-25-1 | Alfalfa | Sheridan | CBM RO 25 | Replicate 1 | 1.36 |
| A-S-C-R-25-2 | Alfalfa | Sheridan | CBM RO 25 | Replicate 2 | 1.30 |
| A-S-C-R-25-3 | Alfalfa | Sheridan | CBM RO 25 | Replicate 3 | 1.26 |
| A-S-C-R-25-4 | Alfalfa | Sheridan | CBM RO 25 | Replicate 4 | 1.58 |
| A-S-C-R-50-1 | Alfalfa | Sheridan | CBM RO 50 | Replicate 1 | 1.81 |
| A-S-C-R-50-2 | Alfalfa | Sheridan | CBM RO 50 | Replicate 2 | 1.85 |
| A-S-C-R-50-3 | Alfalfa | Sheridan | CBM RO 50 | Replicate 3 | 1.93 |
| A-S-C-R-50-4 | Alfalfa | Sheridan | CBM RO 50 | Replicate 4 | 1.39 |
| A-S-C-R-75-1 | Alfalfa | Sheridan | CBM RO 75 | Replicate 1 | 2.14 |
| A-S-C-R-75-2 | Alfalfa | Sheridan | CBM RO 75 | Replicate 2 | 1.82 |
| A-S-C-R-75-3 | Alfalfa | Sheridan | CBM RO 75 | Replicate 3 | 1.75 |
| A-S-C-R-75-4 | Alfalfa | Sheridan | CBM RO 75 | Replicate 4 | 1.30 |
| A-S-C-U-0-1 | Alfalfa | Sheridan | CBM RAW | Replicate 1 | 1.59 |
| A-S-C-U-0-2 | Alfalfa | Sheridan | CBM RAW | Replicate 2 | 1.67 |
| A-S-C-U-0-3 | Alfalfa | Sheridan | CBM RAW | Replicate 3 | 1.48 |
| A-S-C-U-0-4 | Alfalfa | Sheridan | CBM RAW | Replicate 4 | 1.88 |
| A-S-C-X-100-1 | Alfalfa | Sheridan | CBM IX 100 | Replicate 1 | 3.76 |
| A-S-C-X-100-2 | Alfalfa | Sheridan | CBM IX 100 | Replicate 2 | 2.01 |
| A-S-C-X-100-3 | Alfalfa | Sheridan | CBM IX 100 | Replicate 3 | 2.13 |
| A-S-C-X-100-4 | Alfalfa | Sheridan | CBM IX 100 | Replicate 4 | 2.88 |
| A-S-C-X-25-1 | Alfalfa | Sheridan | CBM IX 25 | Replicate 1 | 1.77 |
| A-S-C-X-25-2 | Alfalfa | Sheridan | CBM IX 25 | Replicate 2 | 1.29 |
| A-S-C-X-25-3 | Alfalfa | Sheridan | CBM IX 25 | Replicate 3 | 1.50 |
| A-S-C-X-25-4 | Alfalfa | Sheridan | CBM IX 25 | Replicate 4 | 1.45 |
| A-S-C-X-50-1 | Alfalfa | Sheridan | CBM IX 50 | Replicate 1 | 2.28 |
| A-S-C-X-50-2 | Alfalfa | Sheridan | CBM IX 50 | Replicate 2 | 1.74 |
| A-S-C-X-50-3 | Alfalfa | Sheridan | CBM IX 50 | Replicate 3 | 1.47 |
| A-S-C-X-50-4 | Alfalfa | Sheridan | CBM IX 50 | Replicate 4 | 1.95 |
| A-S-C-X-75-1 | Alfalfa | Sheridan | CBM IX 75 | Replicate 1 | 2.55 |
| A-S-C-X-75-2 | Alfalfa | Sheridan | CBM IX 75 | Replicate 2 | 1.24 |
| A-S-C-X-75-3 | Alfalfa | Sheridan | CBM IX 75 | Replicate 3 | 1.65 |
| A-S-C-X-75-4 | Alfalfa | Sheridan | CBM IX 75 | Replicate 4 | 2.18 |
| A-S-L-U-0-1 | Alfalfa | Sheridan | Control | Replicate 1 | 2.21 |
| A-S-L-U-0-2 | Alfalfa | Sheridan | Control | Replicate 2 | 2.37 |
| A-S-L-U-0-3 | Alfalfa | Sheridan | Control | Replicate 3 | 2.49 |
| A-S-L-U-0-4 | Alfalfa | Sheridan | Control | Replicate 4 | 2.60 |

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|---------------|---------|----------|-------------------------|------|
| A-S-O-E-100-1 | Alfalfa | Sheridan | O&G EDR 100 Replicate 1 | 1.79 |
| A-S-O-E-100-2 | Alfalfa | Sheridan | O&G EDR 100 Replicate 2 | 2.13 |
| A-S-O-E-100-3 | Alfalfa | Sheridan | O&G EDR 100 Replicate 3 | 1.78 |
| A-S-O-E-100-4 | Alfalfa | Sheridan | O&G EDR 100 Replicate 4 | 1.70 |
| A-S-O-E-25-1 | Alfalfa | Sheridan | O&G EDR 25 Replicate 1 | 0.77 |
| A-S-O-E-25-2 | Alfalfa | Sheridan | O&G EDR 25 Replicate 2 | 0.87 |
| A-S-O-E-25-3 | Alfalfa | Sheridan | O&G EDR 25 Replicate 3 | 0.00 |
| A-S-O-E-25-4 | Alfalfa | Sheridan | O&G EDR 25 Replicate 4 | 0.74 |
| A-S-O-E-50-1 | Alfalfa | Sheridan | O&G EDR 50 Replicate 1 | 1.14 |
| A-S-O-E-50-2 | Alfalfa | Sheridan | O&G EDR 50 Replicate 2 | 1.16 |
| A-S-O-E-50-3 | Alfalfa | Sheridan | O&G EDR 50 Replicate 3 | 0.00 |
| A-S-O-E-50-4 | Alfalfa | Sheridan | O&G EDR 50 Replicate 4 | 1.52 |
| A-S-O-E-75-1 | Alfalfa | Sheridan | O&G EDR 75 Replicate 1 | 1.72 |
| A-S-O-E-75-2 | Alfalfa | Sheridan | O&G EDR 75 Replicate 2 | 2.43 |
| A-S-O-E-75-3 | Alfalfa | Sheridan | O&G EDR 75 Replicate 3 | 1.35 |
| A-S-O-E-75-4 | Alfalfa | Sheridan | O&G EDR 75 Replicate 4 | 1.29 |
| A-S-O-R-100-1 | Alfalfa | Sheridan | O&G RO 100 Replicate 1 | 2.30 |
| A-S-O-R-100-2 | Alfalfa | Sheridan | O&G RO 100 Replicate 2 | 2.35 |
| A-S-O-R-100-3 | Alfalfa | Sheridan | O&G RO 100 Replicate 3 | 2.78 |
| A-S-O-R-100-4 | Alfalfa | Sheridan | O&G RO 100 Replicate 4 | 2.22 |
| A-S-O-R-25-1 | Alfalfa | Sheridan | O&G RO 25 Replicate 1 | 0.00 |
| A-S-O-R-25-2 | Alfalfa | Sheridan | O&G RO 25 Replicate 2 | 0.58 |
| A-S-O-R-25-3 | Alfalfa | Sheridan | O&G RO 25 Replicate 3 | 0.00 |
| A-S-O-R-25-4 | Alfalfa | Sheridan | O&G RO 25 Replicate 4 | 0.00 |
| A-S-O-R-50-1 | Alfalfa | Sheridan | O&G RO 50 Replicate 1 | 1.32 |
| A-S-O-R-50-2 | Alfalfa | Sheridan | O&G RO 50 Replicate 2 | 1.70 |
| A-S-O-R-50-3 | Alfalfa | Sheridan | O&G RO 50 Replicate 3 | 2.12 |
| A-S-O-R-50-4 | Alfalfa | Sheridan | O&G RO 50 Replicate 4 | 1.34 |
| A-S-O-R-75-1 | Alfalfa | Sheridan | O&G RO 75 Replicate 1 | 1.65 |
| A-S-O-R-75-2 | Alfalfa | Sheridan | O&G RO 75 Replicate 2 | 1.58 |
| A-S-O-R-75-3 | Alfalfa | Sheridan | O&G RO 75 Replicate 3 | 1.27 |
| A-S-O-R-75-4 | Alfalfa | Sheridan | O&G RO 75 Replicate 4 | 1.60 |
| A-S-O-U-0-1 | Alfalfa | Sheridan | O&G Raw Replicate 1 | 0.00 |
| A-S-O-U-0-2 | Alfalfa | Sheridan | O&G Raw Replicate 2 | 0.00 |
| A-S-O-U-0-3 | Alfalfa | Sheridan | O&G Raw Replicate 3 | 0.00 |
| A-S-O-U-0-4 | Alfalfa | Sheridan | O&G Raw Replicate 4 | 0.00 |
| A-X-C-R-100-1 | Alfalfa | X Ranch | CBM RO 100 Replicate 1 | 1.99 |
| A-X-C-R-100-2 | Alfalfa | X Ranch | CBM RO 100 Replicate 2 | 1.58 |
| A-X-C-R-100-3 | Alfalfa | X Ranch | CBM RO 100 Replicate 3 | 2.08 |
| A-X-C-R-100-4 | Alfalfa | X Ranch | CBM RO 100 Replicate 4 | 1.59 |

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|---------------|---------|---------|-------------|-------------|------|
| A-X-C-R-25-1 | Alfalfa | X Ranch | CBM RO 25 | Replicate 1 | 2.09 |
| A-X-C-R-25-2 | Alfalfa | X Ranch | CBM RO 25 | Replicate 2 | 0.00 |
| A-X-C-R-25-3 | Alfalfa | X Ranch | CBM RO 25 | Replicate 3 | 1.96 |
| A-X-C-R-25-4 | Alfalfa | X Ranch | CBM RO 25 | Replicate 4 | 2.12 |
| A-X-C-R-50-1 | Alfalfa | X Ranch | CBM RO 50 | Replicate 1 | 1.59 |
| A-X-C-R-50-2 | Alfalfa | X Ranch | CBM RO 50 | Replicate 2 | 1.52 |
| A-X-C-R-50-3 | Alfalfa | X Ranch | CBM RO 50 | Replicate 3 | 1.30 |
| A-X-C-R-50-4 | Alfalfa | X Ranch | CBM RO 50 | Replicate 4 | 1.18 |
| A-X-C-R-75-1 | Alfalfa | X Ranch | CBM RO 75 | Replicate 1 | 0.99 |
| A-X-C-R-75-2 | Alfalfa | X Ranch | CBM RO 75 | Replicate 2 | 1.49 |
| A-X-C-R-75-3 | Alfalfa | X Ranch | CBM RO 75 | Replicate 3 | 1.16 |
| A-X-C-R-75-4 | Alfalfa | X Ranch | CBM RO 75 | Replicate 4 | 1.29 |
| A-X-C-U-0-1 | Alfalfa | X Ranch | CBM RAW | Replicate 1 | 1.42 |
| A-X-C-U-0-2 | Alfalfa | X Ranch | CBM RAW | Replicate 2 | 0.00 |
| A-X-C-U-0-3 | Alfalfa | X Ranch | CBM RAW | Replicate 3 | 0.00 |
| A-X-C-U-0-4 | Alfalfa | X Ranch | CBM RAW | Replicate 4 | 0.00 |
| A-X-C-X-100-1 | Alfalfa | X Ranch | CBM IX 100 | Replicate 1 | 1.19 |
| A-X-C-X-100-2 | Alfalfa | X Ranch | CBM IX 100 | Replicate 2 | 0.87 |
| A-X-C-X-100-3 | Alfalfa | X Ranch | CBM IX 100 | Replicate 3 | 1.51 |
| A-X-C-X-100-4 | Alfalfa | X Ranch | CBM IX 100 | Replicate 4 | 1.59 |
| A-X-C-X-25-1 | Alfalfa | X Ranch | CBM IX 25 | Replicate 1 | 1.43 |
| A-X-C-X-25-2 | Alfalfa | X Ranch | CBM IX 25 | Replicate 2 | 0.00 |
| A-X-C-X-25-3 | Alfalfa | X Ranch | CBM IX 25 | Replicate 3 | 0.00 |
| A-X-C-X-25-4 | Alfalfa | X Ranch | CBM IX 25 | Replicate 4 | 0.76 |
| A-X-C-X-50-1 | Alfalfa | X Ranch | CBM IX 50 | Replicate 1 | 1.68 |
| A-X-C-X-50-2 | Alfalfa | X Ranch | CBM IX 50 | Replicate 2 | 1.36 |
| A-X-C-X-50-3 | Alfalfa | X Ranch | CBM IX 50 | Replicate 3 | 2.05 |
| A-X-C-X-50-4 | Alfalfa | X Ranch | CBM IX 50 | Replicate 4 | 1.70 |
| A-X-C-X-75-1 | Alfalfa | X Ranch | CBM IX 75 | Replicate 1 | 1.04 |
| A-X-C-X-75-2 | Alfalfa | X Ranch | CBM IX 75 | Replicate 2 | 1.19 |
| A-X-C-X-75-3 | Alfalfa | X Ranch | CBM IX 75 | Replicate 3 | 1.52 |
| A-X-C-X-75-4 | Alfalfa | X Ranch | CBM IX 75 | Replicate 4 | 1.10 |
| A-X-L-U-0-1 | Alfalfa | X Ranch | Control | Replicate 1 | 1.09 |
| A-X-L-U-0-2 | Alfalfa | X Ranch | Control | Replicate 2 | 0.94 |
| A-X-L-U-0-3 | Alfalfa | X Ranch | Control | Replicate 3 | 0.77 |
| A-X-L-U-0-4 | Alfalfa | X Ranch | Control | Replicate 4 | 0.54 |
| A-X-O-E-100-1 | Alfalfa | X Ranch | O&G EDR 100 | Replicate 1 | 0.48 |
| A-X-O-E-100-2 | Alfalfa | X Ranch | O&G EDR 100 | Replicate 2 | 0.72 |
| A-X-O-E-100-3 | Alfalfa | X Ranch | O&G EDR 100 | Replicate 3 | 0.70 |
| A-X-O-E-100-4 | Alfalfa | X Ranch | O&G EDR 100 | Replicate 4 | 0.74 |

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|---------------|---------|---------|------------------------|------|
| A-X-O-E-25-1 | Alfalfa | X Ranch | O&G EDR 25 Replicate 1 | 0.00 |
| A-X-O-E-25-2 | Alfalfa | X Ranch | O&G EDR 25 Replicate 2 | 0.00 |
| A-X-O-E-25-3 | Alfalfa | X Ranch | O&G EDR 25 Replicate 3 | 0.00 |
| A-X-O-E-25-4 | Alfalfa | X Ranch | O&G EDR 25 Replicate 4 | 0.00 |
| A-X-O-E-50-1 | Alfalfa | X Ranch | O&G EDR 50 Replicate 1 | 0.00 |
| A-X-O-E-50-2 | Alfalfa | X Ranch | O&G EDR 50 Replicate 2 | 0.00 |
| A-X-O-E-50-3 | Alfalfa | X Ranch | O&G EDR 50 Replicate 3 | 0.00 |
| A-X-O-E-50-4 | Alfalfa | X Ranch | O&G EDR 50 Replicate 4 | 0.00 |
| A-X-O-E-75-1 | Alfalfa | X Ranch | O&G EDR 75 Replicate 1 | 0.56 |
| A-X-O-E-75-2 | Alfalfa | X Ranch | O&G EDR 75 Replicate 2 | 0.57 |
| A-X-O-E-75-3 | Alfalfa | X Ranch | O&G EDR 75 Replicate 3 | 0.47 |
| A-X-O-E-75-4 | Alfalfa | X Ranch | O&G EDR 75 Replicate 4 | 0.60 |
| A-X-O-R-100-1 | Alfalfa | X Ranch | O&G RO 100 Replicate 1 | 1.07 |
| A-X-O-R-100-2 | Alfalfa | X Ranch | O&G RO 100 Replicate 2 | 1.06 |
| A-X-O-R-100-3 | Alfalfa | X Ranch | O&G RO 100 Replicate 3 | 0.71 |
| A-X-O-R-100-4 | Alfalfa | X Ranch | O&G RO 100 Replicate 4 | 0.94 |
| A-X-O-R-25-1 | Alfalfa | X Ranch | O&G RO 25 Replicate 1 | 0.80 |
| A-X-O-R-25-2 | Alfalfa | X Ranch | O&G RO 25 Replicate 2 | 0.00 |
| A-X-O-R-25-3 | Alfalfa | X Ranch | O&G RO 25 Replicate 3 | 0.00 |
| A-X-O-R-25-4 | Alfalfa | X Ranch | O&G RO 25 Replicate 4 | 0.00 |
| A-X-O-R-50-1 | Alfalfa | X Ranch | O&G RO 50 Replicate 1 | 0.51 |
| A-X-O-R-50-2 | Alfalfa | X Ranch | O&G RO 50 Replicate 2 | 0.00 |
| A-X-O-R-50-3 | Alfalfa | X Ranch | O&G RO 50 Replicate 3 | 0.00 |
| A-X-O-R-50-4 | Alfalfa | X Ranch | O&G RO 50 Replicate 4 | 0.00 |
| A-X-O-R-75-1 | Alfalfa | X Ranch | O&G RO 75 Replicate 1 | 0.61 |
| A-X-O-R-75-2 | Alfalfa | X Ranch | O&G RO 75 Replicate 2 | 0.60 |
| A-X-O-R-75-3 | Alfalfa | X Ranch | O&G RO 75 Replicate 3 | 0.47 |
| A-X-O-R-75-4 | Alfalfa | X Ranch | O&G RO 75 Replicate 4 | 0.58 |
| A-X-O-U-0-1 | Alfalfa | X Ranch | O&G Raw Replicate 1 | 0.00 |
| A-X-O-U-0-2 | Alfalfa | X Ranch | O&G Raw Replicate 2 | 0.00 |
| A-X-O-U-0-3 | Alfalfa | X Ranch | O&G Raw Replicate 3 | 0.00 |
| A-X-O-U-0-4 | Alfalfa | X Ranch | O&G Raw Replicate 4 | 0.00 |

Western Wheatgrass

| Sample ID | Plant | Soil | Water Type | Replicate | Biomass (g) |
|---------------|--------------------|----------|------------|-------------|-------------|
| W-R-C-R-100-1 | Western Wheatgrass | Riverton | CBM RO 100 | Replicate 1 | 1.76 |
| W-R-C-R-100-2 | Western Wheatgrass | Riverton | CBM RO 100 | Replicate 2 | 0.78 |
| W-R-C-R-100-3 | Western Wheatgrass | Riverton | CBM RO 100 | Replicate 3 | 1.23 |
| W-R-C-R-100-4 | Western Wheatgrass | Riverton | CBM RO 100 | Replicate 4 | 1.35 |

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|---------------|--------------------|----------|-------------|-------------|------|
| W-R-C-R-25-1 | Western Wheatgrass | Riverton | CBM RO 25 | Replicate 1 | 1.44 |
| W-R-C-R-25-2 | Western Wheatgrass | Riverton | CBM RO 25 | Replicate 2 | 1.08 |
| W-R-C-R-25-3 | Western Wheatgrass | Riverton | CBM RO 25 | Replicate 3 | 1.17 |
| W-R-C-R-25-4 | Western Wheatgrass | Riverton | CBM RO 25 | Replicate 4 | 2.60 |
| W-R-C-R-50-1 | Western Wheatgrass | Riverton | CBM RO 50 | Replicate 1 | 1.95 |
| W-R-C-R-50-2 | Western Wheatgrass | Riverton | CBM RO 50 | Replicate 2 | 1.77 |
| W-R-C-R-50-3 | Western Wheatgrass | Riverton | CBM RO 50 | Replicate 3 | 2.22 |
| W-R-C-R-50-4 | Western Wheatgrass | Riverton | CBM RO 50 | Replicate 4 | 1.89 |
| W-R-C-R-75-1 | Western Wheatgrass | Riverton | CBM RO 75 | Replicate 1 | 1.25 |
| W-R-C-R-75-2 | Western Wheatgrass | Riverton | CBM RO 75 | Replicate 2 | 1.37 |
| W-R-C-R-75-3 | Western Wheatgrass | Riverton | CBM RO 75 | Replicate 3 | 1.80 |
| W-R-C-R-75-4 | Western Wheatgrass | Riverton | CBM RO 75 | Replicate 4 | 1.58 |
| W-R-C-U-0-1 | Western Wheatgrass | Riverton | CBM RAW | Replicate 1 | 1.32 |
| W-R-C-U-0-2 | Western Wheatgrass | Riverton | CBM RAW | Replicate 2 | 1.42 |
| W-R-C-U-0-3 | Western Wheatgrass | Riverton | CBM RAW | Replicate 3 | 1.17 |
| W-R-C-U-0-4 | Western Wheatgrass | Riverton | CBM RAW | Replicate 4 | 1.66 |
| W-R-C-X-100-1 | Western Wheatgrass | Riverton | CBM IX 100 | Replicate 1 | 1.22 |
| W-R-C-X-100-2 | Western Wheatgrass | Riverton | CBM IX 100 | Replicate 2 | 0.96 |
| W-R-C-X-100-3 | Western Wheatgrass | Riverton | CBM IX 100 | Replicate 3 | 1.32 |
| W-R-C-X-100-4 | Western Wheatgrass | Riverton | CBM IX 100 | Replicate 4 | 1.27 |
| W-R-C-X-25-1 | Western Wheatgrass | Riverton | CBM IX 25 | Replicate 1 | 1.11 |
| W-R-C-X-25-2 | Western Wheatgrass | Riverton | CBM IX 25 | Replicate 2 | 1.37 |
| W-R-C-X-25-3 | Western Wheatgrass | Riverton | CBM IX 25 | Replicate 3 | 1.23 |
| W-R-C-X-25-4 | Western Wheatgrass | Riverton | CBM IX 25 | Replicate 4 | 1.07 |
| W-R-C-X-50-1 | Western Wheatgrass | Riverton | CBM IX 50 | Replicate 1 | 1.00 |
| W-R-C-X-50-2 | Western Wheatgrass | Riverton | CBM IX 50 | Replicate 2 | 1.58 |
| W-R-C-X-50-3 | Western Wheatgrass | Riverton | CBM IX 50 | Replicate 3 | 1.12 |
| W-R-C-X-50-4 | Western Wheatgrass | Riverton | CBM IX 50 | Replicate 4 | 1.05 |
| W-R-C-X-75-1 | Western Wheatgrass | Riverton | CBM IX 75 | Replicate 1 | 1.42 |
| W-R-C-X-75-2 | Western Wheatgrass | Riverton | CBM IX 75 | Replicate 2 | 1.23 |
| W-R-C-X-75-3 | Western Wheatgrass | Riverton | CBM IX 75 | Replicate 3 | 0.97 |
| W-R-C-X-75-4 | Western Wheatgrass | Riverton | CBM IX 75 | Replicate 4 | 1.51 |
| W-R-L-U-0-1 | Western Wheatgrass | Riverton | Control | Replicate 1 | 1.34 |
| W-R-L-U-0-2 | Western Wheatgrass | Riverton | Control | Replicate 2 | 0.86 |
| W-R-L-U-0-3 | Western Wheatgrass | Riverton | Control | Replicate 3 | 0.61 |
| W-R-L-U-0-4 | Western Wheatgrass | Riverton | Control | Replicate 4 | 1.02 |
| W-R-O-E-100-1 | Western Wheatgrass | Riverton | O&G EDR 100 | Replicate 1 | 1.54 |
| W-R-O-E-100-2 | Western Wheatgrass | Riverton | O&G EDR 100 | Replicate 2 | 1.67 |
| W-R-O-E-100-3 | Western Wheatgrass | Riverton | O&G EDR 100 | Replicate 3 | 0.52 |
| W-R-O-E-100-4 | Western Wheatgrass | Riverton | O&G EDR 100 | Replicate 4 | 0.57 |

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|---------------|--------------------|----------|------------------------|------|
| W-R-O-E-25-1 | Western Wheatgrass | Riverton | O&G EDR 25 Replicate 1 | 0.81 |
| W-R-O-E-25-2 | Western Wheatgrass | Riverton | O&G EDR 25 Replicate 2 | 0.83 |
| W-R-O-E-25-3 | Western Wheatgrass | Riverton | O&G EDR 25 Replicate 3 | 0.38 |
| W-R-O-E-25-4 | Western Wheatgrass | Riverton | O&G EDR 25 Replicate 4 | 0.78 |
| W-R-O-E-50-1 | Western Wheatgrass | Riverton | O&G EDR 50 Replicate 1 | 0.85 |
| W-R-O-E-50-2 | Western Wheatgrass | Riverton | O&G EDR 50 Replicate 2 | 1.28 |
| W-R-O-E-50-3 | Western Wheatgrass | Riverton | O&G EDR 50 Replicate 3 | 0.88 |
| W-R-O-E-50-4 | Western Wheatgrass | Riverton | O&G EDR 50 Replicate 4 | 0.98 |
| W-R-O-E-75-1 | Western Wheatgrass | Riverton | O&G EDR 75 Replicate 1 | 0.51 |
| W-R-O-E-75-2 | Western Wheatgrass | Riverton | O&G EDR 75 Replicate 2 | 0.87 |
| W-R-O-E-75-3 | Western Wheatgrass | Riverton | O&G EDR 75 Replicate 3 | 0.89 |
| W-R-O-E-75-4 | Western Wheatgrass | Riverton | O&G EDR 75 Replicate 4 | 0.80 |
| W-R-O-R-100-1 | Western Wheatgrass | Riverton | O&G RO 100 Replicate 1 | 1.27 |
| W-R-O-R-100-2 | Western Wheatgrass | Riverton | O&G RO 100 Replicate 2 | 0.91 |
| W-R-O-R-100-3 | Western Wheatgrass | Riverton | O&G RO 100 Replicate 3 | 0.41 |
| W-R-O-R-100-4 | Western Wheatgrass | Riverton | O&G RO 100 Replicate 4 | 1.36 |
| W-R-O-R-25-1 | Western Wheatgrass | Riverton | O&G RO 25 Replicate 1 | 0.41 |
| W-R-O-R-25-2 | Western Wheatgrass | Riverton | O&G RO 25 Replicate 2 | 0.33 |
| W-R-O-R-25-3 | Western Wheatgrass | Riverton | O&G RO 25 Replicate 3 | 0.52 |
| W-R-O-R-25-4 | Western Wheatgrass | Riverton | O&G RO 25 Replicate 4 | 0.24 |
| W-R-O-R-50-1 | Western Wheatgrass | Riverton | O&G RO 50 Replicate 1 | 0.48 |
| W-R-O-R-50-2 | Western Wheatgrass | Riverton | O&G RO 50 Replicate 2 | 0.44 |
| W-R-O-R-50-3 | Western Wheatgrass | Riverton | O&G RO 50 Replicate 3 | 0.73 |
| W-R-O-R-50-4 | Western Wheatgrass | Riverton | O&G RO 50 Replicate 4 | 0.72 |
| W-R-O-R-75-1 | Western Wheatgrass | Riverton | O&G RO 75 Replicate 1 | 0.56 |
| W-R-O-R-75-2 | Western Wheatgrass | Riverton | O&G RO 75 Replicate 2 | 0.93 |
| W-R-O-R-75-3 | Western Wheatgrass | Riverton | O&G RO 75 Replicate 3 | 0.41 |
| W-R-O-R-75-4 | Western Wheatgrass | Riverton | O&G RO 75 Replicate 4 | 0.83 |
| W-R-O-U-0-1 | Western Wheatgrass | Riverton | O&G Raw Replicate 1 | 0.42 |
| W-R-O-U-0-2 | Western Wheatgrass | Riverton | O&G Raw Replicate 2 | 0.30 |
| W-R-O-U-0-3 | Western Wheatgrass | Riverton | O&G Raw Replicate 3 | 0.25 |
| W-R-O-U-0-4 | Western Wheatgrass | Riverton | O&G Raw Replicate 4 | 0.70 |
| W-S-C-R-100-1 | Western Wheatgrass | Sheridan | CBM RO 100 Replicate 1 | 1.24 |
| W-S-C-R-100-2 | Western Wheatgrass | Sheridan | CBM RO 100 Replicate 2 | 0.98 |
| W-S-C-R-100-3 | Western Wheatgrass | Sheridan | CBM RO 100 Replicate 3 | 1.16 |
| W-S-C-R-100-4 | Western Wheatgrass | Sheridan | CBM RO 100 Replicate 4 | 0.70 |
| W-S-C-R-25-1 | Western Wheatgrass | Sheridan | CBM RO 25 Replicate 1 | 2.61 |
| W-S-C-R-25-2 | Western Wheatgrass | Sheridan | CBM RO 25 Replicate 2 | 2.70 |
| W-S-C-R-25-3 | Western Wheatgrass | Sheridan | CBM RO 25 Replicate 3 | 2.49 |
| W-S-C-R-25-4 | Western Wheatgrass | Sheridan | CBM RO 25 Replicate 4 | 3.45 |

| | | | | | |
|---------------|--------------------|----------|-------------|-------------|------|
| W-S-C-R-50-1 | Western Wheatgrass | Sheridan | CBM RO 50 | Replicate 1 | 2.15 |
| W-S-C-R-50-2 | Western Wheatgrass | Sheridan | CBM RO 50 | Replicate 2 | 2.03 |
| W-S-C-R-50-3 | Western Wheatgrass | Sheridan | CBM RO 50 | Replicate 3 | 1.52 |
| W-S-C-R-50-4 | Western Wheatgrass | Sheridan | CBM RO 50 | Replicate 4 | 2.44 |
| W-S-C-R-75-1 | Western Wheatgrass | Sheridan | CBM RO 75 | Replicate 1 | 1.67 |
| W-S-C-R-75-2 | Western Wheatgrass | Sheridan | CBM RO 75 | Replicate 2 | 1.39 |
| W-S-C-R-75-3 | Western Wheatgrass | Sheridan | CBM RO 75 | Replicate 3 | 1.41 |
| W-S-C-R-75-4 | Western Wheatgrass | Sheridan | CBM RO 75 | Replicate 4 | 1.53 |
| W-S-C-U-0-1 | Western Wheatgrass | Sheridan | CBM RAW | Replicate 1 | 2.39 |
| W-S-C-U-0-2 | Western Wheatgrass | Sheridan | CBM RAW | Replicate 2 | 2.77 |
| W-S-C-U-0-3 | Western Wheatgrass | Sheridan | CBM RAW | Replicate 3 | 2.38 |
| W-S-C-U-0-4 | Western Wheatgrass | Sheridan | CBM RAW | Replicate 4 | 3.03 |
| W-S-C-X-100-1 | Western Wheatgrass | Sheridan | CBM IX 100 | Replicate 1 | 1.26 |
| W-S-C-X-100-2 | Western Wheatgrass | Sheridan | CBM IX 100 | Replicate 2 | 1.12 |
| W-S-C-X-100-3 | Western Wheatgrass | Sheridan | CBM IX 100 | Replicate 3 | 1.18 |
| W-S-C-X-100-4 | Western Wheatgrass | Sheridan | CBM IX 100 | Replicate 4 | 1.16 |
| W-S-C-X-25-1 | Western Wheatgrass | Sheridan | CBM IX 25 | Replicate 1 | 2.34 |
| W-S-C-X-25-2 | Western Wheatgrass | Sheridan | CBM IX 25 | Replicate 2 | 2.25 |
| W-S-C-X-25-3 | Western Wheatgrass | Sheridan | CBM IX 25 | Replicate 3 | 3.26 |
| W-S-C-X-25-4 | Western Wheatgrass | Sheridan | CBM IX 25 | Replicate 4 | 1.98 |
| W-S-C-X-50-1 | Western Wheatgrass | Sheridan | CBM IX 50 | Replicate 1 | 2.41 |
| W-S-C-X-50-2 | Western Wheatgrass | Sheridan | CBM IX 50 | Replicate 2 | 2.62 |
| W-S-C-X-50-3 | Western Wheatgrass | Sheridan | CBM IX 50 | Replicate 3 | 1.20 |
| W-S-C-X-50-4 | Western Wheatgrass | Sheridan | CBM IX 50 | Replicate 4 | 2.04 |
| W-S-C-X-75-1 | Western Wheatgrass | Sheridan | CBM IX 75 | Replicate 1 | 1.51 |
| W-S-C-X-75-2 | Western Wheatgrass | Sheridan | CBM IX 75 | Replicate 2 | 1.90 |
| W-S-C-X-75-3 | Western Wheatgrass | Sheridan | CBM IX 75 | Replicate 3 | 1.43 |
| W-S-C-X-75-4 | Western Wheatgrass | Sheridan | CBM IX 75 | Replicate 4 | 1.23 |
| W-S-L-U-0-1 | Western Wheatgrass | Sheridan | Control | Replicate 1 | 1.55 |
| W-S-L-U-0-2 | Western Wheatgrass | Sheridan | Control | Replicate 2 | 0.96 |
| W-S-L-U-0-3 | Western Wheatgrass | Sheridan | Control | Replicate 3 | 0.75 |
| W-S-L-U-0-4 | Western Wheatgrass | Sheridan | Control | Replicate 4 | 1.27 |
| W-S-O-E-100-1 | Western Wheatgrass | Sheridan | O&G EDR 100 | Replicate 1 | 1.16 |
| W-S-O-E-100-2 | Western Wheatgrass | Sheridan | O&G EDR 100 | Replicate 2 | 1.45 |
| W-S-O-E-100-3 | Western Wheatgrass | Sheridan | O&G EDR 100 | Replicate 3 | 1.37 |
| W-S-O-E-100-4 | Western Wheatgrass | Sheridan | O&G EDR 100 | Replicate 4 | 1.43 |
| W-S-O-E-25-1 | Western Wheatgrass | Sheridan | O&G EDR 25 | Replicate 1 | 1.67 |
| W-S-O-E-25-2 | Western Wheatgrass | Sheridan | O&G EDR 25 | Replicate 2 | 1.12 |
| W-S-O-E-25-3 | Western Wheatgrass | Sheridan | O&G EDR 25 | Replicate 3 | 1.18 |
| W-S-O-E-25-4 | Western Wheatgrass | Sheridan | O&G EDR 25 | Replicate 4 | 1.16 |

| | | | | |
|---------------|--------------------|----------|------------------------|------|
| W-S-O-E-50-1 | Western Wheatgrass | Sheridan | O&G EDR 50 Replicate 1 | 1.58 |
| W-S-O-E-50-2 | Western Wheatgrass | Sheridan | O&G EDR 50 Replicate 2 | 1.53 |
| W-S-O-E-50-3 | Western Wheatgrass | Sheridan | O&G EDR 50 Replicate 3 | 0.92 |
| W-S-O-E-50-4 | Western Wheatgrass | Sheridan | O&G EDR 50 Replicate 4 | 1.45 |
| W-S-O-E-75-1 | Western Wheatgrass | Sheridan | O&G EDR 75 Replicate 1 | 2.01 |
| W-S-O-E-75-2 | Western Wheatgrass | Sheridan | O&G EDR 75 Replicate 2 | 2.03 |
| W-S-O-E-75-3 | Western Wheatgrass | Sheridan | O&G EDR 75 Replicate 3 | 1.91 |
| W-S-O-E-75-4 | Western Wheatgrass | Sheridan | O&G EDR 75 Replicate 4 | 1.38 |
| W-S-O-R-100-1 | Western Wheatgrass | Sheridan | O&G RO 100 Replicate 1 | 1.57 |
| W-S-O-R-100-2 | Western Wheatgrass | Sheridan | O&G RO 100 Replicate 2 | 0.91 |
| W-S-O-R-100-3 | Western Wheatgrass | Sheridan | O&G RO 100 Replicate 3 | 1.26 |
| W-S-O-R-100-4 | Western Wheatgrass | Sheridan | O&G RO 100 Replicate 4 | 1.03 |
| W-S-O-R-25-1 | Western Wheatgrass | Sheridan | O&G RO 25 Replicate 1 | 1.55 |
| W-S-O-R-25-2 | Western Wheatgrass | Sheridan | O&G RO 25 Replicate 2 | 1.39 |
| W-S-O-R-25-3 | Western Wheatgrass | Sheridan | O&G RO 25 Replicate 3 | 1.36 |
| W-S-O-R-25-4 | Western Wheatgrass | Sheridan | O&G RO 25 Replicate 4 | 1.56 |
| W-S-O-R-50-1 | Western Wheatgrass | Sheridan | O&G RO 50 Replicate 1 | 1.78 |
| W-S-O-R-50-2 | Western Wheatgrass | Sheridan | O&G RO 50 Replicate 2 | 0.81 |
| W-S-O-R-50-3 | Western Wheatgrass | Sheridan | O&G RO 50 Replicate 3 | 1.98 |
| W-S-O-R-50-4 | Western Wheatgrass | Sheridan | O&G RO 50 Replicate 4 | 1.75 |
| W-S-O-R-75-1 | Western Wheatgrass | Sheridan | O&G RO 75 Replicate 1 | 1.54 |
| W-S-O-R-75-2 | Western Wheatgrass | Sheridan | O&G RO 75 Replicate 2 | 2.15 |
| W-S-O-R-75-3 | Western Wheatgrass | Sheridan | O&G RO 75 Replicate 3 | 1.84 |
| W-S-O-R-75-4 | Western Wheatgrass | Sheridan | O&G RO 75 Replicate 4 | 1.37 |
| W-S-O-U-0-1 | Western Wheatgrass | Sheridan | O&G Raw Replicate 1 | 1.48 |
| W-S-O-U-0-2 | Western Wheatgrass | Sheridan | O&G Raw Replicate 2 | 1.13 |
| W-S-O-U-0-3 | Western Wheatgrass | Sheridan | O&G Raw Replicate 3 | 0.44 |
| W-S-O-U-0-4 | Western Wheatgrass | Sheridan | O&G Raw Replicate 4 | 1.24 |
| W-X-C-R-100-1 | Western Wheatgrass | X Ranch | CBM RO 100 Replicate 1 | 0.72 |
| W-X-C-R-100-2 | Western Wheatgrass | X Ranch | CBM RO 100 Replicate 2 | 0.91 |
| W-X-C-R-100-3 | Western Wheatgrass | X Ranch | CBM RO 100 Replicate 3 | 0.80 |
| W-X-C-R-100-4 | Western Wheatgrass | X Ranch | CBM RO 100 Replicate 4 | 0.70 |
| W-X-C-R-25-1 | Western Wheatgrass | X Ranch | CBM RO 25 Replicate 1 | 1.27 |
| W-X-C-R-25-2 | Western Wheatgrass | X Ranch | CBM RO 25 Replicate 2 | 1.59 |
| W-X-C-R-25-3 | Western Wheatgrass | X Ranch | CBM RO 25 Replicate 3 | 1.22 |
| W-X-C-R-25-4 | Western Wheatgrass | X Ranch | CBM RO 25 Replicate 4 | 0.78 |
| W-X-C-R-50-1 | Western Wheatgrass | X Ranch | CBM RO 50 Replicate 1 | 0.88 |
| W-X-C-R-50-2 | Western Wheatgrass | X Ranch | CBM RO 50 Replicate 2 | 0.83 |
| W-X-C-R-50-3 | Western Wheatgrass | X Ranch | CBM RO 50 Replicate 3 | 1.15 |
| W-X-C-R-50-4 | Western Wheatgrass | X Ranch | CBM RO 50 Replicate 4 | 1.05 |

| | | | | | |
|---------------|--------------------|---------|-------------|-------------|------|
| W-X-C-R-75-1 | Western Wheatgrass | X Ranch | CBM RO 75 | Replicate 1 | 0.85 |
| W-X-C-R-75-2 | Western Wheatgrass | X Ranch | CBM RO 75 | Replicate 2 | 0.72 |
| W-X-C-R-75-3 | Western Wheatgrass | X Ranch | CBM RO 75 | Replicate 3 | 1.13 |
| W-X-C-R-75-4 | Western Wheatgrass | X Ranch | CBM RO 75 | Replicate 4 | 1.03 |
| W-X-C-U-0-1 | Western Wheatgrass | X Ranch | CBM RAW | Replicate 1 | 1.22 |
| W-X-C-U-0-2 | Western Wheatgrass | X Ranch | CBM RAW | Replicate 2 | 0.49 |
| W-X-C-U-0-3 | Western Wheatgrass | X Ranch | CBM RAW | Replicate 3 | 1.02 |
| W-X-C-U-0-4 | Western Wheatgrass | X Ranch | CBM RAW | Replicate 4 | 0.84 |
| W-X-C-X-100-1 | Western Wheatgrass | X Ranch | CBM IX 100 | Replicate 1 | 0.62 |
| W-X-C-X-100-2 | Western Wheatgrass | X Ranch | CBM IX 100 | Replicate 2 | 0.75 |
| W-X-C-X-100-3 | Western Wheatgrass | X Ranch | CBM IX 100 | Replicate 3 | 0.64 |
| W-X-C-X-100-4 | Western Wheatgrass | X Ranch | CBM IX 100 | Replicate 4 | 0.66 |
| W-X-C-X-25-1 | Western Wheatgrass | X Ranch | CBM IX 25 | Replicate 1 | 1.01 |
| W-X-C-X-25-2 | Western Wheatgrass | X Ranch | CBM IX 25 | Replicate 2 | 0.72 |
| W-X-C-X-25-3 | Western Wheatgrass | X Ranch | CBM IX 25 | Replicate 3 | 0.72 |
| W-X-C-X-25-4 | Western Wheatgrass | X Ranch | CBM IX 25 | Replicate 4 | 0.80 |
| W-X-C-X-50-1 | Western Wheatgrass | X Ranch | CBM IX 50 | Replicate 1 | 1.02 |
| W-X-C-X-50-2 | Western Wheatgrass | X Ranch | CBM IX 50 | Replicate 2 | 1.04 |
| W-X-C-X-50-3 | Western Wheatgrass | X Ranch | CBM IX 50 | Replicate 3 | 0.49 |
| W-X-C-X-50-4 | Western Wheatgrass | X Ranch | CBM IX 50 | Replicate 4 | 0.70 |
| W-X-C-X-75-1 | Western Wheatgrass | X Ranch | CBM IX 75 | Replicate 1 | 1.05 |
| W-X-C-X-75-2 | Western Wheatgrass | X Ranch | CBM IX 75 | Replicate 2 | 1.05 |
| W-X-C-X-75-3 | Western Wheatgrass | X Ranch | CBM IX 75 | Replicate 3 | 0.95 |
| W-X-C-X-75-4 | Western Wheatgrass | X Ranch | CBM IX 75 | Replicate 4 | 0.88 |
| W-X-L-U-0-1 | Western Wheatgrass | X Ranch | Control | Replicate 1 | 0.74 |
| W-X-L-U-0-2 | Western Wheatgrass | X Ranch | Control | Replicate 2 | 0.75 |
| W-X-L-U-0-3 | Western Wheatgrass | X Ranch | Control | Replicate 3 | 0.87 |
| W-X-L-U-0-4 | Western Wheatgrass | X Ranch | Control | Replicate 4 | 0.70 |
| W-X-O-E-100-1 | Western Wheatgrass | X Ranch | O&G EDR 100 | Replicate 1 | 0.49 |
| W-X-O-E-100-2 | Western Wheatgrass | X Ranch | O&G EDR 100 | Replicate 2 | 0.44 |
| W-X-O-E-100-3 | Western Wheatgrass | X Ranch | O&G EDR 100 | Replicate 3 | 0.40 |
| W-X-O-E-100-4 | Western Wheatgrass | X Ranch | O&G EDR 100 | Replicate 4 | 0.45 |
| W-X-O-E-25-1 | Western Wheatgrass | X Ranch | O&G EDR 25 | Replicate 1 | 0.30 |
| W-X-O-E-25-2 | Western Wheatgrass | X Ranch | O&G EDR 25 | Replicate 2 | 0.35 |
| W-X-O-E-25-3 | Western Wheatgrass | X Ranch | O&G EDR 25 | Replicate 3 | 0.32 |
| W-X-O-E-25-4 | Western Wheatgrass | X Ranch | O&G EDR 25 | Replicate 4 | 0.33 |
| W-X-O-E-50-1 | Western Wheatgrass | X Ranch | O&G EDR 50 | Replicate 1 | 0.81 |
| W-X-O-E-50-2 | Western Wheatgrass | X Ranch | O&G EDR 50 | Replicate 2 | 0.39 |
| W-X-O-E-50-3 | Western Wheatgrass | X Ranch | O&G EDR 50 | Replicate 3 | 0.40 |
| W-X-O-E-50-4 | Western Wheatgrass | X Ranch | O&G EDR 50 | Replicate 4 | 0.54 |

| | | | | |
|---------------|--------------------|---------|------------------------|------|
| W-X-O-E-75-1 | Western Wheatgrass | X Ranch | O&G EDR 75 Replicate 1 | 0.51 |
| W-X-O-E-75-2 | Western Wheatgrass | X Ranch | O&G EDR 75 Replicate 2 | 0.37 |
| W-X-O-E-75-3 | Western Wheatgrass | X Ranch | O&G EDR 75 Replicate 3 | 0.43 |
| W-X-O-E-75-4 | Western Wheatgrass | X Ranch | O&G EDR 75 Replicate 4 | 0.27 |
| W-X-O-R-100-1 | Western Wheatgrass | X Ranch | O&G RO 100 Replicate 1 | 0.59 |
| W-X-O-R-100-2 | Western Wheatgrass | X Ranch | O&G RO 100 Replicate 2 | 0.50 |
| W-X-O-R-100-3 | Western Wheatgrass | X Ranch | O&G RO 100 Replicate 3 | 0.66 |
| W-X-O-R-100-4 | Western Wheatgrass | X Ranch | O&G RO 100 Replicate 4 | 0.73 |
| W-X-O-R-25-1 | Western Wheatgrass | X Ranch | O&G RO 25 Replicate 1 | 0.48 |
| W-X-O-R-25-2 | Western Wheatgrass | X Ranch | O&G RO 25 Replicate 2 | 0.29 |
| W-X-O-R-25-3 | Western Wheatgrass | X Ranch | O&G RO 25 Replicate 3 | 0.30 |
| W-X-O-R-25-4 | Western Wheatgrass | X Ranch | O&G RO 25 Replicate 4 | 0.27 |
| W-X-O-R-50-1 | Western Wheatgrass | X Ranch | O&G RO 50 Replicate 1 | 0.64 |
| W-X-O-R-50-2 | Western Wheatgrass | X Ranch | O&G RO 50 Replicate 2 | 0.52 |
| W-X-O-R-50-3 | Western Wheatgrass | X Ranch | O&G RO 50 Replicate 3 | 1.49 |
| W-X-O-R-50-4 | Western Wheatgrass | X Ranch | O&G RO 50 Replicate 4 | 0.54 |
| W-X-O-R-75-1 | Western Wheatgrass | X Ranch | O&G RO 75 Replicate 1 | 0.60 |
| W-X-O-R-75-2 | Western Wheatgrass | X Ranch | O&G RO 75 Replicate 2 | 0.50 |
| W-X-O-R-75-3 | Western Wheatgrass | X Ranch | O&G RO 75 Replicate 3 | 0.55 |
| W-X-O-R-75-4 | Western Wheatgrass | X Ranch | O&G RO 75 Replicate 4 | 0.42 |
| W-X-O-U-0-1 | Western Wheatgrass | X Ranch | O&G Raw Replicate 1 | 0.30 |
| W-X-O-U-0-2 | Western Wheatgrass | X Ranch | O&G Raw Replicate 2 | 0.30 |
| W-X-O-U-0-3 | Western Wheatgrass | X Ranch | O&G Raw Replicate 3 | 0.26 |
| W-X-O-U-0-4 | Western Wheatgrass | X Ranch | O&G Raw Replicate 4 | 0.23 |

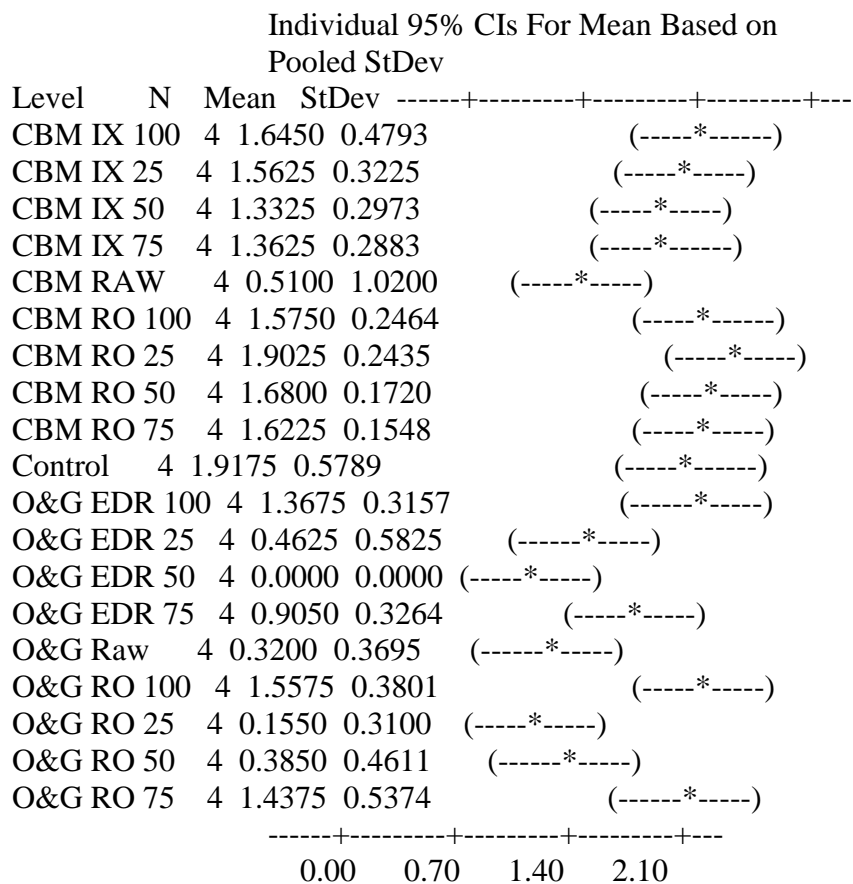
A – alfalfa; W – western wheatgrass; R – Riverton soil; S – Sheridan soil; X – X-Ranch Soil; C – CBNG produced water; O – conventional oil and gas produced water; U – untreated produced water; L – River Water (control); R – reverse osmosis water treatment; X – ion exchange (EMIT technology) water treatment; E – EDR water treatment; 25 – 25% treatment of produced water; 50 – 50% treatment of produced water; 75 – 75% treatment of produced water; 100 – 100% treatment of produced water.

APPENDIX E. Statistical Evaluation of Biomass Production Data by Irrigation Treatment

Riverton Soil - One-way ANOVA: Biomass (g)_1 versus Water Type_1

| Source | DF | SS | MS | F | P |
|--------------|----|--------|-------|------|-------|
| Water Type_1 | 18 | 28.630 | 1.591 | 8.69 | 0.000 |
| Error | 57 | 10.435 | 0.183 | | |
| Total | 75 | 39.065 | | | |

S = 0.4279 R-Sq = 73.29% R-Sq(adj) = 64.85%

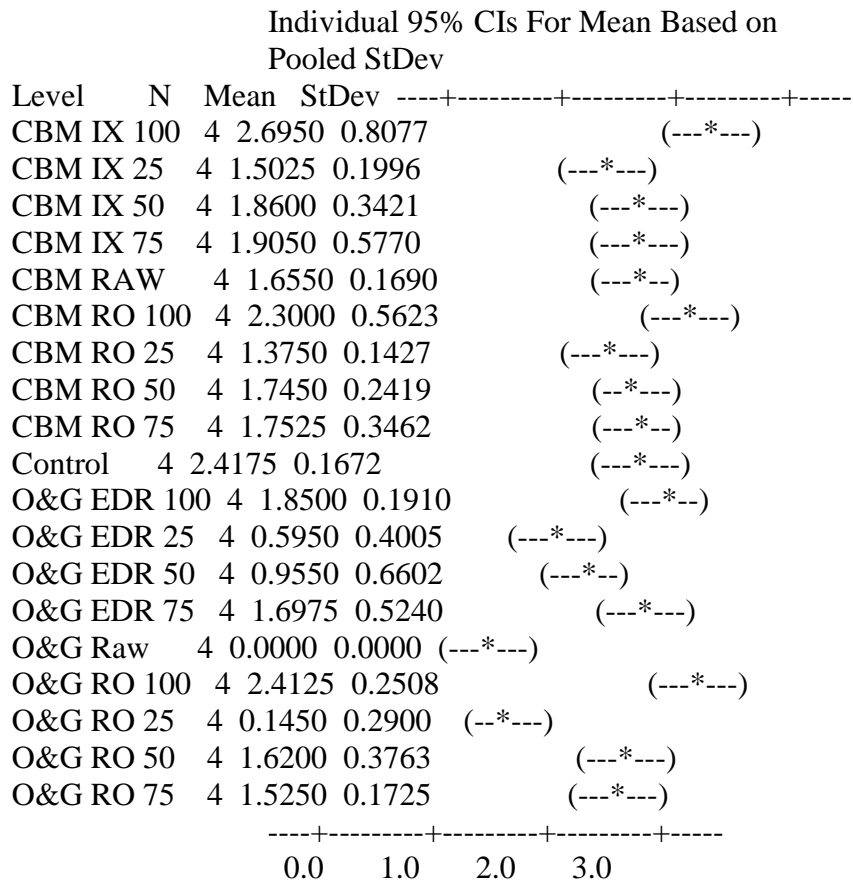


Pooled StDev = 0.4279

Sheridan Soil - One-way ANOVA: Biomass (g)_2 versus Water Type_2

| | | | | | |
|--------------|----|--------|-------|-------|-------|
| Source | DF | SS | MS | F | P |
| Water Type_2 | 18 | 37.834 | 2.102 | 13.59 | 0.000 |
| Error | 57 | 8.818 | 0.155 | | |
| Total | 75 | 46.652 | | | |

S = 0.3933 R-Sq = 81.10% R-Sq(adj) = 75.13%



Pooled StDev = 0.3933

APPENDIX F. Elemental Analysis of Biomass

| Sample ID | NO3 mg/kg | Cl mg/L | B-T mg/kg | Ca-T mg/kg | Cu-T mg/kg | Fe-T mg/kg | Mg-T mg/kg | S-T mg/kg | K-T mg/kg | Mo-T mg/kg | Na-T mg/kg | P-T mg/kg | Zn-T mg/kg |
|-------------|--------------|------------|--------------|---------------|---------------|---------------|---------------|--------------|--------------|---------------|---------------|--------------|---------------|
| W-R-C-U-0 | 57 | 50 | 33 | 3970 | 128 | 223 | 1900 | 2260 | 29500 | <5 | 4550 | 1630 | 51 |
| W-R-C-R-25 | 54 | 37 | 42 | 3890 | 208 | 227 | 1600 | 2000 | 26600 | <5 | 3600 | 1760 | 48 |
| W-R-C-R-50 | 50 | 50 | 40 | 4250 | 248 | 290 | 1690 | 1520 | 26400 | <5 | 2980 | 1890 | 56 |
| W-R-C-R-75 | 34 | 25 | 55 | 4260 | 319 | 400 | 1660 | 1550 | 22700 | <5 | 2340 | 1980 | 44 |
| W-R-C-R-100 | 45 | 37 | 77 | 3960 | 265 | 247 | 1550 | 1590 | 22200 | <5 | 2360 | 2240 | 48 |
| W-R-C-X-25 | 66 | 25 | 33 | 4500 | 200 | 247 | 1910 | 2690 | 29600 | <5 | 5170 | 1790 | 67 |
| W-R-C-X-50 | 52 | 37 | 35 | 3960 | 237 | 180 | 1790 | 2420 | 26700 | <5 | 4500 | 1960 | 56 |
| W-R-C-X-75 | 35 | 69 | 33 | 4360 | 28 | 149 | 1810 | 1590 | 24500 | <5 | 3510 | 2050 | 46 |
| W-R-C-X-100 | 34 | 56 | 30 | 3680 | 13 | 129 | 1460 | 1540 | 20800 | <5 | 3210 | 2060 | 43 |
| W-R-L-U-0 | 39 | 56 | 27 | 5200 | 23 | 202 | 1990 | 3020 | 24300 | <5 | 4210 | 2270 | 55 |
| W-R-O-U-0 | | 125 | 552 | 4660 | 16 | 224 | 1610 | 4980 | 16500 | <5 | 50900 | 1680 | 36 |
| W-R-O-E-25 | 46 | 97 | 302 | 4310 | 71 | 181 | 1250 | 1770 | 16500 | <5 | 23600 | 1660 | 65 |
| W-R-O-E-50 | 44 | 69 | 528 | 4510 | 49 | 128 | 1390 | 1660 | 17400 | <5 | 13200 | 1610 | 51 |
| W-R-O-E-75 | 37 | 87 | 610 | 4430 | 101 | 180 | 1450 | 1460 | 18200 | <5 | 7820 | 2230 | 63 |
| W-R-O-E-100 | 89 | 50 | 642 | 4710 | 33 | 105 | 1330 | 1350 | 20100 | <5 | 2440 | 1480 | 41 |
| W-R-O-R-25 | 79 | 237 | 526 | 4260 | 11 | 123 | 1640 | 2740 | 18700 | <5 | 33200 | 2490 | 53 |
| W-R-O-R-50 | 32 | 112 | 464 | 6910 | 117 | 426 | 2090 | 3620 | 17400 | <5 | 38600 | 1890 | 64 |
| W-R-O-R-75 | 42 | 112 | 191 | 5040 | 43 | 291 | 1690 | 1440 | 23000 | <5 | 11900 | 2000 | 51 |
| W-R-O-R-100 | 77 | 62 | 186 | 3850 | 59 | 170 | 1530 | 1800 | 22400 | <5 | 2190 | 1450 | 51 |
| W-S-C-U-0 | 230 | 75 | 16 | 3570 | 25 | 265 | 1940 | 1800 | 31200 | <5 | 5300 | 1440 | 45 |
| W-S-C-R-25 | 220 | 75 | 21 | 3300 | 23 | 213 | 1770 | 1650 | 31200 | <5 | 5320 | 1620 | 40 |
| W-S-C-R-50 | 150 | 87 | 36 | 3340 | 19 | 198 | 1820 | 1600 | 26000 | <5 | 2410 | 2220 | 38 |
| W-S-C-R-75 | 82 | 50 | 41 | 3160 | 21 | 160 | 1610 | 1320 | 21200 | <5 | 2330 | 2090 | 41 |
| W-S-C-R-100 | 180 | 75 | 119 | 4480 | 134 | 238 | 1810 | 1430 | 22500 | <5 | 1430 | 1810 | 66 |
| W-S-C-X-25 | 160 | 87 | 14 | 3940 | 21 | 310 | 1830 | 1600 | 28700 | <5 | 4480 | 1550 | 44 |
| W-S-C-X-50 | 150 | 75 | 17 | 3500 | 33 | 208 | 1770 | 1550 | 26900 | <5 | 4120 | 1770 | 39 |
| W-S-C-X-75 | 55 | 87 | 26 | 3540 | 49 | 173 | 1690 | 1500 | 27600 | <5 | 2780 | 2190 | 37 |
| W-S-C-X-100 | 63 | 100 | 39 | 4390 | 43 | 166 | 1790 | 1350 | 23300 | <5 | 2530 | 1650 | 42 |
| W-S-L-U-0 | 46 | 75 | 18 | 4740 | 19 | 209 | 2450 | 2270 | 24300 | <5 | 1750 | 1910 | 47 |
| W-S-O-U-0 | 140 | 150 | 154 | 2670 | 24 | 386 | 1310 | 1910 | 17600 | <5 | 25700 | 1780 | 37 |

| | | | | | | | | | | | | | |
|-------------|-----|-----|------|-------|----|-----|------|------|-------|----|-------|------|----|
| W-S-O-E-25 | 110 | 125 | 201 | 3260 | 19 | 204 | 1780 | 2090 | 27800 | <5 | 22100 | 1970 | 42 |
| W-S-O-E-50 | 96 | 112 | 332 | 3600 | 20 | 189 | 1620 | 1650 | 24900 | <5 | 11300 | 1660 | 39 |
| W-S-O-E-75 | 130 | 150 | 541 | 4240 | 17 | 155 | 1640 | 1650 | 31700 | <5 | 6420 | 2500 | 44 |
| W-S-O-E-100 | 42 | 62 | 2120 | 4550 | 31 | 163 | 1550 | 1200 | 24400 | <5 | 1330 | 2250 | 42 |
| W-S-O-R-25 | 130 | 137 | 152 | 2860 | 15 | 137 | 1510 | 1950 | 21300 | <5 | 19300 | 2090 | 30 |
| W-S-O-R-50 | 140 | 100 | 132 | 3360 | 10 | 172 | 1690 | 1990 | 25000 | <5 | 13500 | 2130 | 36 |
| W-S-O-R-75 | 72 | 87 | 135 | 4000 | 12 | 167 | 1670 | 1470 | 26400 | <5 | 7900 | 1980 | 36 |
| W-S-O-R-100 | 57 | 62 | 144 | 4330 | 18 | 168 | 1860 | 1290 | 23600 | <5 | 1210 | 2070 | 37 |
| W-X-C-U-0 | 960 | 87 | 24 | 2780 | 78 | 202 | 2220 | 3040 | 28700 | <5 | 22900 | 1760 | 33 |
| W-X-C-R-25 | | 100 | 26 | 2710 | 28 | 174 | 2170 | 2570 | 28200 | <5 | 14200 | 1710 | 26 |
| W-X-C-R-50 | 96 | 87 | 41 | 3600 | 88 | 198 | 2570 | 2730 | 33600 | <5 | 7340 | 1990 | 40 |
| W-X-C-R-75 | 380 | 100 | 49 | 3520 | 31 | 118 | 2280 | 2330 | 29400 | <5 | 2830 | 2180 | 29 |
| W-X-C-R-100 | 70 | 125 | 47 | 4450 | 8 | 142 | 2280 | 2170 | 27900 | <5 | 772 | 1930 | 29 |
| W-X-C-X-25 | 960 | 125 | 27 | 3200 | 10 | 191 | 2630 | 3790 | 30300 | <5 | 35000 | 2070 | 24 |
| W-X-C-X-50 | 350 | 100 | 19 | 4110 | 73 | 204 | 2580 | 2990 | 31200 | <5 | 8540 | 2290 | 47 |
| W-X-C-X-75 | 46 | 87 | 24 | 3690 | 38 | 132 | 2250 | 2370 | 29000 | <5 | 4220 | 2500 | 30 |
| W-X-C-X-100 | 68 | 112 | 19 | 4500 | 8 | 172 | 2240 | 2050 | 23800 | <5 | 1920 | 1860 | 28 |
| W-X-L-U-0 | 39 | 125 | 13 | 5540 | 8 | 142 | 2930 | 3460 | 26400 | <5 | 1470 | 1990 | 30 |
| W-X-O-U-0 | 130 | 337 | 261 | 4120 | 7 | 110 | 2160 | 1940 | 16700 | <5 | 44900 | 1260 | 24 |
| W-X-O-E-25 | 260 | 387 | 250 | 3370 | 8 | 105 | 1800 | 2240 | 16800 | <5 | 36400 | 1890 | 23 |
| W-X-O-E-50 | 280 | 475 | 337 | 3960 | 9 | 130 | 2140 | 2330 | 21400 | <5 | 29600 | 1770 | 29 |
| W-X-O-E-75 | 120 | 425 | 714 | 4890 | 9 | 153 | 2130 | 2210 | 20700 | <5 | 15600 | 2120 | 31 |
| W-X-O-E-100 | 87 | 237 | 1090 | 4970 | 8 | 127 | 2100 | 2150 | 27600 | <5 | 1730 | 1390 | 27 |
| W-X-O-R-25 | | 350 | 343 | 4160 | 8 | 189 | 2080 | 1810 | 12600 | <5 | 64600 | 956 | 32 |
| W-X-O-R-75 | 120 | 387 | 142 | 4310 | 10 | 166 | 2090 | 2410 | 24000 | <5 | 18100 | 1780 | 35 |
| W-X-O-R-100 | 76 | 325 | 66 | 4930 | 10 | 141 | 2440 | 3010 | 32100 | <5 | 1090 | 1850 | 38 |
| A-R-C-U-0 | 96 | 75 | 107 | 21300 | 30 | 219 | 2660 | 5060 | 30100 | <5 | 6820 | 1530 | 46 |
| A-R-C-R-25 | 81 | 87 | 97 | 19500 | 19 | 286 | 2410 | 3640 | 27200 | <5 | 6440 | 1840 | 39 |
| A-R-C-R-50 | 51 | 75 | 105 | 19300 | 17 | 139 | 2340 | 4150 | 26600 | <5 | 5650 | 1790 | 39 |
| A-R-C-R-75 | 37 | 62 | 103 | 18800 | 18 | 124 | 2170 | 4070 | 27300 | <5 | 6550 | 1620 | 35 |
| A-R-C-R-100 | 170 | 87 | 115 | 22000 | 25 | 199 | 2800 | 3400 | 32300 | <5 | 3640 | 2210 | 51 |
| A-R-C-X-25 | 61 | 100 | 103 | 19800 | 18 | 225 | 2350 | 4250 | 28300 | <5 | 6580 | 1720 | 40 |
| A-R-C-X-50 | 63 | 75 | 101 | 17800 | 15 | 257 | 2600 | 4880 | 25800 | <5 | 9040 | 1930 | 39 |

| | | | | | | | | | | | | | |
|-------------|-----|-----|------|-------|----|-----|------|------|-------|----|-------|------|----|
| A-R-C-X-75 | 49 | 100 | 110 | 19900 | 16 | 144 | 2250 | 4420 | 27800 | <5 | 6010 | 1850 | 38 |
| A-R-C-X-100 | 52 | 100 | 106 | 20900 | 19 | 189 | 2290 | 4180 | 27600 | <5 | 4910 | 2340 | 44 |
| A-R-L-U-0 | 38 | 112 | 113 | 23100 | 18 | 219 | 2840 | 6340 | 27800 | <5 | 3970 | 1920 | 44 |
| A-R-O-U-0 | | 287 | 239 | 14300 | 17 | 454 | 3030 | 3580 | 11600 | 12 | 56100 | 2490 | 40 |
| A-R-O-E-25 | 32 | 337 | 322 | 17900 | 14 | 125 | 2320 | 3880 | 25800 | <5 | 21400 | 2210 | 50 |
| A-R-O-E-50 | | 175 | 306 | 21200 | 19 | 287 | 2410 | 5180 | 8370 | <5 | 49000 | 2170 | 70 |
| A-R-O-E-75 | 27 | 162 | 491 | 20500 | 24 | 151 | 2180 | 3660 | 23900 | <5 | 10900 | 1660 | 37 |
| A-R-O-E-100 | 37 | 112 | 600 | 19500 | 20 | 239 | 2290 | 3210 | 32700 | <5 | 2560 | 1700 | 39 |
| A-R-O-R-25 | | 212 | 198 | 10500 | 15 | 238 | 2060 | 2910 | 12500 | <5 | 48300 | 2550 | 50 |
| A-R-O-R-50 | 140 | 337 | 237 | 19400 | 16 | 180 | 3820 | 4100 | 15200 | <5 | 24300 | 1790 | 46 |
| A-R-O-R-75 | 29 | 100 | 190 | 21300 | 20 | 346 | 2240 | 4140 | 26700 | <5 | 8630 | 1970 | 51 |
| A-R-O-R-100 | 38 | 87 | 132 | 21300 | 18 | 256 | 2250 | 4420 | 30000 | <5 | 6040 | 1700 | 50 |
| A-S-C-U-0 | 250 | 100 | 106 | 17900 | 17 | 299 | 3810 | 3280 | 27800 | 6 | 7460 | 2090 | 43 |
| A-S-C-R-25 | 290 | 150 | 107 | 14700 | 21 | 480 | 2870 | 3760 | 28400 | 6 | 5840 | 1980 | 46 |
| A-S-C-R-50 | 380 | 112 | 121 | 16500 | 18 | 454 | 2910 | 4270 | 30400 | <5 | 5240 | 2110 | 44 |
| A-S-C-R-75 | 200 | 125 | 133 | 19800 | 23 | 339 | 3380 | 4180 | 32600 | <5 | 3830 | 2240 | 60 |
| A-S-C-R-100 | 74 | 125 | 206 | 17900 | 17 | 277 | 2980 | 3330 | 27700 | <5 | 1390 | 1880 | 48 |
| A-S-C-X-25 | 270 | 112 | 106 | 14700 | 23 | 355 | 3180 | 3640 | 25200 | <5 | 6380 | 2140 | 50 |
| A-S-C-X-50 | 140 | 112 | 112 | 16600 | 23 | 454 | 3120 | 3460 | 31800 | <5 | 4370 | 1980 | 47 |
| A-S-C-X-75 | 140 | 150 | 125 | 20000 | 21 | 379 | 3390 | 3650 | 30500 | <5 | 4190 | 2270 | 58 |
| A-S-C-X-100 | 78 | 162 | 128 | 21700 | 20 | 331 | 3490 | 3820 | 30300 | <5 | 1940 | 2100 | 56 |
| A-S-L-U-0 | 76 | 87 | 134 | 21700 | 23 | 692 | 4150 | 5730 | 29100 | <5 | 1550 | 2280 | 66 |
| A-S-O-E-25 | 52 | 462 | 256 | 11600 | 9 | 107 | 2090 | 2830 | 13800 | <5 | 46700 | 1790 | 32 |
| A-S-O-E-50 | 46 | 250 | 302 | 18000 | 25 | 188 | 3040 | 3930 | 17100 | 6 | 24100 | 2020 | 41 |
| A-S-O-E-75 | 67 | 150 | 452 | 19100 | 17 | 240 | 3130 | 3470 | 24300 | <5 | 9270 | 2150 | 46 |
| A-S-O-E-100 | 76 | 87 | 1080 | 18000 | 20 | 192 | 3380 | 2890 | 31100 | <5 | 1640 | 2070 | 54 |
| A-S-O-R-25 | | 137 | 194 | 11800 | 13 | 332 | 2140 | 3110 | 12100 | 11 | 51100 | 1940 | 36 |
| A-S-O-R-50 | 38 | 287 | 183 | 13100 | 12 | 232 | 2450 | 3260 | 17300 | 6 | 23700 | 2120 | 39 |
| A-S-O-R-75 | 65 | 137 | 166 | 17000 | 15 | 189 | 2780 | 3460 | 27000 | <5 | 5500 | 2520 | 42 |
| A-S-O-R-100 | 61 | 112 | 175 | 17800 | 20 | 276 | 3110 | 3450 | 28700 | <5 | 1330 | 2080 | 50 |
| A-X-C-U-0 | 75 | 100 | 93 | 13600 | 9 | 108 | 3450 | 3640 | 21700 | <5 | 9410 | 1410 | 22 |
| A-X-C-R-25 | 70 | 112 | 112 | 19300 | 13 | 656 | 4130 | 4380 | 27200 | <5 | 4640 | 1810 | 28 |
| A-X-C-R-50 | 57 | 137 | 116 | 21600 | 12 | 739 | 4240 | 6010 | 29600 | <5 | 5710 | 1670 | 31 |

| | | | | | | | | | | | | | |
|-------------|-----|-----|-----|-------|----|------|------|------|-------|----|-------|------|----|
| A-X-C-R-75 | 29 | 87 | 119 | 24800 | 11 | 335 | 3890 | 4200 | 26100 | <5 | 3780 | 1380 | 28 |
| A-X-C-R-100 | 28 | 50 | 125 | 22600 | 13 | 1050 | 3440 | 4100 | 26100 | <5 | 1330 | 1380 | 34 |
| A-X-C-X-25 | 35 | 100 | 110 | 19000 | 10 | 630 | 4010 | 4920 | 22500 | <5 | 8410 | 1520 | 22 |
| A-X-C-X-50 | 32 | 137 | 128 | 24100 | 15 | 432 | 4100 | 5320 | 25800 | <5 | 4600 | 1530 | 32 |
| A-X-C-X-75 | 58 | 175 | 140 | 23500 | 12 | 269 | 4130 | 4610 | 26500 | <5 | 5480 | 1590 | 30 |
| A-X-C-X-100 | 27 | 125 | 120 | 25800 | 9 | 1620 | 4800 | 4090 | 22700 | <5 | 1710 | 1250 | 33 |
| A-X-L-U-0 | 27 | 150 | 116 | 25400 | 9 | 489 | 4080 | 5650 | 28500 | <5 | 1420 | 1180 | 25 |
| A-X-O-E-75 | | 325 | 607 | 16200 | 19 | 179 | 3000 | 3220 | 13300 | <5 | 23500 | 1920 | 33 |
| A-X-O-E-100 | 90 | 125 | 984 | 22000 | 11 | 1610 | 3620 | 3460 | 25100 | <5 | 1880 | 1300 | 26 |
| A-X-O-R-25 | | 150 | 234 | 21000 | 16 | 125 | 5570 | 5230 | 23700 | 7 | 4390 | 1920 | 35 |
| A-X-O-R-50 | | 125 | 274 | 14800 | 13 | 202 | 2670 | 3890 | 7350 | <5 | 30500 | 1310 | 39 |
| A-X-O-R-75 | 160 | 300 | 217 | 16500 | 11 | 209 | 3060 | 3040 | 10900 | <5 | 19600 | 1710 | 33 |
| A-X-O-R-100 | 270 | 150 | 130 | 26300 | 12 | 3180 | 4820 | 3000 | 23200 | <5 | 1060 | 1190 | 41 |

A – alfalfa; W – western wheatgrass; R – Riverton soil; S – Sheridan soil; X – X-Ranch Soil; C – CBNG produced water; O – conventional oil and gas produced water; U – untreated produced water; L – River Water (control); R – reverse osmosis water treatment; X – ion exchange (EMIT technology) water treatment; E – EDR water treatment; 25 – 25% treatment of produced water; 50 – 50% treatment of produced water; 75 – 75% treatment of produced water;