Wyoming Water Research Program
Annual Technical Report
FY 2015

Introduction

The NIWR/State of Wyoming Water Research Program (WRP) coordinates participation in the NIWR program through the University of Wyoming's Office of Water Programs (OWP). The primary purposes of the WRP are to support and coordinate research relative to important water resources problems of the State and Region, support the training of scientists in relevant water resource fields, and promote the dissemination and application of the results of water-related research.

Primary participants in the WRP are the USGS, the WWDC, and the University of Wyoming. An advisory committee, consisting of representatives from State and Federal agencies, solicits and identifies research needs, recommends projects, and reviews and monitors project progress. The Director of the OWP serves as a point of coordination for all activities and serves to encourage research by the University of Wyoming addressing the needs identified by the advisory committee. State support for the WRP includes direct funding through the WWDC and active State participation in identifying research needs and project selection and oversight.

The WRP supports faculty and students in University of Wyoming academic departments. Faculty acquire their funding through competitive peer reviewed grants. Since its inception in the year 2000, the WRP has funded a wide array of water related projects across several academic departments.

Research Program Introduction

Since inception of the NIWR program in 1965, the Wyoming designated program participant has been the University of Wyoming. Until 1998, the Wyoming NIWR program was housed in the Wyoming Water Resources Center (WWRC). However, in 1998 the WWRC was closed. In late 1999, the Wyoming Water Research Program (WRP) was initiated to oversee the coordination of the Wyoming participation in the NIWR program. The primary purpose of the Wyoming Institute beginning with FY00 has been to identify and support water-related research and education. The WRP supports research and education by existing academic departments rather than performing research in-house. Faculty acquire funding through competitive peer-reviewed proposals.

In conjunction with the WRP, an Office of Water Programs (OWP) was established by State Legislative action beginning July 2002. The duties of the Office are specified by the legislation as: (1) to work directly with the Director of the Wyoming Water Development Office to identify research needs of State and Federal agencies regarding Wyoming water resources, including funding under the National Institutes of Water Resources (NIWR), (2) to serve as a point of coordination for and to encourage research activities by the University of Wyoming to address research needs, and (3) to submit a report annually prior to each legislative session to the Select Water Committee and the Wyoming Water Development Commission on the activities of the office.

The WRP, which is coordinated through the OWP, is a cooperative Federal, State, and University effort. Activities are supported by the NIWR, Wyoming Water Development Commission, and University of Wyoming. A State Advisory Committee serves to identify research priorities, recommend projects for funding, and monitor project progress. Reports for the following FY15 WRP research projects are given herein in the order listed below:

Project 2013WY86B Final Report: “Use of Fe(VI) for the Improvement of Water Quality in Wyoming”, Maohong Fan, SER Assoc. Prof., Dept. of Chemical & Petroleum Engr. and et al., UW, Mar 2013 – Feb 2016.

Project 2013WY87B Final Report: “Rumen Microbial Changes Associated with High Sulfur -- A Basis for Developing Treatments for Ruminant Livestock in High Sulfur Water Regions”, Kristi M. Cammack, Assist. Prof. and Kathy J. Austin, Research Scientist, Animal Science, UW; Cody L. Wright, Ph.D., Prof. and Ken Olson, Assoc. Prof., Animal Science, S. D. State Univ.; and Gavin Conant, Assist. Prof. and William Lamberson, Prof., Animal Sciences, Univ. of Missouri, Mar 2013 – Feb 2016.

Project 2015WY88B Annual Report: “High-Resolution Modeling of Precipitation, Snowpack, and Streamflow in Wyoming: Quantifying Water Supply Variations in Future Decades”, Bart Geerts, Atmospheric Science, UW, Mar 2015 – Feb 2017.

Project 2015WY89B Annual Report: “Quantifying Return Flow in the Upper Wind River Basin”, Ginger Paige and Scott Miller, Ecosystem Science and Management, UW, Mar 2015 – Feb 2017.

Use of Fe(VI) for the Improvement of Water Quality in Wyoming

Basic Information

Title:	Use of Fe(VI) for the Improvement of Water Quality in Wyoming
Project Number:	2013WY86B
Start Date:	3/1/2015
End Date:	2/29/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Water Quantity, Water Quality, Water Use
Descriptors:	None
Principal Investigators:	Maohong Fan

Publications

1. Tuwati, Abdulwahab M. Ali., New Technologies for Dealing with CO2 Emission and Carbonate Discharge Control Issues Associated with Energy Production, Ph.D. Dissertation, Department of Chemistry, University of Wyoming, December 2013, 100 pgs.
2. Dong, S., Feng, J., Fan, M., Pi, Y., Hu, L., Han, X., Liu, M., Sun, J., 2015. Recent Developments in Heterogeneous Photocatalytic Water Treatment Using Visible Light-responsive Photocatalysts: A Review, RC Advance, Vol. 5, PP. 48901-48904.
3. Irani, M, Ismail, H., Ahmad, Z., Fan, M., 2015. Synthesis of Linear Low-density Polyethylene-g-poly (Acrylic Acid)-Co-Starch/Organo-Montmorillonite Hydrogel Composite as an Adsorbent for Removal of Pb from Aqueous Solutions, Journal of Environmental Sciences. Vol. 27, No.1, PP 9-20.
4. Sharrad, O. M., Fan, M., 2015. Adsorption of Carbonate and Bicarbonate on FeOOH, International Journal of Advanced Technology in Engineering and Science, Vol. 3, No. 1, 2348-7550.

Use of Fe(VI) for Removal of Total Organic Carbons (TOC) and Heavy metals from Coproduced Water in Wyoming

Final Report

Submitted to
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Director of Office of Water Programs

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Abstract

The objective of the research is to develop a new, simple, and environmentally friendly method for the simultaneous removal of heavy metals and total organic carbon (TOC) in coproduced water (CW) from the energy production industry. Ferrate anions (FeO_4^{2-}) or Fe(VI) oxidation ability is very strong over the whole pH scale. Fe(VI) has been considered one of the future-generation water quality improvement agents. The oxidation of CWs TOC into CO_2 and H_2O can be done via Fe(VI). The result of the reduction of Fe(VI) is Fe(III) which is an excellent adsorbent for removal of heavy metals in CWs. Once the heavy metals and TOC have been removed from the CWs it is much easier to then remove the total dissolved solid (TDS) from the CWs. Water supply around the world is becoming insufficient for the growing populations and sources for additional water supplies must be established. Treated CWs can potentially be used to partly mitigate the tight water supply dilemmas in states such as Wyoming.

1. Description of Proposed Research

Wyoming is widely considered to be in a semi-arid hydro-climatic region. A vast majority of the time, rivers and streams throughout the state have little flow, granted during rare events, these rivers and streams can swell to very large levels. Wyoming has limited sustainable surface water available for use in general. Furthermore natural disasters such as droughts and tornadoes can suddenly scourge some regions of Wyoming by undermining agricultural and industrial productivity as well as the well-being and social fabric of communities. Point and nonpoint pollution is a manmade disaster that has been a long-standing concern that may further weaken Wyoming's capability to reach its water requirements. It is vital that Wyoming will not be threatened indefinitely due to a lack of water resources. In response to the water crisis, Wyoming statute Title 35, Chapter 11, Article 3 (35-11-309) declares "water is one of the Wyoming's most important natural resources, and the protection, development and management of Wyoming's water resources is essential for the long-term public health, safety, general welfare and economic security of Wyoming and its citizens." Wyoming mining and energy production companies have generated a great deal of water known as coproduced water (CW). These CWs regularly contain difficult to remove inorganic heavy metals and organic compounds whose disposal will not only cause serious environmental problems, but also waste the precious water resources that are desperately required in Wyoming. Consequently, treatment of CWs for use in Wyoming is a win-win approach.

CWs from various energy production industries [1] have been considered as important new water resources. Nonetheless some of the CWs need to be treated due to quality issues including heavy metals, total dissolved solids (TDS), and high total organic carbon (TOC) associated with fossil fuels [2-3], natural gas and coal. Removal of heavy metals and TOC can greatly help facilitate TDS reduction and removal. Presently there are two separate steps and two different technologies to remove heavy metals and TOC. The first step is to remove the TOC. TOC can be degraded through biological processes that are environmentally friendly, but slow [4]. TOC can also be destroyed using UV photolytic [5] and electrochemical [6] methods, but they are expensive and difficult to control. Most recently a combination of the methods has been studied [7-10] to achieve high removal efficiencies of TOC with some progress being made, however these processes are complex. To overcome these downfalls of a multistep method efforts have been put into using a simple multifunctional technology for simultaneous removal of the organic compounds and heavy metals to improve the overall CW quality of Wyoming. Specifically, a proprietary green method to produce a multifunctional K_2FeO_4 (simply called Fe(VI) henceforth) and propose to use it for the simultaneous removal of total organic carbons (TOC) and heavy metals in numerous CWs preceding their further treatments for total dissolved solids (TDS) removal with other technologies such as reverse osmosis. Success in this project will benefit water resource conservation, environmental quality protection, and agricultural and energy development. These benefits will be accomplished with the following results. Firstly, the optimal Fe(VI) quality for removal of TOC and heavy metals in CWs will be established. Second, the operation conditions for the proposed CW contaminant removal technology will be obtained from laboratory bench-scale data collection. A TOC analyzer will be used to find the concentrations of TOC before and after treatment to determine the effectiveness of Fe(VI) on removing TOC from the CWs. The concentrations of heavy metals will be measured before and after treatment with an inductively coupled plasma mass spectrometer (ICP-MS) to determine the performance of Fe(VI) in removing the heavy metals. Lastly, to demonstrate the applicability of the proposed technology, a pilot-scale test set-up will be designed and built based upon test results from the laboratory bench-scale setup. The results from the pilot-scale set-up are expected to reveal the operation conditions needed for use of the proposed technology in industry for future use. Studies in the use of Fe(VI) have not been done for its application in CW treatment, but it has for other water treatments. Success in the proposed project will advance the application of Fe(VI) in the energy industry as well as other industries working with organic compounds and heavy metals.

Ferrate anions (FeO_4^{2-}) or Fe(VI) oxidation ability is very strong over the whole pH scale. Fe(VI) has been considered one of the future-generation water quality improvement agents. The oxidation of CWs TOC into CO_2 and H_2O can be done via Fe(VI). The result of the reduction of Fe(VI) is Fe(III) which is an excellent adsorbent for removal of heavy metals in CWs.

2. Tasks

Task 1 includes building the laboratory setups seen in Figure 1 and Figure 2. The first step for treatment of CW will be to add 1 L of collected CW to the vessel followed by turning on and setting the stirrer to the desired speed. The temperature control unit will then be turned on to control the operating temperature (5, 10, 15, 20, or 25 ˚C) depending on the test. Next a chosen amount of Fe(VI) will be added once the CW reaches the desired temperature. The reaction will be conducted for a predetermined amount of time with samples being taken periodically to monitor TOC and heavy metal concentrations during the reaction.

Task 2 includes analyzing the samples from the as-received CWs as well as the CWs treated with Fe(VI) under varying conditions. A TOC analyzer will be used to measure the concentrations of TOC and an ICP-OES will be used to measure the concentrations of heavy metals. Other water quality parameters such as suspended solids (SS), total dissolved solids (TDS), electrical conductivity (EC), and pH values of CWs will also be monitored using corresponding instruments available on UW campus. Also, the concentrations of Fe(VI) solution used to treat the CWs will be determined using UV spectroscopy.

Task 3 is the performance evaluation of Fe(VI) on the removal of TOC and heavy metals from CWs on the bench-scale set-up under different conditions. These tests will be used to investigate the TOC and heavy metal removing efficiencies of Fe(VI) under different CW conditions including TOC and heavy metal concentration levels, SS, pH, TDS, temperature, stirring speed and Fe(VI) dosage. The major organic compounds (major TOC contributors) in the CWs will be identified, as well as the kinetics associated with reactions between major organic compounds and Fe(VI).

Task 4 will be to test if the sludge resulting from treatment of CW with Fe(VI) is stable when landfilled. The TOC is expected to be completely decomposed into CO_2 and H_2O when the optimal treatment conditions and dosage of Fe(VI) are used. So, this task is designed to evaluate the stability of heavy metals in the sludge using EPA SW-846 Method 1311 (Toxicity Characteristic Leaching Procedure (TCLP)). The optimal CW treatment conditions for achieving the greatest heavy metal stabilities in sludge will be investigated.

Task 5 is to perform industrial/commercial-scale demonstration of the proposed CWs management technology based on the results achieved with bench-scale tests. The volume of the batch vessel will be scaled to up to 1,000-2,000 L. The on-site industrial/commercial-scale demonstrations will be done in one of oil or natural gas production companies. The specific location of the project will be determined by discussing with the associated landowner and oil/gas companies. Less than 0.5 acre of land will be used for pilot-scale and industrial/commercial-scale demonstrations of the proposed technology. The quality parameters (including TOC and heavy metal concentrations, pH, SS and TDS) of the as-received CW from the chosen company will be characterized. The data obtained from bench-scale tests will be used as the references of the industrial/commercial-scale tests. Factorial tests will be done to assess the performance of Fe(VI) on CWs treatment at industrial/commercial-scale.

3. Methods

3.1 Jar tester

A photo (Figure 1) shows the PB-700 jar tester that is being used for water sample mixing. It is equipped with six stainless steel 1” x 3” paddles which are spaced six inches apart and are adjustable to a maximum depth of nine inches. An electronic motor control system offers regulated variable speeds of all paddles simultaneously, from 1-300 rpm, with the exact speed clearly displayed on a digital readout. A fluorescent lamp illuminator is built into the jar tester base to provide soft, diffused lighting of samples being tested. This setup is used in the first part of this project and the final analysis of water samples are analyzed via Total Organic Carbon (TOC) analyzer.

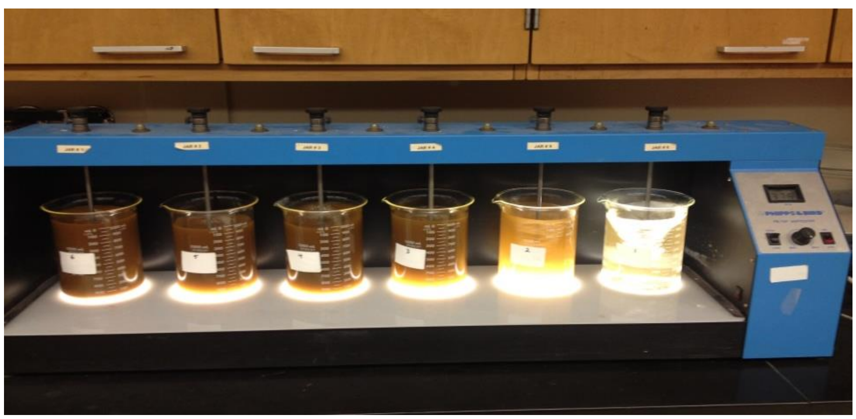

Fig. 1 Photo of the jar tester setup

3.2 Glass reactor

A comparative laboratory scale set-up that will be used to remove TOC and heavy metals from CWs with Fe(VI) is schematically illustrated in Figure 2. Each of the experiments will be executed in a 1 L stirred glass vessel (5). The glass vessel will have five inlets through its lid. In the center inlet of the glass lid a Teflon shaft with a propeller will be inserted (6). The next inlet will be used to introduce CWs and Fe(VI) into the vessel (4). A thermometer will be inserted into another one of the five inlets (7) to monitor the temperature that will be controlled by a separate temperature control unit (3). The fourth inlet will be used to introduce nitrogen when needed to increase the efficiency of mixing in the vessel, which will be controlled by a rotameter (2). A condenser (8) will be connected to the last inlet to condense any vapor released from the reaction mixture and return it to the vessel. The condenser regulating unit (9) will be used to control the condenser temperature. A sampling port will be fitted at the bottom of the vessel as can be seen in Figure 2.

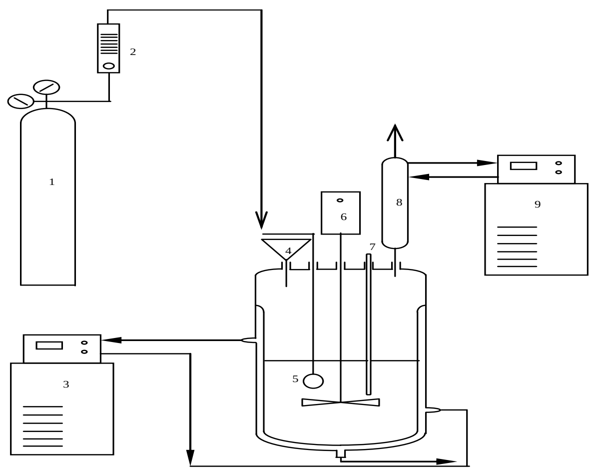

Fig. 2 Experimental setup for removal of TOC and heavy metals from CWs with Fe(VI) [(1) nitrogen tank (2) rotameter (3) temperature control unit (4) funnel (5) vessel (6) stirrer motor (7) thermometer (8) condenser (9) condenser regulating unit]

4. Progress

4.1 Fe(VI) Synthesis

In accordance to task 1 the first set-up as seen in Figure 1 is currently running and being used for experiments. Original results have shown that TOC was not being removed effectively. To determine the source of this problem the Fe(VI) that had been used was tested using Mössbauer spectroscopy. The results from this have shown that our original Fe(VI) samples were less than two percent of the Fe(VI) oxidation state, with the rest being Fe(III). To overcome this difficulty we had decided to produce our own Fe(VI) samples. To complete this we have developed a process of oxidizing Fe(III) into Fe(VI) using ozone. The solid preparation method has been realized through the reaction seen in R1.

$$2FeOOH + 4KOH + 3O_3 \rightarrow 2K_2FeO_4 + 3H_2O + 3O_2 \qquad R1$$

Fe(VI) preparation consists of two principal steps. First the loading of KOH onto the surface and pores of FeOOH through adsorption is completed to prepare the reactants. Next, oxidation of the reactant complex by ozone is done to produce potassium ferrate. The setup for preparation of Fe(VI) can be seen in Figure 3. The first step consists of measuring a quantity of FeOOH and introducing it into a KOH solution. Next this mixture was slightly heated to about 60 ° C and simultaneously stirred for one minute. The resulting solution is then placed into and oven at 90 ℃ to evaporate the water from the solution. Once dried the complex (FeOOH+KOH) was then placed in the fluidized bed reactor. Step two consists of the following stages. Ozone is produced from oxygen by an ozone generator and streamed into a humidifier containing distilled water. The humidified ozone is then fed to fluidized bed reactor to oxidize the KOH FeOOH complex. Glass wool is used to retain the reactants in the reactor. The reaction product is a dark purple powder containing a proportion of potassium ferrate and unreacted reactant.

4.2 Fe(VI) Analysis

4.2.1 Spectrometry

At the end of the reaction the solid product purity is measured using a UV/vis spectrophotometer. The solid product is filtered with a large quantity of deionized water. This filtrate is what is measured using the UV/vis spectrophotometer at 510 nm. Molar absorptivity at 510nm had been determined previously as 1150 M^{-1} cm^{-1} by Bielski and Thomas (1987), based on the Beer-Lambert law as shown in the equation A=εbc, in which "A" is absorbance (no units, since $A = \log_{10} P_0 / P$); "ε" is molar absorptivity, with units of L mol^{-1} cm^{-1}; "b" is the path length of the sample (i.e., the path length of the cuvette in which the sample is contained, expressed in centimeters); and "**c**" the concentration of the compound in solution, expressed in mol L^{-1}. The determination of the molar absorptivity of the ferrate and the immediate measurement of the filtrate with the spectrophotometer gives the absorbance of light by Fe(VI). This value can then be used to calculate the concentration of Fe(VI) in the product through the equation E1.

$$Conversion = \frac{\left(\frac{Abs}{1150 \times 1}\right) \times 56 \times Vol(filtrate)}{Iron(content) \times FeOOH(weight)} \qquad \text{E1}$$

Abs is the value from the spectrophotometer, Vol(filtrate us the volume of deionized water used in the filtration, expressed in L. Iron(content) is the proportion of iron contained in the FeOOH used for the reaction, FeOOH(weight) is the weight of FeOOH used for the reaction in grams, and last the 1=1cm for the path length of the cuvette used in the spectrophotometer. 10% conversion is the current maximum we have achieved with the current set-up. Optimization will be completed.

Fe(VI) has been purchased as well to make sure ferrate properties are constant throughout the study of organic removal. This potassium ferrate has been analyzed using UV/vis in conjunction with Beer-Lamberts law to give a concentration of 30% ferrate w/w.

4.2.2 Titration

The previous analysis of Fe(VI) purity in potassium ferrate only works for samples that were made in the lab. K_2FeO_4 has also been bought from a chemical company. To determine the purity of this Fe(VI) another method is needed. A method from J.M. Schreyer of the University of Kentucky [12] will be used. This method is based on the oxidation of chromite in strongly alkaline solution with the ferrate(VI) ion as shown in reaction 2.

$$CrOH_4^- + FeO_4^{2-} + 3H_2O \rightarrow Fe(OH)_3(H_2O)_3 + CrO_4^{2-} + OH^- \qquad R2$$

This method is applicable to the analysis of solutions containing low concentrations of the ferrate(VI) ion. The procedure is as follows. First saturated sodium hydroxide is added to a chromic chloride solution.

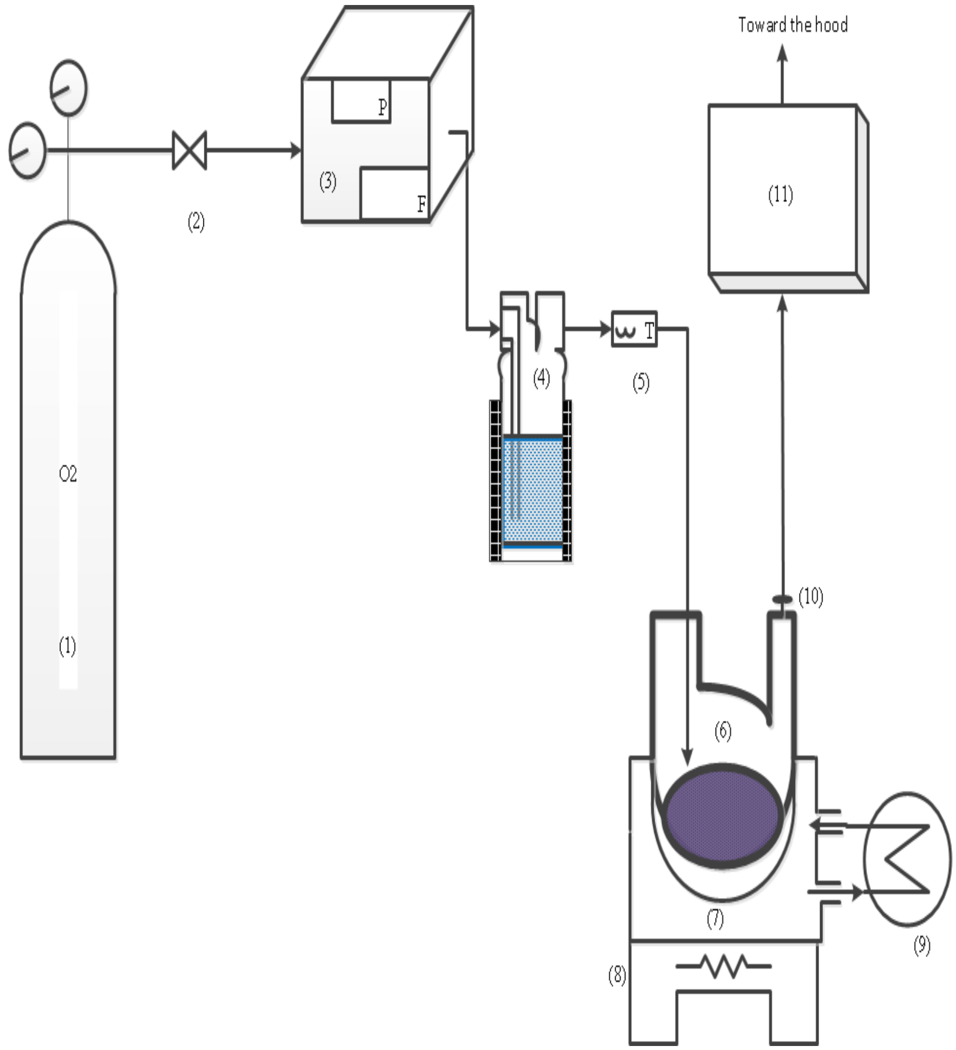

Fig. 3 Diagram of Fe(VI) preparation setup (1) Oxygen cylinder; (2) Valve; (3) Ozone generator; (4) Humidifier containing distilled water and heat tape; (5) Set of thermometers for wet and dry temperatures; (6) Fixed bed reactor containing FeOOH+KOH particle to be oxidized; (7) Jacket heat exchanger; (8) Magnetic stirring machine; (9) Temperature controller for heat exchanger; (10) Particle filter; (11) Ozone analyzer.

To this the sample to be analyzed is added and stirred until dissolution of the potassium ferrate is complete. Dilution is then done with distilled water followed by addition of sulfuric and phosphoric acids. Titration is then completed with a standard ferrous solution and a sodium diphenylamine sulfonate indicator. The end point is marked by a change from purple to light green. From the known amount used of the ferrous solution titrant the percent potassium ferrate can be calculated as seen in equation 2.

$$Percent\ K_2FeO_4 = \frac{(ml\ of\ Fe^{2+} * N\ Fe^{2+}) * K_2FeO_4\ MW}{3000 * m} \qquad E2$$

Where Fe^{2+} is the titrant solution used, N is nomal, MW is molecular weight, and m is the weight of sample used in the analysis.

Due to the inherent properties of this method only low concentrations of ferrate can be measured accurately. For our study we want to analyze much larger concentrations therefore this is not practical unless solutions are diluted. Dilutions will be performed and analysis will be done to compare the values from different analysis methods.

4.3 Total Organic Carbon (TOC) Removal

Studies by the United States Geological Survey have found that many organics are present in produced water from shale and coal bed methane (CBM) wells across the United States, including Wyoming. This is due waters interaction with coal during the natural gas production process. The total organic carbon varies across the wells, but on average it was found that there is 1.18-4.5 ppm TOC in produced water from CBM wells and 8.12-346 ppm TOC in produced water from shale gas wells. The values for Wyoming only included CBM wells with an average of 4.5 ppm TOC. A large variation of organic components make up the TOC in produced waters; for Wyoming these were categorized as polycyclic aromatic hydrocarbons (PAH), heterocyclic compounds, phenols, aromatic amines, other aromatics, and non-aromatic compounds [13]. Of these categories PAH's, phenols, and heterocyclic compounds were the most prolific. In this study components have been chosen from these categories for further research. So far compounds from the phenol group and the heterocyclic group have been chosen including phenol, and benzothiazole respectively.

Reactions studied include variation of Fe(VI) dosage, pH, and reaction times to find the optimal conditions at which Fe(VI) oxidizes the most efficiently. Later studies will also be done at varying initial organic concentrations, varying temperatures, and varying volumes.

4.3.1 Phenol removal

Phenol removal tests at varying initial Fe(VI) concentrations were completed. The reactions for the variation of Fe(VI) concentrations was done at a pH=4 for 15 min., an initial TOC concentration of 20 ppm, and a stirring rate of 250 RPM. It has been found that after adding more than 1.2 g/L of Fe(VI) the percent of TOC removal plateaued, meaning the extra Fe(VI) did not oxidize anymore organics giving an optimal Fe(VI) concentration of 1.2 g/L as seen in Figure 4. This concentration of Fe(VI) was then used to measure the removal efficiencies at varying pH's. This data can be seen in Figure 10. An optimal pH of 4 has been found to be the condition where phenols oxidation occurs most efficiently by Fe(VI). Reactions were also run at longer times to see if any oxidation occurs later then 30 min. Studies show that after 30 min no reaction is occurring and the TOC concentrations stay constant, as seen in Figure 5.

A high performance liquid chromatograph (HPLC) was recently purchased for use in Dr. Fan's research group. Using this it has been found that all the phenol is being oxidized in the reaction. Figure 6 shows the 20 ppm phenol peak that appears at a resonance time of 1.784 min. An analysis of the water after oxidation shows that this peak completely disappears at 1.784 min. as seen in Figure 7. A negative peak shows up in the water after oxidation suggesting that

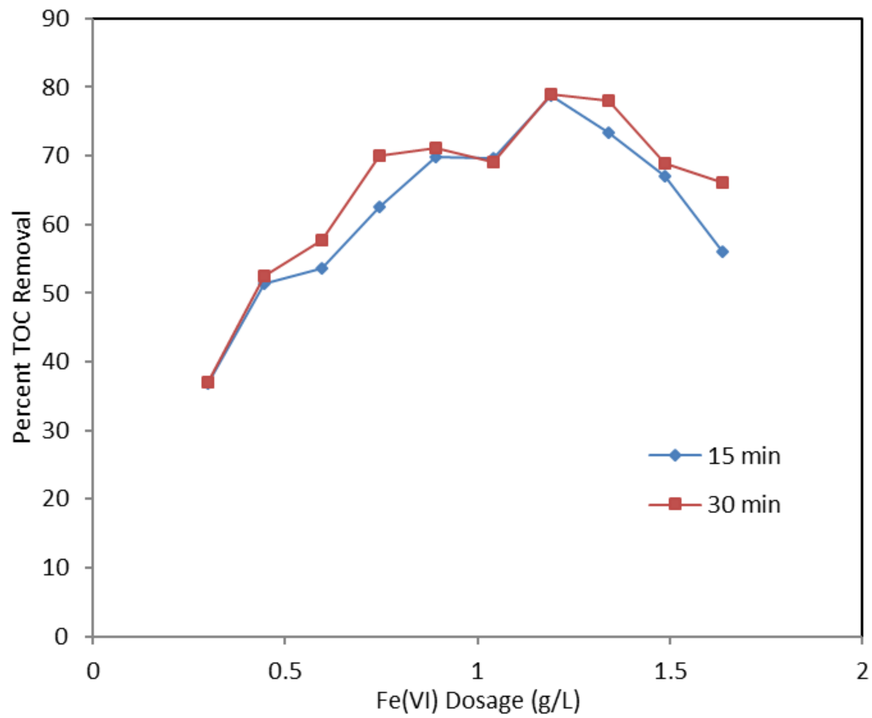

Fig. 4 Percent TOC removal at varying Fe(VI) concentrations. The initial concentration of TOC as phenol was 20 ppm with pH value of 4. The reaction was run for 30 min. at a stirring speed of 250 RPM with samples taken at the end of reaction and in the middle of the reaction.

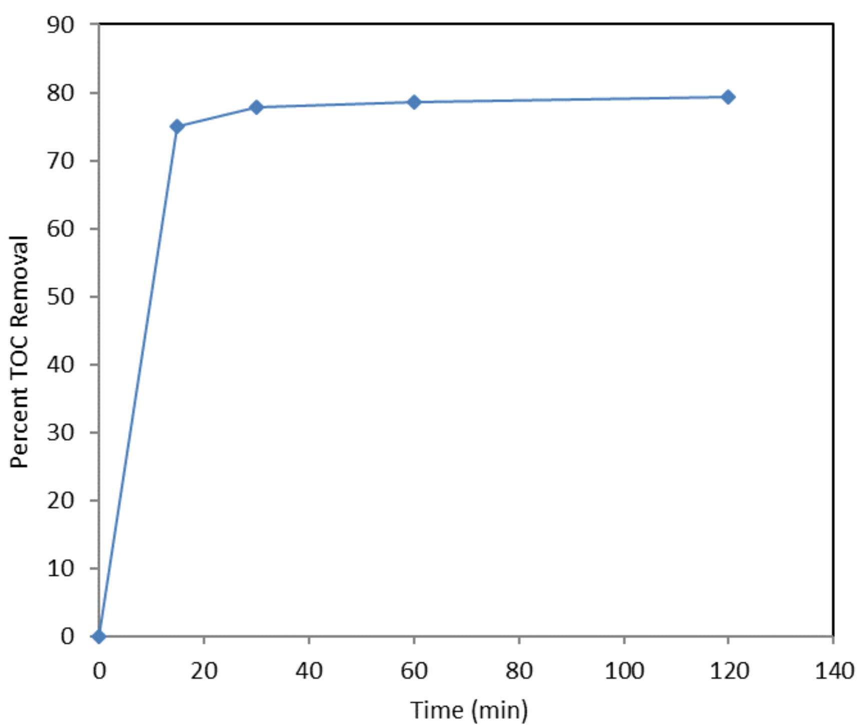

Fig. 5 Percent TOC removal at varying times. The initial concentration of TOC as phenol was 20 ppm with an initial dosage of 1.2 g/L Fe(VI). The reaction was run for 120 min. at a stirring speed of 250 RPM with samples taken at 15, 30, 60, and 120 min

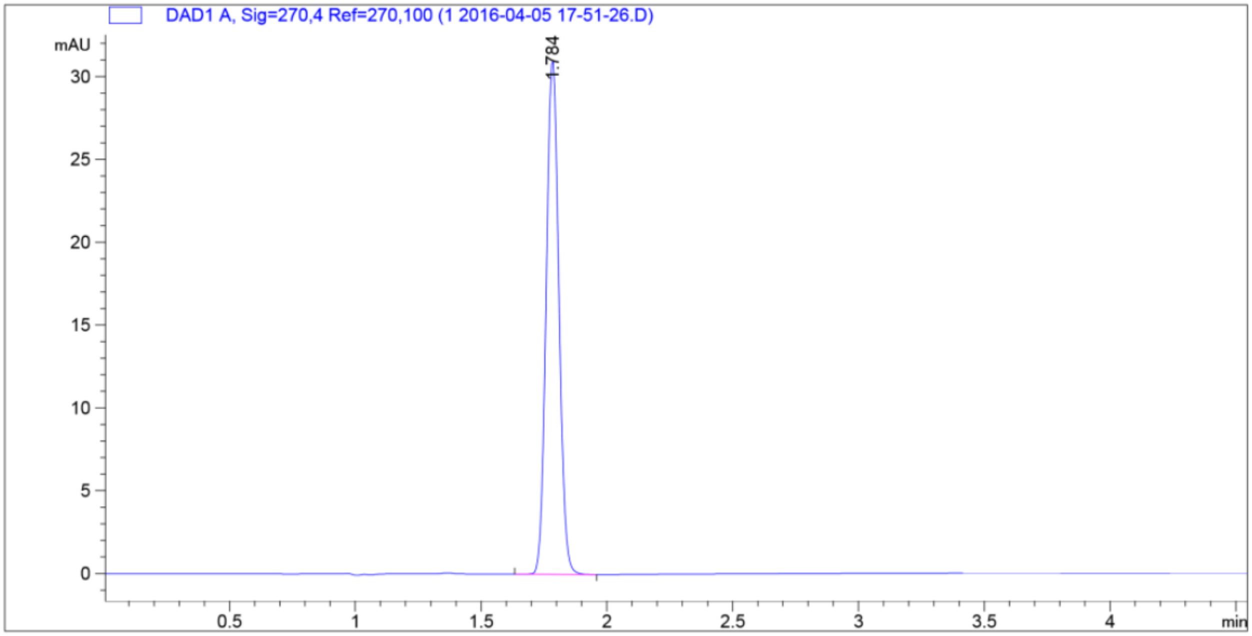

Fig. 6 HPLC chromatogram for initial 20 ppm phenol sample before Fe(VI) oxidation reaction

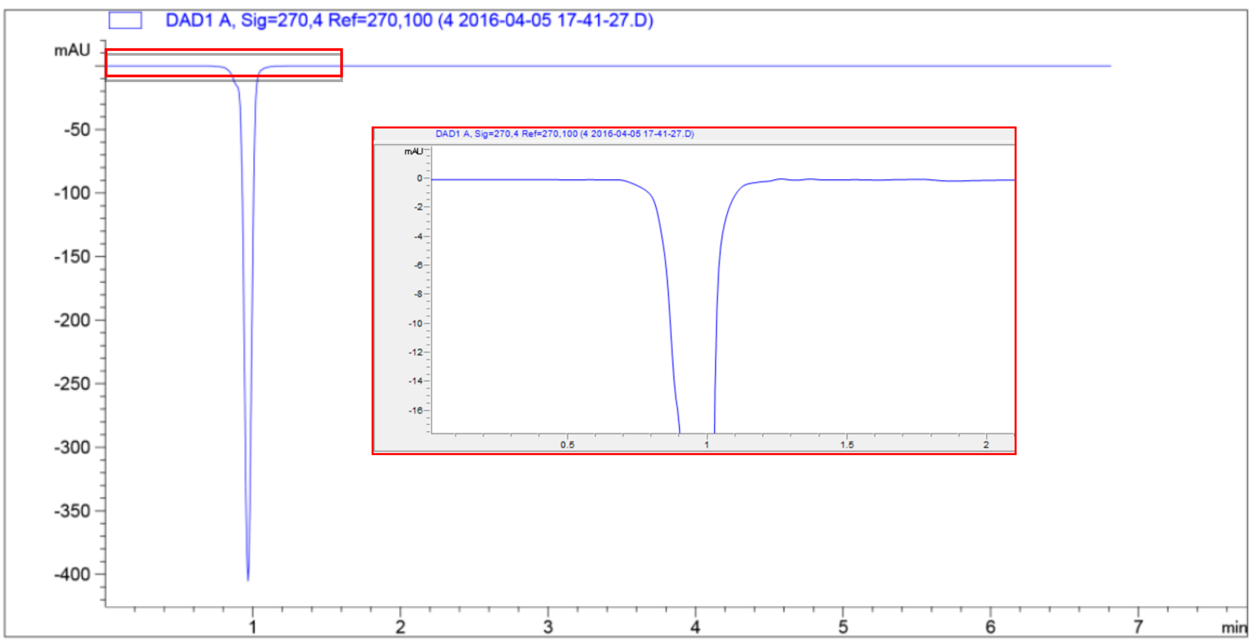

Fig. 7 HPLC chromatogram for Phenol removal after 15 min reaction with initial dosage of 1.2 g/L Fe(VI) and phenol initial concentration of 20 ppm at a pH of 4

phenol is being oxidized into other organics that remain in the water, and the peak being negative because the absorbance of the component is lower than that of the HPLC carrier compounds. A UV/Vis spectrum analysis was then completed as seen in Figures 8 and 9. Here it can be seen that the phenol peak at 270 nm is gone and new peaks have formed at 300 nm and below 250 nm. These unknown organic compounds will be identified using nuclear magnetic resonance (NMR) as well as liquid chromatography mass spectrometry (LC-MS).

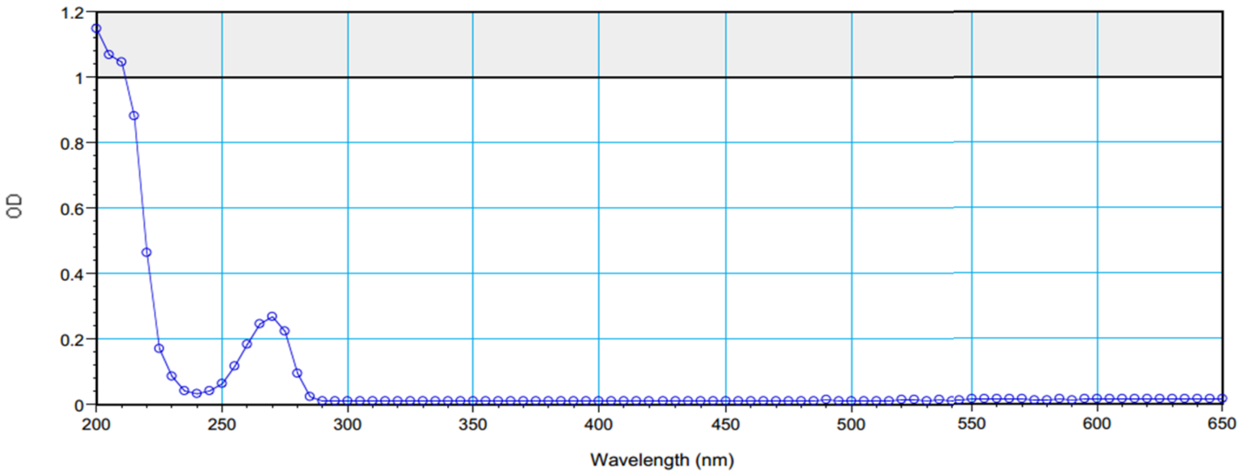

Fig. 8 UV/Vis spectrum for initial 20 ppm phenol sample before Fe(VI) oxidation reaction

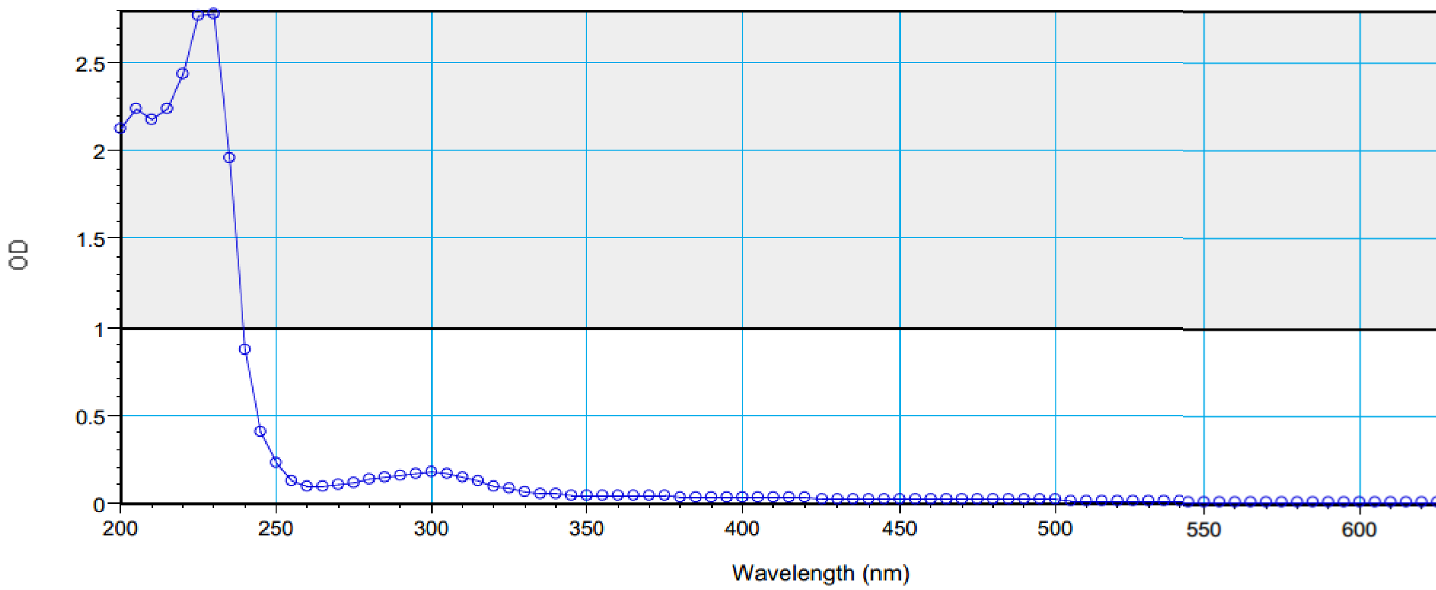

Fig. 9 UV/Vis spectum for Phenol removal after 15 min reaction with initial dosage of 1.2 g/L Fe(VI) and a phenol initial concentration of 20 ppm at a pH of 4

Chemical oxygen demand (COD) analysis was also completed on the samples obtained from experiments. The same trend exists in COD removal as in TOC removal. The optimal pH of three and four can be seen in Figure 6 where 100% COD removal occurred. The pH of one was not able to be completed due to the reagents used in the COD analysis not being compatible to such a low pH value.

4.3.2 Benzothiazole Removal

Benzothiazole removal has also been studied. The same variation of conditions as seen in phenol removal has also been done. This includes variation of pH and Fe(VI) concentrations. It can be seen in Figure 13 that the optimal Fe(VI) concentration still has yet to be found as the removal efficiency is still increasing. Samples were taken at 15 and 30 minutes. There is no notable difference at Fe(VI) concentrations below 1.35 g/L, meaning the reaction has finished. Although above this concentration more removal is done at the 30 minute sampling time. This means with the higher Fe(VI) concentrations the reaction takes longer to finish, but more benzothiazole removal is achieved.

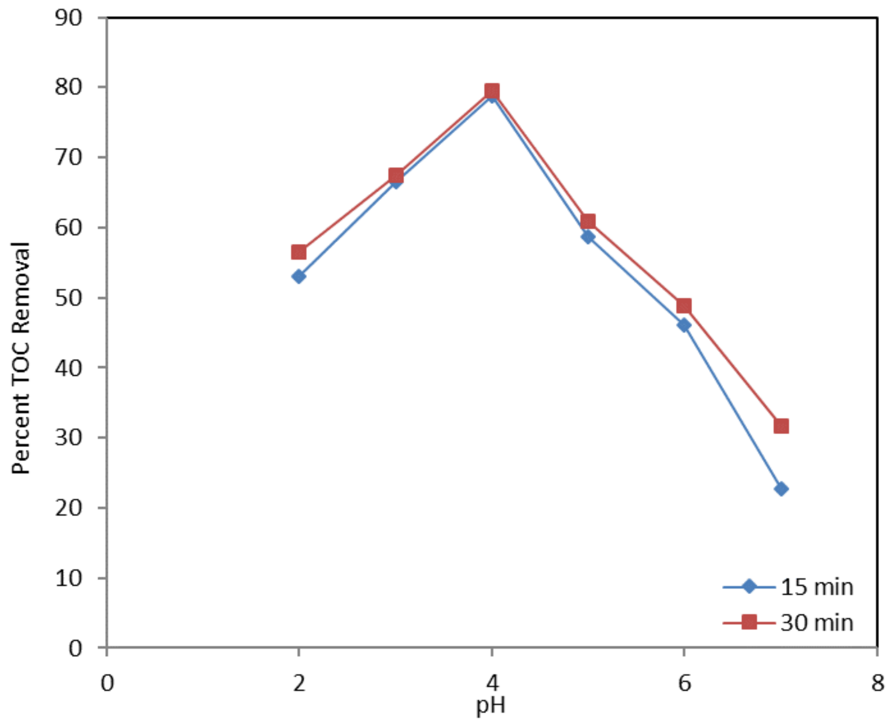

Fig. 10 Percent TOC removal at varying pH levels. The initial concentration of TOC as phenol was 20 ppm with an initial dosage of 1.2 g/L Fe(VI). The reaction was run for 30 min. at a stirring speed of 250 RPM with samples taken at the beginning, end, and middle of the reaction.

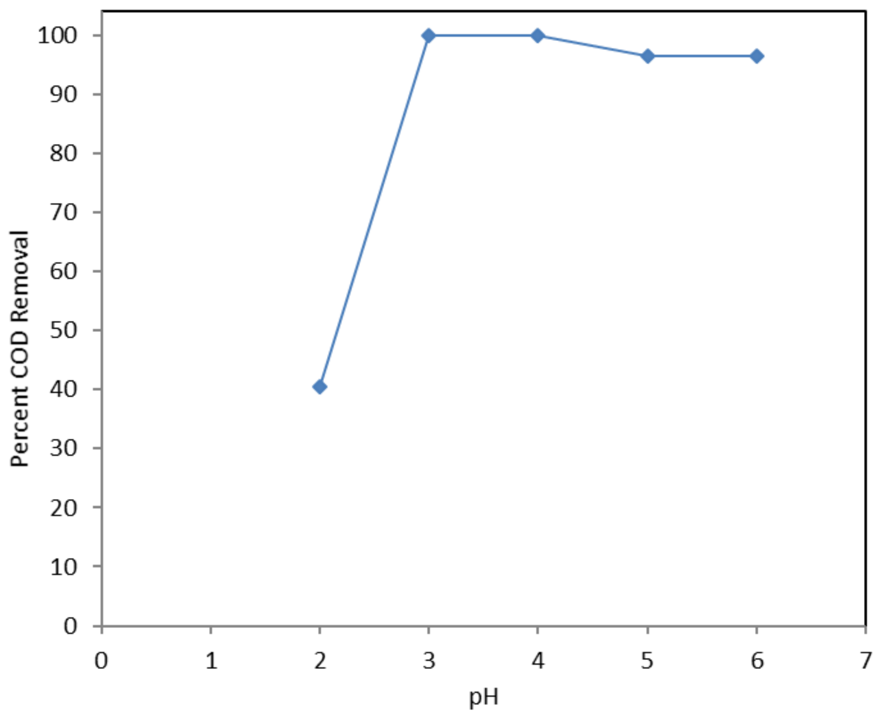

Fig. 11 Percent COD removal at varying pH levels. The initial concentration of TOC as phenol was 20 ppm with an initial dosage of 0.4 g/L of Fe(VI). The reaction was run for 15 min. at a stirring speed of 250 RPM.

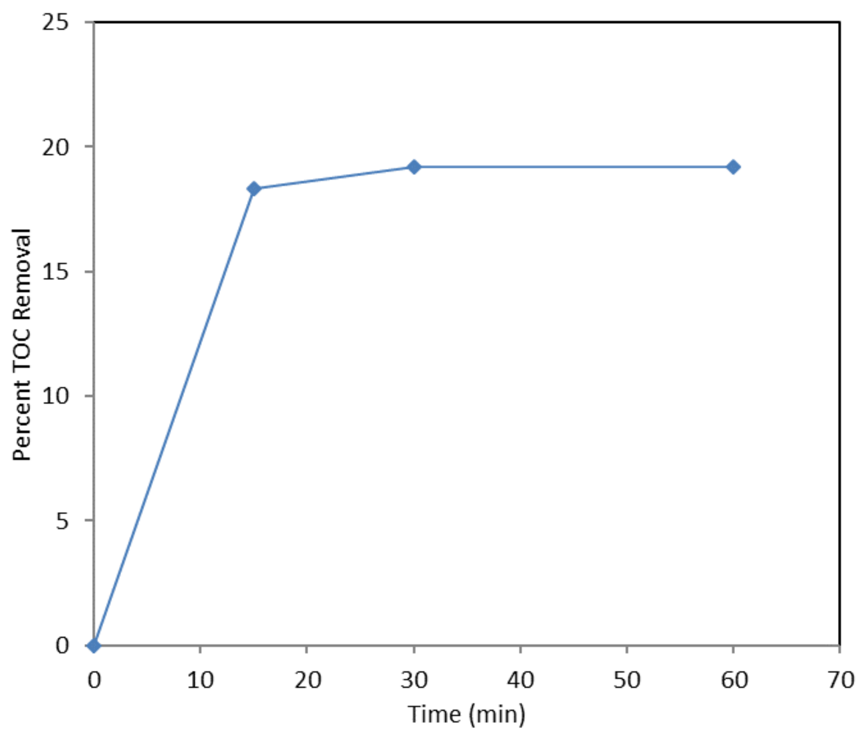

Fig. 12 Percent TOC removal at varying time. The initial concentration of TOC as benzothiazole was 20 ppm with an initial dosage of 1.05g/L Fe(VI). The reaction was run for 60 min. at a stirring speed of 250 RPM with samples taken at 15, 30, and 60 min

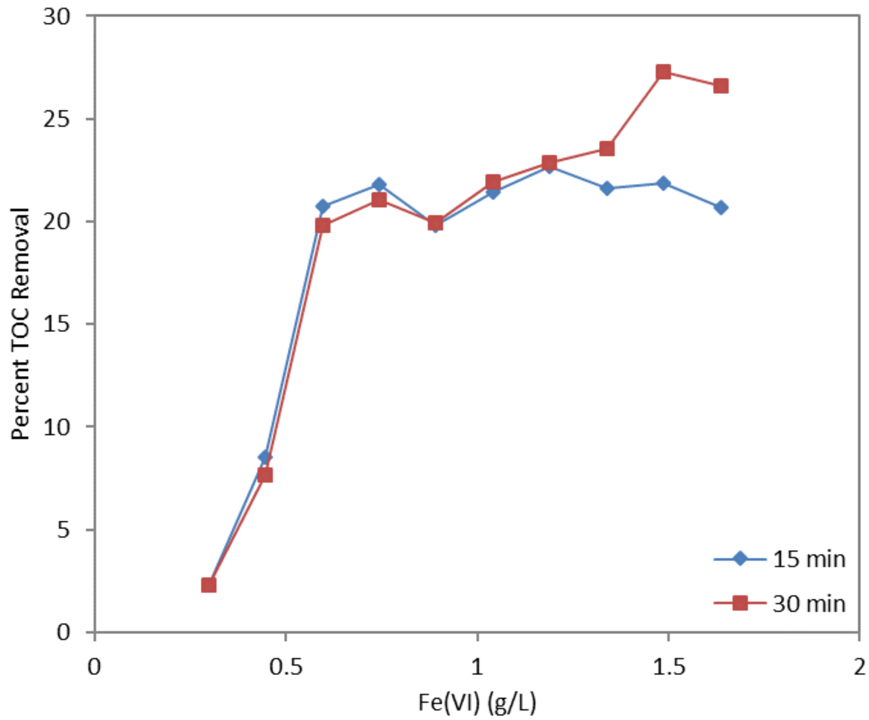

Fig. 13 Percent TOC removal at varying Fe(VI) concentrations. The initial concentration of TOC as benzothiazole was 15 ppm at a pH of 4.0. The reaction was run for 30 min at 250 RPM with sampling taken at the end and the middle of the reaction.

Variation of pH on benzothiazole removal after 15 min. can be seen in Figure 14. For pH values of 2, 3, and 4 the samples that were taken at 30 minutes had no notable difference to the 15 minute samples. For the rest of the pH values the 30 minute TOC values actually increased instead of decreasing. The reason behind this is unknown and will be figured out in future work.

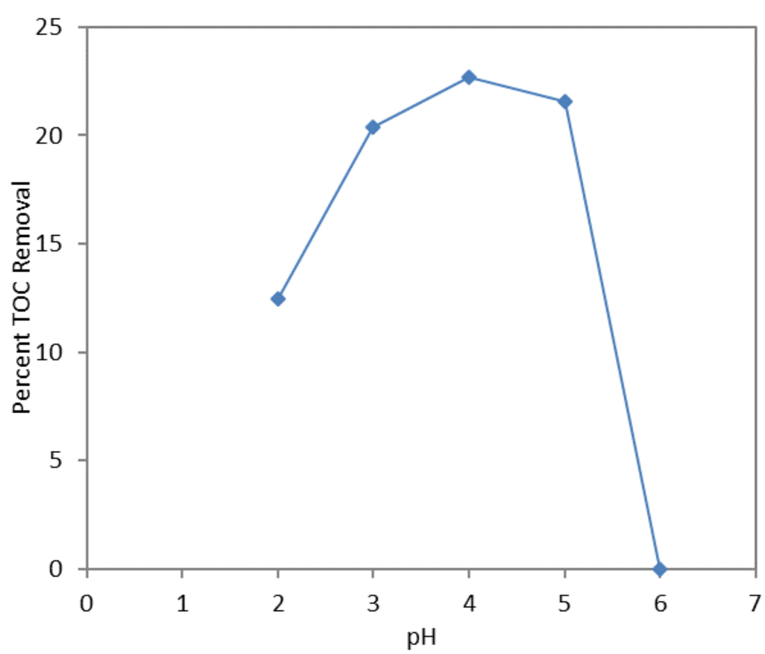

Fig. 14 Percent TOC removal at varying pH values. The initial concentration of TOC as benzothiazole was 15 ppm at a Fe(VI) concentration of 4 g/L. The reaction was run for 15 min at 250 RPM with sampling taken at the end of the reaction.

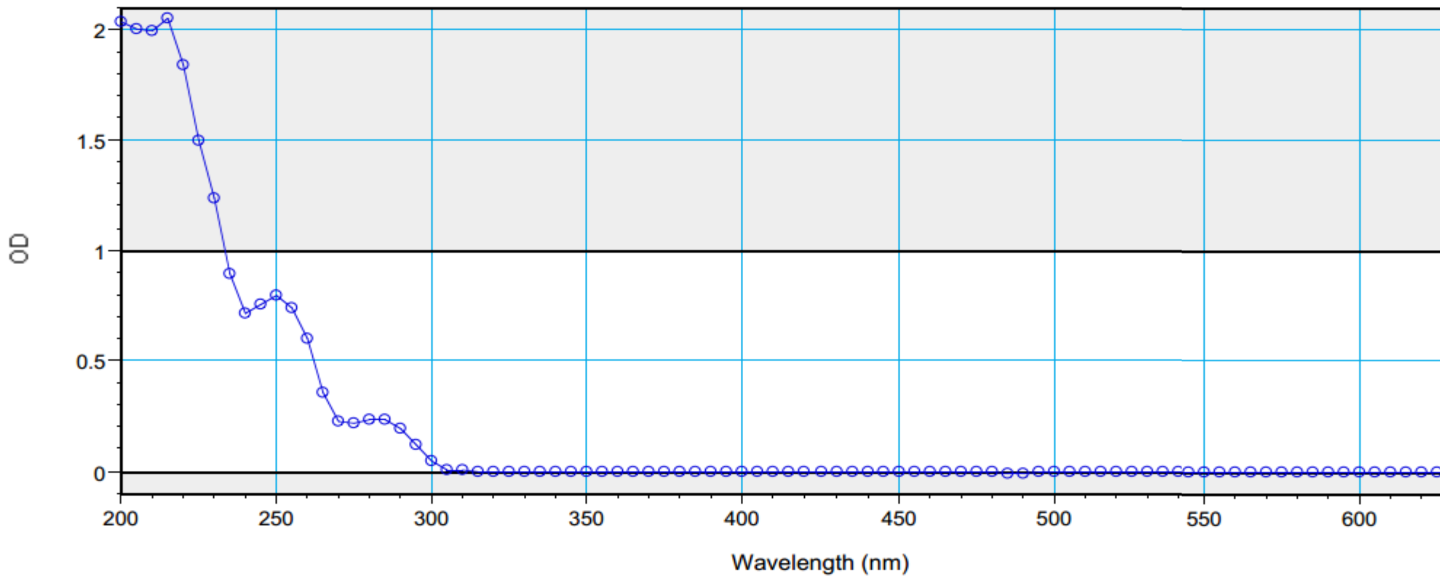

Fig. 15 UV/Vis spectrum for initial 20 ppm benzothiazole sample before Fe(VI) oxidation reaction

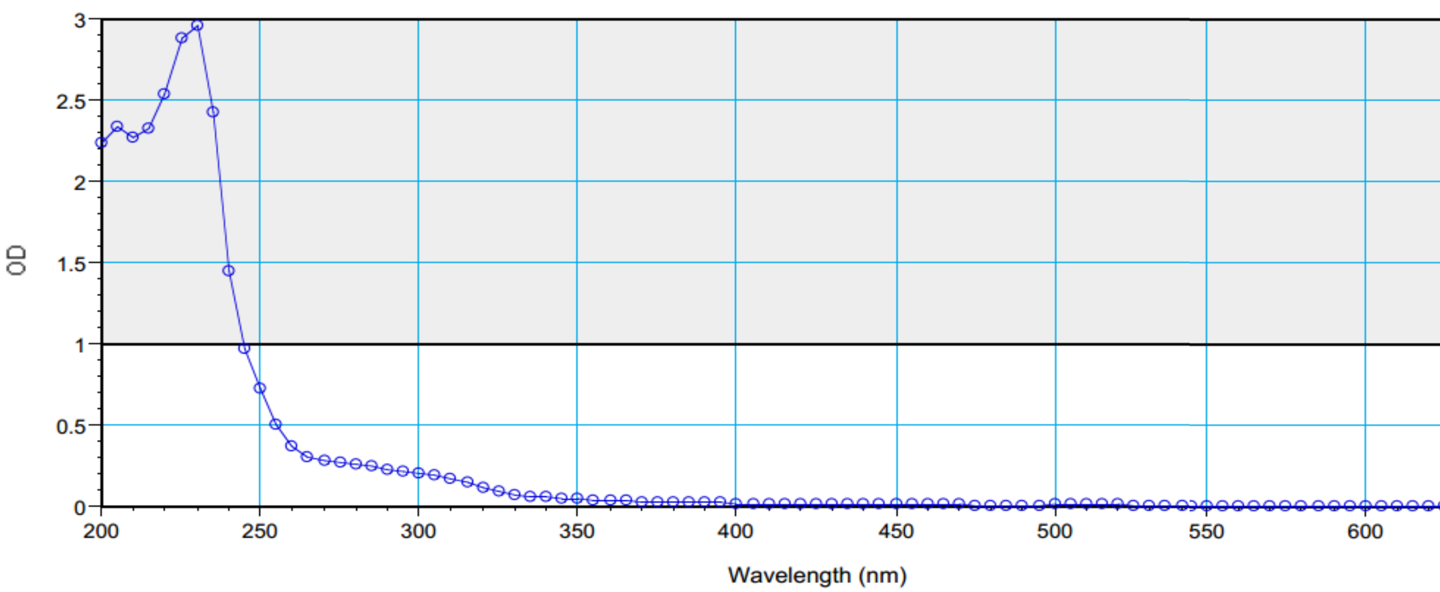

Fig. 16 UV/Vis spectrum for benzothiazole removal after 15 min reaction with initial dosage of 0.72 g/L Fe(VI) and benzothiazole initial concentration of 20 ppm at a pH of 4

UV/Vis analysis has also been done for benzothiazole removal. Figure 15 shows 20 ppm benzothaizole in water before any oxidation has taken place. Peaks at 250 nm and 285 nm can be seen, as well as a peak around 220 nm. Since only benzothiazole is present these peaks are characteristic of benzothiazole. Figure 16 shows the UV/vis spectrum of the benzothiazole removal solution after the reaction has taken place. The characteristic peaks of 250 nm and 285 nm seem to have gone away, however they may be too small to see. HPLC analysis will be done on this to see if all the benzothiazole is removed. Peaks at 205 nm, 230 nm, and 300 nm have appeared though. These are the products of the reaction and need to be analyzed using NMR/LC-MS to be identified. The peaks are in the same location as the phenol removal peaks seen in Figure 9. This leads to a belief that the phenol and benzothiazole oxidation products are the same compounds. This hypothesis will be decided valid through the use of analysis techniques such as NMR and LC-MS to identify these compounds.

4.3 Analysis Methods

4.3.1 TOC Analyzer

TOC analysis requires that 20 mL samples of the treated water be introduced to a glass vial. These glass vials are then placed into the ASI-V Shimadzu auto sampler. A calibration curve is then set-up for the TOC analysis. Air zero is used as the supply gas for the TOC-V_{CSN} Shimadzu total organic carbon analyzer.

4.3.2 COD Analyzer

Small portions of the treated water samples were taken out for Chemical Oxygen Demand (COD) measurements via a colorimetric technique. Prior to the colorimetric determination of COD, specified amount of the samples were added into reagent vials containing dichromate solutions provided by Hach Co., followed by vigorous mixing and then placed in a pre-heated COD reactor for two hours at 150^{o}C. The vials were then cooled down to room temperature, removed from the reactor and then analyzed colorimetically via Hach DR/4000 instrument at a wavelength of 620 nm.

4.3.3 High Performance Liquid Chromatography

An Agilent Technologies 1260 infinity high performance liquid chromatograph system was used. For phenol analysis a ratio of 60/40 water to methanol was used as they carrier. The HPLC is equipped with a diode array detector and phenol was analyzed at a wavelength of 270 nm.

4.4 Parties Involved

The completion of this project has been assumed by Abdulwahab M. Ali Tuwati, a post doc with a PhD in chemistry, Andrew Thomas Jacobson, a Masters candidate in chemical engineering at the University of Wyoming, and Mohammad Tarabzoni an undergraduate student in chemical engineering at the University of Wyoming; all under the supervision of Professor Maohong Fan. The ideas behind the project have also been introduced to students through the GK-12 Environmental and Energy Nanotechnology NSF Fellowship through Andrew Jacobson. As a fellow, travel has been done to Chugwater, WY to introduce science topics including this ongoing research. Students from around Wyoming have also been given lab tours explaining the ideas behind the setups of this research and what the goal of this research is.

5. Future Work

Future work will contain a number of duties. First and foremost other molecules besides phenol and benzothiazole need to be investigated. Since phenols and benzothiazole fall into two main groups that have been found in Wyoming produced water (heterocyclic compounds and phenols) the next component to be studied will be a polyaromatic hydrocarbon (PAH) due to their abundance in produced water across the US including Wyoming. Also removal of a combination of these compounds will be completed to find the selectivity of the Fe(VI) ion for oxidation on the simultaneous removal of multiple contaminants. More analyses will be completed using high performance liquid chromatography (HPLC) with a mass spectrometer along with NMR to identify the products from the oxidation reactions with Fe(VI). The method in synthesizing potassium ferrate from KOH and FeOOH will be optimized by varying initial conditions to give rise to higher Fe(VI) conversion. This higher conversion will be beneficial in that less Fe(VI) powder will need to be used in oxidation reactions. Once the Fe(VI) has been oxidized to Fe(III) for the removal of TOC there is still potential for the removal of heavy metals such as arsenic and selenium. This work will be completed once optimal conditions for the removal of TOC have been studied. Once the method has been validated for removal of multiple organic carbon types and inorganic molecules it will be applied to real water samples from various places in Wyoming.

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Rumen Microbial Changes Associated With High Sulfur A Basis for Developing Treatments for Ruminant Livestock in High Sulfur Water Regions

Basic Information

Title:	Rumen Microbial Changes Associated With High Sulfur A Basis for Developing Treatments for Ruminant Livestock in High Sulfur Water Regions
Project Number:	2013WY87B
Start Date:	3/1/2015
End Date:	2/29/2016
Funding Source:	104B
Congressional District:	1
Research Category:	Biological Sciences
Focus Category:	Agriculture, Treatment, Water Quality
Descriptors:	None
Principal Investigators:	Kristi Cammack, Kathy Austin, Gavin Conant, William Lamberson, Ken C Olson

Publications

1. Clarkson, Cara, 2014. Effect of high sulfur water on lamb performance and rumen microbial populations. M.S. Thesis, Animal Science, Univ. Wyoming.
2. Clarkson, C.J., H.C. Cunningham, L.E. Speiser, M.J. Ellison, K.J. Austin, and K.M. Cammack, 2014. Effect of high sulfur water on behavior, performance, and volatile fatty acid production in lambs. Proceedings Abstract, Western Section – American Society of Animal Science.
3. Powell, S., A.N. Abrams, K.J. Austin, D.C. Rule, E.A. Van Kirk, M.J. Ellison, H.C. Cunningham, G. Conant, W.R. Lamberson, T. Taxis, and K.M. Cammack. 2016. High sulfate water affects volatile fatty acid profiles in lambs. Plant & Animal Genomes XXIV Conference. P0608.
4. Abrams, A.N., K.J. Austin, M.J. Ellison, H.C. Cunningham, G. Conant, T. Taxis, W.R. Lamberson, and K.M. Cammack. 2016. Effect of high sulfate water on rumen microbial populations in lambs. Plant & Animal Genomes XXIV Conference. P0607.
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Rumen Microbial Changes Associated With High Sulfur – A Basis for Developing Treatments for Ruminant Livestock in High Sulfur Water Regions

Final Report

(Year 3 of 3)

FINAL REPORT: 04/20/2016

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Abstract: Reliable drinking water sources that meet minimum quality standards are essential for successful livestock production. Recent surveys have shown that many water sources, especially throughout the semi-arid rangelands of the U.S., are not of sufficient quality to support optimum herd/flock health and performance, in particular because of high concentrations of sulfur (S) and S-compounds present in the water. High S concentrations in water sources can arise from several factors. First, water sources can be naturally high in S. Second, drought conditions can cause S to be concentrated within the water source. Third, conventional oil and gas production can also increase S content within the water source. Combinations of these conditions can further exacerbate S levels in the water. Many of these water sources are used for livestock production systems, especially throughout the western states. However, high-S water is associated with poor performance and health in ruminant livestock, and is a primary cause of polioencephalomalacia (PEM), a disease state that can cause 25% morbidity and 25-50% mortality in affected populations. Producers are typically limited in available water resources and cannot avoid high S water situations; there are also no practical means of treating high S water. Although no effective treatments are currently available for animals suffering from the effects of high dietary S, it has been noted that animals vary in their response to elevated levels of S. While some animals consuming high S water exhibit reduced performance and/or poor health, others appear unaffected. We hypothesize that differences in rumen microbial populations, which are responsible for the breakdown of S and S-compounds, are associated with the variation in animal response to high S. Therefore, in this study we aim to determine 1) how rumen microbial populations change in response to high S water; 2) if the extent of those changes are associated with host ability to better tolerate high S; and 3) the functionality of the rumen microbial changes through a more global analysis of the rumen microbiome. A better understanding of the rumen microbial response to high S will lead to development of treatments for affected animals.

Title: Rumen Microbial Changes Associated With High Sulfur – A Basis for Developing Treatments for Ruminant Livestock in High Sulfur Water Regions
Final Report

Statement of Critical Regional or State Water Problem: *Need for Project.* Ruminant livestock consuming water high is sulfur (S) and S-compounds (e.g., sulfate) are prone to poor performance and health. High S can also cause polioencephalamalcia (PEM), a disease state in that can cause 25% morbidity and 25-50% mortality in affected population. Ruminants are especially susceptible to S toxicity because of S metabolism in the rumen by sulfate-reducing bacteria (SRB). High S triggers metabolism by SRB to sulfide, which ultimately increases hydrogen sulfide (H_2S) production in the rumen. It is this increase in H_2S production that is thought to be causal to the poor performance and health (including PEM) of ruminant animals.

Unfortunately, many livestock water sources, especially throughout the semi-arid rangelands of the U.S. and Wyoming, are high in S and S-compounds because of underlying soil conditions or man-made contaminants (e.g., conventional gas and oil water), and are exacerbated by evaporation concentrating S during persistent drought conditions. Producers are typically limited in available water resources, and there are no practical means of treating high S water, especially in range conditions, nor animals suffering the effects of high S water.

The literature is replete with studies aimed at identifying treatments for animals affected by high S. Why, then, have no effective, consistent treatments been discovered yet? Most studies have identified potential treatments *in vitro*, or in laboratory studies using rumen bacterial cultures. However, once these treatments were tested *in vivo*, or in the live animal, limited effects on animal health or performance were typically observed. It is apparent from these studies that *in vivo* and *in vitro* conditions respond differently to high S, indicating the need for a whole-animal approach. A better understanding of how rumen microbial populations (e.g., bacteria) *in vivo* change in response to high S is a critical first step to whole animal studies aimed at targeted treatment development.

Who Would Benefit and Why. Many water sources high in S are still used for livestock production due to lack of alternative available sources, especially in range production settings. Additionally, in many of these areas it is neither feasible nor practical to haul in water low in S. Therefore, identification of an effective treatment for either 1) high S water sources or 2) animals suffering from high S would benefit livestock producers by 1) preventing the health and performance problems associated with livestock consuming high S water, and 2) allowing them to use available water resources despite high S concentrations.

Statement of Results or Benefits: *Information Gained.* Past studies of changes in rumen microbial population in response to high S have utilized technologies either limited to determining the presence/absence of microbial species, or have utilized *in vitro* culture methods capable of altering bacterial metabolism so that *in vivo* conditions are not truly reflected [1]. We used DNA sequencing techniques [2] to better identify and quantify changes in rumen microbial populations in response to high S water.

How Information Was/Will Be Used. Identification of rumen microbial species important to the response to high S water is a critical steps towards development of effective prevention and treatment strategies. The results from study enabled us to determine microbial species that responded (via changes in abundance – either lesser or greater abundance) to the high S drinking water, and furthermore determine those species that appear to 'adapt' to the high S challenge by returning to pre-challenge abundance. Microbial species that are particularly responsive to high S water may help to identify treatments for high S water, such as promoting microbial species that help process and eliminate the excess S or limiting growth of species associated with the H_2S generation that leads to impaired animal health and performance. Our *next step* will be to closely study the confirmed microbial species to determine functional properties that convey this responsiveness to high dietary S, and then determine means to optimize abundances to improve overall animal response.

Nature, Scope, and Objectives of the Project: The basic nature of the proposed research was to determine changes in rumen microbial populations in response to high S water. Our objective was to use DNA sequencing to quantify and characterize rumen microbial populations in sheep (our model ruminant) consuming high S water; this approach allowed us to more accurately determine important rumen microbial changes in response to high S. We hypothesized that differences in rumen microbial populations, which are responsible for the breakdown of S and S-compounds, were associated with the host animal response to high S. Therefore, our objectives were to 1) determine how rumen microbial populations change in response to high S water, 2) determine if the extent of those changes were associated with variation in host animal response, and 3) determine functionality of the rumen microbial changes through a more global analysis of the rumen microbiome.

Timeline of Research Activities: ***Year 1*** – Completed animal trial, serum mineral analyses, production data analyses, and DNA extractions and preparations. ***Year 2*** – DNA sequencing (conducted at the DNA Core Laboratory in Columbia, Missouri) completed. Bioinformatic analyses were conducted to identify specific rumen microbial species that change (in abundance) in response to high S water, and importantly identify if such changes infer a "tolerance" to high S. Analysis of ruminal volatile fatty acids (VFAs) was also completed to determine shifts in rumen function. M.S. student Cara Clarkson completed her M.S. thesis in the summer of 2014. ***Year 3*** – Project was extended to include a second animal trial to confirm responsive microbial species and perform a functional analysis to better understand the biology underlying host response to high S water. M.S. student Amy Abrams is on-track to complete her M.S. thesis in summer of 2016.

Methods, Procedures, and Results: The initial animal study used Hampshire wether lambs (n = 40; 6 months of age) maintained at the UW Stock Farm. Lambs were administered a high S water treatment (~3,000 mg/L) over a 28 d trial period; they were individually penned to enable collection of individual feed and water intake. This level of S was chosen based on previous studies and because sheep have a higher tolerance to S because of S requirements for wool [3]. A 28 d trial period was chosen as signs of S toxicity would be more easily observed with the collection of individual feed and water intake; a common sign of S toxicity is decreased feed and water intake. Individual water and feed intake were estimated, along with average daily gain and feed efficiency measures. Blood and rumen fluid samples were collected on d 0 (baseline), d 7, and d 28.

Blood samples were analyzed for S, Cu, and Mo content, and no differences between individual animals were detected. Lambs were selected as highly tolerant (n = 4) and lowly tolerant (n = 4) to high dietary S based on individual water and feed intake, average daily gain and feed efficiency measures, and daily behavioral responses (recorded on a scale of 1 to 5). Rumen fluid samples collected on d 0, d 7, and d 28 (n = 24 samples in total were used for both VFA and DNA analyses. The VFA analysis indicated that intolerant lambs had greater concentrations of isobutyrate and isovalerate, but a lower concentration of valerate. The response in valerate has been observed in other high-S studies, and may indicate a potential adaptation by the rumen microbial population in response to high S. Also, initial concentrations of propionate were greater in tolerant lambs. Propionate is an end-product of starch and sugar fermentation, and considered a more efficient energy source for fermentation. The greater initial concentrations of propionate in tolerant animals may have given rise to greater ability to metabolize high levels of S.

The DNA analysis was used to generate rumen microbial profiles associated with response to high S water. In total, 145 microbial taxa (assumed to be single microbial species) were identified in the rumen fluid, with 29 affected by the tolerance class (tolerant or intolerant) by sampling day interaction; 39 affected by tolerance classification; and 26 affected by sampling day. Species in the *Prevotella* genus were highly detected as would be expected, but there were also numerous specie differences that may be potential indicators of tolerance to high S water. Also, some species responded initially to the high-S water challenge, but then returned to more 'normal' abundances, indicating that certain microbial species are capable of, and important for, adapting to a high S water challenge.

The second animal trial used Hampshire-cross lambs (n = 12; 6 months of age) also maintained at the UW Stock Farm. Similar to the first animal trial, these lambs were administered a high S water treatment (~3,000 mg/L) over a 28 d trial period; they were individually penned to enable collection of individual feed and water intake. Lambs remained individually penned for another 7 d after the trial period to allow for individual data collection to monitor recovery after removal of the high S water treatment. Individual water and feed intake were estimated, along with average daily gain and feed efficiency measures. Blood and rumen fluid samples were collected on d 0 (baseline), d 7, d 28, and d 35.

The DNA analysis revealed a total of 287 taxa in the samples from the second trial; abundance of 39 of those taxa differed with sampling day. When looking at abundance changes in association with the high S water treatment, several of the microbial species were in common between the two animal trials. While some of these were not in agreement across the two trials, several were and may be candidates for future treatment development. Two species of particular interest, due to their functions and agreement between the two trials, include *Prevotella nigrescens* and *Butyrivibrio fibrisolvens.* The functional analysis, based on sequence data from the second trial, is near completion and is expected to add new insights into host response to high dietary S.

Significance. Results overall confirm that the rumen microbiome does respond to high S water, and suggests that certain microbial species are particularly important to the host animal response to high S. Future research efforts will be aimed at using these results to develop treatments to improve animal response to high S water.

Student Training. This research served as two M.S. thesis projects – one for Ms. Cara Clarkson (M.S. – Summer 2014) and one for Ms. Amy Abrams (M.S. – Summer 2016). Both students were trained the areas of animal production, toxicity, genomics, water quality, and laboratory analyses (DNA sequencing, VFAs, etc.) and were responsible for carrying out all aspects of this research project, including both the animal and laboratory components. Ms.

Clarkson's portion of the research generated two research abstracts and two meeting proceedings; one manuscript has been prepared and is in the process of peer-review prior to journal submission (*Small Ruminant Research*). Ms. Clarkson is currently employed in management in the animal industry (Assistant Ranch Manager; Cheley Colorado Camps; Estes Park), with plans of seeking a Ph.D. program in the near future. Ms. Abrams' portion has generated two research abstracts and one meeting proceeding to-date; we anticipate an additional manuscript from this portion of the work shortly. Ms. Abrams was recently honored as an Outstanding Young Scholar by the Western Section of the American Society of Animal Science and was also selected as the Outstanding M.S. Student by the University of Wyoming's Chapter of Gamma Sigma Delta. She will be starting a Ph.D. program in Fall of 2016 at South Dakota State University. Finally, many undergraduates have assisted with these projects, further adding to the student training portion of this grant.

Publications To-Date:

- Abrams, A.N., C.J. Clarkson, K.J. Austin, M.J. Ellison, H.C. Cunningham, G. Conant, W.R. Lamberson, T. Taxis, and K.M. Cammack. 2016. Altered rumen microbial populations in response to high sulfate water in lambs. Proc. Western Sec. Young Scholar. *Accepted*.
- Powell, S., A.N. Abrams, K.J. Austin, D.C. Rule, E.A. Van Kirk, M.J. Ellison, H.C. Cunningham, G. Conant, W.R. Lamberson, T. Taxis, and K.M. Cammack. 2016. High sulfate water affects volatile fatty acid profiles in lambs. Plant & Animal Genomes XXIV Conference. P0608.
- Abrams, A.N., K.J. Austin, M.J. Ellison, H.C. Cunningham, G. Conant, T. Taxis, W.R. Lamberson, and K.M. Cammack. 2016. Effect of high sulfate water on rumen microbial populations in lambs. Plant & Animal Genomes XXIV Conference. P0607.
- Clarkson, C.J., A.N. Abrams, K.J. Austin, M.J. Ellison, H.C. Cunningham, G. Conant, W.R. Lamberson, T. Taxis, and K.M. Cammack. Effect of high sulfate water on rumen microbial populations in lambs. Proc. Western Sec. ASAS. *In Press.* (Abstract and Meeting Proceeding)
- Clarkson, C.J., H.C. Cunningham, L.E. Speiser, M.J. Ellison, K.J. Austin, and K.M. Cammack. 2014. Effect of high sulfur water on behavior, performance, and volatile fatty acid production in lambs. Western Sec. ASAS. *In press*. (Abstract and Meeting Proceeding)
- Abrams, A. N., K. J. Austin, M. J. Ellison, H. C. Cunningham, G. Conant, W. R. Lamberson, T. Taxis, and K. M. Cammack. 2015. High sulfate water affects rumen microbial populations in lambs. (Abstract.) High Plains Nutrition and Management Roundtable, Lingle, Wyoming. September 10, 2015.

Related Research: The current NRC recommendation for dietary sulfur is < 0.3% dry matter (DM), with the maximum tolerable concentration estimated at 0.4% DM [4]. Sulfur content in water, however, is typically reported in parts per million (ppm), and the most common form of S in water is SO_4^2. Polioencephalmalacia is associated with water SO_4^{2-} concentrations of ≥ 2,000 mg/L, which when combined with a typical 0.2% DM S feedstuff results in 0.53% DM total dietary S [5]. Therefore, when S or SO_4^{2-} content of water is included in the estimation of dietary S, the total dietary S is often much higher than anticipated.

Mechanism in the Rumen: In ruminants, production of toxic metabolites from S occurs in the rumen. Two classes of bacteria, assimilatory and dissimilatory, are present in the rumen capable of reducing SO_4^{2-}. Sulfide is produced by assimilatory S-reducing bacteria (SRB) and is used immediately for incorporation into metabolic processes [6]. The assimilatory SRB also reduce SO_4^{2-} to create amino acids. Dissimilatory SRB use SO_4^{2-} in respiration pathways and for energy to fuel growth and metabolism. However, in the respiratory pathways excess S^{2-} and H_2S are produced [7]. It is the dissimilatory class of SRB that cause the overproduction of toxic S products leading to cell damage, secondary infections, and the development of sPEM. These bacteria can also produce high amounts of S^{2-} [7], causing H_2S levels to increase rapidly.

Rumen Microbes. The rumen ecosystem is incredibly complex, and limitations in past technology have made it difficult to accurately classify and characterize rumen microbes. Traditional methods for determining microbial composition have relied on culture techniques. However, not all microbes can be cultivated with conventional laboratory procedures; therefore, the microbes that are cultured do not accurately represent the microbial communities [2]. These traditional methods have also been cited for lack of sensitivity [1]. DNA sequencing is a more sensitive technique, allowing for accurate identification of known and previously unknown microbes [2]. Recently other molecular techniques, such as PCR, have been used to successfully detect changes in SRB in response to S [8]. However, PCR techniques are dependent upon the probe sets chosen for specific bacteria; DNA sequencing quantifies each strain present and is not limited to detecting differences in only those bacteria queried.

Sources of High-S Water: Survey and field data have consistently shown surface and subsurface water can be high in SO_4^{2-}, particularly throughout the western regions of the U.S. The Water Quality for Wyoming Livestock & Wildlife review [9] reported that of > 450 forage and water collection sites located throughout the U.S., 11.5% exceeded the dietary S concentrations considered safe for livestock. Of those sites, 37% were located in the western U.S., including Wyoming. Drought further exacerbates the high SO_4^{2-} problem, as SO_4^{2-} is concentrated in the water due to greater evaporation and reduced moisture recharge [10]. Conventional gas and oil produced water discharge can also be high in SO_4^{2-}, particularly in arid regions such as the Big Horn Basin (John Wagner, personal communication). Of five water discharge sites sampled in the Big Horn Basin, two exceeded 2,000 mg SO_4^{2-}/L [11], well above the limit for livestock consumption. Although many CBM water sources are low in SO_4^{2-}, including those in the Powder River Basin, there have been reports of high and variable SO_4^{2-} concentrations (hundreds to thousands of mg/L) in CBM waters from the Fort Union Formation in Campbell County [11]. Because of the limited availability of water resources in those regions, many of those sources high in SO_4^{2-} are still the only option for livestock production, and there are no feasible methods for removing SO_4^{2-} from water (especially in a range situation).

High-S Water Effects on Livestock: Several experimental and field studies have reported reductions in performance of animals exposed to high S drinking water sources. Declines in average daily gain in cattle consuming high SO_4^{2-}water have been reported in both grazing and confined environments [12]. In addition, decreases in feed consumption and overall body weight gain are consistently reported. Polioencephalomalacia is characterized by necrosis of the cerebral cortex and remains one of the most prevalent central nervous system diseases in cattle and sheep [4]. Clinical signs of PEM include head pressing, blindness, incoordination, and recumbency accompanied by seizures, with young ruminants more commonly affected. The limited amount and availability of quality water is problematic for producers, especially when livestock consuming SO_4^{2-} contaminated water are also exposed to forages with elevated S levels.

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High-Resolution Modeling of Precipitation, Snowpack, and Streamflow in Wyoming: Quantifying Water Supply Variations in Future Decades

Basic Information

Title:	High-Resolution Modeling of Precipitation, Snowpack, and Streamflow in Wyoming: Quantifying Water Supply Variations in Future Decades
Project Number:	2015WY88B
Start Date:	3/1/2015
End Date:	2/28/2017
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Water Quantity, Climatological Processes, Hydrology
Descriptors:	None
Principal Investigators:	Bart Geerts

Publications

There are no publications.

High-resolution modeling of precipitation, snowpack, and streamflow in Wyoming: quantifying water supply variations in future decades

Annual Report: March 2015 – February 2016

Bart Geerts, PI
Yonggang Wang, co-PI

Major research findings and education activities

Abstract

This grant uses a community-supported weather forecast model to study precipitation, snowpack dynamics, and streamflow in and around Wyoming, a key headwaters region for the nation. The Weather Research and Forecasting (WRF) model has been run over a 30 year period (1980/10-2010/09) driven by actual weather (using a "reanalysis" product) at a sufficiently fine resolution (4 km) to capture orographic precipitation and runoff, which are very terrain-sensitive. Our simulations show that WRF, with a land surface model (the NOAH multiphysics scheme) accurately captures observed seasonal precipitation and snowpack build-up in Wyoming. The rather long simulation time is needed to validate statistical probabilities of extreme precipitation amounts at timescales ranging from hourly to annual, 1 April snowpack water loading, and streamflow at various times of the year for all streams in Wyoming at locations upstream of the first reservoir.

The proposal aims to answer two questions: firstly, how well does WRF simulate the observed year-to-year variations in precipitation, snowpack dynamics, and streamflow in the headwaters region of Wyoming? And secondly, how is the distribution of these parameters expected to change in a changing climate? As to the latter, a pseudo-global warming technique is used to perturb the retrospective reanalysis with the anticipated change according to the consensus global model guidance under IPCC's most likely scenario. This technique preserves low-frequency general circulation patterns and the characteristics of storms entering the domain. The model then is being rerun over 30 years with perturbed conditions representing anno ~2050, and any changes in the probability density functions of the above-mentioned parameters are examined. Thus we aim to quantify changes in water supply parameters in Wyoming not just in an average sense, but also in terms of probabilities of water excesses and shortages.

We compared the 30 year retrospective simulation against SNOTEL and PRISM precipitation. While precipitation amounts validate very well (better than 10% over the mountains, at SNOTEL sites), the snowpack's water loading (snow water equivalent or SWE) tends to be underestimated by 20-30%. The seasonal cycle of SWE is captured well, including the rate of spring ablation.

In the original proposal we called for WRF Hydro to be run offline to simulate streamflow in the WRF-simulated current and future climates. It is not possible to evaluate the land surface model's water fluxes, in particular evapotranspiration and soil infiltration, at least not to the same level of accuracy as precipitation or temperature, mainly because good-quality, reliable gridded data are not available. Therefore, and because groundwater release (in springs) depends on unresolved sub-soil water flow characteristics, the conversion of rainwater and snow melt to run-off and stream flow, requires calibration of WRF Hydro streamflow against observed streamflow (gauge data). This watershed-specific calibration (or "training") process optimally captures unknown sub-surface and surface parameters. This WRF-Hydro training will be based on the 30

year retrospective run, and because the unknown sub-surface and surface parameters are largely permanent (not affected by climate change), the same watershed-specific training can and will be used to estimate changes in seasonal and extreme streamflow in an anno ~2050 climate. Our limited experience with WRF Hydro, developed in Year 3 of this project, will be used as basis for one or more new research proposals.

1. Relevance to critical regional and State water problems

Water is essential to the economy and the natural resources of the arid western USA. The interannual variation of water availability is significant in this region, and remains essentially unpredictable. In a warming climate the snowpack may melt off earlier in spring and water may become less readily available in the warm season for most years. But predictions of the climate over the next few decades are highly uncertain, especially regarding precipitation, snowpack dynamics, and streamflow. And an average change carries far less meaning in Wyoming than a change in probabilities of a dry or wet year.

Gaining a better understanding of such change matters. For instance, water treaties between Wyoming and its neighboring states involve rigid parameters such as growing season streamflow expectations based on 1 April snowpack conditions. Long-term changes in the relationship between the snowpack's water loading on 1 April and spring runoff are entirely speculative at this time, and better guidance would be most welcome, for instance to the State's Engineer's Office. A better understanding of long-term changes in typical and extreme patterns of snowpack accumulation & ablation and in seasonal water discharge in the North Platte, the Snake, and especially the Green River watersheds is of great interest to Wyoming's water obligations and water development opportunities, as well as to agricultural and forestry interests in the state, and to downstream stakeholders.

2. Objectives

The objectives of this project are twofold: firstly, we will calibrate the WRF model, with atmospheric physics choices determined in our previous work, by selecting land surface parameter choices that optimally simulate a 30-year record of precipitation, snowpack dynamics, and streamflow in the headwaters region of Wyoming. And secondly, we will use this calibrated WRF model to examine differences in the distribution of precipitation, snowpack SWE, and streamflow in a 2050s climate, compared to the climate of the last three decades. The term "distribution" implies that we do not only examine the mean, but also the spread and the probability of extremes. The focus will be on the seasonal cycle and specific times of the year (e.g. 1 April, by which time water allocations to downstream states have to be negotiated), but we will also look at daily and hourly precipitation distributions and their changes, because of the relevance to agricultural interests and hydraulic structures engineering.

3. Methods, procedures, and facilities

3.a Numeric model and validation datasets

The Weather Research and Forecasting (WRF-ARW) model version 3.7.1 is applied to the western interior U.S. (**Fig. 1**). The computational domain has 420 × 410 grid points with 51 stretched vertical levels topped at 50 hPa. The model domain has a 4 km grid spacing in the horizontal, which is fine enough to resolve deep convection and the details of the terrain. The model integration is conducted over a 30 year period from 1 October 1980 through 30 September 2010. The model was configured with the Thompson cloud microphysics scheme, the Rapid Radiative Transfer Model (RRTMG) shortwave and longwave radiation scheme, the Yonsei University (YSU) planetary boundary layer scheme, and the revised Monin-Obukhov surface layer scheme, as well as the Noah-MP land surface schemes. No cumulus scheme is used because the 4 km resolution can resolve convection explicitly. These schemes were chosen based on the sensitivity investigation of three years of 4 km WRF simulations over the studied domain (Fig. 1) for three parameters. i.e., the monthly mean diurnal minimum and maximum temperatures and monthly precipitation, including snow accumulation during the cold season. Validation datasets include all SNOTEL (Snow Telemetry) sites, providing precipitation rate and snowpack snow water equivalent (SWE), and the 4 km PRISM (Parameter-elevation Regressions on Independent Slopes Model) estimates of monthly mean values of precipitation and temperature.

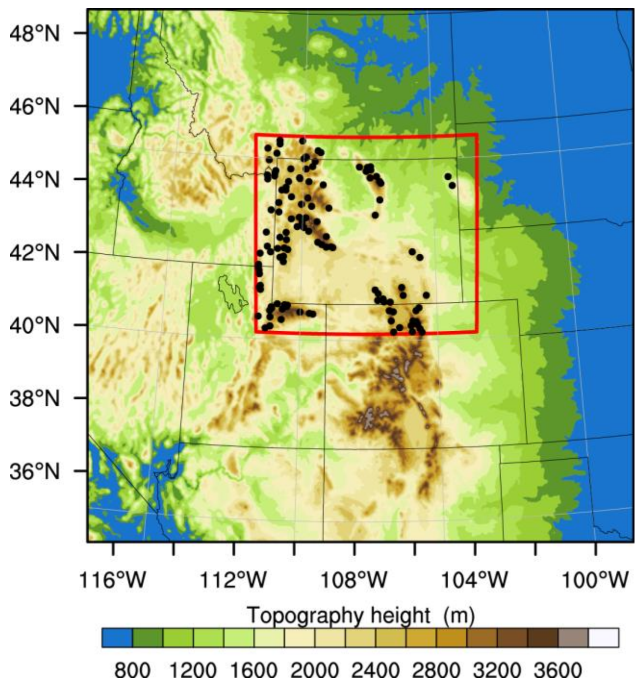

Fig. 1. Model domain of the 4-km regional climate simulation. The black dots are SNOTEL sites within Wyoming and vicinity.

3.b Current climate reanalysis data, CMIP-5 model guidance, and the PGW technique

Several "reanalysis" products (i.e., balanced 3D representations of the atmosphere and the underlying surface at a specific time in the recent past) have been developed. The Climate Forecast System Reanalysis (CFSR) is used in this work to provide initial and lateral boundary conditions. This dataset has a 0.5^o x 0.5^o spatial resolution and a 6-hourly temporal resolution. The 2050s climate will use the same reanalysis data in the same domain at the same resolution, but the initial and boundary conditions are continuously perturbed using the pseudo-global-warming (PGW) technique. The perturbations are the monthly-mean Coupled Model Intercomparison Project 5 (CMIP-5) predicted changes in a 50-year period. The PGW technique allows unbiased climate change assessment relative to current low-frequency variability such as El Niño. The PGW technique is based on the premise that changes in intra- to inter-annual atmosphere-ocean teleconnections are inadequately understood, therefore it is best to preserve low-frequency general circulation patterns and the characteristics of storms entering the domain. We have followed NCAR's guidance as to which the ensemble of 19 CMIP-5 models has been used. All climate models have been run for several emission scenarios out to 2050 and beyond. We have used the Regional Concentration Pathway 8.5 scenario, as it is the most likely one.

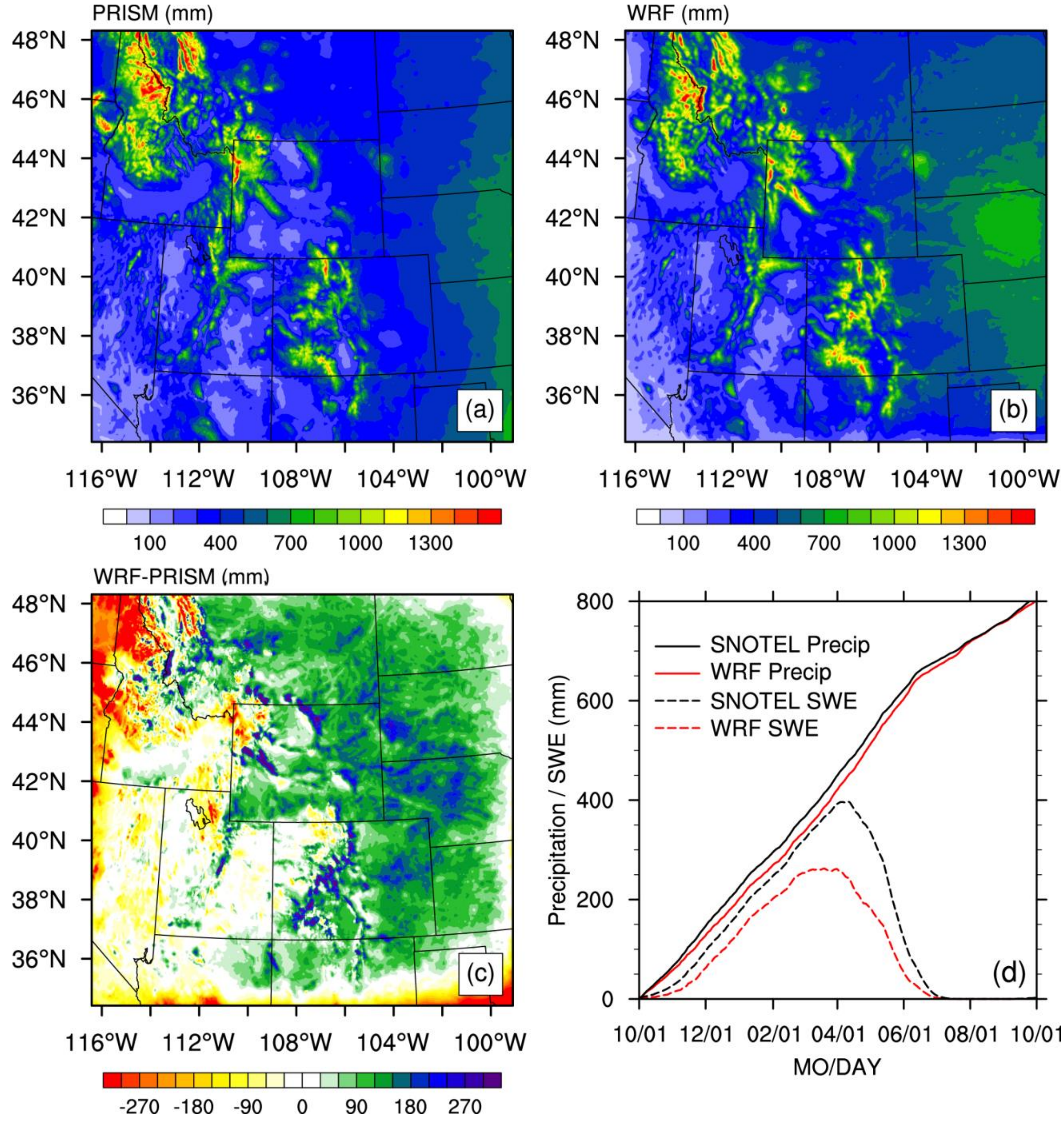

Fig. 2. Evaluation of 25 years of WRF (3.7.1) simulations. (a) PRISM annual precipitation; (b) WRF annual precipitation; (c) absolute difference between (b) and (a); (d) average seasonal precipitation accumulation and snowpack SWE at all SNOTEL sites shown in Fig. 1 as modelled (WRF) and observed (SNOTEL).

3.c NCAR Wyoming Supercomputer Center (NWSC)

The proposed modeling work would not be possible without access to the facilities at the NWSC, in particular the Yellowstone system and massive data storage. Our current work has been supported by three separate NWSC allocations totaling 18.96 M core hours on Yellowstone. Large Allocation Requests under the "Wyoming allowance" (20%) can be submitted twice a year, most recently in May and November. These are no-cost high performance computing requests, reviewed by the Wyoming–NCAR Resource Advisory Panel (WRAP). This opportunity is designed specifically for federally-funded research in atmospheric, earth system and closely related sciences. The present grant from the UW Office of Water Programs (partly funded by the USGS) qualifies for a large NWSC allocation request. We will apply for a new allocation in May 2016.

4. Progress to date

4.a Retrospective simulations

In July 2015 we completed the full 30-year simulation using an earlier version of WRF (v. 3.5.1). After some analysis we found a characteristic, seasonally dependent spatial precipitation bias pattern across the mountains, changing sign across the continental divide range. This bias remained small in the first 20 years of simulations, but became quite large in the last 10 years. WRF developer Jimy Dudhia found that it was caused by a deficient treatment of lateral boundary conditions, causing severe problems for long-term (multi-decadal) simulations particularly when a very high resolution is used. This bug was fixed in the new version 3.7.1. We have almost completed the entire 30-year simulation with WRF v. 3.7.1. Results from the first 25 years of this simulation are shown in **Fig. 2**.

Wang et al. (2016a) describes this new 30-year retrospective simulation including WRF's architecture, calibration technique, and performance in comparison with SNOTEL (precipitation) and PRISM (precipitation and surface temperature) datasets. Results show that WRF v3.7.1 accurately captures observed seasonal precipitation, snowpack build-up, and snowpack ablation in the headwaters region around Wyoming (Fig. 2). The differences in annual precipitation between WRF and PRISM are quite small compared to the total (Fig. 2c against Fig. 2a or b). WRF seems to overpredict precipitation in the high ranges of the Wind River and Bighorn mountains. This may reflect an underestimate in the PRISM dataset (there are no SNOTEL sites above the tree line). WRF may slightly underestimate precipitation over lower ranges, such as the Wyoming range, Yellowstone NP, and the Sierra Madre. Precipitation is overestimated in the High Plains, mostly because thunderstorm activity is overestimated in summer. Please ignore the WRF underestimation along the upstream domain boundaries. In short, it is captured quite well in the Colorado-Wyoming headwater region (Fig. 2c). Overall, WRF underestimates precipitation by 7% at the SNOTEL sites shown in Fig. 1 (Fig. 2d).

Snowpack dynamics at SNOTEL sites in this region are captured well (Fig. 2d), although the SWE are underestimated somewhat, by 20-30%. The seasonal distribution of SWE is captured well in particular the rate of spring ablation.

The retrospective and future simulations will be archived by the USGS North Central Climate Science Center, and will be publically available as soon as they will be completed. A framework agreement with the director (Dr. Morisette) is in place, and they already archived the earlier retrospective simulations (based on WRF v3.5.1).

Jing et al. (2016a) compares precipitation simulated by WRF with that from the datasets of SNOTEL, PRISM, and National Centers for Environmental Prediction (NCEP) National Hourly Multisensor Precipitation Analysis Stage IV dataset, using the 10-year subset of the 30-year retrospective simulation described in Wang et al. (2016a). The results show WRF compares well against SNOTEL, especially for wintertime precipitation, as well as against NCEP IV and

PRISM in the plains and valleys in the vicinity of NEXRAD radars. However, NCEP IV significantly underestimates orographic precipitation. PRISM is good in areas near SNOTEL sites but questionable in areas without gauges, esp. in areas above the treeline. Statistical analysis of wintertime precipitation suggests the bias and correlation between PRISM and WRF depend on gauge density and elevation.

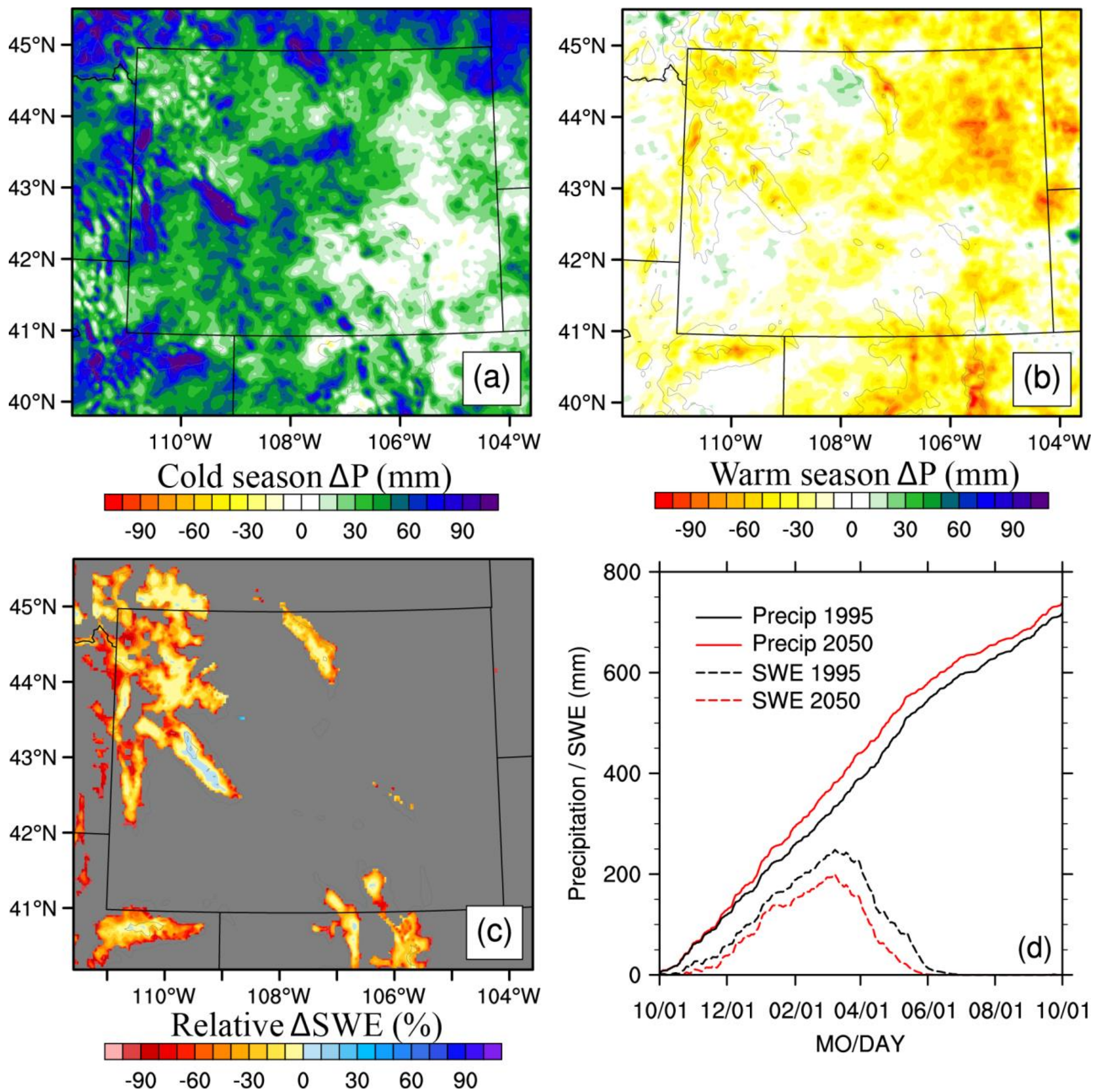

Fig. 3. Comparison of 5 years of retrospective and PGW simulations over Wyoming and vicinity. (a) The 5-yr average difference of precipitation during the cold season (future minus current); (b) same as (a), but for warm season; (c) the 5-yr average difference of SWE on 1 April (future minus current); (d) average seasonal precipitation accumulation and snowpack SWE at all SNOTEL sites shown in Fig. 1 from retrospective (black curves) and PGW (red curves) simulations. The thin grey contours in (a)-(c) show the terrain.

4.b PGW simulations

We are conducting 30 year future climate simulations centered on 2050 using the PGW technique over the same domain in Fig. 1. So far we have rerun the WRF v. 3.7.1 model over five years with the perturbed 2050-era initial and boundary conditions, and find more winter precipitation over Wyoming and vicinity (Fig. 3a), but summer precipitation decreases in general (Fig. 3b). Less SWE is predicted on 1 Apr in future climate (Fig. 3c), and a significantly earlier date of peak SWE and earlier snowmelt at most places (Fig. 3d), except at high-elevation places (> ~3,300 m MSL), on account heavier spring snowfall there. The fraction of precipitation falling as snow decreases in future climate (not shown). We should have the WRF v3.7.1 future climate simulation completed by June 2016. The results will be used to examine the effect of climate variability and projected global warming on the statistical distributions of precipitation amounts and SWE in the interior western US (Wang et al. 2016b).

4.c Publications and presentations

Wang, Y., B. Geerts and C. Liu, 2015: Regional climate simulations of cold-season precipitation and snowpack over the US northern Rockies: validation and examination of factors controlling the precipitation distribution. Presented at the 2015 annual meeting of the American Meteorological Society, Phoenix AZ.

Wang, Y., B. Geerts, and C. Liu, 2016a: Retrospective high-resolution regional climate simulations over interior Western US: validation of fine-scale patterns of precipitation and snowpack over complex terrain. *J. Climate*, to be submitted.

Jing, X, B. Geerts, Y. Wang and C. Liu, 2016a: Regional climate simulation of precipitation in interior western us: comparisons with gauge and high-resolution datasets. *J. Climate*, to be submitted.

Wang, Y., B. Geerts, and C. Liu, 2016b: Changing precipitation and snowpack dynamics over US northern Rockies in a changing climate: insights from high-resolution WRF simulations. *J. Appl. Meteor. Climat.*, in preparation.

Wang, Y., B. Geerts, and C. Liu, 2016c: Precipitation and snowpack dynamics over mountains in the interior Western US in a changing global climate. Will be presented at the AMS 17th Conference on Mountain Meteorology, Burlington VT.

Jing, X, B. Geerts, Y. Wang and C. Liu, 2016b: Regional Climate Simulation of Precipitation in the Interior Western US: Comparisons with High-Resolution Datasets and Ambient Factors Controlling Wintertime Orographic Precipitation Distribution. Will be presented at the AMS 17th Conference on Mountain Meteorology, Burlington VT.

5. Training potential

This project will build Dr. Yonggang Wang's <u>post-doctoral</u> expertise in regional climate modeling and will foster his collaborative ties with NCAR. This work builds on the expertise developed by Dr. Roy Rasmussen's group at NCAR in their "Colorado Headwaters project", in particular the expertise of Dr. Changhai Liu. Dr. Liu's guidance in this project has been invaluable.

Xiaoqin Jing, a PhD student, is being trained as part of this project. Her dissertation focuses on the general validation of orographic precipitation, and the ambient factors controlling wintertime orographic precipitation distribution using the 30-year retrospective simulation. She uses our retrospective model output and observational precipitation datasets (PRISM and NCEP-stage IV).

Quantifying Return Flow in the Upper Wind River Basin

Basic Information

Title:	Quantifying Return Flow in the Upper Wind River Basin
Project Number:	2015WY89B
Start Date:	3/1/2015
End Date:	2/28/2017
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Water Quantity, Hydrology, Irrigation
Descriptors:	None
Principal Investigators:	Ginger Paige, Scott Miller

Publication

1. Gordon, B.L., 2014. Measuring return flows. Western Confluence Magazine Vol. 1, Ruckelshaus Institute, Laramie WY.

Quantifying Return Flow in the Upper Wind River Basin
Annual Report: March 2015 – February 2016

Principle Investigators:
Ginger B. Paige, Associate Professor, Dept of Ecosystem Science and Management, University of Wyoming, **gpaige@uwyo.edu**, (307) 766-2200.
Scott N. Miller, Professor, Dept of Ecosystem Science and Management, University of Wyoming, **snmiller@uwyo.edu** (307) 766-4274.
Additional Investigator:
Andrew D. Parsekian, Assistant Professor, Dept of Geology and Geophysics, University of Wyoming, aparseki@uwyo.edu (307) 766-3603.

Abstract:
Population growth in the intermountain west, coupled with frequent drought and the prospects of climate change, are challenging the security of water supplies and the agricultural economy in Wyoming and the region. Agriculture is the largest user of water in Wyoming and the intermountain west and accounts for approximately ninety percent of the total amount of water withdrawn from streams and aquifers. However, only a portion of applied water is consumptively used. The rest is returned to streams or aquifers. Some of the potential benefits include recharge of alluvial (shallow) aquifers that serve as underground storage reservoirs, increased likelihood of maintaining late season flow and a steadier more reliable source of water downstream resulting from the return flow pattern of an interactive stream-aquifer system. This project will apply new methods and techniques to directly quantify return flow from controlled agricultural systems in the Spence/Moriarty Wildlife Habitat Management Area in the East Fork watershed in the Upper Wind River Sub-Basin in Wyoming. This location is ideal for this study as we can work directly with the managers controlling the application and timing of the irrigation water. We will use a water balance approach at the "reach scale" to quantify the return flow in the system. To directly measure and monitor the pathways and timing, we will employ new methods in hydrogeophysics and tracers at the field scale. Geophysics tools will be used to map subsurface flow paths, monitor and quantify return flow. In addition, we will use tracers such as isotopes and geochemical markers to directly measure and monitor return flow in the system. Results from this study will be compared to an irrigation return flow study conducted in the Upper Green River Basin in the 1980s. An understanding of the quantity and timing of return water flow is critical for effective water management for downstream water users and maintaining agriculture water security in the state.

Statement of critical regional or State water problem:
Agriculture is the largest user of water in Wyoming and the intermountain west. However, increasing population in the intermountain west and changing demands on limited water resources from energy and municipal use are challenges for effectively managing our water resources. Agriculture accounts for approximately

ninety percent of the total amount of water withdrawn from streams and aquifers. However, only a portion of applied water is consumptively used. The rest is returned to streams or aquifers by overland flow, subsurface lateral flow and by percolation through the soil to an aquifer, which stores or returns it to the stream system. Some of the potential benefits of irrigation can include recharge of alluvial (shallow) aquifers that serve as underground storage reservoirs, increased likelihood of maintaining late season flow and a steadier more reliable source of water downstream resulting from the return flow pattern of an interactive stream-aquifer system. An understanding of the quantity and timing of return water flow is critical for effective water management for downstream water users and maintaining agriculture water security.

Objectives:

This study uses a water balance approach coupled with intensive field investigations and characterizations of the subsurface using geophysics tools to quantify and document return flow process in the Spence/Moriarty Wildlife Habitat Management Area (WHMA) in the Upper Wind River Basin, in Northwest Wyoming.
The specific objectives are to: 1) quantify the contribution of return flows to sustained late-season flow (baseflow); 2) assess the quality of the return-flow water; and 3) compare results of this study to the results from the return flow study of a flood irrigation system that was conducted in the New Fork in the Upper Green River Basin (Wetstein et al., 1989).

Methods:

To quantify the return flow, we are using a water balance approach at the reach scale coupled with targeted sets of field experiments designed to specifically track and quantify the water that moves through the sub-surface and returns to the stream system.

Our research efforts are focused on Bear Creek a major tributary of the East Fork in the Spence/Moriarty WHMA (Figure 1). The Bear Creek section of the Spence/Moriarty WHMA is ideal for this study as there is a well-defined irrigated section of the watershed that can be isolated to capture a reach scale water balance (Figure 2). At the upper end of the reach, water is diverted into the Fosher ditch to deliver water to the four identified fields (outlined in red.) Pressure transducers to measure water depth have been installed at key locations within Bear Creek and Fosher ditch to capture changes in flow during the irrigation season within the reach. Rating curves were developed for each site to convert depths into stream flow.

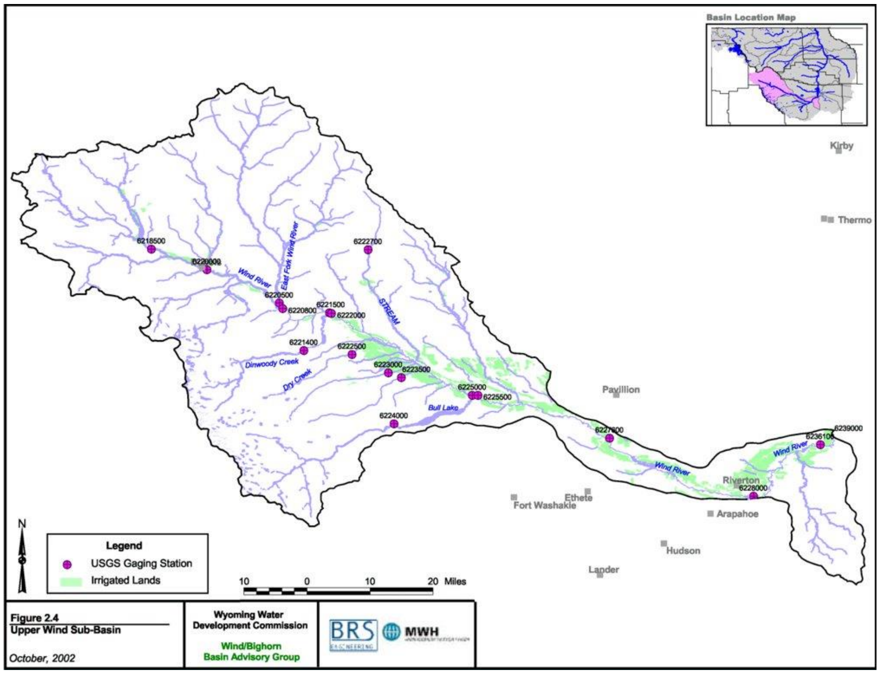

Figure 1. Location of the East Fork in the Upper Wind River Sub-Basin (courtesy: Wyoming Water Development Office *http://waterplan.state.wy.us/plan/bighorn/*)

Geophysics:
A suite of background geophysical measurements are made on each field to characterize the subsurface structure of the irrigated fields. Measurements include: Seismic, ERT, and GPR (ground penetrating radar).

Surface NMR (Nuclear Magnetic Resonance) is used to measure water content in the subsurface. Measurements are taken before and after the irrigation season in each of the irrigated fields to capture changes in soil moisture storage with depth in each irrigated field.

Evapotranspiration:
A Large Aperture Scintillometer (which measures sensible heat flux) is coupled with a meteorological station to measure climatic conditions and evapotranspiration on one of the irrigated fields.

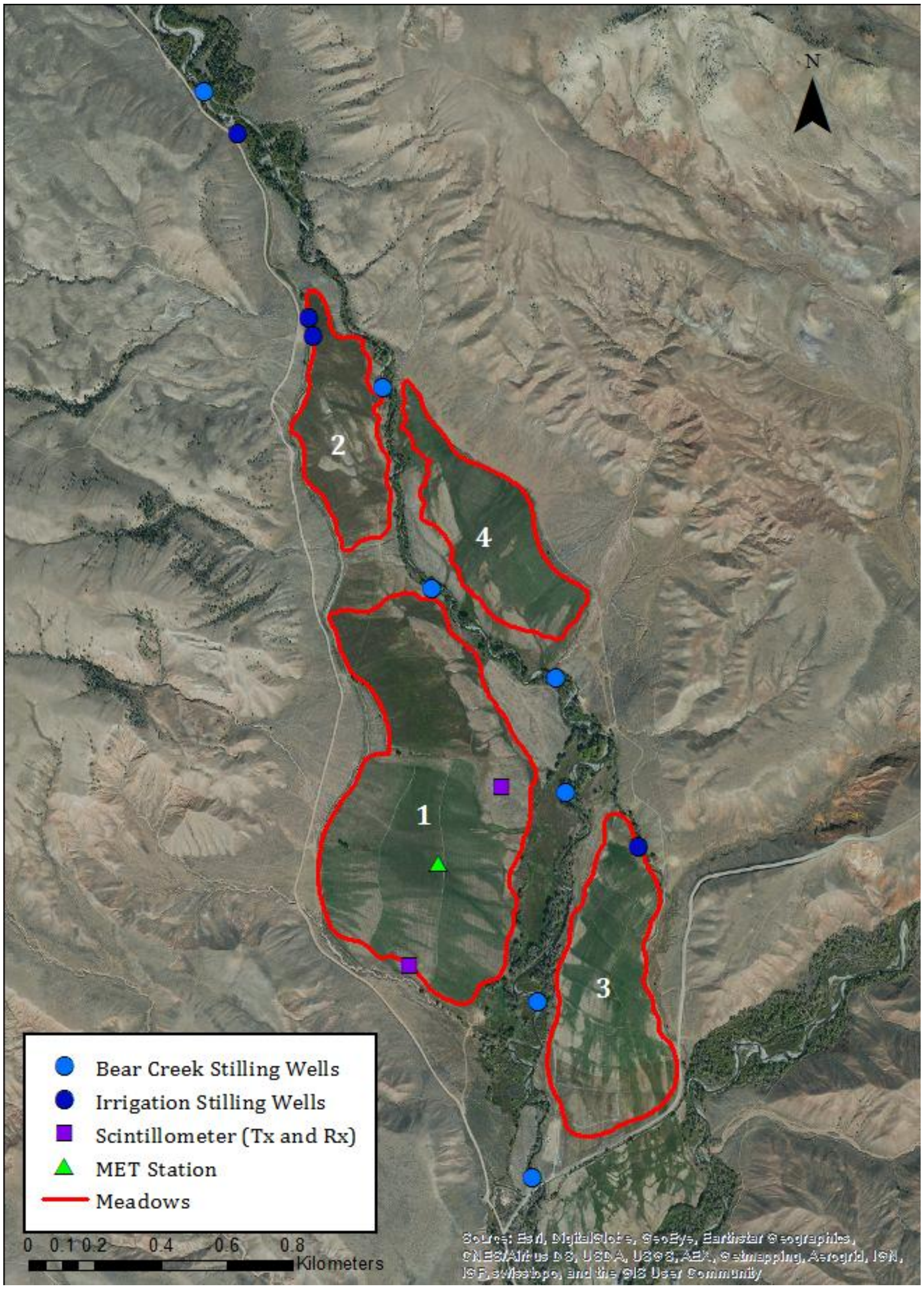

Figure 2. Location of installed instrumentation relative to irrigated meadows and stream.

Reach Scale Water Balance:

The reach scale water balance for Bear Creek is calculated using the following equation:

$$(P+Q_{IRR}) = \Delta S+Q_{RT}+(ET_B+ET_{NB})+\Sigma$$

where P is precipitation (mm), Q_{IRR} is applied irrigation water (mm), ΔS is the change in storage in the subsurface (mm), Q_{RT} is return flow (mm) = (Q_{IN}-Q_{OUT}), ET_B, beneficial evapotranspiration (mm), ET_{NB} is non-beneficial evapotranspiration - riparian vegetation (mm), and Σ is error (mm). To calculate Qrt, Q_{IN} is stream discharge at stream gage at the upper end of the reach and Q_{OUT} is stream discharge at the down stream gage.

Intensive Field Investigations:
Intensive field scale measurements using Electrical Resistivity Tomography (ERT) during irrigation are used to capture changes in soil moisture (Zhou et al. 2001). ERT measures electrical potential differences between a series of electrodes, which are generated by the electric current injected into the subsurface. The resistivity is directly related to the soil water content in the soil. We use time-lapse ERT measurements over a 60 m. transect to quantify the changes in soil water content during wetting and drying cycles over time.

Water Quality:
Water quality is monitored continuously at two locations, above and below the study reach using in-situ water quality probes. These measurements allow us to continuously monitor water quality, in particular EC and temperature, throughout the irrigation season and assess any changes in water quality with changes in flow. *We have seen no significant changes in EC over the course of the study to date.*

Progress to date:
Significant progress has been made to address the project objectives over the past two years. Much effort has been devoted to developing and refining the study design and methods to meet the site characteristics. This included focusing our research efforts on Bear Creek, a major tributary of the East Fork. The section of Bear Creek just upstream of the confluence with East Fork is ideal of isolating an irrigated reach to conduct in-depth, high-resolution investigations to quantify return flow in this system.

A large suite of hydrologic and hydrogeophysical instrumentation have been installed or deployed in the Bear Creek Study area (Table 1) over the 2014 and 2015 field seasons. Locations of the permanent instrumentation relative to Bear Creek are shown in Figure 2. Together, these measurements are used to 1) characterize the near subsurface and 2) measure the components of the water balance over the irrigation season. Though the research will continue and expand over the next year, a summary of the results to date is presented below.

Geophysics:
Background geophysical and hydrogeophysical characteristics were measured in the four irrigated meadows in 2014 and 2015. Surface NMR data were collected in June 2014 to map water content with depth. This process was repeated in 2015, but at two time steps – before and after the irrigation season - to quantify the change in water content in the subsurface over the irrigation season.

Table 1. Instrumentation installed in Bear Creak study area to measure components of the water balance and quantify return flow.

INSTRUMENTATION	Criteria Measured	Approx. Date
Permanent:		
10 Pressure Transducers (7 Bear Creek & 4 Ditches)	Water Pressure, Depth, and Temperature	Jul-'14/Jun –'15
3 Conductivity Meters (2 Bear Creek & 1 Focher Ditch)	Specific Conductance and Salinity	Jul-'14
Meteorological Station:		
Anemometer	Wind Speed & Direction	Jul-'14
Net Radiometer	Net Radiation (Rs, Rl, Albedo)	Jul-'14
Air Temperature Sensor	Temperature, Humidity	Jul-'14
Tipping Bucket Rain Gage	Precipitation	Jul-'14
Soil Moisture Sensors	Volumetric Water Content	Jul-'14
Heat Flux Plates	Soil temperature	Jul –'15
Large Aperture Scintillometer	Sensible Heat Flux	Sept '14
Eddie Covariance Flux Tower	Transpiration	*to be installed: May '16*
PERIODIC:		
Nuclear Magnetic Resonance (NMR)	Water Content	Jun '14 Jun & Oct '15
Electrical Resistance Tomography (ERT)	Resistance	Aug '14 & Aug '15
Seismic/Ground Penetrating Radar/Electrical Magnetic	Subsurface Structures	Jul- Aug '15

Stream flow and irrigation:
Stream flow within the reach is measured using a series of 7-stream flow gaging stations (stilling wells, Figure 2) were installed in Bear Creek and monitored over the 2014 and 2015 irrigation seasons. In addition, flow is measured in the irrigation ditches to quantify water removed from Bear Creek and applied through the irrigation system. Results from 2015 are shown in Figure 3. Rating curves developed for each of the gaging station sites had very good stage – discharge relationships (average R^2 = 0.97).

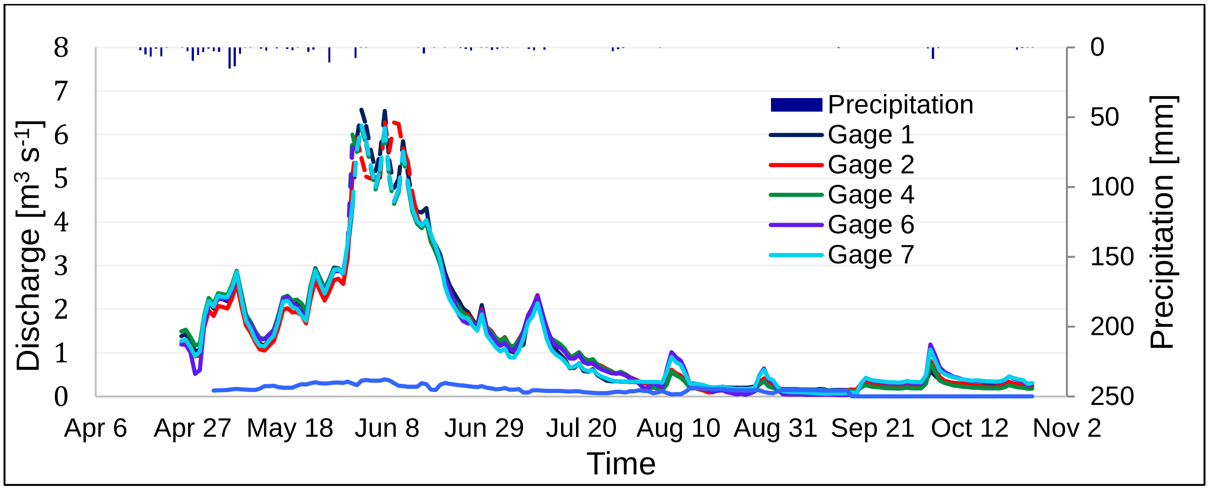

Figure 3. Seasonal hydrographs, precipitation and irrigation from all sites (2015).

Return flow for the entire reach was calculated by subtracting outflow from inflow over the irrigation season (Fig. 4). The shift in hydrographs between June 20 and August 1 shows that return flow occurs during the irrigation season.

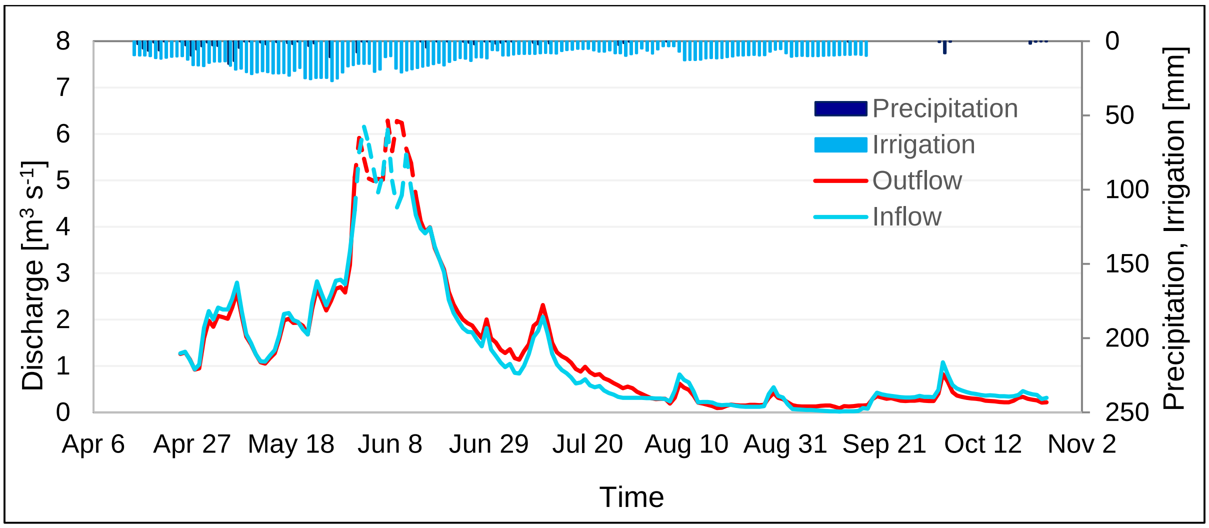

Figure 4. Inflow and outflow hydrographs used to calculate return flow (Q_{RT}).

Evapotranspiration:

Evapotranspiration for the irrigated meadow was calculated for the growing season using the scintillometer and met station measurements. The results from meadow 1 were extrapolated to the other meadows using area vegetation measurements collected before mowing of the fields. Strong correlations between Penman-Monteith and the scintillometer provided foundation for using Penman- Monteith to estimate ET from the riparian areas (Fig. 5).

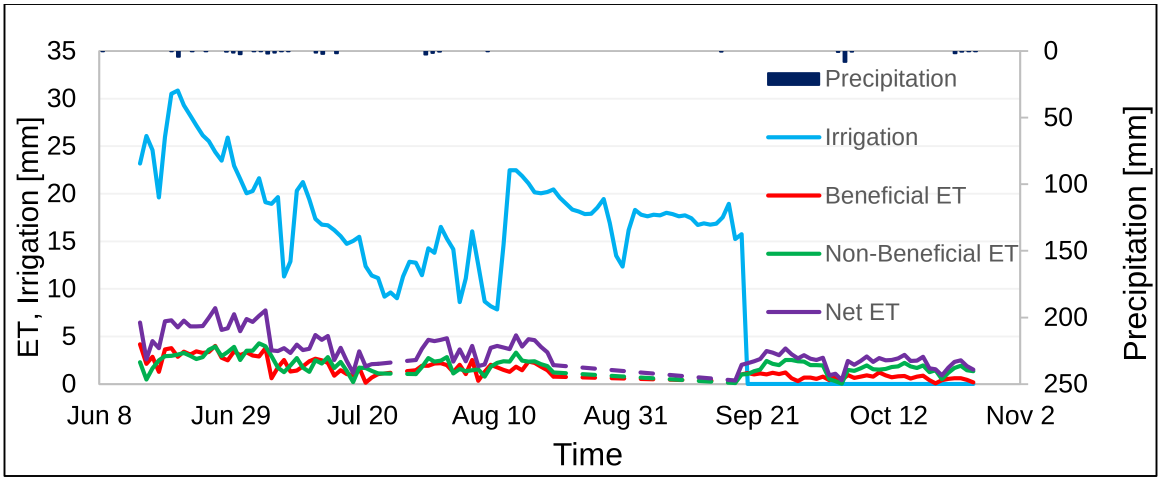

Figure 5. Evapotranspiration for the 2015 irrigation season. Non-beneficial ET is the evapotranspiration for the riparian areas calculated from using Penman-Montheith. Beneficial ET was calculated from the scintillometer.

Closing the Water Balance:
Each of the components of the water balance was measured or calculated independently for the 2015 irrigation season. This allowed us to close the reach water balance equation:

$$(P+Q_{IRR}) = \Delta S+Q_{RT}+(ET_B+ET_{NB})+\Sigma$$

$$36 \text{ mm} + 867 \text{ mm} = 110 \text{ mm} + 345 \text{ mm} + (184 \text{ mm} + 209 \text{ mm}) + 54 \text{ mm}$$

This resulted in a calculated return flow for the reach of 38.2%. This value is less than the four-year average return flow of 70% for the New Fork Irrigation district in the Upper Green River Basin (Wetstein et al., 1989). We also found that the return flow was quick and not a slow, delayed response as observed in the New Fork. This result was not unexpected due to the significant differences in the characteristics of these two basins. Additional years of data are necessary to determine the average return flow response for this system.

Intensive Field Experiment:
Time lapse ERT has been used to map changes in resistivity in meadow 1 (Fig. 2) during irrigation. The changes in resistivity can be directly related to increases in soil water content (Fig. 6). These studies will be repeated and expanded over the next field season to quantify subsurface flow and map potential flow paths. These measurements, coupled with the reach water balance metrics, will be used to identify the mechanisms controlling the quantity and timing of return flow in this system.

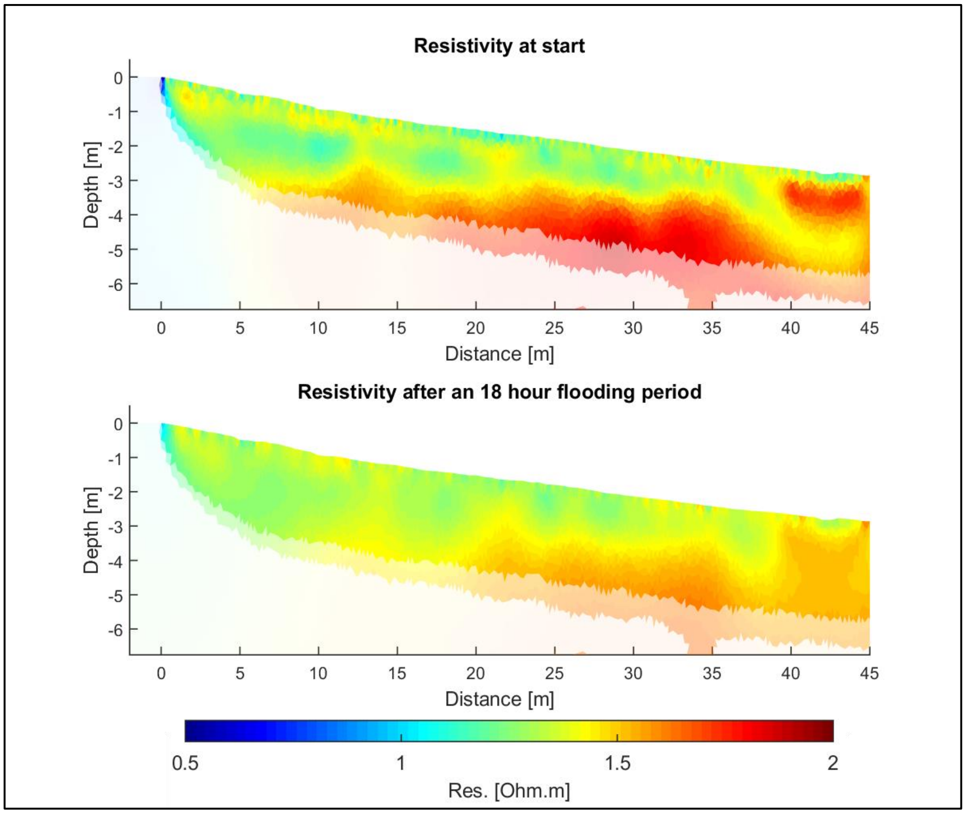

Figure 6. Time Lapse ERT during wetting and drying (before, during and after irrigation applications).

Next Steps:
For the upcoming 2016 irrigation season, we will continue to measure the components of the water balance.

In addition, we will:

- Continue and expand ET measurements
- Continue and expand geophysical measurements
  Conduct intensive field scale studies using time-lapse ERT (MPT) on multiple fields
- Develop a network of boreholes to monitor subsurface flow using time-lapse borehole NMR to track soil water in the subsurface.

References:
Wetstein, J.H., V.R. Hasfurther and G.L. Kerr (1989). Return Flow Analysis of a Flood Irrigated Alluvial Aquifer: Final Report to Wyoming Water Research Center and Wyoming Water Development Commission.

Zhou, Y. Q., Shimada, J., and Sato, A., (2001). Three Dimensional Spatial and Temporal Monitoring of Soil Water Content Using Electrical Resistivity Tomography. Water Resour. Res., Vol. 37, pp. 273–285.

Additional Project Support:
This project has leveraged additional support from two funding sources to expand the instrumentation and provide additional funding to support graduate student research.
1) Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG, (NSF EPS-1208909))
2) Walton Foundation (through the Haub School of Environment and Natural Resources, University of Wyoming) provided funding for MS graduate student (Bea Gordon).

Presentations:
Paige, G.B., Miller S.N., Parsekian A.D., Gordon B.L., Claes, N. 2016. Quantifying Return Flow in the Upper Wind River Basin. Big Horn Basin Planning Meeting, March 15, 2016, Worland, WY. (invited presentation)

Claes, N., G.B. Paige, A.D Parsekian, and S.N Miller. 2016. Time-lapse ERT and NMR for quantification of the local hydrologic impact of irrigation management. 29th Annual Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), March 20-24, 2016, Denver, CO. (poster)

Parsekian A.D., Paige, G.B., Miller S.N., Gordon B.L., Claes, N. 2015. Return flow: untangling the water budget on flood-irrigated fields. 2015 Water Interest Group Meeting, Oct. 13, 2015, Laramie, WY. (invited presentation)

Gordon, B.L., Miller, S.N., Paige, G.B, Claes, N., Parsekian, A., Beverly, D. 2015. A Comparison of Methods for Calculating Evapotranspiration in a Semi-Arid Agricultural System, 2015 AGU Fall Meeting, December 14-18, 2015, San Francisco, CA. (poster)

Claes, N., Paige, G.B, Parsekian, A.D., Miller, S.N., Gordon, B.L. 2015. Characterization of return flow pathways during flood irrigation. 2015 AGU Fall Meeting, December 14-18, 2015, San Francisco, CA. (poster)

Gordon, B.L., Miller, S.N., Paige, G.B, Claes, N., Parsekian, A., Beverly, D. 2015. Calculating Return Flows and Consumptive Use in a Semi-Arid Agricultural System, 2015 Water Interest Group Meeting, Oct. 13. 2015, Laramie, WY. (poster)

Gordon, B.L., Paige, G.B, Miller, S.N. (2014), East Fork return flow study, Wyoming Game and Fish Department, Aquatic Habitat Managers. Dubois, WY.

Claes, N., Paige, G.B, Parsekian, A. D., Miller, S. N., Gordon, B. L., 2015. Characterization of flood irrigation: merging hydrology and geophysics. WyCEHG Water Interest Group and Wyoming Round-Up, 2015, 14th October, Laramie, WY. (poster)

Claes, N., Paige, G.B, Parsekian, A. D., Miller, S. N., Gordon, B. L. 2015. Time-lapse ERT: detailed characterization of return flow from flood irrigation. RAD-seminar, 2015, 13th November, Laramie, WY.

Publications:
Gordon, B.L. (2014), *Measuring return flows*. Western Confluence Magazine Vol. 1, Ruckelshaus Institute, Laramie WY.

Graduate Students:
Directly Funded:
Neils Claes, PhD. Program in Hydrology, University of Wyoming.
Started January 2015.

Partially Supported:
Bea Gordon, MS, Rangeland Ecology and Watershed Management/Water Resources. University of Wyoming. Defended April 2016.
Thesis Title: *Determination of Evapotranspiration and Return Flow in a Semi-Arid Agricultural System*

Joe Cook, MS. Visiting Graduate Student from Dept., Observatoire des Sciences, Universite de Rennes, Rennes, France. Started March 2016.

Undergraduates:
Over 20 undergraduates have conducted field investigations for the project as part of the WyCEHG Geophysics Team: Collected background geophysical characteristics of the field site. (partial support for the undergraduates from WyCEHG)

Information Transfer Program Introduction

Information transfer activities for Wyoming are reported under Project 2015WY90B: Wyoming Information Transfer, Greg Kerr, Director, UW Office of Water Programs. The FY15 Annual Report for the project is given below.

Wyoming Information Transfer

Basic Information

Title:	Wyoming Information Transfer
Project Number:	2015WY90B
Start Date:	3/1/2015
End Date:	2/28/2018
Funding Source:	104B
Congressional District:	1
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	None
Principal Investigators:	Greg Kerr

Publication

1. Wilkinson, C., J.A. Robison, L.J. MacDonnell, J.E. Thorson, B.W. Griggs, M. Bryan, and A. Mackinnon, 2015. Big Horn General Stream Adjudication Symposium Division, Wyoming Law Review, Vol. 15, No. 2, University of Wyoming, College of Law, 591 pgs. (Symposium co-sponsored by University of Wyoming Office of Water Programs.)

Wyoming Information Transfer

FY15 Annual Report

Greg Kerr, Director, University of Wyoming Office of Water Programs, email: rrek@uwyo.edu

Introduction

Information transfer activities are an important component of the Wyoming Water Research Program (WRP). Activities include Office of Water Program (OWP) interactions with the Wyoming Water Association, Wyoming Water Forum, Wyoming Water Development Commission, Wyoming Legislative Select Water Committee, Wyoming Weather Modification Pilot Program Technical Advisory Team, and other water-related interests such as the Wyoming Stock Growers, Wyoming Governor's Water Strategy Group, Wyoming State Legislature House and Senate Agriculture Committees, University of Wyoming Water Interest Group, and Wyoming Center for Environmental Hydrology and Geophysics Water Interest Group. The WRP supports other technology and information transfer activities throughout the year. In order to facilitate dissemination of results of WRP funded research projects, and other closely related water research projects, information transfer includes support of peer publications and conference and meeting presentations for PIs and students of ongoing and completed WRP funded research projects and other closely related projects. The OWP maintains a web site which includes the most recent request for proposals and project reports. The WRP Advisory Committee serves as a group which facilities information transfer throughout various State and Federal agencies.

The OWP Director, Greg Kerr, has averaged over thirty information dissemination related presentations, meetings, and service activities each of the past few years. The following includes descriptions of the major interactions within the information transfer activities and general descriptions of the other interactions and of the as-requested information transfer activities which involve University personnel including both faculty and students.

WRP Advisory Committee

The WRP Advisory Committee serves as a group which facilities information transfer through various State and Federal agencies. The Advisory Committee consists of representatives from nine State, Federal, and Public agencies. The OWP Director meets at a minimum twice during the year with the WRP Advisory Committee. The project PIs report to the Institute Advisory Committee on an annual basis. Presentations discussing final results are made by PIs of projects which were completed during the year at the July advisory committee meeting. Presentations discussing interim results are made by PIs of continuing projects at the fall/winter or spring advisory committee meetings.

- UW Water Research Program. WRP Advisory Committee meeting to develop FY2016 RFP topics and research priorities. Cheyenne, WY., April 8, 2015.
- UW Water Research Program. WRP Advisory Committee meeting to select research priorities and review final project reports. Cheyenne, WY., July 30, 2015.
- Wyoming Water Research Program Meeting. WRP Advisory Committee review and ranking of water research projects. Cheyenne, WY., November 20, 2015.

Wyoming Water Development Commission (WWDC)

The Wyoming Water Development program provides, through a commission, procedures and policies for the planning, selection, financing, construction, acquisition, and operation of water projects. This includes projects for the conservation, storage, distribution and use of water. The commission is composed of 10 members appointed by the governor to represent the four state water divisions and the Wind River Reservation. The Wyoming Water Development Office (WWDO), which administers the program, is staffed by 26 professional, legal, and support employees. The Program receives funding from severance tax distributions. The OWP Director attends all meetings and workshops of the WWDC and reports on a regular basis on activities of the WRP (a list of FY15 meetings is given below). The Wyoming Water Development Program provides funding each year to the UW Office of Water Programs to fund non-project water related research. The OWP Director serves as the University of Wyoming Advisor to the WWDC (the other three advisors include the Wyoming State Engineer and representatives from the State Attorney General's Office and the Wyoming Business Council).

- Wyoming Water Development Commission workshop and project approval meetings. Cheyenne, WY., March 5-6, 2015.
- Wyoming Water Development Commission, member of Interview and Selection Committee for Weather Modification projects in Wyoming. Cheyenne, WY., May 4-7, 2015
- Wyoming Water Development Commission, presentation of WRP Research Areas from State Agencies, and water project consultant selection approval. Cheyenne, WY., May 8, 2015.
- Wyoming Water Development Commission/Select Water Committee joint workshop. Presentation on the UW Office of Water Programs and Water Research Program. Cheyenne, WY., June 3-4, 2015.
- Wyoming Water Development Commission/Select Water Committee joint meeting/summer tour. Worland, WY., August 19-21, 2015.
- Wyoming Water Development Commission/Select Water Committee joint workshop. Presentation on the UW Office of Water Programs and Water Research Program-preliminary funding recommendation. Casper, WY., November 4-6, 2015.
- Wyoming Water Development Commission/Select Water Committee joint workshop. Presentation of Water Research Program-project selection for FY2016 research funding recommendation. Cheyenne, WY., January 5-6, 2016.

Wyoming Legislative Select Water Committee

The Select Water Committee provides legislative oversight for the Wyoming Water Development Program and reviews and approves funding recommendations developed by the WWDC. The committee's approval comes in the form of its willingness to sponsor the "Omnibus" Planning and Construction bills. The Select Water Committee is comprised of 6 senators and 6 representatives. The Select Water Committee meets both jointly with the WWDC and separate from the WWDC. The OWP Director attends all meetings of the Select Water Committee and reports on a regular basis on activities of the WRP.

- Legislative Select Water Committee meeting. Presentation on the UW Office of Water Programs and Water Research Program FY2016 projects-funding recommendation for Legislative session. Cheyenne, WY., January 7, 2016.

- Legislative Select Water Committee meeting. Final approval of Omnibus Water Bill funding. UW Office of Water Programs and Water Research Program FY2016 projects. Cheyenne, WY., March 1, 2016.

Wyoming Weather Modification Pilot Program Technical Advisory Team

Funded by the Wyoming Water Development Commission, the Wyoming Weather Modification Pilot Program (WWMPP) has been conducted to assess the feasibility of increasing Wyoming water supplies through winter orographic cloud seeding. The program has been ongoing since 2005. The WWMPP consisted of an orographic cloud seeding research program in three Wyoming mountain ranges: the Medicine Bow, Sierra Madre, and Wind River Ranges. A Technical Advisory Team (TAT) was established early during the project to provide guidance to the Wyoming Water Development Office on the oversight of the program. The TAT consists of representatives from the many participants in the WWMPP and other interested stakeholders. The OWP Director is included among the representatives on the TAT (FY15 Director activities are listed below). In addition, the WRP has funded several ancillary glaciogenic cloud seeding research projects complementary to the WWMPP.

- North American Weather Modification Council, Wyoming Weather Modification pilot program project updates. Fargo, ND., April 21, 2015.
- Weather Modification Association -- Annual Conference, Wyoming Pilot Program presentations. Fargo, ND., April 22-23, 2015.
- WY Weather Modification Technical Advisory Team - Summer 2015 Meeting, Pinedale, WY., July 21, 2015.
- North American Weather Modification Council annual meeting and tour (Utah Weather Modification/Water Projects). Salt Lake City, UT., October 21, 2015.
- Wyoming Weather Modification pilot program Technical Advisory Team meeting. Cheyenne, WY., January 27, 2016.

Wyoming Water Forum

The Wyoming Water Forum is an information exchange mechanism in an informal setting that occurs from September to May each year. The Water Forum provides state and federal agency personnel a regular opportunity to share information and insight on water activities that are ongoing in their respective agencies. At each monthly meeting, a special program is presented providing a more in-depth review of a particular water related issue or topic. Example topics of discussion at past Water Forum meetings range from agriculture and water quality, instream flow, watershed case studies, groundwater, invasive species management and water supply updates. The State Engineer serves as the Chairman of the Wyoming Water Forum. The OWP Director attends the Water Forum meetings on a regular basis (a FY15 list is given below), participates in the discussions, and presents summaries on WRP activities.

- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., March 3, 2015.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., April 7, 2015.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., May 5, 2015.

- Wyoming Water Forum, Presentation on Water Research Program final project reports. Cheyenne, WY. September 1, 2015.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., October 6, 2015.
- Wyoming Water Forum, Presentation on Water Research Program Update. Cheyenne, WY., November 3, 2015.
- Wyoming Water Forum, Presentation on Water Research Program Update. Cheyenne, WY., December 1, 2015.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., January 5, 2016.
- Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., February 2, 2016.

Wyoming Water Association

The Wyoming Water Association (WWA) is the only statewide water resources association serving as a voice representing all Wyoming water interests. Membership consists of any individual, organization, agency, or group wishing to participate, including: private citizens, elected officials, and representatives of business, government agencies, industry, and water user groups and districts. Association activities include efforts to educate the public, government agency personnel, and elected decision makers through the association's quarterly Wyoming Water Flow newsletter, the annual meeting and educational seminar, a summer meeting and tour, and a winter meeting and legislative review sessions. The OWP Director's participation in the WWA includes service as a Board Advisor, co-sponsor of the Annual Meeting, and inclusion in the Summer Water Tour. PIs and students of WRP supported projects present at the Annual Meeting. FY15 OWP Director WWA activities and an agenda for the 2015 WWA Annual Meeting are given below.

- Wyoming Water Association Board meeting, (Advisor), Torrington, WY., June 10, 2015.
- Wyoming Water Association Summer Water Tour, (Advisor), Torrington, WY., June 9, 2015.
- Wyoming Water Association Board meeting (Advisor), Casper, WY., October 28, 2015.
- Co-Sponsor Wyoming Water Association Annual Meeting & Educational Seminar, University of Wyoming Water Research Initiatives. Casper, WY., October 28-29, 2015.
- Wyoming Water Association Board Meeting, Legislative Review, (Advisor), Cheyenne, WY., February 10, 2016.
- Wyoming Water Association, Legislative Review, (Advisor), Cheyenne, WY., January 24, 2016.

WYOMING WATER ASSOCIATION

Annual Meeting & Education Seminar
Conference Program
Co – Sponsored by the University of Wyoming
Office of Water Programs

Roundhouse
Evanston, Wyoming

October 28th and October 30th, 2015

"State and Federal Regulatory Issues Facing Wyoming"

<u>Wednesday, October 28, 2015</u>

12:30 p.m.	**Registration**
1:00 p.m.	**Opening Remarks – Bryant Startin**, WWA President
1:10 p.m.	**Welcome – Mayor, Mayor of Evanston**
1:15 p.m.	**WWA Advisor Update**
1:20 p.m.	**Todd Parfitt, WY Department of Environmental Quality Director**
1:40 p.m.	**Scott Talbot, Wyoming Game and Fish Director** *(confirmed)*
2:00 p.m.	**Harry LaBonde, Wyoming Water Development Director** *(confirmed)*
2:20 p.m.	**Rick Deuell, Surface Water Administrator, Wyoming State Engineer's Office *(confirmed)***
2:40 p.m.	**Networking break**
3:00 p.m.	**Waters of the US – an overview**
	Julia McCarthy, EPA *(confirmed)*
	Michelle Bushman, Legal Council Western States Water Council *(confirmed)*
	Aaron Maier, Trihydro *(confirmed)*
	Question and Answer Session
5:30 p.m.	**Adjourn**
6:30 p.m.	**WWA Board of Director Dinner and Meeting**

Thursday, OCTOBER 29th

Morning Session

8:30 a.m. **Annual Business Meeting - Call to Order – Bryant Startin**, WWA President

9:30 a.m. **Networking Break**

9:45 a.m. **Wyoming Water Development Program Changes, Kevin Boyce WWDO** ***(confirmed)***

Rural Development Criteria Changes, Lorraine Werner, Rural Development ***(confirmed)***

State Revolving Fund, Brian Mark, DEQ ***(confirmed)***

11:00 a.m. **Wyoming Water Law, Rick Deuell** *(confirmed)*

Bear River, Kevin Payne, Division 4 Superintendent ***(confirmed)***

Colorado River

12:00 p.m. **Adjourn for noon program**

12:00 – 1:00 p.m. Noon Session

Invocation and Lunch
Luncheon address – Todd Adams, Deputy Director of Utah Division of Water Resources ***(confirmed)***

Thursday, OCTOBER 29th

1:10 p.m. **Split Session**

Tract A	**Tract B**
DEQ Training Session	**Bear River Watershed Tour**

5:10 p.m. **Adjourn for evening program and banquet**

6:30 p.m.

Friday, October 30th

2

8:25 a.m.	**Call to Order – Bryant Startin, WWA President**
8:30 am.	**Office of Water Programs, Greg Kerr Director**
8:50 a.m.	**Water Research, Chris Laursen** *(confirmed)*
9:20 a.m.	**Water Research, Brent Ewers** *(confirmed)*
9:50 a.m.	**Networking break**
10:10 a.m.	**Jim Waseen, Wyoming Landscape Conservation Initiative** *(confirmed)*
10:40 a.m.	**WYPDES, Leah Craft, DEQ**
11:00 a.m.	**DEQ Storm Water Program, Barb Sahl** *(confirmed)*
11:45 a.m.	**Closing discussions/Certificates**
Noon	**Adjourn**

Other Water-Related Activities of the OWP Director

These include, but may not be limited to these in a given year, the Wyoming Stock Growers, Wyoming Governor's Water Strategy Group, Wyoming State Legislature House and Senate Agriculture Committees, University of Wyoming Water Interest Group, and Wyoming Center for Environmental Hydrology and Geophysics Water Interest Group. The OWP Director attends meetings/presents on a random schedule (a FY15 list is given below) with these various water groups. The OWP occasionally co-sponsors selected meetings/conferences.

- Wyoming State Legislature – Senate Agriculture Committee. Wyoming Water Development Commission (Advisor), Omnibus Water Plan. State Capital Bld., Cheyenne, WY., March 5, 2015.
- AGU Fall Meeting, PI presentations on Wyoming Water Research Institute projects. San Francisco, CA., December 14-18, 2015.
- The National Institutes for Water Resources (NIWR) annual meetings. Washington, DC., February 8-10, 2016.
- Wyoming State Legislature – Senate Agriculture Committee. Wyoming Water Development Commission (Advisor), Omnibus Water Plan. Cheyenne, WY., January 11, 2016.
- Wyoming State Legislature – House Agriculture Committee. Wyoming Water Development Commission (Advisor), Omnibus Water Plan. Cheyenne, WY., February 23, 2016.

Information Transfer Activities of Project PIs

Activities include those of PIs and students of ongoing and completed WRP funded research projects and other closely related water research and education projects. Includes support for peer publications and conference and meeting presentations for PIs and students of ongoing and completed WRP funded research projects and other closely related projects. Publications are listed in the individual research reports.

FY15 presentations for **Project 2013WY86B**: "Use of Fe(VI) for the Improvement of Water Quality in Wyoming", Maohong Fan, SER Assoc. Prof. and et al., Dept. of Chemical & Petroleum Engr., UW.

- The ideas behind the project have been introduced to students through the GK-12 Environmental and Energy Nanotechnology NSF Fellowship through MS student Andrew Jacobson. As a fellow, travel has been done to Chugwater, WY to introduce science topics including this ongoing research. Students from around Wyoming have also been given lab tours explaining the ideas behind the setups of this research and what the goal of this research is.

FY15 presentations for **Project 2013WY87B**: "Rumen Microbial Changes Associated with High Sulfur -- A Basis for Developing Treatments for Ruminant Livestock in High Sulfur Water Regions", Kristi M. Cammack, Assist. Prof. and Kathy J. Austin, Research Scientist, Animal Science, UW; Cody L. Wright, Ph.D., Prof. and Ken Olson, Assoc. Prof., Animal Science, S. D. State Univ.; and Gavin Conant, Assist. Prof. and William Lamberson, Prof., Animal Sciences, Univ. of Missouri.

- Abrams, A.N., K.J. Austin, M.J. Ellison, H.C. Cunningham, G. Conant, T. Taxis, W.R. Lamberson, and K.M. Cammack, 2016. Effect of high sulfate water on rumen microbial populations in lambs. Plant & Animal Genomes XXIV Conference. P0607.
- Clarkson, C.J., A.N. Abrams, K.J. Austin, M.J. Ellison, H.C. Cunningham, G. Conant, W.R. Lamberson, T. Taxis, and K.M. Cammack. Effect of high sulfate water on rumen microbial populations in lambs. Western Sec. ASAS.
- Abrams, A. N., K. J. Austin, M. J. Ellison, H. C. Cunningham, G. Conant, W. R. Lamberson, T. Taxis, and K. M. Cammack, 2015. High sulfate water affects rumen microbial populations in lambs. High Plains Nutrition and Management Roundtable, Lingle, Wyoming. September 10, 2015.

FY15 Presentation for **Project 2015WY88B**: "High-Resolution Modeling of Precipitation, Snowpack, and Streamflow in Wyoming: Quantifying Water Supply Variations in Future Decades", Bart Geerts, Atmospheric Science, UW.

- Wang, Y., B. Geerts and C. Liu, 2015: Regional climate simulations of cold-season precipitation and snowpack over the US northern Rockies: validation and examination of factors controlling the precipitation distribution. Presented at the 2015 annual meeting of the American Meteorological Society, Phoenix AZ.

FY15 Presentations for **Project 2015WY89B**: "Quantifying Return Flow in the Upper Wind River Basin", Ginger Paige and Scott Miller, Ecosystem Science and Management; and Andrew Parsekian, Dept. of Geology and Geophysics, UW.

- Parsekian A.D., Paige, G.B., Miller S.N., Gordon B.L., Claes, N. 2015. Return flow: untangling the water budget on flood-irrigated fields. 2015 Water Interest Group Meeting, Oct. 13, 2015, Laramie, WY. (invited presentation)
- Gordon, B.L., Miller, S.N., Paige, G.B, Claes, N., Parsekian, A., Beverly, D. 2015. A Comparison of Methods for Calculating Evapotranspiration in a Semi-Arid Agricultural System, 2015 AGU Fall Meeting, December 14-18, 2015, San Francisco, CA. (poster)
- Claes, N., Paige, G.B, Parsekian, A.D., Miller, S.N., Gordon, B.L. 2015. Characterization of return flow pathways during flood irrigation. 2015 AGU Fall Meeting, December 14-18, 2015, San Francisco, CA. (poster)
- Gordon, B.L., Miller, S.N., Paige, G.B, Claes, N., Parsekian, A., Beverly, D. 2015. Calculating Return Flows and Consumptive Use in a Semi-Arid Agricultural System, 2015 Water Interest Group Meeting, Oct. 13. 2015, Laramie, WY. (poster)
- Gordon, B.L., Paige, G.B, Miller, S.N. (2014), East Fork return flow study, Wyoming Game and Fish Department, Aquatic Habitat Managers. Dubois, WY.
- Claes, N., Paige, G.B, Parsekian, A. D., Miller, S. N., Gordon, B. L., 2015. Characterization of flood irrigation: merging hydrology and geophysics. WyCEHG Water Interest Group and Wyoming Round-Up, 2015, 14th October, Laramie, WY. (poster)

<u>OWP Web Site</u>
The OWP maintains a basic web site which includes the most recent request for proposals and project reports. The web site address is uwyo.edu/owp.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	12	0	0	0	12
Masters	3	0	0	0	3
Ph.D.	2	0	0	0	2
Post-Doc.	2	0	0	0	2
Total	19	0	0	0	19

Notable Awards and Achievements

Project 2013WY87B Final Report: “Rumen Microbial Changes Associated with High Sulfur -- A Basis for Developing Treatments for Ruminant Livestock in High Sulfur Water Regions”, Graduate student Ms. Amy Abrams was honored as an Outstanding Young Scholar by the Western Section of the American Society of Animal Science.

Project 2013WY87B Final Report: “Rumen Microbial Changes Associated with High Sulfur -- A Basis for Developing Treatments for Ruminant Livestock in High Sulfur Water Regions”, Graduate student Ms. Amy Abrams was selected as the Outstanding M.S. Student by the University of Wyoming’s Chapter of Gamma Sigma Delta.

Project 2015WY89B: “Quantifying Return Flow in the Upper Wind River Basin”, has leveraged additional support from two funding sources to expand the instrumentation and provide additional funding to support graduate student research, (1) Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG, (NSF EPS-1208909)) and (2) Walton Foundation (through the Haub School of Environment and Natural Resources, University of Wyoming) provided funding for MS graduate student (Bea Gordon).

Publications from Prior Years

1. 2012WY81B ("Multi-frequency Radar and Precipitation Probe Analysis of the Impact of Glaciogenic Cloud Seeding on Snow") - Articles in Refereed Scientific Journals - Pokharel, B., Geerts, and X. Jing, 2015: The impact of ground-based glaciogenic seeding on clouds and precipitation over mountains: a case study of a shallow orographic cloud with large supercooled droplets. J. Geophys. Res., 120, 6056–6079.
2. 2012WY81B ("Multi-frequency Radar and Precipitation Probe Analysis of the Impact of Glaciogenic Cloud Seeding on Snow") - Articles in Refereed Scientific Journals - Jing, X., B. Geerts, K. Friedrich, and B. Pokharel, 2015: Dual-polarization radar data analysis of the impact of ground-based glaciogenic seeding on winter orographic clouds. Part I: mostly stratiform clouds. J. Appl. Meteor. Climat., 54, 1944-1969.
3. 2012WY81B ("Multi-frequency Radar and Precipitation Probe Analysis of the Impact of Glaciogenic Cloud Seeding on Snow") - Articles in Refereed Scientific Journals - Jing, X., and B. Geerts, 2015: Dual-polarization radar data analysis of the impact of ground-based glaciogenic seeding on winter orographic clouds. Part II: convective clouds J. Appl. Meteor. Climat., 54, 2034-2056.
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