Wyoming Water Research Program
Annual Technical Report
FY 2012

Introduction

The NIWR/State of Wyoming Water Research Program (WRP) coordinates participation in the NIWR program through the University of Wyoming 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. In addition to administrating the WRP, the Director of the OWP serves as the University of Wyoming advisor to the Wyoming Water Development Commission (WWDC).

State support for the WRP includes direct funding through the WWDC and active State participation in identifying research needs and project selection and oversight. Primary participants in the WRP are the USGS, the WWDC, and the University of Wyoming. A Priority and Selection Committee (P&S Committee), consisting of representatives from State and Federal agencies, solicits and identifies research needs, selects 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 P&S Committee. The State provides direct WWDC funding for the OWP to identify water related research needs, coordinate research activities, coordinate the Wyoming WRP, and serve as the University advisor to the WWDC.

The WRP supports faculty and students in University of Wyoming academic departments. Faculty acquire their funding through competitive, peer reviewed grants, submitted to the WRP. 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. A goal of the WRP is to minimize administrative overhead while maximizing the funding allocated toward water-related research and training. Another goal of the program is to promote coordination between the University, State, and Federal agency personnel. The WRP provides interaction from all groups involved rather than being solely a University of Wyoming research program.

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. All activities reported herein are in response to the NIWR program, with additional funding provided by the Wyoming Water Development Commission and the University of Wyoming. The OWP Director reports to the University of Wyoming Vice President of Research and Economic Development. A State Advisory Committee (entitled the Priority and Selection Committee) serves to identify research priorities, select projects for funding, and monitor project progress. The Director coordinates all activities.

Reports for the following FY12 WRP research projects are given herein in the order listed below:

Project 2010WY57B, Final Report (Project extended past Feb 2012): Development of a Contaminant Leaching Model for Aquifer Storage and Recovery Technology, Maohong Fan, SER Associate Professor, Dept. of Chemical & Petroleum Engineering, UW, Mar 2010 thru Feb 2012.

Project 2010WY60B, Final Report: Multi-Century Droughts in Wyomings Headwaters: Evidence from Lake Sediments, Bryan N. Shuman, Associate Prof., Dept. of Geology & Geophysics, Jacqueline J. Shinker, Assistant Prof., Dept. of Geography, Thomas A. Minckley, Assistant Prof., Dept. of Botany, UW, Mar 2010 thru Feb 2013.

Project 2010WY61B, Final Report: Impact of Bark Beetle Outbreaks on Forest Water Yield in Southern Wyoming, Brent E. Ewers, Assoc. Prof., Dept. of Botany, Elise Pendall, Assoc. Prof., Dept. of Botany, and David G. Williams, Prof., Dept. of Renewable Resources, UW, Mar 2010 thru Feb 2013.

Project 2011WY74B, Final Report: Fate of Coalbed Methane Produced Water in Disposal Ponds in the Powder River Basin, T.J. Kelleners, Assist. Prof. and K.J. Reddy, Professor, Dept. of Renewable Resources, UW, Mar 2011 thru Feb 2013.

Project 2011WY75B, Final Report: Instrumentation for Improved Precipitation Measurement in Wintertime Snowstorms, Jefferson Snider, Professor, Dept. of Atmospheric Science, UW, Mar 2011 thru Feb 2013.

Project 2012WY79B Annual Report: A Treatise on Wyoming Water Law, Lawrence J. MacDonnell, Professor of Law, UW, Mar 2012 thru Feb 2014.

Project 2012WY80B Annual Report: Integrated Accelerated Precipitation Softening (APS) Microfiltration (MF) Assembly and Process Development to Maximize Water Recovery during Energy Production and CO2 Sequestration, Jonathan A. Brant, Assist. Prof., Dept. of Civil and Architectural Engineering, and Dongmei (Katie) Li, Assist. Prof., Dept. of Chemical and Petroleum Engineering, UW, Mar 2012 thru Feb 2014.

Project 2012WY81B Annual Report: Multi-Frequency Radar and Precipitation Probe Analysis of the Impact of Glaciogenic Cloud Seeding on Snow, Bart Geerts, Prof., Dept. of Atmospheric Science, UW, Mar 2012 thru Feb 2015.

Project 2012WY82B Annual Report: Decadal Scale Estimates of Forest Water Yield After Bark Beetle Epidemics in Southern Wyoming, Brent E. Ewers, Assoc. Prof., Dept. of Botany; Elise Pendall, Assoc. Prof., Dept. of Botany and Program in Ecology; Urszula Norton, Asst. Prof., Plant Sciences Dept.; and Ramesh Sivanpillai, Academic Professional Research Scientist, WyGISC/Dept. of Botany, UW, Mar 2012 thru Feb 2015.

Development of a Contaminant Leaching Model for Aquifer Storage and Recovery Technology

Basic Information

Title:	Development of a Contaminant Leaching Model for Aquifer Storage and Recovery Technology
Project Number:	2010WY57B
Start Date:	3/1/2010
End Date:	2/28/2013
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Water Quantity, Water Quality, Water Use
Descriptors:	Aquifer storage and recovery; Water injection; Contaminant leaching
Principal Investigators:	Maohong Fan

Publication

1. Sharrad, M. O., H. Liu, and M. Fan, 2012. Selenium Removal from Water by FeOOH, Separation and Purification Technology, Vol. 84, No. 1, pp. 29-34.

Development of a Contaminant Leaching Model for Aquifer Storage and Recovery Technology

Project Period: 7/2010-6/2012

Reported

by

Abdulwahab M. Ali Tuwati and Maohong Fan*

**PI, SER Associate Professor in the Department of Chemical & Petroleum Engineering*
University of Wyoming
Phone: (307) 766 5633 Email: mfan@uwyo.edu

January 13, 2013

1. ABSTRACT

Wyoming is lacking in water resources. Aquifer storage and recovery (ASR) through water injection could be an important method to solve the water problem in Wyoming. However water injection could lead to contamination of ASR due to the leaching of heavy metals and other elements. Therefore prediction of the potential of leaching of contaminants with a model is critically important to the successes of the application of ASR technology in Wyoming and other states in the US. The proposed project was designed to provide a solution to the universal issue facing many potential ASR technology customers. Both batch leaching and continuous flow leaching tests were conducted under different conditions and the associated leaching models were obtained.

2. INTRODUCTION

The state of Wyoming is considered part of a semi-arid hydro-climatic region, with water levels varying throughout the year due to the warm temperatures and relatively little precipitations. Wyoming is ranked as the third driest state in US, and drought is a constant threat in this region. According to the National Climatic Data Center (NCDC) [1], Wyoming is placed as the 48th wettest in the U.S with annual precipitation average of 12.97 inches. In general, the state has limited sustainable surface water available for use. Furthermore, Wyoming is one of the largest fossil fuel suppliers in the country [1], with large quantities of water generated during production released either onto land or into nearby lakes or rivers with no beneficial use. Worldwide, the oil and gas industry generates more than 70 billion barrels of produced water per year. Within the US alone, between 15 and 20 billion barrels of produced water are generated each year. This is equivalent to a volume of 1.7 to 2.3 billion gallons per day. Of the above total of produced water, state of Wyoming has shown a share of approximately 2 billion barrels per year as reported in the year 2007 [2]. Accordingly, an environmentally friendly and relatively inexpensive method could be used to store this large volume of the co-produced water after a necessary partial or comprehensive treatment. An aquifer storage and recovery (ASR) injection method could be a feasible technology for conserving natural and/or produced water that would otherwise be wasted. ASR technology provides a cost-effective solution to many of the world's water management needs, storing water during times of flood or when water quality is good, and recovering it later during emergencies or times of water shortage, or when water quality from the source may be poor. Large quantities of water are stored deep underground, which reduces or eliminates the need for construction of large and expensive surface reservoirs. In addition to the abovementioned driving force, ASR technology can also be used to protect environment, aquatic and terrestrial ecosystems. Most ASR storage zones are ranged in depth from 200 to 2,700 ft. Water is stored in different water-bearing geologic formations that may be in sand, clay sand, sandstone, gravel, limestone, dolomite, glacial drift, basalt and other types of geologic settings.

The types of aquifers in North America are generally classified into six groups: unconsolidated and semi-consolidated sand and gravel aquifers, sandstone aquifers, carbonate-rock aquifers, aquifers in interbedded sandstone and carbonate rocks, and aquifers in igneous and metamorphic rocks [3]. Sand and gravel, sandstone, carbonate-rock, and interbedded sandstone and carbonate rock aquifers exist to some extent in the state of Wyoming. Regardless of the aquifer type, the injected "stored" water displaces the natural water that is present in the aquifer and causes a very large bubble around the well. This bubble is usually confined by overlying and underlying geologic formations that do not produce water. These bubbles have water storage capacities as small as about 13 million gallons in individual ASR wells to as much as 2.5 billion gallons or more in large ASR well fields [4]. However, in order for the ASR to be a successful technology for water storage, potential contamination should be addressed. The contamination might occur during water injection and storage as a result of the leaching of toxic metals.

The present project was designed to study continuous and batch leaching of heavy metals [5] for prediction of the potential leaching of contaminants into aquifers. The effects of varying certain parameters on the mobility of heavy metals through rocks, including pH and temperature, will be studied using both leaching processes. Flow rate was also used as a variable for continuous process studies. This work seeks to study mobility and investigate the leaching kinetics of several heavy metals that may be present in "sandstone" rock types. Sandstones are arenaceous sedimentary rocks composed mainly of feldspar and quartz, and exhibit different colors. They are broadly divided into three groups: arkosic sandstones, which have a high (>25%) feldspar content, quartzose sandstones, such as quartzite, which have a high (>90%) quartz content; and argillaceous sandstones, such as greywacke, which have a significant fine-grained element.

The term "heavy metal" refers to any metallic element that has a relatively high density, and typically refers to the group of metals and metalloids with atomic densities greater than 4 g/cm^3 [6]. Heavy metals are well known to be toxic to human beings and most other organisms when present in high concentrations in the environment [6]. Table 1 lists the standard levels of these elements considered safe in water, according to World Health Organization (WHO) [7] and the United States Environmental Protection Agency (EPA) [8].

Table 1 WHO/EU drinking water standards.

Element	WHO standard (ppb)	EPA standards (ppb)
Arsenic (As)	10.0	10.0
Barium (Ba)	300.0	200.0
Beryllium (Be)	No guideline	4.0
Boron (B)	300.0	N/A
Cadmium (Cd)	3.0	5.0
Chromium (Cr)	50.0	100.0
Copper (Cu)	2000.0	1300.0
Iron (Fe)	No guideline	N/A
Lead (Pb)	10.0	15.0
Manganese (Mn)	500.0	N/A
Nickel (Ni)	20.0	N/A
Selenium (Se)	10.0	50.0
Silver (Ag)	No guideline	N/A
Zinc (Zn)	300.0	N/A

The leaching of heavy metals occurs naturally, as in the case of sulfide minerals in rocks that are oxidized upon contact with water and atmospheric oxygen, resulting in the formation of sulfates that generate so-called “acid rock drainage” and “metal leaching” (ARD-ML). ARD-ML is usually characterized by high concentrations of metals and sulfates in solution and lower pH values (2-4), which leads to the accelerated release of certain metals into aquifers [9-10]. The mobility of arsenic (As) as toxic element in the presence of pyrite in ASR has been reported in various studies as an example of such leaching, and geochemical modeling has examined the stability of pyrite in limestone during the injection into wells of surface water [11]. The goal of those modeling studies was to stabilize pyrite under certain conditions in order to alter the high leaching of As levels into ASRs. Another leaching model investigated interactions among immobilization reactions and transport mechanisms affecting the overall leaching of contaminants [12], and a characteristic leaching procedure for assessing the toxicity of soils contaminated with heavy metals has been reported elsewhere [13]. In addition, several reports have been cited for the release to groundwater of heavy metals from sources such as fly ash [14], water springs [15], soil [16], mine waste material (i.e., tailings) [17], acidic sandy soil amended with dolomite phosphate rock (DPR) fertilizers [18], and contaminated calcareous soil [15].

All of these reports indicate the mobility of heavy metals in soil to some extent under various amendment conditions. Further, it has been reported that the addition of organic material could result in the fixation of metals such as zinc (Zn) and lead (Pb) in soil, which in turn might help to reduce leaching of these metals into aquifers [19]. The study of metal leaching from various fly ash samples [14] showed different behavior patterns. The chemical partitioning of lead (Pb) and zinc (Zn) in soils, clays and rocks has been documented [17], with their migration showing an increase under low pH conditions. In the present study, we found it both necessary and useful to design and develop leaching models to study the kinetics of each individual contaminant species; to investigate the potential leaching of some of these heavy metals from sandstone rocks using both continuous and batch leaching processes; and to measure the effects of varying parameters such as pH and temperature of the leachate on both leaching processes, as well as the effects of flow rate on the continuous leaching process.

3. METHODS

3.1 Leaching kinetics of heavy metals

Heavy metal leaching models were derived using batch system. Assuming that the leaching of contaminant species, i , follows a first order kinetic model, then its leaching kinetics of can be written as

$$\frac{dC_i}{dt} = k_i[C_{e,i} - C_i] \qquad \text{E1}$$

or

$$-\frac{d[C_{e,i} - C_i]}{dt} = k_i[C_{e,i} - C_i] \qquad \text{E2}$$

where k_i is the leaching rate constant of species *i*, $C_{e,i}$ is the leaching concentration of contaminant *i* at leaching equilibrium state, and C_i is the concentration of species *i* at any time *t*.

With the boundary condition, $C_{i,\,t=0} = 0$, the integral form of E1 is:

$$-\ln\frac{(C_{e,i} - C_i)}{C_{e,i}} = k_i t\,. \qquad \text{E3}$$

Rearranging E3, we have

$$-\ln[C_{e,i} - C_t] = k_i t - \ln C_{e,i}\,. \qquad \text{E4}$$

The left side, $-\ln[C_{e,i} - C_t]$ in E4 can be plotted against time (t). If the experimental data fits the plot, then the assumed leaching rate order (1st order) is correct. Otherwise, an alternative leaching rate order needs to be assumed and checked until the experimental data fit the associated kinetic model.

3.2 Experiments

3.2.1 Sample collection and preparation

Sandstone rock samples were collected from an open pit (Figure 1) operated by Black Butte Coal and Mining Company, and located about 170 miles west of Laramie, Wyoming. The samples were obtained from an adjusted depth of about 169 feet to 214 feet, as shown in Table 2.

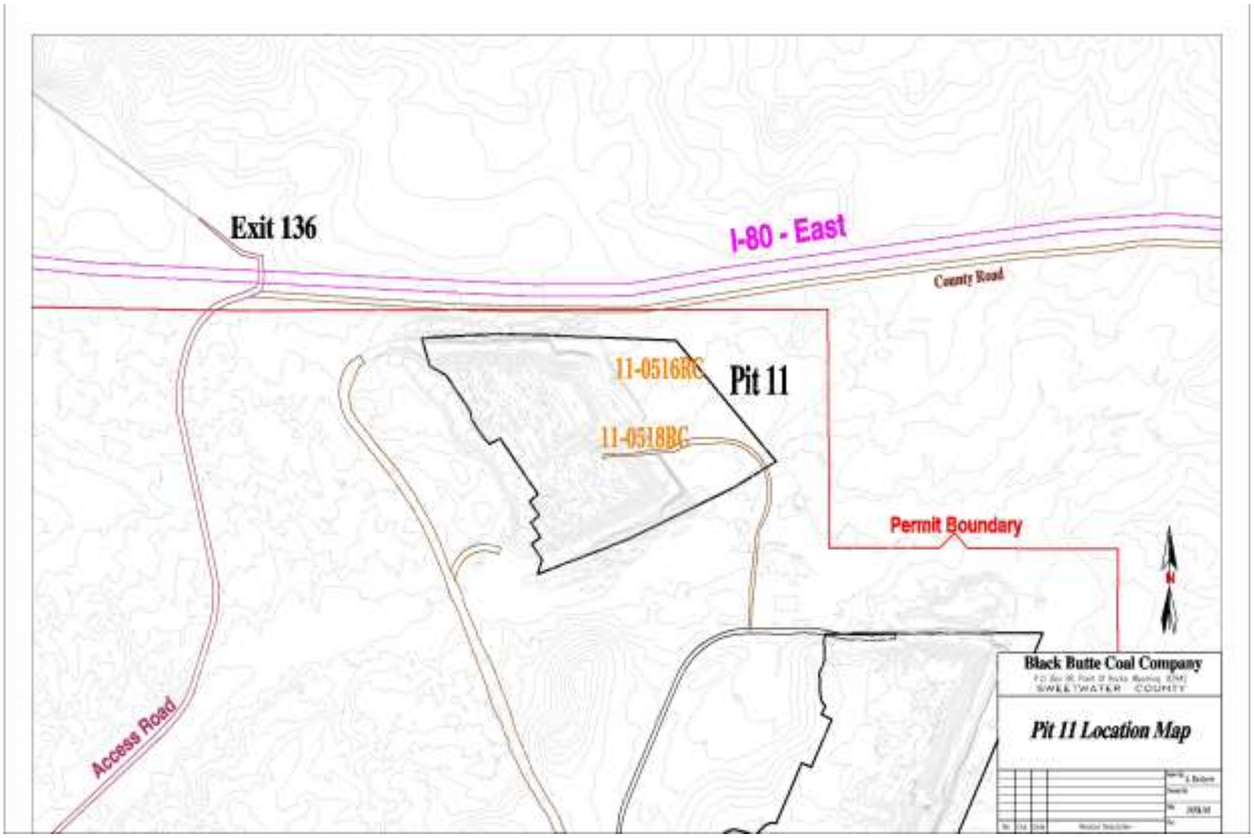


Figure 1. Rock Sample collection location (source: Black Butte Company).

The samples were transported to UW lab in containers, and upon arrival their surfaces were cleaned with water and left to dry at room temperature. After drying, all samples were crushed with a jaw crusher and screened with a sieve (mesh opening of 0.185 inch). The retained particles were then mixed several times to obtain representative samples and kept in closed containers until use.

Table 2 Drill Hole Lithology (Source: Black Butte Company).

Raw depths (feet)	Adjusted depths (feet)	Lithology type	Color
0.00-5.00	0.00-5.05	Soil	Yellowbrown
5.00-22.00	5.05-22.21	Sandstone	Greybrown
22.00-25.00	22.21-25.24	Siltstone	Brown
25.00-29.00	25.24-29.27	Sand	Grey
29.00-56.00	29.27-56.53	Siltstone/mudstone	Grey
56.00-61.00	56.53-61.58	Siltstone	Grey
61.00-74.00	61.58-74.70	Mudstone	Grey
74.00-83.00	74.70-83.78	Siltstone	Grey
83.00-85.00	83.78-85.80	Mudstone	Grey
85.00-93.00	85.80-93.88	Siltstone	Grey
93.00-98.00	93.88-98.92	Mudstone	Grey
98.00-129.00	98.92-130.22	Siltstone	Grey
129.00-135.00	130-22-136.27	Mudstone	Grey
135.00-143.00	136.27-144.35	Siltstone	Grey
143.00-144.00	144.35-145.36	Mudstone	Grey
144.00-150.00	145.36-151.42	Sandstone	Grey
150.00-153.20	151.42-154.65	Mudstone	Grey
153.20-155.00	154.65-156.46	Coal	Black
155.00-158.70	156.46-160.20	Carbonaceous mudstone	Brown
158.70-160.00	160.20-161.51	Coal	Black
160.00-168.00	161.51-169.58	Mudstone	Grey
168.00-212.00	169.58-214.00	Sandstone	Grey
212.00-240.20	214.00-241.20	Coal	Black
240.20-245.00	241.20-245.68	Carbonaceous mudstone	Brown
245.00-247.50	245.68-248.01	Coal	Black
247.50-255.00	248.01-255.00	Sandstone/mudstone	Grey

3.2.2 Sample analysis

An adapted procedure [17] was partially followed for rock sample digestion in order to screen for the following elements: Ag, As, Ba, Be, Cd, Co, Cr, Cu, Mn, Ni, Pb, Se, V and Zn. The first step of the digestion method involved the addition of 5ml aqua regia (1:3 v/v, HNO_3: HCl) and 2 ml hydrofluoric acid (HF) to a 0.2 g fine powder of sandstone rock sample in a Teflon beaker. The sample mixture was then placed on a hotplate and heated at 100°C until dry. Another 5ml of aqua regia was then added to bring the dissolved metals back to the solution. The resulting mixture was then filtered with Whatman 2 filter paper (pore size: 8μm) and rinsed with deionized (DI) water. The filtrate was then transferred into a 50 ml plastic vial and diluted to its mark. The digestion method was performed three times. The final solutions were analyzed by an ICP-OES Spectrometer (ICAP 6000 series, Thermo Scientific).

3.2.3 Leaching apparatus

Two schematic diagrams of continuous and batch percolation extraction set-ups are shown in Figures 2 and 3, respectively; a photo of the actual apparatus (continuous and batch) is shown in Figure 4. The columns are clear PVC columns approximately 7-feet long with an outside diameter (O.D) of 2.5 inches. Each is sufficiently high to contain about 5 kg of rock sample (particle size of 0.185 inch), with additional height to contain applied water in the event of poor percolation. A sampling point at the bottom of the column was used for sampling collection. A cotton filter medium was placed near the sampling point for easy sample withdrawal. Each column has a punch plate and punch plate support, with the bottoms sealed tightly with bubble caps. An adjustable metering pump was used in the continuous leaching model to ensure a constant flow rate of extraction fluid (water). In the continuous leaching model, containers to hold both influent and effluent liquids were used during extraction.

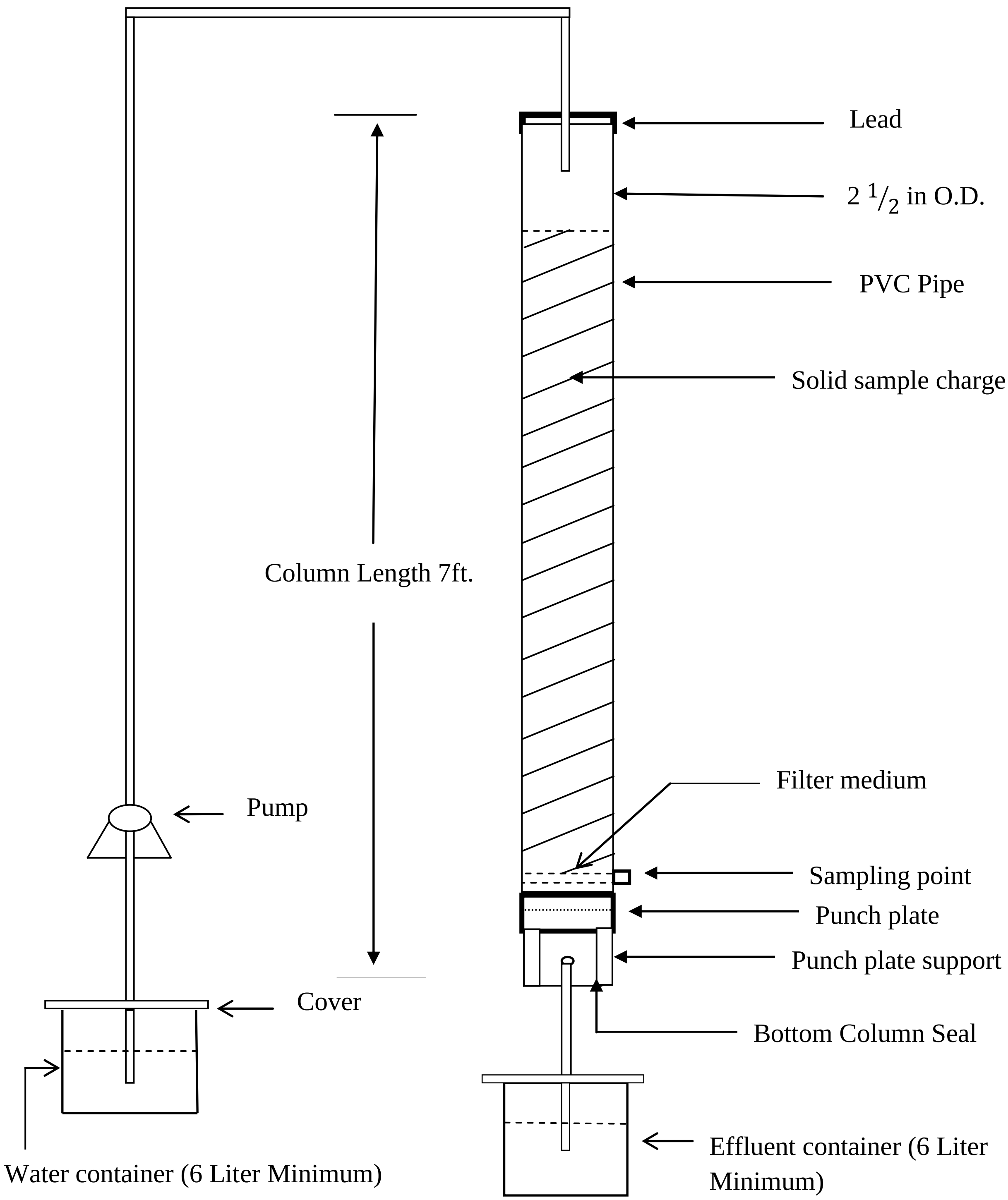


Figure 2 Schematic setup diagram for continuous leaching.

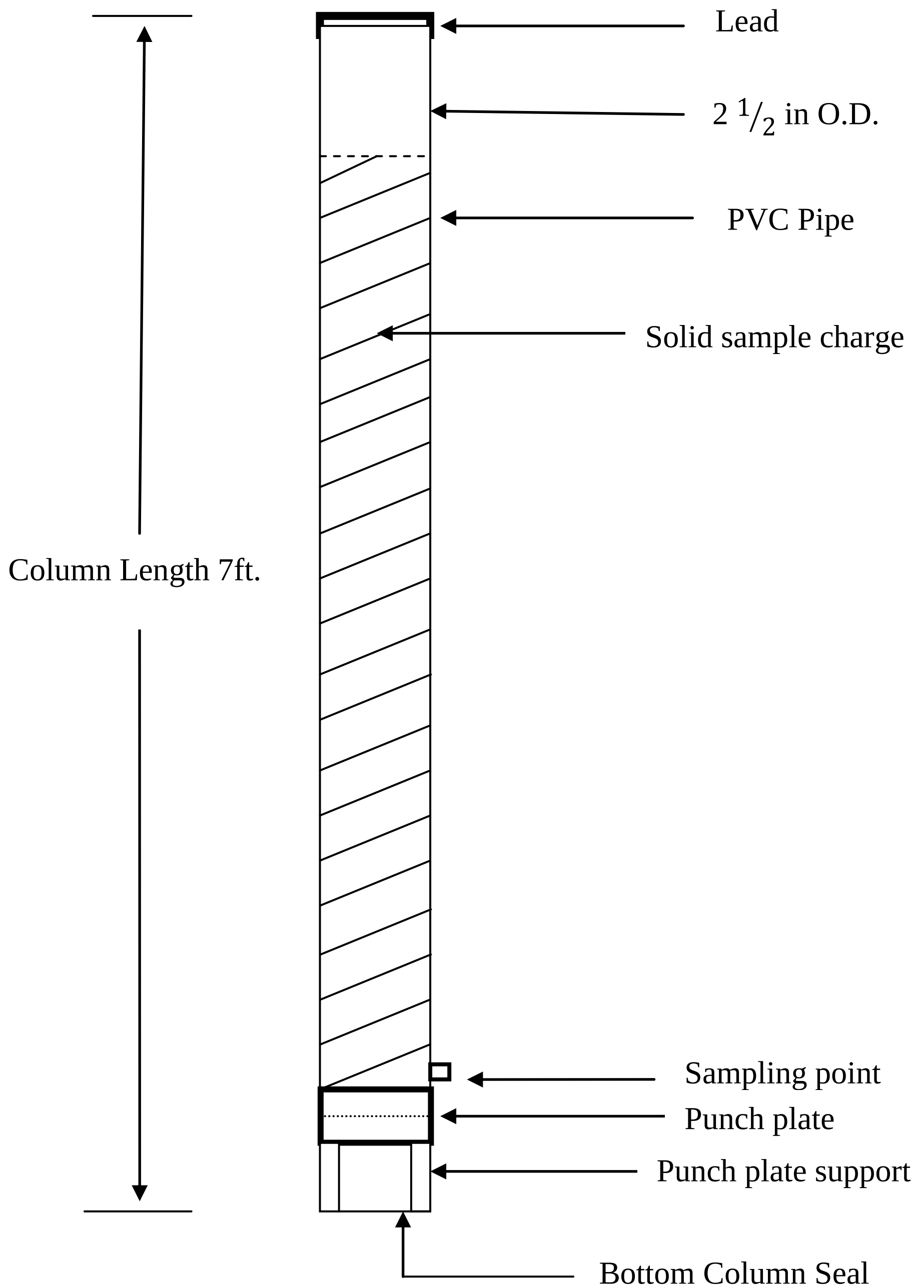


Figure 3 Schematic setup diagram for batch leaching

.

Figure 4 Photo of continuous and batch apparatus.

3.2.4 Operation Procedure

Continuous leaching method

A 5 kg dry rock sample was loaded in increments into the PVC column. In order to minimize particle segregation and compaction, the sample increments were carefully loaded without shaking or tamping. Cotton filter medium was inserted into the column near the sampling point in order to withdraw sample effluents using a syringe during the extraction process. Deionized water (DI) was pumped from a container holding a minimum of 6 liters into the column at a specified flow rate using a diaphragm-type metering pump (series 100/150). The initial temperature and pH of the leachate water, as well as the date and starting time of the leaching process, were recorded in accordance with ASTM D 1293[19]. Extraction sample of about 10ml was collected in plastic vials from the sampling point at different time periods. Collected leachate samples were then analyzed for leachable metals using an ICP-OES Spectrometer (ICAP 6000 series, Thermo Scientific). The same procedure was used under different experimental conditions, including flow rate and pH.

Batch leaching method

With the exception of the use of a metering pump, a procedure largely similar to method (1) was used to assess the batch leaching method. A set volume of DI water (~1800ml) was added to the column at the start of the leaching process, and small aliquot samples (10ml) were withdrawn and placed into 15 ml vials every 8 hours over a period of 40 hours (unless otherwise specified) from the column sampling point. Procedure was repeated at different pH's and temperatures.

4. FINDINGS/RESULTS AND DISCUSSIONS

4.1 Reference sample analysis

Table 3 lists (in mg/kg) the results of heavy metal concentrations potentially present

Table 3 Metal concentrations in rock sample (sandstone).

Element	Concentration in ppm (mg/Kg)
Arsenic (As)	5.51
Barium (Ba)	206.81
Berillium (Be)	0.93
Cadmium (Cd)	0.85
Cobalt (Co)	4.97
Chromium (Cr)	18.09
Copper (Cu)	8.68
Manganese (Mn)	275.84
Nickel (Ni)	6.19
Lead (Pb)	7.55
Selenium (Se)	5.44
Zinc (Zn)	33.37
Vanadium (V)	38.91

in sandstone rock samples. Because of the chemical composition, matrix complexity, and insolubility of the rock type in mild acidic media (due mainly to a high silica content of approximately 95-97% and various other resistant mineral constituents), the fine powder sample was treated under harsher acidic conditions to ensure complete elemental extraction into the aqueous solution. The method used for the sample dissolution is outlined in section 3.2.2. In order to minimize errors due to the varying distribution of elements within different rocks, the concentrations shown in Table 3 are based on an average of three representative sandstone samples. The reported data are based on the average of three independent runs with a calculated relative standard deviation of ~2%. The sandstone samples were found to contain a total of thirteen heavy metals at various concentrations, all within the calibration curve and the ICP detectable range. Compared to the remaining elements, barium (Ba) and manganese (Mn) concentration levels were observed to be highest. However, Ba and Mn are considered less harmful contaminants, and their levels in the sample were far below the allowable limits set by the WHO and EPA for standard potable water. Other more toxic elements such as Cd, As, Be, Co, Cu, Ni, Pb and Se were present as well, but with lower ppm-range concentrations. The remaining elements (Cr, Zn and V) showed moderate ppm concentration levels. Iron appeared to be present in high quantities but showed inconsistency (possibly from the jaw crusher's blades) among the samples, so was not included in this study. Actual Fe concentrations will be included in the next report.

In order to get some clue about the chemical composition of the sandstone sample, approximately 4g of finely ground sample was pressed into a solid pellet and scanned by XRF (PANalytical Axios XRF analyzer, PANalytical Inc., Almelo, The Netherlands). Table 4 illustrates the concentrations of some major constituents that are present in the sample. Elements in the actual sandstone rocks are tabulated as "metal oxides" and were reported in weight percent (W %) with absolute errors less than 0.080 percent. It can be seen that, alumina "aluminum oxide" (Al_2O_3) and silica "silicon dioxide" (SiO_2) are predominantly present due to the fact that the rock used in the study is sandstone type. Other metal oxides are present with lower concentrations.

Table 4 The concentrations of major oxides in rock sample (sandstone).

Compound Name	Concentration in weight (%)
Al_2O_3	16.99
BaO	0.07
CaO	3.29
CeO_2	0.02
Cl	0.03
Cr_2O_3	0.01
Fe_2O_3	2.71
K_2O	2.76
MgO	1.55
MnO	0.05
Na_2O	1.12
Nb_2O_5	0.00
NiO	0.01
P_2O_5	1.89
Rb_2O	0.01
SO_3	0.27
SiO_2	68.60
SrO	0.01
TiO_2	0.55
Y_2O_3	0.00
ZnO	0.01
ZrO_2	0.04

4.2 Effect of flow rates on metal leaching

Variations in flow rate were examined in order to determine any effects they might have on the fractionation or the desorption of metals from the sandstone rocks and the dissociation from their counter anions. Aliquots were collected every 8 hours from the column's sampling point over a period of 40 hours and analyzed by ICP. Other experimental parameters such as temperature and pH were kept constant at 21 ^oC and 6, respectively. Water was introduced from the top of the column and percolated downward through the sandstone particles at four specified constant flow rates. The water flow rates used in the study ranged from 11.67 ml/min to 33.33 ml/min. Figures 5 to 9 represent (in ppb) concentrations of soluble metals in the leachate tending toward mobilization through the sandstone particles at various flow rates from the bottom column's sampling point; these were collected at the specified sampling periods.

The results obtained were generated from the average of three independent experiments. Regardless of the flow rate applied, only five of thirteen elements were observed to have any desorption capability through rocks and dissociation from their minerals under the specified conditions. Their easy fractionation might be attributed to their weak physical or chemical adsorption bonding in their minerals, or might instead be due their solubility tendency relative to the other heavy elements.

The majority of the other heavy metals in the studied rock particles did not show any leaching under the given conditions. Their immobility might possibly owe either to their chemical bonding interactions with the rock's particle surfaces or to the formation of complexes with the rock's minerals. Another explanation could be that some might have leached or desorbed out but formed complexes with minerals in the rock and, as a result, showed no solubility toward water. However, as evidenced by its high concentrations at all flow rates and collection times, one of the leached species, boron (B), showed the highest mobility of all the elements. All plots show that concentrations of B exhibited a direct relationship with flow rate, indicating that its migration or desorption increased as it contacted the water flow. By contrast, the fractionation of other leached elements within the run showed somewhat less mobility based on flow-rate variation.

Figures 5 to 9 also show desorption of these metal species with respect to sampling time. It can be observed that prolonged water contact with the particles' surfaces significantly impacted the metals' mobility. Maximum concentration levels of leached metals occurred at the first sampling collection time (8hrs); leachate collected at later sampling times (i.e., 16, 24, 32 and 40 hours) showed lower concentrations of leachable metals. Prolonged contact with the water flow caused desorption within shorter time periods, due either to solubility or the weak physical bonding of these species with the rock surface. It is worth noting that all of the leached metals' concentrations at all flow rates were observed to be below the WHO/EPA drinking water standard limits (Table 1). From these findings, it was determined that to complete the remaining task of determining the effect of pH on metal leaching, a lower flow rate would be recommended in order to minimize desorption of the leachable metals (especially B and Mn).

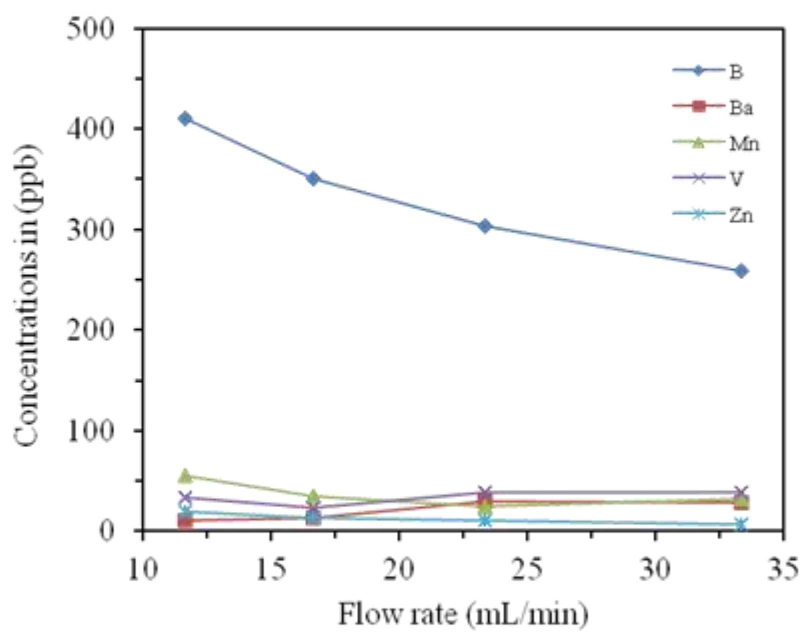


Figure 5 Effect of flow rate on metal leaching (collection time 8 hours).

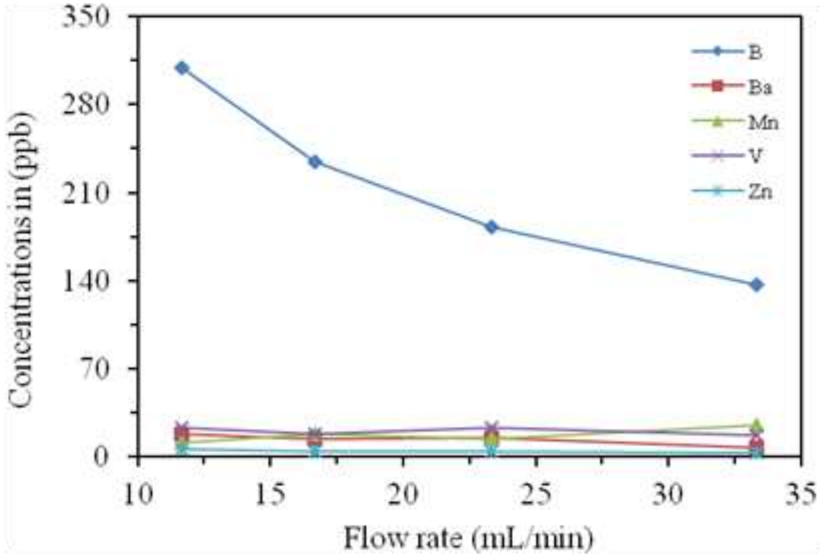


Figure 6 Effect of flow rate on metal leaching (collection time 16 hours).

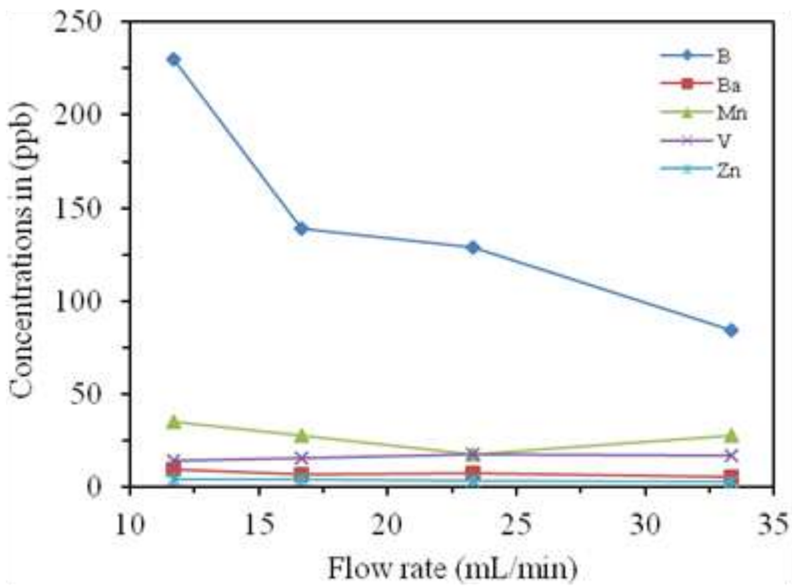


Figure 7 Effect of flow rate on metal leaching (collection time 24 hours).

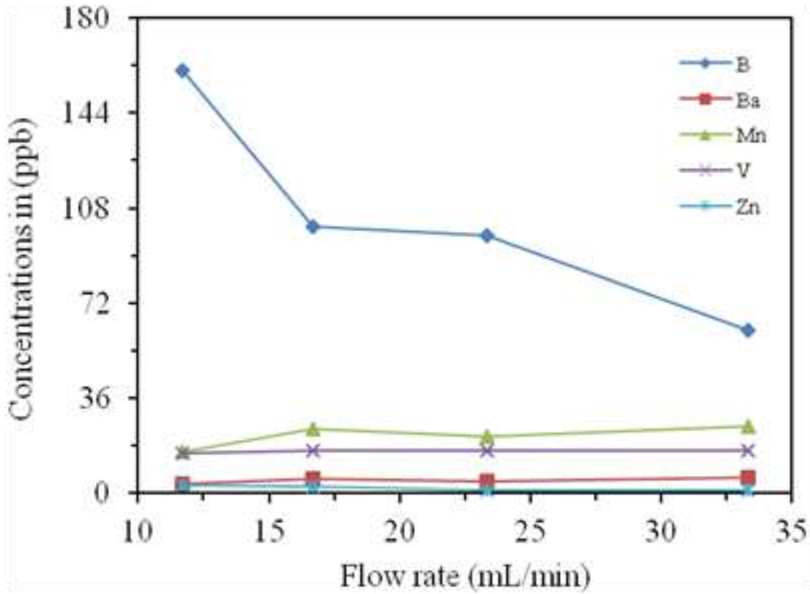


Figure 8 Effect of flow rate on metal leaching (collection time 32 hours).

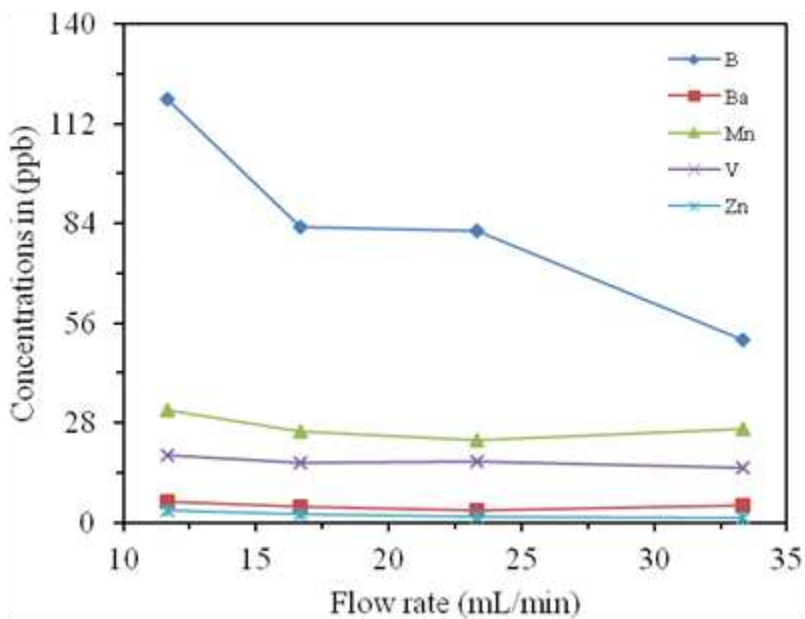


Figure 9 Effect of flow rate on metal leaching (collection time 40 hours).

4.3 Continuous vs. batch leaching

A comparison of continuous and batch processes for the leachable heavy metals is presented in Figures 10 and 11, with levels of the extracted amounts shown in ppb concentrations. The concentrations are plotted against collection sampling time periods of 8, 16, 24, 32 and 40 hours. Experiments were conducted at a constant temperature of 21 ^{o}C and a pH of 6. A water flow rate of 6.33 ml/min was used in the continuous leaching. In the case of batch leaching, a quantity of water (about 1800 ml) was added from the top of the column sufficient to immerse the 5 kg of sandstone particles at the beginning of the process. Samplings were taken periodically every 8 hours. Only four metals (B, Ba, Mn and Zn) appeared to have any mobility in either leaching process. The amounts of Ba and Zn leached were comparable regardless of the leaching process. Steady water contact with the particle surfaces in batch leaching did not cause any noticeable desorption enhancement of the leached metals, rendering extracted metal concentration levels similar to those of the continuous process. However, B was an exception to this finding, evincing a slightly higher mobility in the continuous process compared to the batch process. The reason for this might be due to the flow of water moving downward through the particles, causing the greater mobility of B. By contrast, the behavior of Zn was opposite that of B, due perhaps to the physical interaction or bonding of Zn to the particle surface. Finally, water contact and flow rate were not shown to have any significant effect on leaching of the remaining elements present in the studied rock material. V was not detected as in the previous plots and this could be attributed to the uneven metal’s distribution within the rocks.

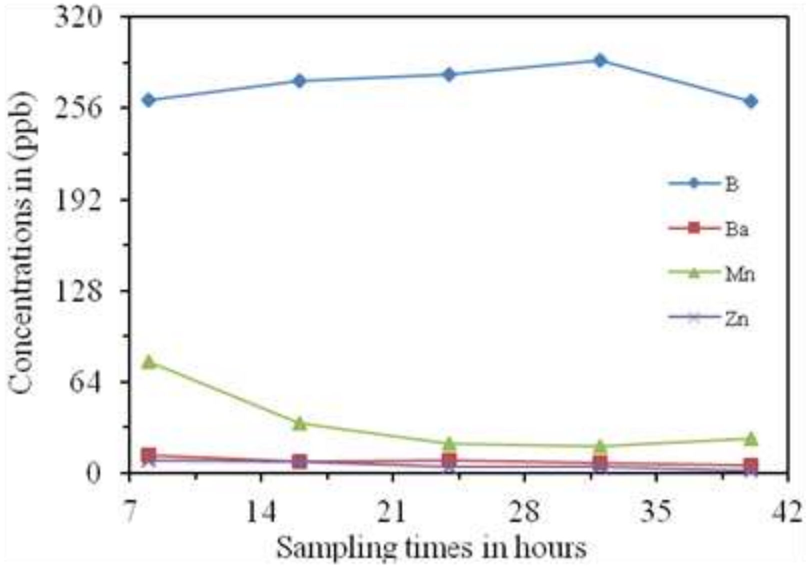


Figure 10 Continuous leaching (flow rate 6.33 ml/min).

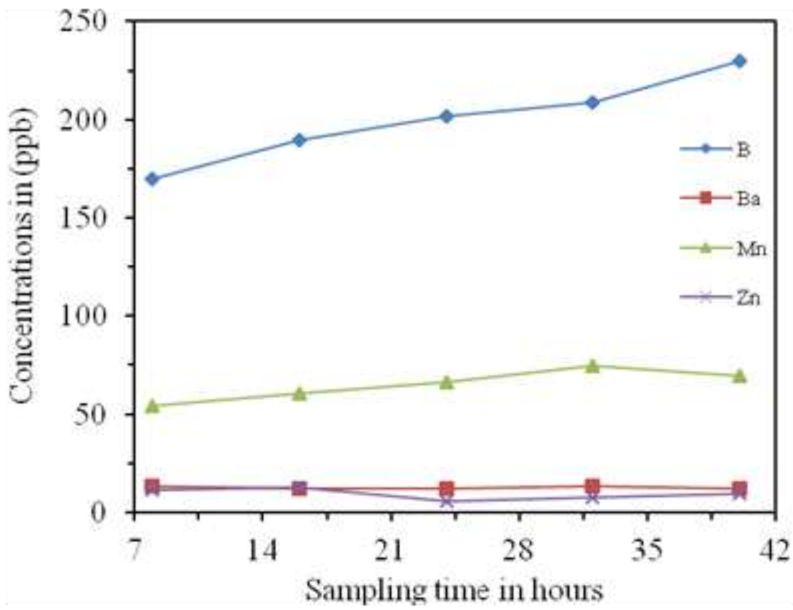


Figure 11 Batch leaching (total volume 1800ml).

4.4 Effect of pH on the heavy metals mobility

Figures 12 to 15 represent leaching of some of the heavy metals that showed their tendency to dissociate or desorb from their minerals and their dependency on pH change. Samples were taken every 12 hours over 10 sampling times. Results obtained in the study showed that only four out of the total thirteen heavy metals present in the sandstone rocks were soluble and fall within the detectable range of ICP calibration curve. These are namely boron, barium, manganese, and vanadium. The concentrations of these cations and their degree of pH dependency have some similar trends. All four metals have a higher solubility at lower pH. An increase in the pH tends to gradually decrease their solubility and as a result they become more immobile and hence less leachable. The lower mobility could be attributed to their precipitations and formation of insoluble (i.e. aluminum oxides or iron hydroxides) complexes in the basic media. Prolonged contact did not seem to cause significant effect on the rate of the dissociation of the metals and particularly in the case Mn and V, whereas B indicated some solubility rate increase with contact time. The solubility profiles are not perfectly graphed which is mainly due to the heterogeneity and the less uniform distribution of the heavy metals within and between the rock samples. Due to the above reason Zn was not present in any of the plots and this could be due to its concentration variation among the rocks or the possibility of its precipitation with iron hydroxides media of higher pH.

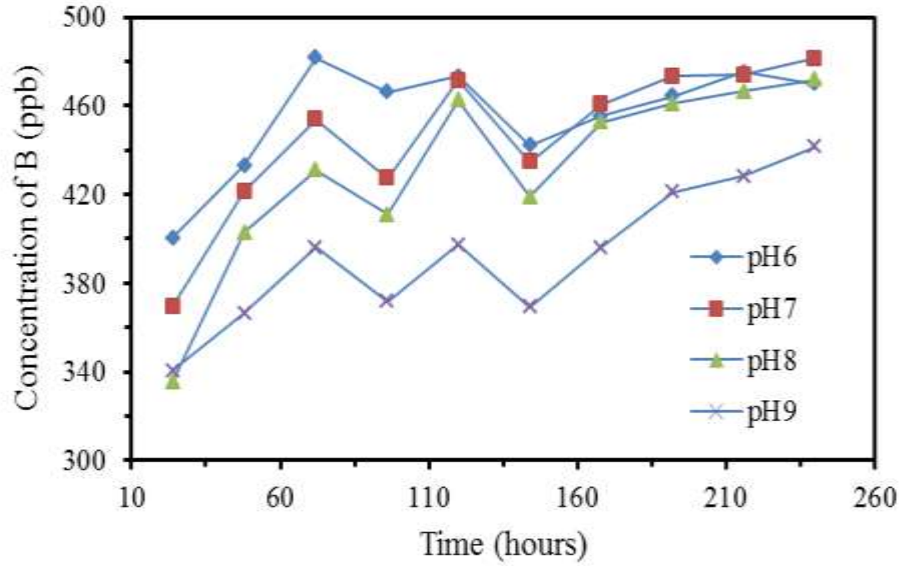


Figure 12 Effect of pH on boron (B) leaching (sampling interval: 12 hours).

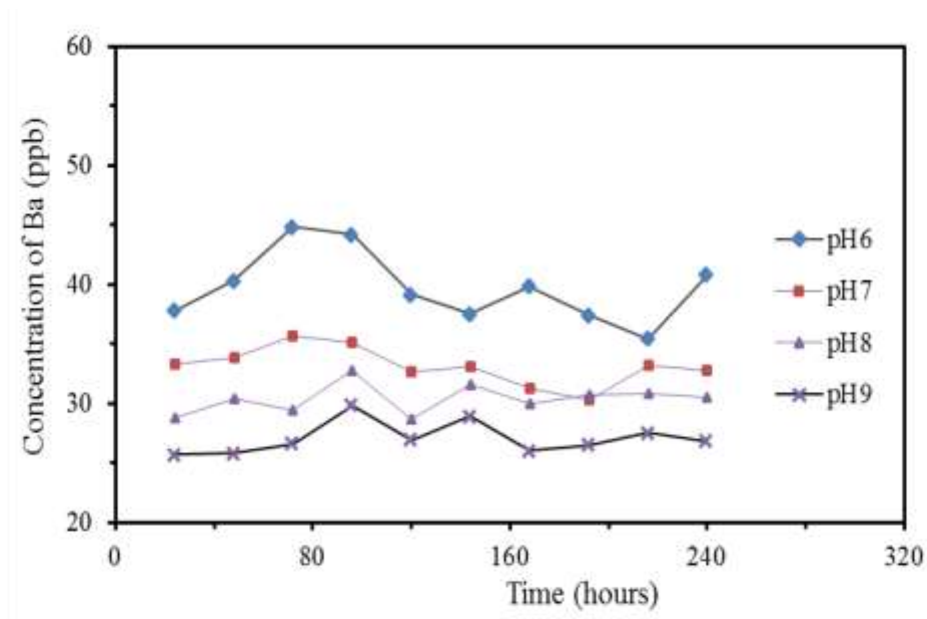


Figure 13 Effect of pH on barium (Ba) leaching (sampling interval: 12 hours).

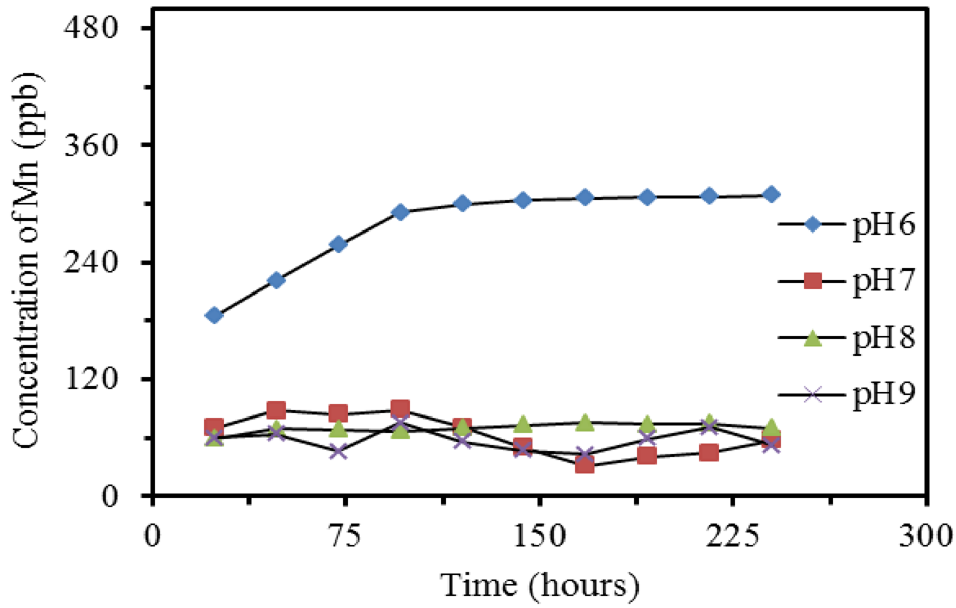


Figure 14 Effect of pH on manganese (Mn) leaching (sampling interval: 12 hours).

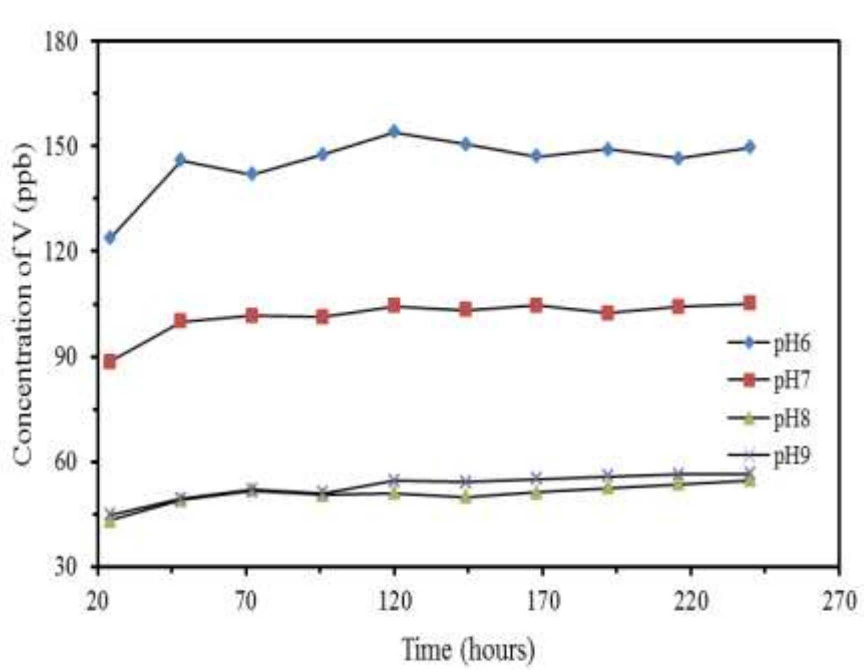


Figure 15 Effect of pH on vanadium (V) leaching (sampling interval: 12 hours).

4.5 Determination of inorganic anions in the leachates

Table 5 lists all possible anions present in the leachate that were collected from the different pH solution media and analyzed via Ion Chromatography (Metrohm 792 IC). In Table 5, sulfate ion has the highest concentrations (441 mg/L to 560 mg/L) among all the anions. This may indicate that most of the leached heavy metal cations originally bonded with sulfate in

Table 5 Anions in leachate.

Sample (mg/L)	pH 6	pH 7	pH 8	pH 9
Fluoride	1.5	1.7	1.7	1.7
Chloride	28.4	29.1	30	45
Nitrite as N	1.7	2.0	0.30	2.2
Nitrate as N	5.7	4.4	4.9	17.4
Bromide	0.2	0.2	0.10	<0.1
Phosphate	<0.1	<0.1	<0.1	<0.1
Sulfate	484	443	441	560

minerals. However, Ba tends to have low solubility in the presence of sulfate which forms BaSO4, but the presence of chloride ion as the second major ion in the leachate (28 mg/L to 45 mg/L) and nitrate ion (4 mg/L to 17 mg/L) would indicate that Ba could be fractionated or desorbed from minerals that contain chloride or nitrates. BaCl2 and Ba(NO3)2 are known to be more soluble, and the presence of high levels of chloride ion may enable sulfate-rich water to retain more Ba in solution. In the case of Mn, it was mentioned that most of its salts are readily soluble in water, with the exception that its carbonate and phosphate have low solubilities in water. Boron salts are generally soluble, although some boron salts such as boron nitrite are completely insoluble in water. Boron halides are soluble in water, which would suggest that boron could be fractionated or desorbed from chloride mineral complexes. The major anions in the leachate are listed in Table 5.

4.6 Determination of the desorption order of leachable heavy metals

A batch leaching run is presented in Figure 16. Rate of leaching of each individual metal varies with time. B and Mn have similar leaching profiles, where the concentrations show a direct increase with time. Similar leaching behaviors were observed for Ba and V. Leaching rates of Ba an V were almost constant regardless of sampling time. The concentrations of each leached species were plotted against time. If the leaching data of contaminant species *i* fits a first order kinetic model, then plot of $-\ln[C_{e,i} - C_t]$~t should be linear with a high regression coefficient. Figures 17-20 are used to establish the reaction orders of B, Ba, Mn, and V. Generally speaking, the leaching of the four species follows a first order kinetic model. However, the regression values (R^2) for all plots are not very high, which could be attributed to the uneven distribution of heavy metal within the rock particles. Dissociation or desorption rate constant (k_i in E1-E4) for each leached metal can be obtained from the slope of the corresponding plot and they are presented in Table 6.

Table 6 Desorption rate constants ($k_{i.}$ in E1-E4) for leachable metals.

Element	Desorption rate constant [k_i (1/hr) in E1-E4]
Boron (B)	3.68×10^{-2}
Barium (Ba)	3.74×10^{-2}
Manganese (Mn)	3.81×10^{-2}
Vanadium (V)	2.77×10^{-2}

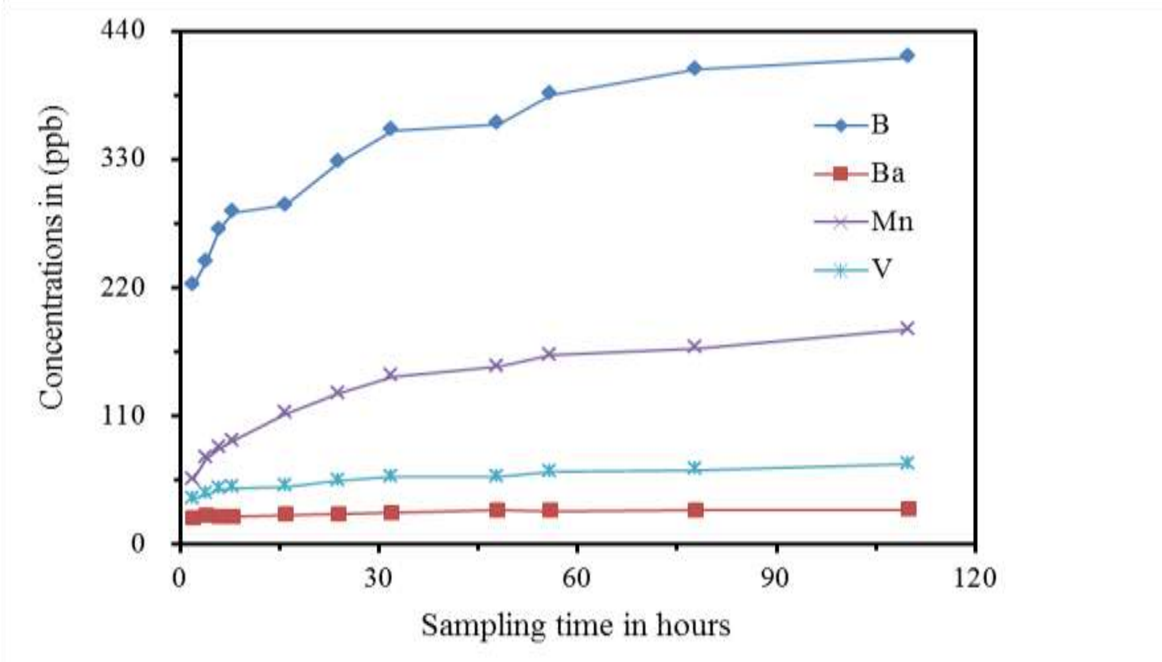


Figure 16 Batch leaching (total volume 2 L).

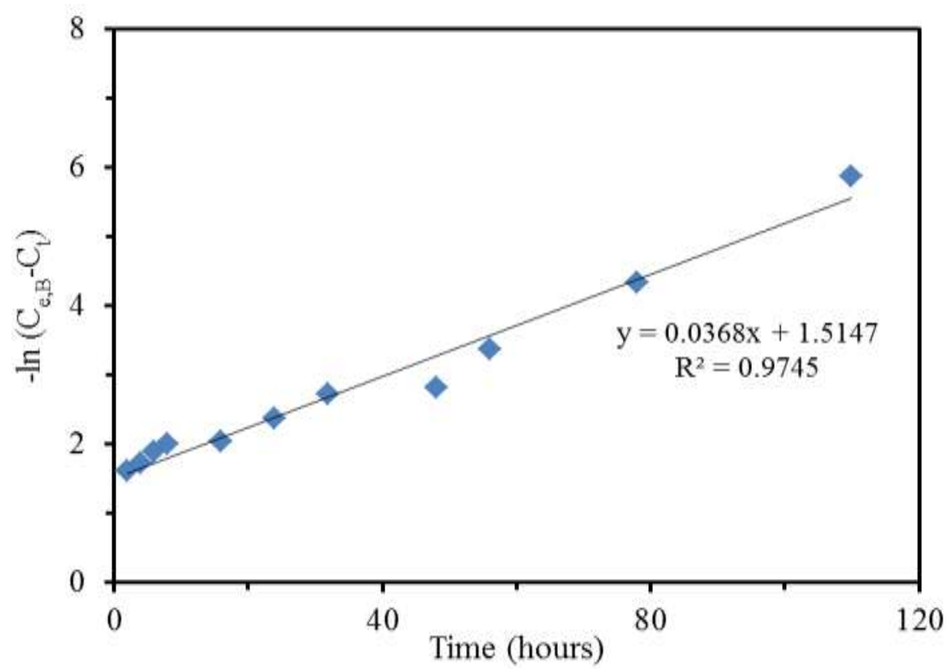


Figure 17 Determination of reaction order of Boron (B).

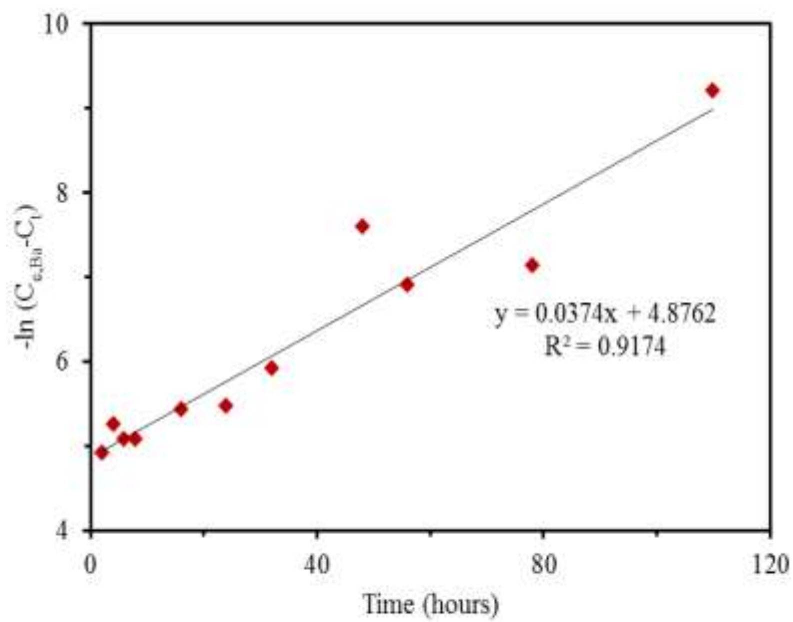


Figure 18 Determination of reaction order of Barium (Ba).

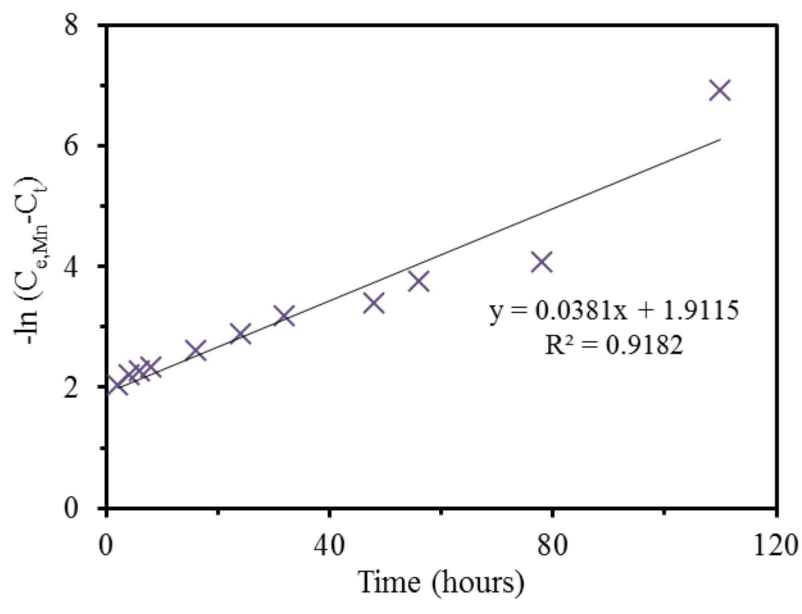


Figure 19 Determination of reaction order of Manganese (Mn).

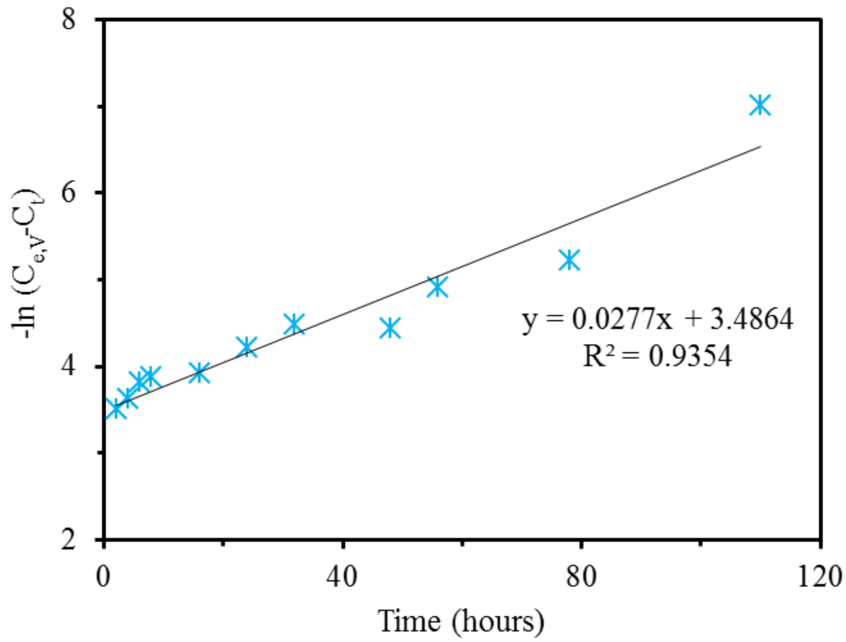


Figure 20 Determination of reaction order of vanadium (V).

4.7 Effect of temperature on the desorption of heavy metals

The depth of an aquifer is another indirect factor to be considered when it comes to the storage of water. Temperature within the Earth increases with depth. It has been reported that the increase is about 25 °C per km of depth in most of the world [19]. As a result it is important to examine the effect of temperature on the desorption of the heavy metals from their minerals. In this study the temperature variations over the range of 5 ^{o}C to 55 ^{o}C were tested to find out their effects on the desorption of the heavy metals. The investigations in this study have shown that only four metals have been desorbed to some degree and dissolved in water regardless of temperature. However, the dissolution of these leached metals has shown an increasing trend with temperature. Tables 7-10 represent the average concentrations of triplicate independent runs of B, Ba, Mn and V at the specified temperatures. A noticeable increase of the concentration was observed of each metal within each table as going down (as temperature increases) the tables regardless of sampling times. However, the horizontal trend shows no major concentration variations between sampling times, rather a constant rate of leaching and therefore a dynamic status.

Table 7 Boron (B) concentration (ppb).

Day/Temperature (^oC)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
5	234.4	259.5	215.4	209.9	190.5	211.6
15	252.6	243.8	265.8	248.9	247.4	245.1
25	364.2	379.8	370.9	377.0	379.5	385.5
35	520.2	550.3	583.9	566.7	576.0	606.5
45	671.2	778.5	765.4	795.3	826.0	800.2
55	937.9	966.5	909.4	885.5	897.9	877.9

Table 8 Barium (Ba) concentration (ppb).

Day/Temperature (^oC)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
5	47.3	38.7	37.8	36.2	39.9	30.0
15	41.6	43.3	41.3	42.9	42.1	40.1
25	51.9	51.0	52.2	49.0	50.1	50.4
35	69.2	67.0	65.7	70.6	65.4	65.3
45	75.4	72.1	73.8	72.1	72.9	70.9
55	89.1	87.2	87.2	86.1	78.4	75.4

Table 9 Manganese (Mn) concentration (ppb).

Day/Temperature (^oC)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
5	26.6	12.5	9.3	1.7	6.1	6.4
15	4.8	16.8	11.4	9.8	21.6	26.9
25	13.3	32.3	14.3	40.7	60.8	58.4
35	29.7	39.9	78.8	120.7	86.9	68.2
45	41.5	108.3	84.9	124.0	120.9	134.2
55	192.9	252.8	272.6	296.9	291.2	296.1

Table 10 Vanadium (V) concentration (ppb).

Day/Temperature (^oC)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
5	120.7	117.2	112.0	115.9	107.2	111.1
15	126.2	127.1	138.6	127.6	128.3	128.3
25	150.8	150.3	144.8	143.4	148.2	137.8
35	161.1	149.7	147.5	157.0	149.7	154.6
45	169.5	150.5	153.1	148.7	151.2	151.8
55	159.4	166.6	173.5	165.4	169.6	162.9

4.8 Determination of solubility-product constant, K_{sp}.

The Solubility Product Constant, K_{sp} is the equilibrium constant for a solid substance dissolving in an aqueous solution. It represents the level at which a solute dissolves in solution. This constant can be applied in this study for the leachable metals to check their degree of desorption and hence their solubility in water. The general adsorption/desorption equation of the leaching metals can be written as:

$$M_xA_y(s) \leftrightarrow x\ M^{y+}(aq) + y\ A^{x-}(aq) \qquad \text{R1}$$

where $M_xA_y(s)$ represents the undissolved solid or mineral complexes in the rock particle that has shown some tendency to dissolve and dissociate in contact with water to give M^{y+} and A^{x-}. M^{y+} is the leached metal cations such as B, Ba, and Mn dissolved in water. On the other hand A^{x-} is the counter part of the cations (anions listed in table 5). Since the cations and anions concentrations are measured and known, then the equilibrium constants (K_{sp}) for the desorbed species can be found by the following equation:

$$K_{sp} = [M^{y+}]^x[A^{x-}]^y \qquad \text{E5}$$

where K_{sp} is the product of the concentration of the ions that are present in the saturated water solution. Tables 11-13 present the K_{sp} values for the data collected at day 6 at temperatures of 5 ^oC to 55 ^oC for the expected low soluble compounds along with their corresponding literature values. As it can be seen from these tables, the experimental K_{sp} values turned out to be slightly different than that of the ones reported in the literature. The difference may be contributed to the matrix complexity and the chemical composition of the minerals present in the rock. Hence, these metals are not purely dissociated from their counter ions species i.e H^+, SO_4^{2-} and OH^- , but rather from other minerals. Another reason for this inconsistency could be due to the presence of some precipitating metals or oxides which altered the solubility of these compounds. No K_{sp} values have been found in the literature for Vanadium compounds, as result the experimental Ksp values were not included in the study. Vanadium has been reported to exist as vanadyl and vanadate ions with the chemical formulas (VO^{2+}, $VO(OH)^+$) and ($H_2VO^-_4$ and HVO^{2-}_2) [20]. These two forms are found to be soluble and easily transfer from geological sediments to water. However, the concentration of vanadium was not high in the water and this is due to the fact that both compound species are known to bind strongly to some minerals and cations and are either adsorbed or form complexes.

Table 11 $B(OH)_3$ solubility product constants.

Temperature (^oC)	Conc. Of B (ppb)	Conc. Of $B(OH)_4^-$ (mol/L)	Conc. Of H^+ (mol/L)	Experimental K_{sp}	Literature *K_{sp}
5	211.6	1.9573×10^{-5}	5.0118×10^{-9}	9.8094×10^{-14}	5.80×10^{-10}
15	245.1	2.2671×10^{-5}	5.0118×10^{-9}	1.1362×10^{-13}	5.80×10^{-10}
25	385.5	3.5658×10^{-5}	5.0118×10^{-9}	1.7871×10^{-13}	5.80×10^{-10}
35	606.5	5.6100×10^{-5}	5.0118×10^{-9}	2.8116×10^{-13}	5.80×10^{-10}
45	800.2	7.4017×10^{-5}	5.0118×10^{-9}	3.7096×10^{-13}	5.80×10^{-10}
55	877.9	8.1204×10^{-5}	5.0118×10^{-9}	4.0698×10^{-13}	5.80×10^{-10}

* Literature values at 25 ^oC

Table 12 $BaSO_4$ solubility product constants.

Temperature (^oC)	Conc. Of Ba^{2+} (ppb)	Conc. Of Ba^{2+} (mol/L)	Conc. Of SO_4^{2-} (mol/L)	Experimental K_{sp}	Literature *K_{sp}
5	30.0	2.1846×10^{-7}	$5.04x10^{-3}$	$1.1007x10^{-9}$	$1.10x10^{-10}$
15	40.1	2.9200×10^{-7}	$5.04x10^{-3}$	$1.4713x10^{-9}$	$1.10x10^{-10}$
25	50.4	3.670110^{-7}	$5.04x10^{-3}$	$1.8492x10^{-9}$	$1.10x10^{-10}$
35	65.3	$4.7551x10^{-7}$	$5.04x10^{-3}$	$2.3958x10^{-9}$	$1.10x10^{-10}$
45	70.9	$5.1629x10^{-7}$	$5.04x10^{-3}$	$2.6013x10^{-9}$	$1.10x10^{-10}$
55	75.4	$5.4905x10^{-7}$	$5.04x10^{-3}$	$2.7664x10^{-9}$	$1.10x10^{-10}$

*Literature values at 25 ^oC

Table 13 $Mn(OH)_2$ solubility product constants.

Temperature (^oC)	Conc. Of Mn^{2+} (ppb)	Conc. Of Mn^{2+} (mol/L)	Conc. Of OH^- (mol/L)	Experimental K_{sp}	Literature *K_{sp}
5	6.4	1.1650×10^{-7}	1.9952×10^{-6}	4.6377×10^{-19}	1.9×10^{-13}
15	26.9	4.8964×10^{-7}	1.9952×10^{-6}	1.9493×10^{-18}	1.9×10^{-13}
25	58.4	1.0630×10^{-6}	1.9952×10^{-6}	4.2319×10^{-18}	1.9×10^{-13}
35	68.2	1.2414×10^{-6}	1.9952×10^{-6}	4.9421×10^{-18}	1.9×10^{-13}
45	134.2	2.4428×10^{-6}	1.9952×10^{-6}	9.7248×10^{-18}	1.9×10^{-13}
55	296.1	5.3897×10^{-6}	1.9952×10^{-6}	2.1457×10^{-17}	1.9×10^{-13}

*Literature values at 25 ^oC

4.9 Determination of enthalpies (ΔH) and entropies (ΔS) for the leachable elements

Determination of the thermodynamic quantities, i.e ΔH and ΔS, for the leachable elements can be obtained by measuring K_{sp}, over a specified temperature range. These thermodynamic quantities can be expressed by the following equation as;

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ \qquad \text{E6}$$

where ΔG, is the free energy change in a reaction. It can also be related to K_{sp} for the reaction by the equation,

$$\Delta G° = -RT \ln(K_{sp}) \quad \text{E7}$$

Substitution of the left side of E6 with the right side of E7 yields E8.

$$-RT\ln(K_{sp}) = \Delta H° - T\Delta S° \quad \text{E8}$$

Rearrangement of E8 can lead to the following form, E9;

$$\ln(K_{sp}) = -\frac{\Delta H^{\circ}}{R}\frac{1}{T} + \frac{\Delta S^{\circ}}{R} \quad \text{E9}$$

Equation E9 is well suited for finding ΔH° and ΔS° by linear regression. Plotting Ln (K_{sp}) vs. 1/T as illustrated in Figures 21-23 would give the quantities of ΔH° and ΔS° from slopes (m = - ΔH°/R) and intercepts (b = ΔS°/R). The experimental thermodynamic values ΔH°, ΔS° and ΔG° for each leachable species are presented in Table 14.

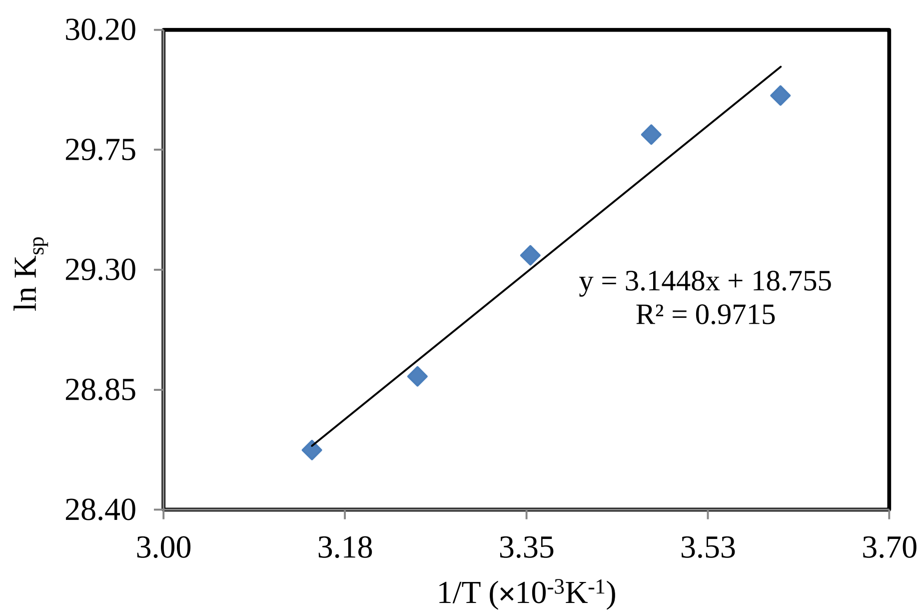


Figure 21 Determination of enthalpy and entropy of $B(OH)_3$.

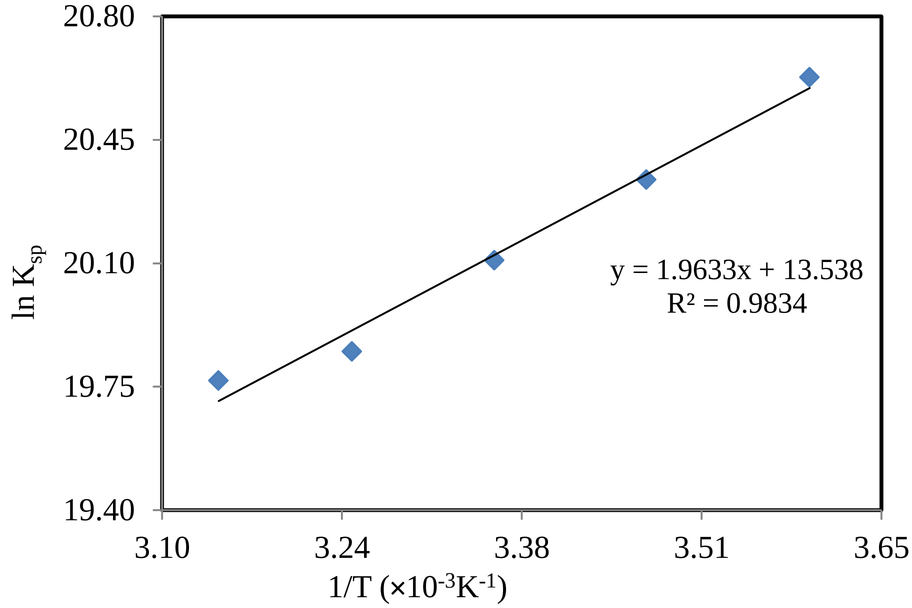


Figure 22 Determination of enthalpy and entropy of $BaSO_4$.

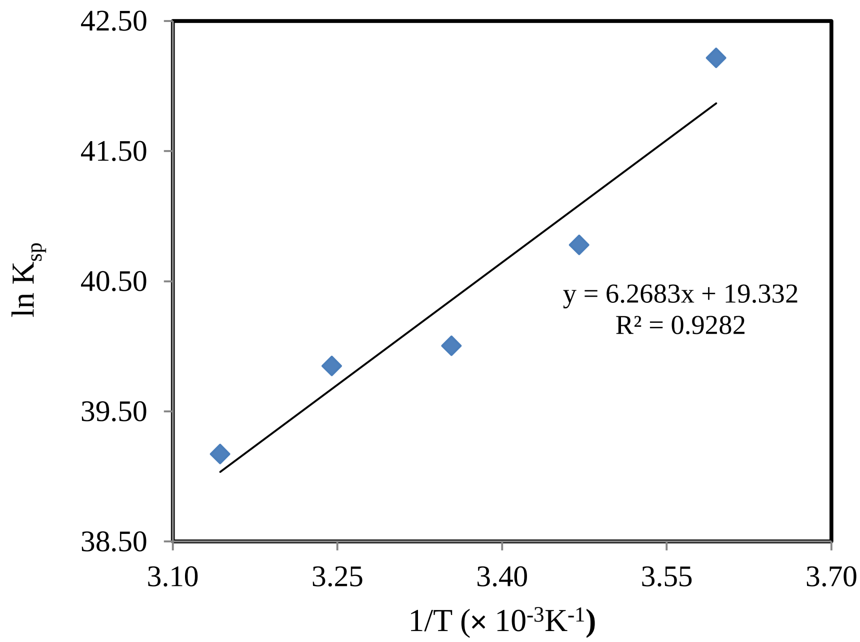


Figure 23 Determination of enthalpy and entropy of $Mn(OH)_2$.

Table 14. Leachable metals thermodynamic values ΔH°, ΔS° and ΔG°.

Compound	ΔH° [KJ/mol]	ΔS° [KJ/(K·mol)]	ΔG° [KJ/mol]
$B(OH)_3$	26.15	155.93	-20.34
$BaSO_4$	16.32	112.55	-17.23
$Mn(OH)_2$	52.12	160.74	41.93

5. CONCLUSIONS

Contaminant leaching model for aquifer storage and recovery technology (ASR) has been investigated in this study. The first part of the study was focused on a number of factors that could contribute or enhance the mobility of metals. These factors included pH, water injection flow rate, and temperature variation. The second part of the study examined the kinetic and thermodynamic properties of the leachable metals. The fractionation or the desorption of the leached metals from the studied sandstone rock samples were examined under the above mentioned conditions. However, only four metals out of the fifteen initially present in the rock samples desorbed and appeared to show minimal concentrations in the water leachate compared to that of reference samples. These concentrations were also found to be significantly below the WHO/EU standard limits for drinking water. Due to the very small contaminants found in the leachate, this puts the ASR as a promising and an alternative technology that would be used as way to replace some other more expensive methods such as surface reservoirs.

6 PROJECT PUBLICATIONS AND PRESENTATIONS

1. Abdulwahab Tuwati, Environmental Issues and Their Solutions Associated with Fossil Fuel Energy Production, PhD Dissertation, Department of Chemistry, University of Wyoming, Laramie, WY.
2. Sharrad, M. O., Liu, H., and Fan, M. (2012), "Selenium Removal from Water by FeOOH," Separation and Purification Technology, Vol. 84, No. 1, PP. 29-34.
3. Presentations
   a. Wyoming Water Research Program, Thursday, December 2, 2010, in the WWDC conference room, 6920 Yellowtail Rd, Cheyenne
   b. Department of Chemistry at University of Wyoming, December 8, 2010.

7 STUDENT SUPPORT AND TRAINING

1. Abdulwahab Tuwati, Department of Chemistry, University of Wyoming
2. Mustafa Sharrad, Department of Chemical & Petroleum Engineering, University of Wyoming
3. Mohamad Rizan Fazily, Department of Chemical & Petroleum Engineering, University of Wyoming
4. Andrew Thomas Jacobson, Department of Chemical & Petroleum Engineering, University of Wyoming

8 REFERENCES

1. I. McBeth, K. J. Reddy, Q. D. Skinner, Chemistry of trace elements in coalbed methane product water, Water Research, 37(2003) 884-890.
2. Nevada Mining Association (1996), Meteoric Water Mobility Procedure, *Standardized Column Percolation Test Procedure*, Nevada Mining Association, Reno, NV, 5p.

   http://ndep.nv.gov/bmrr/mobilty1.pdf.
3. R. B. Lai, Effect of heavy metal toxicity and exposure on human health, Indian Journal of Environment and Ecoplanning, 2(2005) 533-536.
4. Water Treatment Solutions, Lenntech. WHO/EU drinking water standards comparative table, http://www.lenntech.com/who-eu-water-standards.htm.
5. Drinking Water Contaminants, National Primary Drinking Water Regulations, http://water.epa.gov/drink/contaminants/index.cfm.
6. K. A. Mortin, N. M. Hutt, Environmental geochemistry of mine site drainage: Practical and case studies. Minesite Drainage Assessment Group (MDAG) Publishing, (1997) 333.
7. J. G. Skousen, Acid mine drainage, Acid Mine Drainage Control and Treatment: West Virginia University and National Mine Land Reclamation center, 91(1995) 12.
8. W. Gregg, P. Thomas, Relationship between pyrite stability and arsenic mobility during aquifer storage and recovery., Environmental Science & Technology, 41(2007) 723-730.
9. B. Batchelor, Leach models for contaminants immobilized by pH-dependent mechanisms, Environmental Science & Technology, 32(1998) 1721-1726.
10. Y. Sun, Z. Xie, J. Xu, Z. Chen, R. Naidu, Assessment of toxicity metal contaminated soils by the toxicity characteristic leaching procedure, Environmental Geochemistry and Health,

28(2006) 73-78.

11. B. Ludwig, P. Khanna, J. Prenzel, F. Beese, Heavy metal release from different ashes during serial batch tests using water and acid, Waste Management, 25(2005) 1055-1066.
12. A. Batayneh, Heavy metals in water springs of the Yarmouk Basin, North Jordan and their potentiality in health risk assessment, Internal Journal of Physical Science, 5(2010) 997-1003.
13. K. M. Banat, F.M. Howari, A.A. Al-Hamad, Heavy metals in urban soils of central Jordan: Should we worry about their environmental risks? Environmental Research, 97(2005) 258-273.
14. B. A. Mendez-Ortiz, A. Carrillo-Chavez, M. G. Monroy-Fernandez, Acid rock drainage and metal leaching from mine waste material (tailings) of Pb-Zn-Ag skarn deposit: environmental assessment through static and kinetic laboratory tests, Revista Mexicana de Ciencias Geologicas, 24(2007) 161-169.
15. G. C. Chen, Z. L He, P. J. Stoffella, X. E. Yang, S. Yu, J. Y. Yang, D. V. Calvert, Leaching potential of heavy metals (Cd, Ni, Cu and Zn) from acidic sandy soil amended with dolomite phosphate rock (DPR) fertilizers, Journal of Trace Elements in Medicine and Biology, 20(2006)127-133.
16. R. Clemente, A. Escolar, M. P. Bernal, Heavy metals fractionation and organic matter mineralization in contaminated calcareous soil amended with organic materials, Bioresource, 97(2006) 1894-1901
17. J. E. Maskall, I. Thornton, chemical partitioning of heavy metals in soils, clays and rocks at historical lead smelting sites, Water, Air, and Soil Pollution, 108(1998) 391-409.
18. M. Bettinelli, U. Baroni, N. Pastorelli, Analysis of coal fly ash and environmental materials

by Inductively Coupled Plasma Atomic Emission Spectrometry: comparison of different decomposition procedures, Journal of Analytical Atomic Spectrometry, 2(1987) 485-489.

19. MadScience Network: Earth Sciences, www.madsci.org/posts/archives/200203/1017275290 .Es.r.html.
20. W. Bernhard, S. Werner, Vanadyl in natural waters: Adsorption and hydrolysis promote Oxygenation, Geochimica et Cosmochimica Acta, 53(1989) 69-77.

Multi-Century Droughts in Wyoming's Headwaters: Evidence from Lake Sediments

Basic Information

Title:	Multi-Century Droughts in Wyoming's Headwaters: Evidence from Lake Sediments
Project Number:	2010WY60B
Start Date:	3/1/2010
End Date:	2/28/2013
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Drought, Water Supply, Climatological Processes
Descriptors:	
Principal Investigators:	Bryan N Shuman, Thomas A Minckley, Jacqueline J Shinker

Publications

1. Shinker, J.J., B.N. Shuman, T.A. Minckley, and A.K. Henderson, 2010. Climatic Shifts in the Availability of Contested Waters: A Long-term Perspective from the Headwaters of the North Platte River, Annals of the Association of American Geographers (Special Issue on Climate Change), 100 (4), 866-879.
2. Shuman, B., P. Pribyl, T.A. Minckley, and J.J. Shinker, 2010. Rapid hydrologic shifts and prolonged droughts in Rocky Mountain headwaters during the Holocene, Geophysical Research Letters, DOI:10.1029/2009GL042196.
3. Fredrickson, J., 2012. Hydroclimatic variability in Wyoming headwaters. University of Wyoming, Masters of Arts thesis, 68 pp.
4. Kelly, R., T. Surovell, B. Shuman, G. Smith, 2013. A Continuous Climatic Impact on Holocene Human Population in the Rocky Mountains. Proceedings of the National Academy of Sciences 110 (2): 443-447.
5. Minckley, T. A., R. Shriver, B. Shuman, 2012. Resilience and regime change in a southern Rocky Mountain ecosystem during the past 17000 years. Ecological Monographs 82(1): 49-68.
6. Shuman, B., 2012. Recent Wyoming temperature trends, their drivers, and impacts in a 14,000-year context. Climatic Change 112 (2): 429-447.

Multi-Century Droughts in Wyoming's Headwaters: Evidence from Lake Sediments
March 2011-February 2013 Final Report
Bryan Shuman, J. J. Shinker, and Thomas Minckley

Abstract

Wyoming has historically experienced extended periods of drought, which have had significant economic and social impacts. Tree-ring records and archeological evidence indicate that past centuries have contained multi-decadal "megadroughts" far more severe than any drought of the past 150 years. This project has studied past dry periods that likely exceeded even the severity of multi-decadal "megadroughts" in Wyoming watersheds. In doing so, we built upon funding from a previous Wyoming Water Research Program grant, and have found evidence of consistent moisture histories across the water-producing regions of the state. Evidence derives from prehistoric shoreline elevations in lakes in the Medicine Bow, Wind River, Beartooth and Bighorn Mountains, and shows that climatic shifts can rapidly generate new hydrologic regimes that persist for centuries to millennia. Aridity, at least as severe and extensive as during the AD 1930s Dust Bowl, prevailed from 9300-5500, 4500-3000, and 1400-900 years before AD 1950, although some dry periods in the north were wet in the south. The lake-shoreline elevations as well as watershed moisture budget calculations indicate that at least portions of the North Platte and Bighorn River systems were probably ephemeral for several millennia when dune activity was common across parts of Wyoming, Colorado, and Nebraska. High temperatures commonly increased evaporative losses from the region and coincided with the most severe aridity. Work included 1) surveys of lakes in the Bighorn drainage basins, using sub-surface radar, to determine the extensiveness of past periods of low lake levels, 2) sediment core collection and analysis, including radiocarbon dating and fossil analyses, of representative lakes in the Bighorn and Beartooth Ranges to date and quantify past climate conditions, 3) fossil pollen analyses used to evaluate temperature and vegetation changes associated with periods of aridity, and 4) hydroclimatic analysis, comparing paleoclimate estimates with modern climatic and stream flow data, to examine the factors that contributed to the periods of prolonged drought. Additionally, collaboration with UW archeologists has revealed that the human history of the Bighorn Basin was strongly linked to the changes in regional water supplies over the past 13,000 years. This work involved several graduate students, undergraduates, and high school interns in different activities from field work to data analysis and presentation.

Progress

Objectives

Water in the western United States, and Wyoming in particular, has long been a source of conflict within the region (e.g., long-running Supreme Court cases regarding the allocation of the North Platte, Green and Bighorn Rivers), and the past century has revealed that the availability of water can change significantly over time. Climate changes are likely to exacerbate uncertainties in water supplies, including the potential for hydroclimatic outcomes that may persist beyond reasonable resource planning horizons. Yet, water is critical for energy development, agriculture, urban use, and recreation in Wyoming, and planning requires estimates of the potential range of future availability. Long-term records of drought history, therefore, are needed to provide empirical data regarding past variability, particularly as a means to test predictive models.

Our previous work in the northern Wind River Range and in the southern portions of the Platte River basin indicates centennial to millennial periods since the last ice age when lakes across the region were lower than today – and when rivers such as the North Platte probably had ephemeral flows (Shuman et al., 2010; Shinker et al., 2010). Historic observations, therefore, do not adequately represent the full range of natural climate variability. Tree-ring data are also limited by biological and methodological constraints, which cause long-term trends to be undetected or perhaps underestimated, and **this project aimed to enhance the long-term record of drought in Wyoming** by generating new records of water-level change over the past >12,000 years from lakes across northern portions of the state (particularly in the mountain ranges that ring the Wind-Bighorn watershed).

To reach our goal, the project incorporated four activities:

1. **Confirm the extent and magnitude of past droughts**: are drought-history reconstructions from new study sites consistent with our prior results in terms of the estimated magnitude of past aridity? How geographically consistent or patterned were past droughts?
2. **Compare the lake sediment records of drought with other datasets**: at the locations of recent dendroclimatic studies, do lakes capture similar long-term variations? Do the changes relate to ecological or cultural changes?
3. **Examine the predictability of drought**: Was the timing of past drought in Wyoming consistent with sea-surface temperatures as expected from historic relationships? How do hydrologic changes relate to changes in temperature?
4. **Reconstruct in-stream flow** based on lake sediment analyses from areas of high flow contributions: did the Bighorn River have prolonged periods of extremely low flows such as we have reconstructed for the North Platte?

Methods

Previous studies have demonstrated that small lakes, such as kettle and moraine-dammed lakes in glaciated areas, can produce consistent records of climate-controlled lake-level fluctuations (e.g., Shuman et al., 2010; Shinker et al., 2010). In such lakes, the water table of the surrounding aquifer is exposed at the surface, and the lake level generally reflects the climate-controlled water budget of the aquifer. Therefore, we analyzed shore-to-basin transects of sediment cores (Fig. 1) and sub-surface profiles (Fig. 2) from multiple lakes to determine past shoreline elevations and measure regional moisture balance.

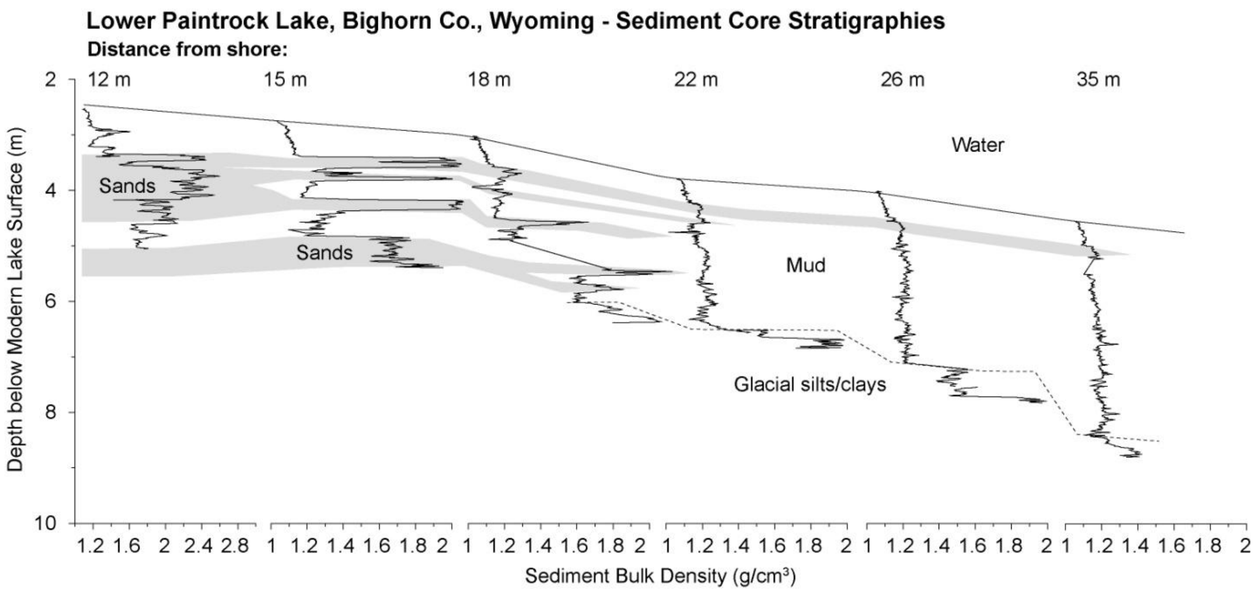


Figure 1. Sediment characteristics (such as sediment density above) in a transect of sediment cores collected perpendicular to shore can be used to track shifts in a lake's shoreline over time. Here, cores collected in July 2010 from Lower Paintrock Lake show layers of sand associated with periods of low water when the shoreline moved toward the lake center.

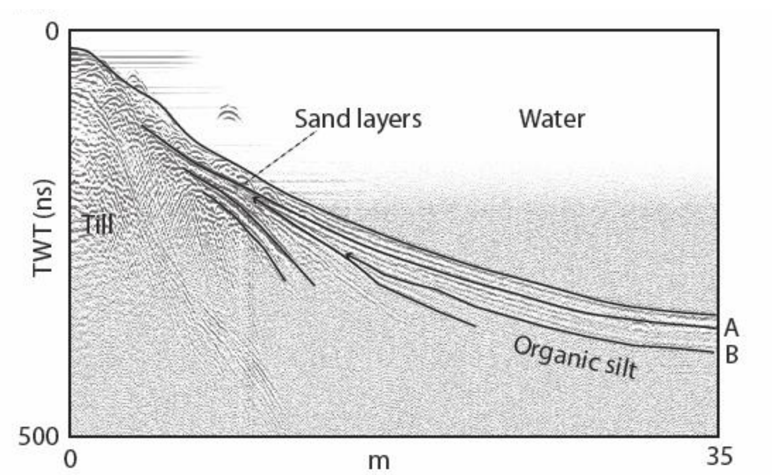


Figure 2. Ground-penetrating radar profiles show submerged paleoshorelines (sand layers marked by the convergence of stratigraphic layers and large amplitude radar reflections) in Lower Paintrock Lake. This profile spans the area of core locations (see Fig. 1), and confirms that the sand layers in the cores are associated with episodes of near-shore erosion (truncation of off-shore layers, such as layer B, at arrows). Data are presented in nanoseconds of the two-way travel time (TWT) of the radar signal, which is a function of depth.

In 2010 and 2011, we surveyed multiple lakes throughout the Bighorn River drainage with a ground-penetrating radar (GPR), as was previously done at Lake of the Woods in the northern Wind River Range and elsewhere (Shuman et al., 2010; Shinker et al., 2010), and identified changes in the geometry of the sediments that indicate past shifts in shoreline position (Fig. 2). We assume that sandy, macrophyte-rich substrates expanded toward the center of the lake and that sedimentation slowed near shore when lake levels were low (Fig. 1, 2).

Targeted sediment coring at representative lakes, Upper Medicine Lodge, Lower Paintrock Lake, and Duncan Lake in the west-central Bighorn Mountains (Fig. 1), and Rainbow and Lily Lakes on the Beartooth Plateau enabled us to measure the elevations and ages of past shoreline deposits (Fig. 3). Shifts in sediment composition and grain size have been assessed using loss on ignition, magnetic susceptibility, grain-size analysis, and other core logging techniques that can be conducted in the UW Geology and Geophysics Department, using equipment in Shuman's lab. To determine the ages of sedimentary and thus hydrologic changes, one-cm thick slices were removed from sediment cores and sieved to find plant macrofossil material for AMS radiocarbon dating. Thirty-nine radiocarbon ages were obtained from four cores at Lower Paintrock Lake; twenty-nine from six cores at Duncan Lake; and twenty-seven from four cores at Rainbow Lake. Additionally, we used standard pollen analysis techniques, carried out in Minckley's lab, to reconstruct vegetation composition during periods of long-term drought. The fossil pollen data also provided a basis for inferring regional temperature trends for comparison with the lake-level histories (Fig. 4, 5).

We focused our effort on lakes with well-defined watersheds and groundwater inputs, because such lakes can be used to estimate long-term moisture-balance changes. By reconstructing the change in lake volumes, we were able to reconstruct past changes in precipitation minus evaporation (ΔP-E). To calculate long-term ΔP-E (e.g., Fig. 4B), we have developed a new method for systematically estimating elevational shifts in each lake's shoreline from the maximum depths of the paleoshoreline sediments compared to the water depths of similar sediment today (Pribyl and Shuman, in review). We then calculated changes in lake volume by accounting for lake size and bathymetry, and divide by the watershed area and lake-equilibration times to obtain a ΔP-E value for the watershed in mm/day (Shuman et al., 2010; Shinker et al., 2010). Analyses of climatologically patterns and processes consistent with the observations were completed in Shinker's lab in UW Geography (e.g., Frederickson, 2012).

<u>Activities</u>

- <u>Fieldwork:</u> GPR profiles were collected from nine lakes in Bighorn Range and six lakes on the Beartooth Plateau, as well as Brooks Lake near Togwottee Pass; sediment cores were collected from three lakes and four small ponds in the Bighorn Mountains, and two lakes on the Beartooth Plateau. Additional profiles and cores were collected from Long Lake, Medicine Bow Mountains, as a training exercise for undergraduates and SRAP (Summer Research Apprenticeship Program) high-school interns.
- <u>Lab work:</u> Core analyses have focused on Lower Paintrock Lake (Bighorn Co.), Duncan Lake (Sheridan Co.), Rainbow and Lily Lakes (Park Co.), and Long Lake (Carbon Co.), including loss-on-ignition, grain-size, sediment density, sedimentary charcoal, macrofossils and radiocarbon analyses.
- <u>Analyses:</u> We developed a new methodology to quantify lake-level reconstructions and calculate associated changes in watershed moisture balance. We also incorporated results from Wyoming lakes into a continental-scale database of similar data, and conducted analyses of historic droughts in Wyoming to examine climatic processes that might have contributed to past aridity.
- <u>Paper writing:</u> See list of publications and manuscripts below.
- <u>Outreach:</u> The 2010 meeting of the American Quaternary Association (AMQUA) was held in Laramie in August 2010, and the PIs organized related field trips for >60 people to several of our study sites in the Platte River watershed. Shuman was also the program organizer for the 2012 AMQUA meeting (Duluth, MN), which had droughts, floods, and

hydrologic variability as its theme; the meeting provided an opportunity to present our results to a focused scientific audience as we have also done at meetings of the American Geophysical Union and Association of American Geographers. Presentations were also given to Wyoming Farm Bureau, State Engineer's Office Water Forum, the Wyoming Water Association, the Geologists of Jackson Hole, and at the Teton County Library. Shuman also discussed findings on *Morning Edition* on National Public Radio, as well as on newscasts and *Open Spaces* on Wyoming Public Radio.

Principal Findings

1. **The extent and magnitude of past droughts**: Our new methodology (Pribyl and Shuman, in review) enabled us to systemically produce comparable time series of water-level changes from our sediment core data, and then calculate watershed hydrologic balance based on these data. We have produced reconstructions of the balance of precipitation and evaporation for the Beartooth Plateau, Wind River Range, Bighorn Mountains, and Medicine Bow Mountains, and compared these datasets with those from other areas, such as central Colorado (Fig. 3, blue lines). The reconstructions show similarities, such as a rapid increase in lake levels across the region at ca. 5500 years ago (gray bar, Fig. 3), but also meaningful differences such as periods when northern lakes were low and southern lakes high (dashed lines, Fig. 3). The patterns can help reveal processes involved, such as the potential for factors like El Nino to shift storm tracks north or south and cause opposite patterns of change in different areas (Shuman et al., in review-a).

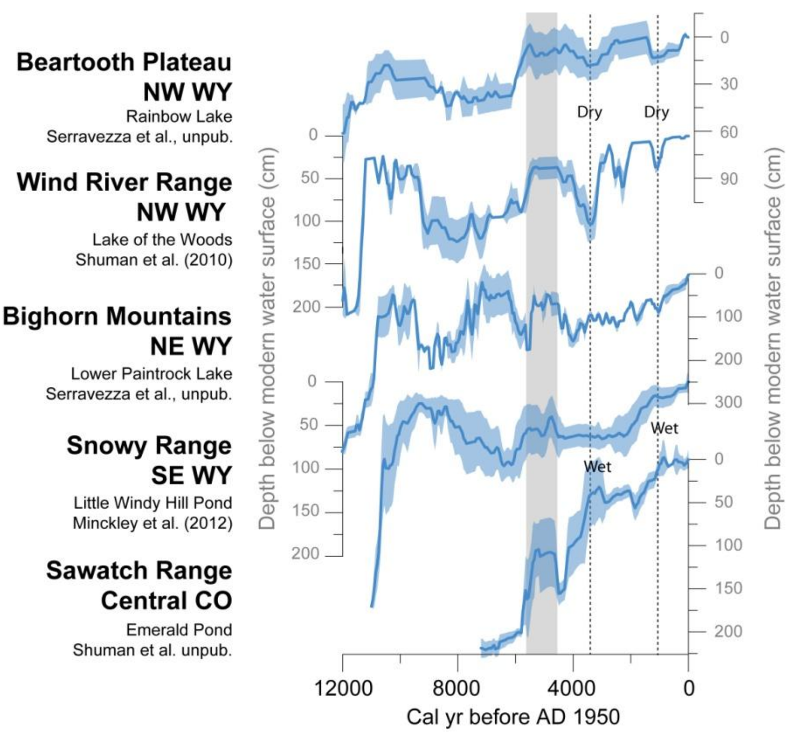


Figure 3. Lake elevations reconstructed at several sites across Wyoming as part of the WWRP-funded work compared with an NSF-funded study of a lake from central Colorado. The comparisons reveal that most Wyoming lakes rose substantially at ca. 11000 years before AD 1950 (BP) and remained high until extended drought after ca. 9300 years BP. The duration and timing of the aridity varies, possibly due to interactions between lake-specific levels of evaporation (see below) and north-south shifts in storm tracks (e.g., opposite timing of wet-dry phases in the Bighorns and Snowy Ranges before ca. 5500 yrs BP). All lakes record a rapid rise at 5500 yrs BP (gray bar), and then show broad-scale evidence of north-south contrasts in wet/dry phases in the past 4000 years (dashed lines).

2. **Comparisons with other types of data**: The most recent periods of low water recorded by the lakes coincide in time with periods of frequent or prolonged drought captured by tree-ring studies (Shuman et al., 2010; Shuman et al., in review-a; Calder et al., in review). In addition, long-term changes in forest composition also coincide with the hydrologic shifts that we documented, although some forests may be less sensitive to such changes than others because of the ecological influence of frequent forest fires (Minckley et al., 2012).

   Additionally, the observed hydrologic changes appear to have had cultural significance, and likely controlled the size of the human population in northern Wyoming (Kelly et al., 2013). During wet periods the numbers of archeological sites (and thus the estimated human population) grew exponentially, but during dry periods the numbers fell (Fig. 4). In fact, during the warmest and driest period from ca. 9300-5500 years BP (Fig. 3, 4), the Bighorn Basin was essentially de-populated (Fig. 4C).

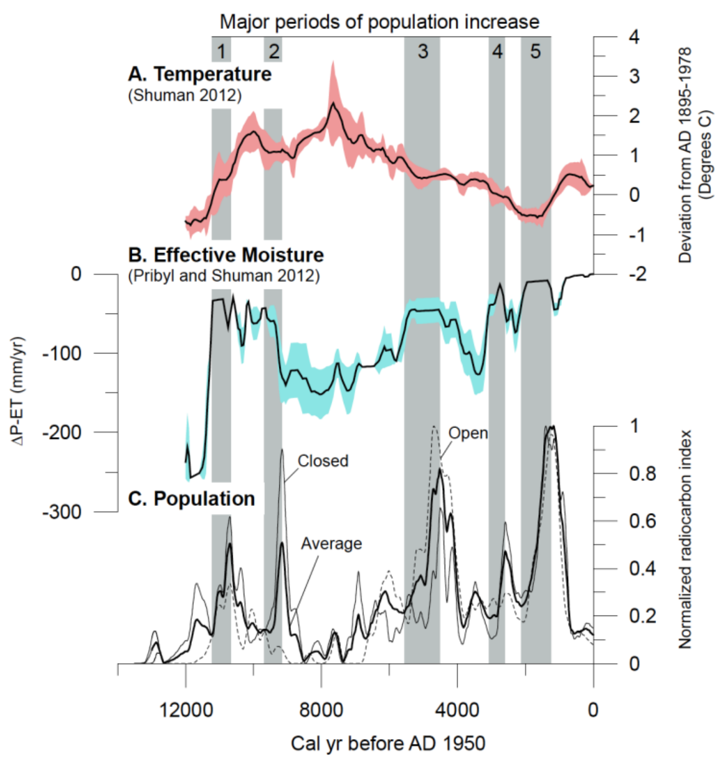


*Figure 4. Trends in temperature (A, annual mean shown) and moisture availability (B) in Wyoming correlate (r=0.71) with high temperatures coinciding with long-term low water periods. Additional millennial-scale moisture variations (gray bars) explain significant changes in the regional human population with the population growing during millennial wet/cool phases (Kelly et al., 2013). A linear regression of temperature and moisture reconstructions correlates well with the population reconstruction (r=0.656, p=7.7 * 10^{-30}); a meaningful lag of ~300 years in the population trends is well explained by slow exponential population growth following shifts in environmental carrying capacity (Kelly et al., 2013).*

3. **The predictability of drought**: Both the common patterns of change in the lake-level histories, and the site-to-regional scale differences (Fig. 3), can provide insight into important processes that influence Wyoming's water supply. For example, the water-level history of Lower Paintrock Lake (Bighorn Co.) differs from that of other lakes around the Bighorn Basin, such as Rainbow Lake (Park Co.) and Lake of the Woods (Fremont Co.) shown in Fig. 3. Paintrock Lake also differs hydrologically from the other two because none of the other lakes have surface streams flowing through them, and water flows into and out of Paintrock Lake from Paintrock Creek sufficiently fast that water (hydrogen and oxygen) isotope measurements show no evaporative loss from the lake. All of our other study sites have water isotopic values consistent with long water-residence times and important losses of water by evaporation from the lake surface.

   The hydrologic differences have allowed us to separate out the long-term influence of temperature-driven evaporation from precipitation changes on the regional hydrologic history (Fig. 5)(Serravezza and Shuman, in prep). A comparison of Lower Paintrock Lake and other lakes around the Bighorn Basin shows that evaporative loss of water can cause aridity (negative P-E) even if precipitation rates were as high or higher than today during periods of high temperatures such as ca. 8000 years BP (Fig. 5). Precipitation changes recorded at Paintrock Lake explain 43% of the explained variation at Lake of the Woods, but the remaining 57% can be attributed to long-term evaporation trends predicted by our reconstructed temperature history (derived from fossil pollen data; Shuman 2012); 17% of the variation in the Lake of the Woods hydrologic history is not explained by these two factors and reflects our level of uncertainty.

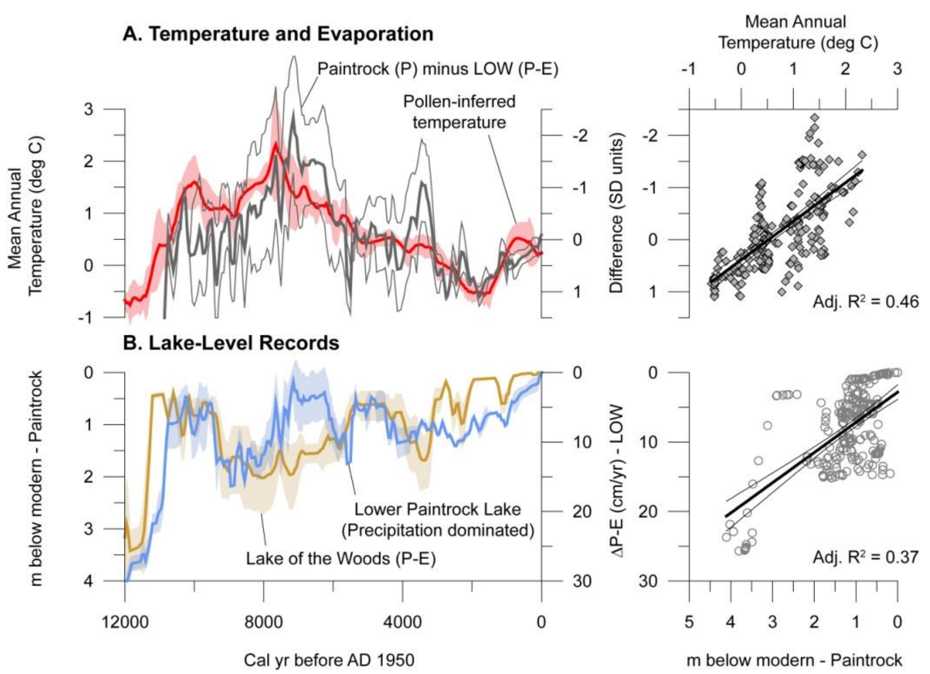


Figure 5. Most lakes in the Bighorn Basin (such as Lake of the Woods, orange in B) reflect the difference between precipitation and evaporation (P-E) and were low from 9300-5500 yrs BP, but Lower Paintrock Lake (blue, B) has almost no evaporative losses today and was high from ca. 7800-6300 yr BP. The episode of high water likely indicates a period of high precipitation (B), and difference in lake-level histories (e.g., Paintrock minus Lake of the Woods) correlates well with temperature trends (A) consistent with the difference resulting from evaporation of any added precipitation (Serravezza and Shuman, in prep).

The timing of past drought in Wyoming also appears to be linked to the histories of Pacific and Atlantic sea-surface temperatures (Fig. 6). Such a relationship is consistent with modern influences on storm tracks that deliver most of Wyoming's snow. For example, periods of frequent El Nino events (Fig. 6E) coincide in time with wet episodes in Wyoming (Fig. 6D) and drought to the south in Colorado (dashed lines, Fig. 3).

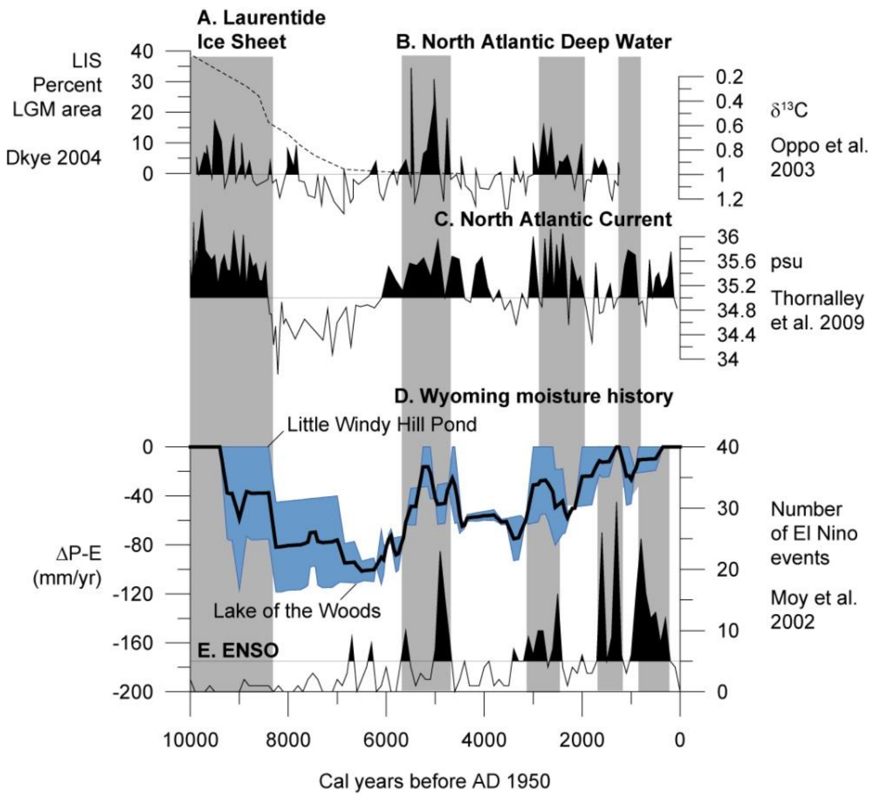


Figure 6. Wyoming moisture reconstructions (plotted in blue as change in precipitaiton minus evaporation, ΔP-E, versus time) have variations consistent with documented oceanic variability. Before ca. 8000 years before AD 1950, the presence of the Laurentide Ice Sheet in central Canada (A, dashed line) likely contributed to wet conditions in Wyoming. Since then, wet phases have coincided with periods of frequent El Nino events (E), and may have also been influenced by variability in the North Atlantic (B, C).

Additional work by Shinker and students (Frederickson 2012) has examined the atmospheric dynamics and circulation associated with dry episodes in Wyoming to help explore the mechanistic linkages that may have been the underpinning to the events of the past 11,000 years.

4. **<u>Significant reductions in in-stream flow:</u>** Based on lake sediment analyses from Lower Paintrock Lake, which today overflows into Paintrock Creek and ultimately the Bighorn River, past arid periods may have substantially reduced regional river flow (which is consistent with decreases in the human population of the Bighorn Basin, Fig. 4). Sand layers, which mark the periods of low water, date to the same intervals as changes in the North Platte River watershed (e.g., Little Windy Hill Pond, Carbon Co., in Fig. 3) when the North Platte was likely ephemeral (Shinker et al., 2010). The layers also lie at elevations (Fig. 2) below the modern outlet of Lower Paintrock Lake (<50 cm below the modern lake surface), and indicate periods of reduced overflow. Analyses of Upper Big Creek Lake (Jackson Co., Colorado) reveal similar low water episodes, which also produced shoreline deposits below the modern lake spill over point and thus contributed to the lack of water in Platte River tributaries (Pribyl and Shuman, in prep.).

Significance

Our results are confirming that climatic processes, including intrinsic and forced variability in regional temperatures and the state of the global oceans, can drive large and persistent changes in the availability of water in Wyoming. Severe dry episodes have lasted for centuries to millennia across much of the state's water producing regions, including 1) the North Platte River headwaters in the Snowy Range of southeastern Wyoming and the Park Range of northern Colorado, 2) the convergence of the Snake (Columbia), Green (Colorado), and Bighorn (Missouri-Mississippi) River watersheds on the Continental Divide in the Wind River Range, and 3) the eastern Bighorn River watershed in the Bighorn Mountains. Evidence that lakes that today overflow into these major river systems have not overflowed for prolonged intervals in the past indicates that climate changes can dramatically reduce flow rates in rivers that are already fully allocated to various uses. Surface flow rates and the availability of shallow groundwater, which feeds most of our study sites, may fall if temperature increases, even if precipitation rates rise.

Severe changes in Wyoming water supplies were part of larger continental shifts in moisture availability (Shuman et al., in review-b), and also had impacts on regional vegetation (Minckley et al., 2012), wildfire regimes (Calder et al., in review; Minckley et al., 2012; Minckley and Shriver, 2012), and pre-historic human populations (Kelly et al., 2013). Our inferences appear robust given the consistency of results across watersheds, and evidence that they were part of larger climatic changes with meaningful landscape and cultural impacts. If so, water supplies in Wyoming may be susceptible to dramatic and persistent shifts, which should be considered in water management plans.

Publications and Presentations (* Undergraduate author, † Graduate student author)**:**

Published

Fredrickson, J. (2012) Hydroclimatic variability in Wyoming headwaters. University of Wyoming, Masters of Arts thesis, 68 p.

Kelly, R., T. Surovell, B. Shuman, G. Smith. (2013) A Continuous Climatic Impact on Holocene Human Population in the Rocky Mountains. *Proceedings of the National Academy of Sciences* 110 (2): 443-447.

Minckley, T. A., R. Shriver*, B. Shuman. (2012) Resilience and regime change in a southern Rocky Mountain ecosystem during the past 17000 years. *Ecological Monographs* 82(1): 49-68.

Minckley, T.A., and R.K. Shriver*. (2012) Vegetation response to different fire-types in a Rocky Mountain forest. *Journal of Fire Ecology*.

Shinker, J. J., Shuman, B. N., Minckley, T. A., and Henderson, A. K.† (2010). Climatic Shifts in the Availability of Contested Waters: A Long-term Perspective from the Headwaters of the North Platte River, *Annals of the Association of American Geographers (Special Issue on Climate Change)*, 100 (4), 866-879.

Shuman, B. (2012) Recent Wyoming temperature trends, their drivers, and impacts in a 14,000-year context. *Climatic Change* 112 (2): 429-447.

Shuman, B., Pribyl, P.*, Minckley, T. A., and Shinker, J. J**.** (2010). Rapid hydrologic shifts and prolonged droughts in Rocky Mountain headwaters during the Holocene, *Geophysical Research Letters*, DOI:10.1029/2009GL042196.

Submitted publications

Calder, J.†, Stopka, C.*, and B. Shuman. Evaluating the influence of drought and temperature change on fire regimes of high-elevation sub-alpine forests in the southern Rocky Mountains. *Rocky Mountain Geology*. Peer Reviewed.

Minckley, T.A. Postglacial vegetation and climate history of southeastern Wyoming. *Rocky Mountain Geology*. Peer Reviewed.

Pribyl, P.*, and B. Shuman. Quantifying sediment-based lake-level reconstructions: A Holocene case study from the headwaters of the Green, Snake, and Bighorn Rivers, Wyoming, USA. *Quaternary Research*. Peer Reviewed.

Shuman, B. Carter, G.†, Hougardy, D.,* Powers, K.*, Shinker, J.J. (A) A north-south moisture dipole at millennial scales in the central and southern Rocky Mountains during the late-Holocene. *Rocky Mountain Geology*. Peer Reviewed.

Shuman, B., A. K. Henderson*, and C. Plank*. (B) Moisture Patterns in the United States and Canada over the Past 15,000 Years: A New Synthesis of Lake Shoreline-Elevation Data. *Quaternary Science Reviews*. Peer Reviewed.

Publications in preparation

Pribyl, P.*, and B. Shuman. Severe regional river-flow reductions during the Younger Dryas and mid-Holocene, northern Colorado. Plan to submit to *Geology*. Peer Reviewed.

Serravezza, M†, Shuman, B. The role of temperature-driven evaporation in Holocene hydrologic changes in the Bighorn Basin, Wyoming USA. Plan to submit to *Quaternary Research*. Peer Reviewed.

Shuman, B., J. Marsicek† The structure of Holocene climate change in mid-latitude North America. Plan to submit to *Earth and Planetary Science Letters*. Peer Reviewed.

Presentations

2010

Shinker, J. J**.**, B. N. Shuman, T. A. Minckley, and A. K. Henderson†. 2010. “Climatic shifts in the availability of contested waters: A long-term perspective from the headwaters of the North Platte River,” Poster presenter, American Quaternary Association, Laramie, WY.

Shinker, J. J., B. N. Shuman, T. A. Minckley, and A. K. Henderson†. 2010. "Climatic shifts in the availability of contested waters: A long-term perspective from the headwaters of the North Platte River," Association of American Geographers, Washington, DC.

Shinker, JJ. 2010, Women in Science Conference, Career Panelist, University of Wyoming.

Shuman, B. N., J.J. Shinker and T. A. Minckley. 2010. "Millennial-scale hydroclimatic variation and prolonged episodes of ephemeral river flow in the Rocky Mountains during the Later-Quaternary," Geological Society of America, Denver, CO.

Shuman, B., 2010. Late-Quaternary Hydroclimatic Changes in North America and their Ecological Impacts. VU (Vrie) University – Amsterdam, Geology.

<u>2011</u>

Shinker, J. J., 2011, Spatial Heterogeneity of Western U.S. Climate Variability. Association of American Geographers, Seattle, Washington.

Heyer, J.* and Shinker, J.J., 2011. "An Investigation of Climatic Controls in the Upper Laramie River Watershed During Low Stream Flow Years", at UW Undergraduate Research Day, April, 2011.

Serravezza, M. †, 2011. "Ground-penetrating radar as a tools for reconstructing past droughts in Wyoming," UW Roy J. Shlemon Center for Quaternary Studies, Quaternary Research Symposium, Fall 2011.

Shuman, B., 2011. From Causes to Impacts of Holocene Hydroclimatic Change in the Mid-Latitudes. U. Colorado – Boulder, INSTAAR (Institute for Arctic and Alpine Research).

<u>2012</u>

Fredrickson, J. † , 2012. Hydroclimatic variability in Wyoming headwaters. Master's defense, UW Geography, May 15, 2012.

Fredrickson, J. † and Shinker, J.J., 2012. Hydroclimatic variability and drought in Wyoming headwater regions. Annual meeting of the Association of American Geographers, New York City.

Heyer, J.*, Fredrickson, J. † and Shinker, J.J., 2012. Climate, drought and low stream flow in the headwaters of the North Platte River. Annual meeting of the Association of American Geographers, New York City.

Serravezza, M. † and Shuman, B., 2012. Millennial-scale hydrologic fluctuations during the Holocene in the Bighorn Basin, northern Wyoming. Poster presentation, American Quaternary Association, Duluth, MN.

Shuman, B. 2012. A Mid-Holocene Regime Shift in Mid-Latitude North Hemisphere: Pollen and

Lake-Level Datasets. NSF/NCAR SynTrace Climate Model Workshop, Providence RI.

Shuman, B. 2012. Patterns and Impacts of millennial-scale hydroclimatic change in North American during the Holocene. American Geophysical Union Fall meeting, San Francisco.

Student Involvement
Marc Serravezza, a Ph.D. student in Geology & Geophysics, was supported by this grant and took the lead on reconstructing the water-level histories of Lower Paintrock, Duncan, and Rainbow Lakes. Serravezza is a continuing UW student, but his experience in this project helped him to secure an ExxonMobil Research Corporation internship for summer 2013.

Joshua Fredrickson, a Geography/Water Resource master's student was also supported through this grant and a one-year fellowship from the Geography Department. Fredrickson analyzed climate data associated with recent low stream flow events in the Platte and Colorado River drainages. He is also partially funded through the McNair Scholars program to mentor undergraduate Joshua Heyer. Fredrickson was offered a position through the Wyoming State Engineer's Office as a Hydrographer-Commissioner in Worland beginning March 2013.

Serravezza was supported in his work by UW undergraduates, Devin Hougardy (Geology), Jacob Buettner (Geology, McNair Scholar), and Tyler Dooley (Geography), and by graduate students John Calder (Geology/PiE) and Fredrickson (Geography/Water Resources). The students contributed to field work in the Bighorn Mountains and Beartooth Plateaus, and helped to complete our lab analyses (in particular preparing samples for radiocarbon analyses). Likewise, Grace Carter and Jeremiah Marsicek, Ph.D. students in Geology & Geophysics contributed to field work in summer 2010 and 2011, and have generated complementary datasets from other regions (via support from the National Science Foundation and NASA Space Grant), which is providing a broader-scale perspective on the events documented in Wyoming (such as the shift in moisture availability at ca. 5500 years before AD 1950). Two other undergraduate students, T.J. Gajda (Geography) and Reid Olson (Botany), contributed to the project by completing the chemical processing of sediment samples for fossil pollen analyses.

Joshua Heyer (Geography) and Jacob Buettner (Geology & Geophysics) were partially supported through the McNair Scholars program, which supports first-generation undergraduate student research in preparation for a graduate school. Heyer's contribution to our research project included training in climate analysis related to understanding drought and low stream flow years. Heyer presented his preliminary research, "An Investigation of Climatic Controls in the Upper Laramie River Watershed During Low Stream Flow Years", at UW Undergraduate Research Day, April, 2011. Buettner helped to evaluate the potential of north-south contrasts in regional moisture trends by working on sediment cores from a lake in southern Colorado. He presented his results at the 2012 annual meeting of the Geological Society of America (GSA) and at UW Undergraduate Research Day, April 2013, and will be attending graduate school in geochemistry in Fall 2013 at New Mexico State University.

Noah Berg-Mattson, an undergraduate in Botany, worked with Devin Hougardy (Geology & Geophysics) on the cores collected at Long Lake, Carbon Co. David Webster at visiting undergraduate from the Cardiff University (UK) counted sedimentary charcoal from the lake sediment cores for comparison with the moisture history. Likewise, three visiting high-school students were involved in field work and some lab analyses through the Summer Research Apprenticeship (SRAP) program at UW.

Leveraging of funds

Results from this study help to motivate UW's successful NSF EPSCoR proposal, "Water in a Changing West: The Wyoming Center for Environmental Hydrology and Geophysics (WYCEHG)," which is providing $20 million over five years to enhance hydrologic research in Wyoming. One of the core WYCEHG science teams is focusing on paleohydrology using the methods applied and refined in this WWRP grant. In particular, the WYCEHG project will examine how hydrologic connectivity (e.g., via deep groundwater transfer) within watersheds influences sensitivity of water resources to changes in temperature.

Impact of Bark Beetle Outbreaks on Forest Water Yield in Southern Wyoming

Basic Information

Title:	Impact of Bark Beetle Outbreaks on Forest Water Yield in Southern Wyoming
Project Number:	2010WY61B
Start Date:	3/1/2010
End Date:	2/28/2013
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Surface Water, Water Quantity
Descriptors:	None
Principal Investigators:	Brent E. Ewers, Holly Barnard, Elise Pendall, David Williams

Publications

1. Biederman, JA, PD Brooks, AA Harpold, DJ Gochis, E Gutmann, DE Reed, E Pendall, BE Ewers, 2013. Multi-Scale Observations of Snow Accumulation and Peak Snowpack Following Widespread, Insect-Induced Lodgepole Pine Mortality. Ecohydrology. DOI 10.1002/eco.1342.
2. Frank, JM, WJ Massman, BE Ewers, 2013. Underestimates of sensible heat flux due to vertical velocity measurements in non-orthogonal sonic anemometers. Agricultural and Forest Meteorology. 171-172:72-81.
3. Edburg, SL, JA Hicke, PD Brooks, EG Pendall, BE Ewers, U Norton, D Gochis, and E Gutmann, 2012. Cascading Impacts of Bark Beetle-Caused Tree Mortality to Coupled Biogeophysical and Biogeochemical Processes. Frontiers in Ecology and Environment. 10:416-424.

Final Report to Wyoming Water Development Commission for the Project:
Impact of bark beetle outbreaks on forest water yield in southern Wyoming
(March 2010 – February 2013)
PIs Brent E Ewers, Elise Pendall and David G Williams

Abstract
A Rocky Mountain Region outbreak of bark beetles and their associated fungi from British Columbia to New Mexico is having profound impacts on forest function and ecosystem services. These forests are key components of major river watersheds which could magnify any impacts on downstream users of water including those in Wyoming. Current and ongoing research is documenting the potential extent, causes and impacts on carbon exchange and evapotranspiration but less is known about how water yields will be impacted on short to long time scales. This project will enhance preliminary measurements of evapotranspiration and soil moisture from a mid-elevation lodgepole pine forest undergoing infestation by 1) reasonably closing stand water budgets to better quantify and thus predict water yield and 2) extending replicate measurements and analyses to post-infection management to facilitate future scaling to landscape water yield. New stands will be established in mid elevation former lodgepole pine that has been clearcut after infestation. We will provide complete water budgets that are closed on a stand basis by measuring 1) spatially explicit snow accumulation and loss, 2) detailed liquid canopy interception and stem flow, 3) appropriately scaled transpiration from living, dying and dead trees' water use (or lack thereof) through sap flow and leaf gas exchange, 4) soil hydraulic characteristics and modeling and runoff for water yield and 5) stable isotopes of soil, plant and atmospheric water as a further test of water budget component closure. Our proposed data collection and analysis will provide highly probable predictions of water yield during the first 5 to 10 years of the outbreak and provide the basis for first order predictions of the next 10 to 100 years of impact. The results of this project will be communicated with State and Federal agency personnel, providing data necessary for future water management decisions in all areas of Wyoming impacted by the bark beetle outbreak.

Objectives
1) Quantify how precipitation is partitioned into evapotranspiration, throughfall, stemflow, soil storage and water yield across forest types (including a clearcut) as trees die and the forests begin initial recovery from bark beetle-induced mortality

2) Determine errors and associated uncertainty in closing a water budget across forest types

Methodology
All major components of forest stand water budgets were measured at the lodgepole pine bark beetle sites with a select group of major components at the higher elevation spruce and fir bark beetle site. Some of the following measurements were also funded by a National Science Foundation Hydrologic Science and UW Agriculture Experiment Station grants. **Precipitation** was measured with multiple approaches to obtain incoming liquid and frozen preciptiation as well as throughfall and snowpack depth and density

prior to infiltrating or running off of soil. **Drainage** was estimated by combining soil physical properties with soil water storage measurements. Piezometers measured **streamflow** out of the forests at multiple spatial locations. **Evapotranspiration** was quantified through eddy covariance methods at the lodgepole pine, clear cut lodgpole pine and spruce and fir forests. **Tree transpiration** was measured in nearly 50 trees representing a range of bark beetle infestation and responses of trees to forest management such as thinning or clear cutting. Stable isotope measurements of water vapor fluxes were used to partition evapotranspiration into transpiration and **evaporation**. Measurements of leaf gas exchange and plant hydraulic conductance were made to test mechanisms of tree mortality in response to the bark beetle epidemic. A spatial grid of 144 plot level measurements of tree and understory characteristics was sampled to scale up plot level flux measurements to watersheds.

Principal Findings (Cited Papers are Publications Section)

We accomplished both objectives of the project; the outcomes of each objective are listed as the following specific findings. 1) Tree transpiration declines 50% within a month and is zero by the end of the first growing season in lodgepole pine while spruce takes two years (Edburg et al 2012). 2) Water fluxes to the atmosphere from the stands drop at the same rate as carbon fluxes resulting in a near constant water use efficiency until dead trees become a significant component of the stand (Reed et al In Review, Frank et al In Review). 3) Snowpack increases slightly in stands dominated by dead trees but sublimation is increased and snowmelt occurs earlier (Biederman et al 2012). 3) Liquid water interception is 25% lower in stands with high mortality. 5) Soil moisture increases with the decline in transpiration and evapotranspiration in all stands (Reed et al In Revision). 6) Energy balance closure is low (~50%) unless spatial heterogeneity and energy storage changes from mortality are included then closure is higher (~80%) (Reed et al In Revision). 7) Common sonic anemometers likely underestimate sensible and latent (i.e. evapotranspiration) heat fluxes (Frank et al 2013). 8) Increased soil moisture does not appear to increase streamflow likely due to a) earlier snow melt with declining canopy structure, b) increased evaporation and sublimation as indicated by stable isotopes of water and c) potential storage effects at the watershed scale (Somor et al In Review). Some of the key figures for these findings are included below.

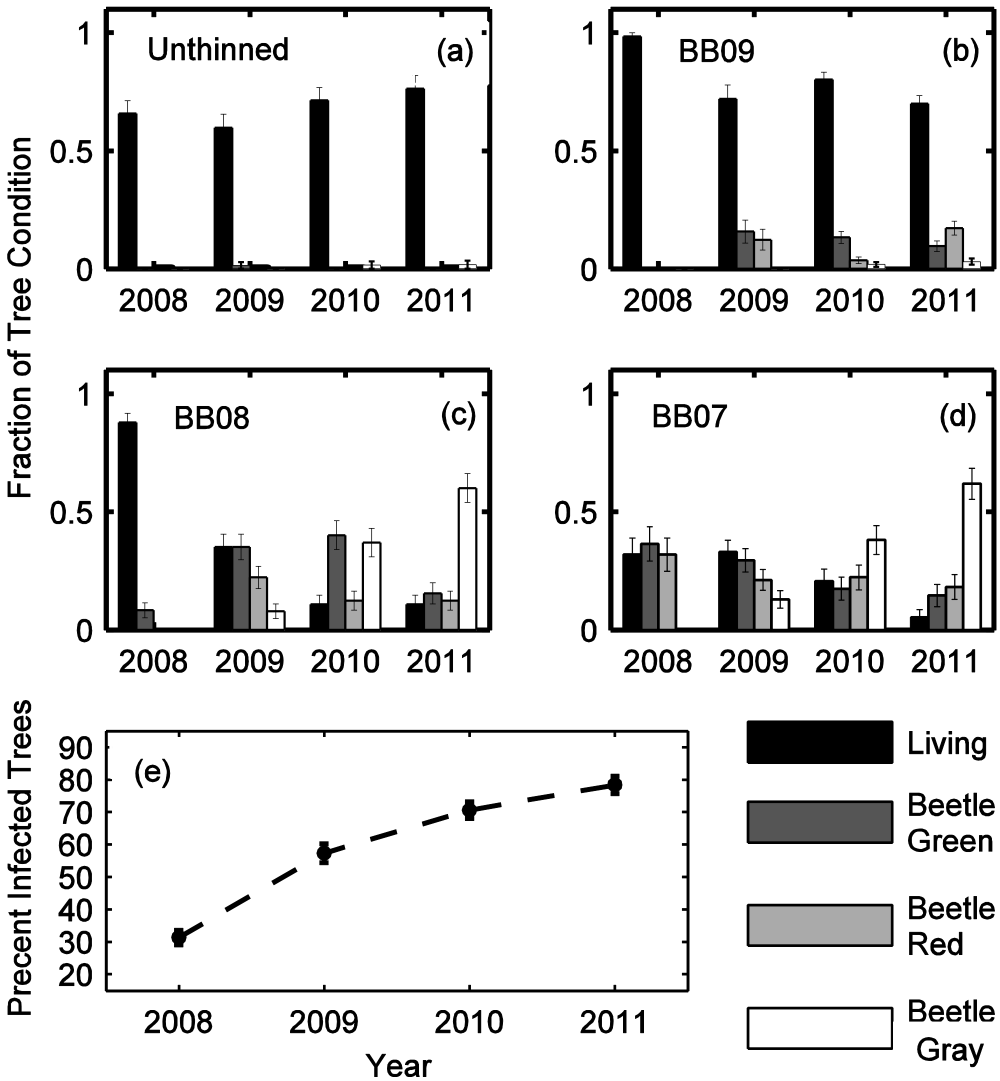
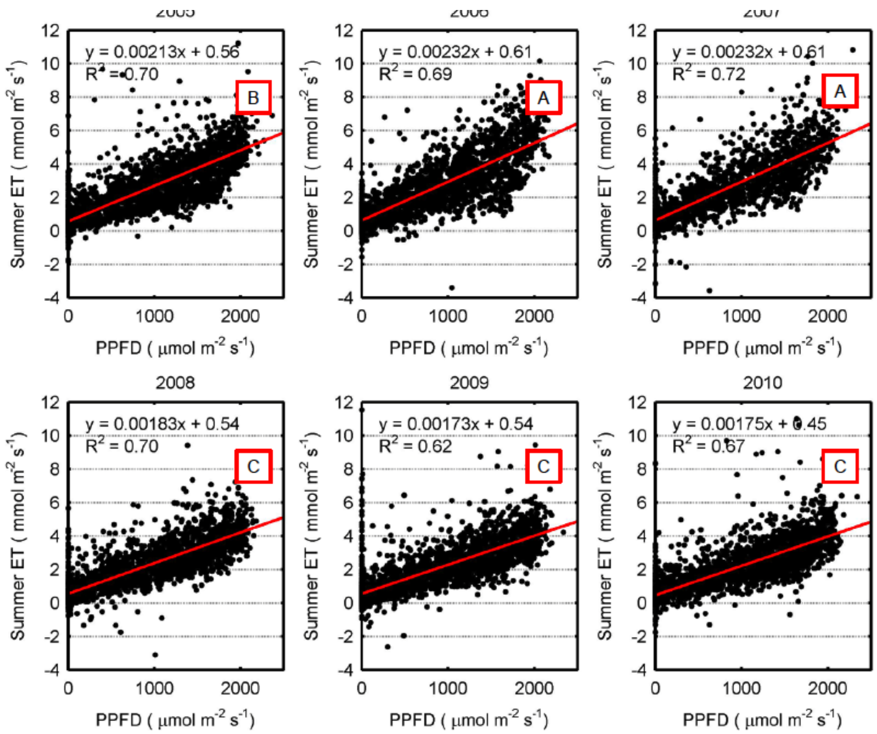


Figure 1 Mortality progresses quickly in lodgepole pine forests because the trees die in one growing season from fungal occlusion of the xylem. The process takes two years in spruce trees but the results are largely the same, dramatic decreases in tree transpiration. (Reed et al. In Revision).



Evapotranspiration (ET) response to radiation that drives photosynthesis (PPFD). Letters indicate significant differences in the response; before the beetles (2005 – 2007) have higher ET values at the same radiation.

Figure 2 Because of the drop in tree transpiration, all of the post-beetle epidemic years have evapotranspiration rates that are at least 20% lower. (Frank et al In Review).

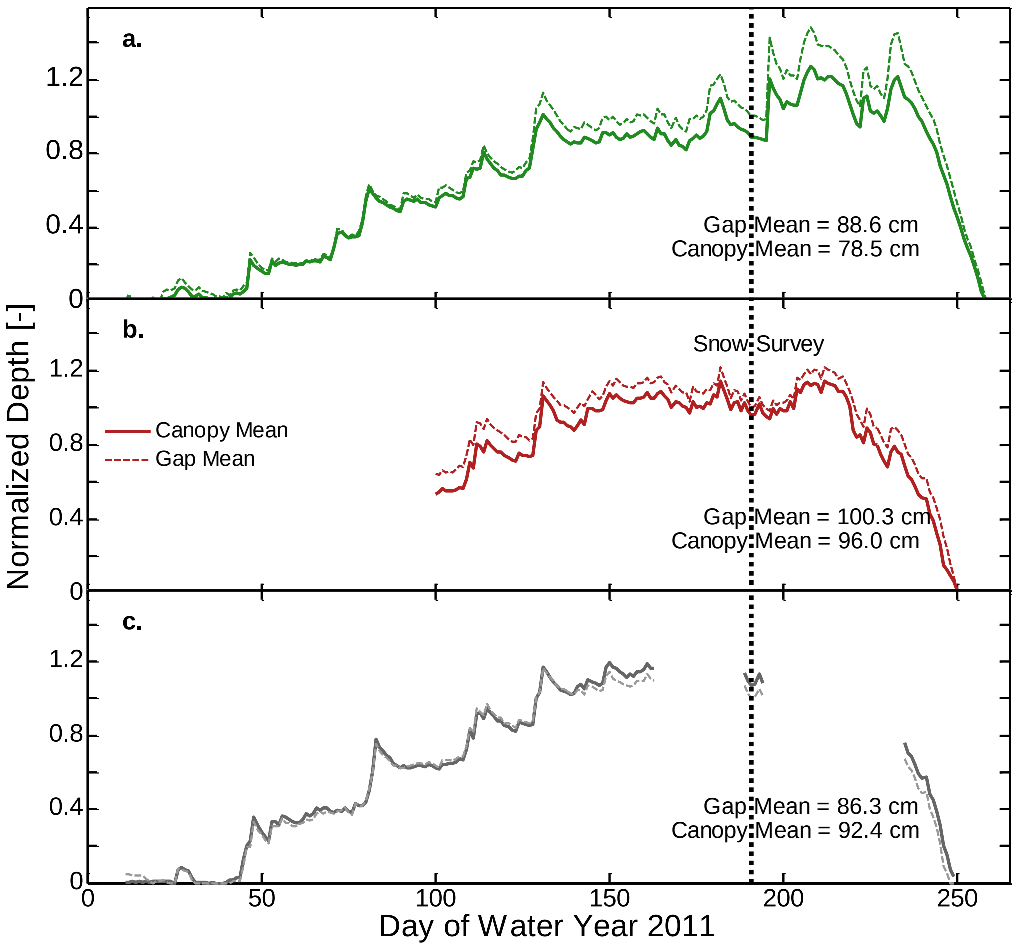


Figure 3 Snow pack depths are greater in beetle red and gray stands (used as line colors above). However, the snow pack is reduced faster due to increased sublimation and melt occuring 1-2 weeks faster due to darker albedos and more radiation and turbulence in dying and dead stands. (Biederman et al 2012).

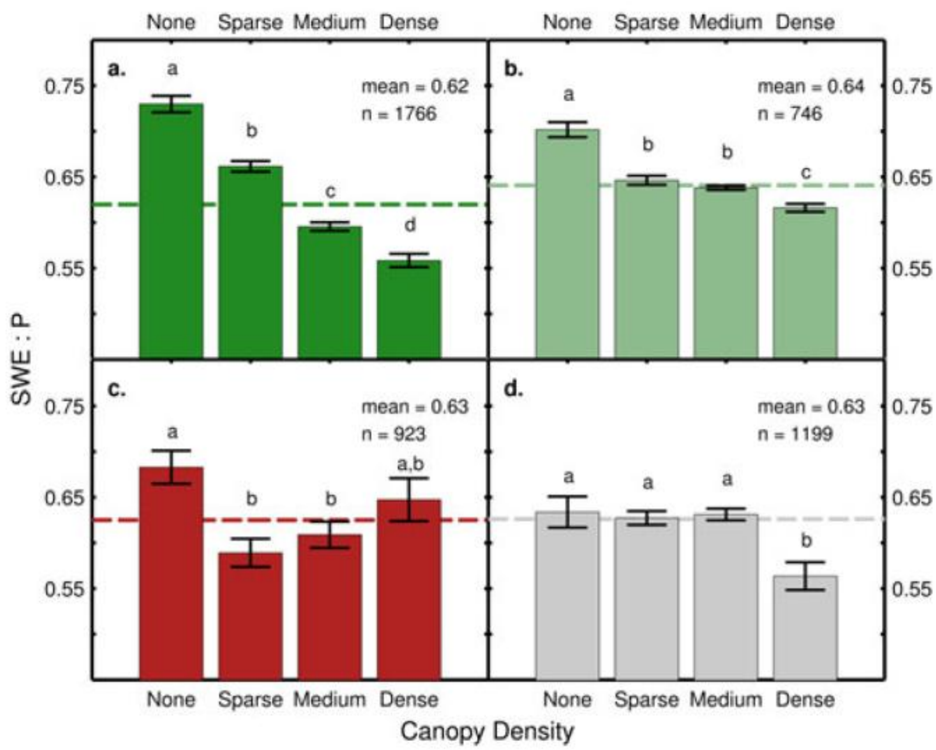


Figure 4 The ratio of soil water equivalent to precipitation (SWE:P) normalizes for precipitation differences. There was no difference in the mean value of the ratio across living (a), green but infested (b), red (c) or gray stage (d) stands. The difference between no tree and dense trees also became less as the epidemic progressed. (Biederman et al 2012).

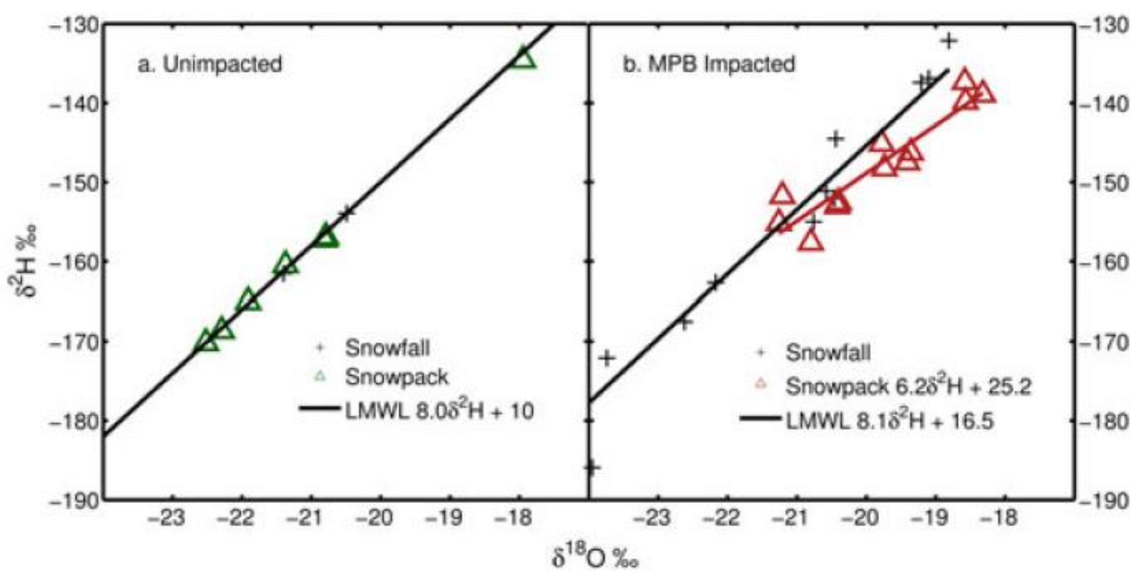
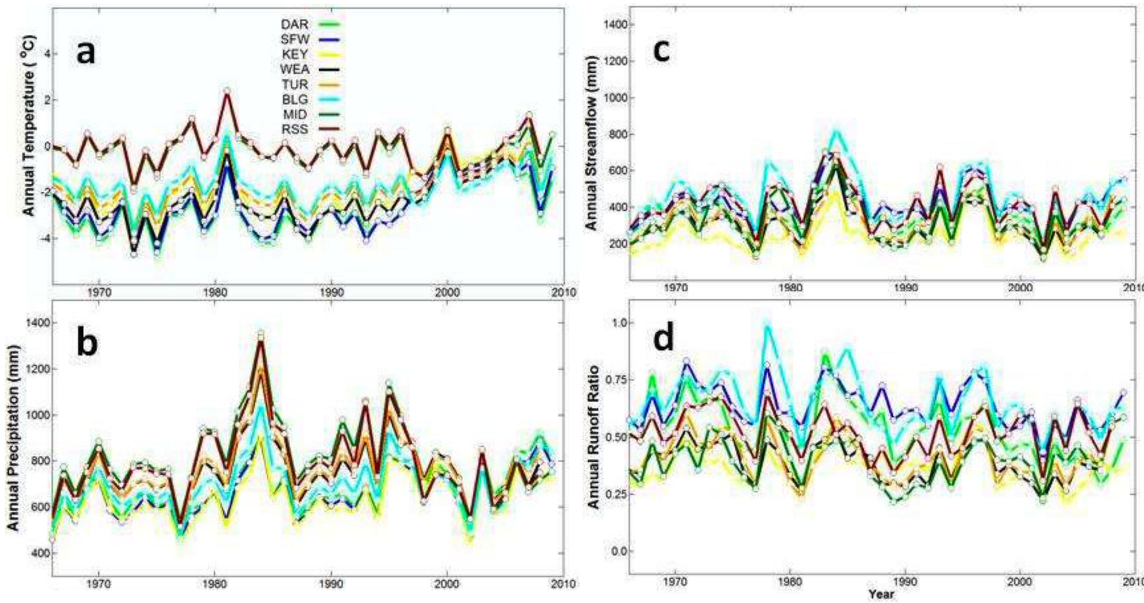


Figure 5 Unimpacted stands show little isotopic enrichment in the snowpack compared to new snowfall (a) while MPB impacted stands show enrichment suggesting increased sublimation due to increased turbulence and radiation drivers. (Biederman et al 2012).



Somor et al In Review

Eight watersheds from northern Colorado that were hit by bark beetles from 2003-2007. Neither streamflow nor runoff ratio (runoff/ precipitation) responded to the beetle outbreak. Temperatures were consistently high during the beetle outbreaks.

Figure 6 Stand level data from evapotranspiration, transpiration and soil moisture suggests that more water should leave infested stands while snow data suggests less water is available. The resulting streamflow from eight infested stands in Colorado (infestation began in 2002) does not show an increase in streamflow (Somor et al In Revision).

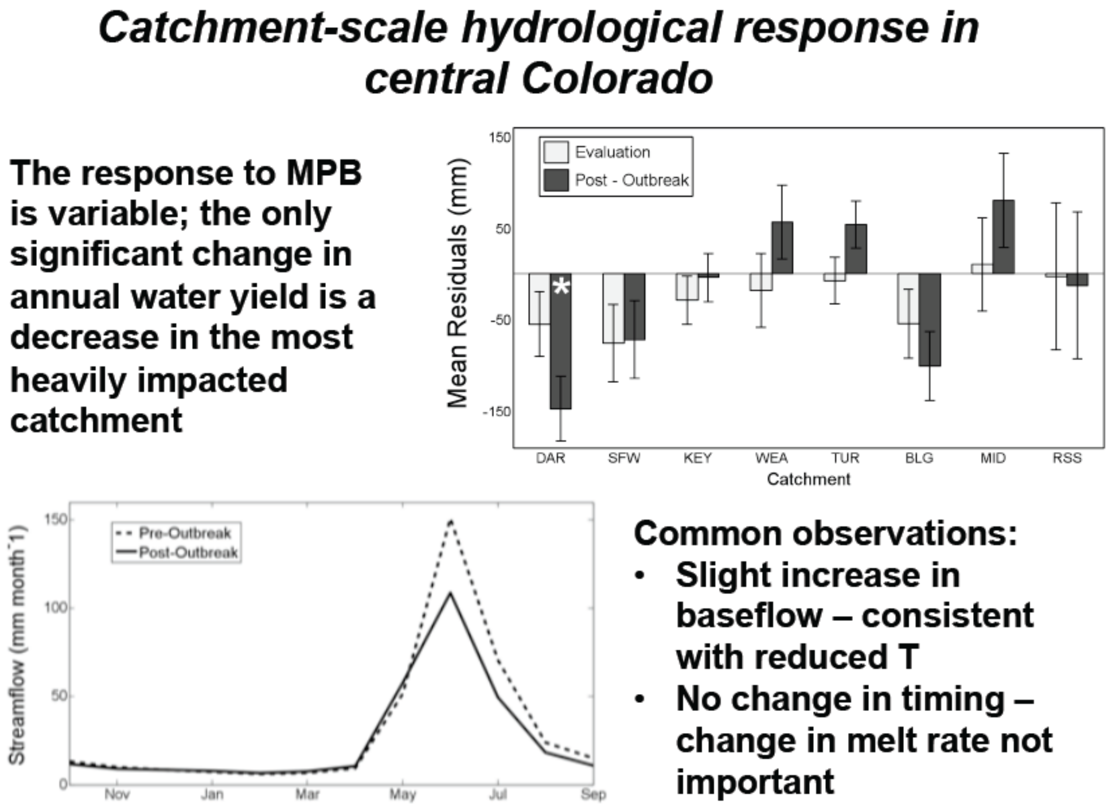


Figure 7. Analysis of data from Figure 6 showing that there was no increase in streamflow once climate variability between years was incorporated with empirical models.

Significance

This work provided measurements and analysis of stand-level water balance that are critical to developing and testing forecasting tools for determining the impact of bark beetles on streamflows from primary streams to major river systems. We found very clear and compelling direct impacts of mortality on precipitation partitioning at the stand scale as expected. However, the mechanistic impact of bark beetles on streamflow is unresolved. Empirical data shows that soil moisture increases do not lead directly to streamflow increase. Thus, the scaling of bark beetle-induced water budget changes from stands to watersheds is the most uncertain result of this project.

Our work from this project has lead to the following significant impacts. First, Wyoming State and regional water managers cannot assume that the reduction in evapotranspiration from forests with high bark beetle mortality will lead directly to increased streamflow. The PI of this project has given many talks around the state and region with this message which has led to heated, ongoing policy debates. Second, our results suggest a clear research path. Models of bark beetle impacts on streamflow must be able to replicate the stand-scale changes in water budgets; our new funding from this agency will test a model at this scale and then use the resulting parameterization to explore the watershed consequences. The same model will also be used to examine how long the stand scale consequences of bark beetle mortality will last. This research effort will additionally require resources to investigate sublimation more thoroughly as well as alternative sources of error in watershed scaling including storage by geological substrates. The results of this project were used as a major, scientific justification for the largest NSF Award to U.W (see leveraged support below). Third, many undergraduate and graduate students as well as a post-doc were partially supported on this project. Several of these students will continue to work in the state and region resulting in ongoing benefits to the state.

Students/Post-Docs Supported

Julia Angstmann, PhD student, helped establish research sites, graduated before project began. Currently employed at Indiana University.

Tim Aston- ongoing PhD student, helped set up sap flux measurements, no direct support from project beyond logistics.

Bujidma Borkhuu-ongoing PhD student, main responsibilities are soil measurements and assistance with atmospheric measurements. Received partial support from project.

John Frank- ongoing PhD student, main responsibilities are all of the flux measurements from the spruce and fir bark beetle site (note: John Frank is a full time employee of the USFS RM Exp St in Ft. Collins, and does not receive any salary support from this project). Support from this project is used for field visits and site maintenance through a USFS subcontract.

David Reed-ongoing PhD Student, main responsibilities are the atmospheric and streamflow measurements. Received partial support from project.

Faith Whitehouse-MS Student, main responsibilities were the tree physiology measurements. Faith decided to leave graduate school and become a full time photographer; she is currently operating her own photography business in Laramie. Received partial support from project.

Claire Hudson-Undergraduate Student, main responsibilities were assisting with soil trace gas measurements and lab processing and vegetation measurements. Now a graduate student at UW working on an MS regarding Alaskan Forests and Climate Change. Received partial support from project.

Margo Hamann-Undergraduate Student, main responsibilities are assisting with tree physiology field measurements and lab processing. Received partial support from project.

Holly Barnand-Post-doc, main responsibilities were isotopic measurements for ET partitioning. Holly is now an Assistant Professor at CU-Boulder. Received partial support from project.

Publications (*Students and Post-Docs are italicized*)

Reed D, BE Ewers, E Pendall, R Kelley. In Revision. Bark Beetle Mortality Increases Energy Imbalance in Eddy Covariance Measurements Due to Canopy Heterogeneity. Agriculture and Forest Meteorology.

Frank JM, Ewers BE, Massman MJ, Hackaby, LS, Negron, JF. In Review. Bark beetles cause predictable declines in ecosystem carbon and water fluxes. Ecology.

Reed D, BE Ewers, E Pendall. In Review. Impact of mountain pine beetle induced mortality on forest carbon and water fluxes. Environmental Research Letters.

Biederman, JA, PD Brooks, AA Harpold, DJ Gochis, E Gutmann, ***DE Reed***, E Pendall, BE Ewers. 2013. Multi-scale observations of snow accumulation and peak snowpack following widespread, insect-induced lodgepole pine mortality. Ecohydrology. DOI *10.1002/eco.1342*.

Frank, JM, WJ Massman, BE Ewers. 2013. Underestimates of sensible heat flux due to vertical velocity measurements in non-orthogonal sonic anemometers. Agricultural and Forest Meteorology. 171-172:72-81.

Edburg, SL, JA Hicke, PD Brooks, EG Pendall, BE Ewers, U Norton, D Gochis, and E Gutmann. 2012. Cascading Impacts of Bark Beetle-Caused Tree Mortality to Coupled Biogeophysical and Biogeochemical Processes. Frontiers in Ecology and Environment. 10:416-424.

-----Following manuscript was cited in Principle Findings none of the authors were funded by this project.
Somor et al. In Review. Mountain pine beetle mortality does not lead to increased streamflow. Water Resources Research.

Presentations (*Students and Post-Docs are bolded*)

(Invited) Ewers BE. Hydraulic Limitations Help Explain the Behavior of Plants: from clocks to mortality to ghosts. Department of Biology, U. of New Mexico, February, 2013

(Invited) Ewers BE. Hydraulic Limitations Help Explain the Behavior of Plants: from clocks to mortality to ghosts. Department of Biology, Los Alamos National Labs, February, 2013

(Invited) Ewers BE. Impact of Fire and Insect Disturbance on Water Cycling in Ecosystems. Land Managers of the Laramie District of the Medicine Bow National Forest. February 2013

(Invited) Ewers BE. Surprising effects of bark beetle-induced mortality on snowpacks and water yield. Wyoming Weather Modification Technical Advisory Team Meeting, Cheyenne, WY January, 2013.

(Invited) Ewers BE. Impact of bark beetle outbreaks on forest water yield. Wyoming Association of Conservation Districts. Casper, WY, December, 2012.

P.D. Brooks; A.A. Harpold; J.A. Biederman; M.E. Litvak; P.D.Broxton; D. Gochis; N.P. Molotch; P.A. Troch; B.E. Ewers. Insects, firests, and climate change: implications for snow cover, water resources and ecosystem recovery in Western North America. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012.

Ewers, BE, DS Mackay, C Guadagno, **SD Peckham**, E Pendall, B Borkhuu, **T Aston**, **JM Frank**, WJ Massman, **DE Reed**, Y Yarkhunova, C Weinig. Nonstructural carbon dynamics are best predicted by the combination of photosynthesis and plant hydraulics during both bark beetle induced mortality and herbaceous plant response to drought. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012.

King A, BE Ewers, R Sivanpillai, E Pendall. Testing remote sensing estimates of bark beetle induced mortality in lodgepole pine and Engelmann spruce with ground data. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012.

Peckham, SD, BE Ewers, DS Mackay**, JM Frank**, WJ Massman, MG Ryan, H Scott, E Pendall. Modeling net ecosystem exchange of carbon dioxide in a beetle-attacked subalpine forest using a data-constrained ecosystem model. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012.

Mackay, DS, BE Ewers, **DE Reed**, E Pendall, NG McDowell. Plant hydraulic controls over ecosystem responses to climate-enhanced disturbances. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012.

(Invited) Ewers BE. Impact of bark beetle outbreaks on forest water yield. Wyoming Water Development Commission. Cheyenne, WY, November, 2012.

(Invited) Ewers BE. Impact of bark beetle outbreaks on forest water yield. Joint meeting of the Wyoming Water Development Commission and the Select Water Subcommittee of the Wyoming Legislature. Casper, WY, November, 2012.

(Invited) Ewers BE. Impact of bark beetle outbreaks on forest water yield. Wyoming Water Association Annual Meeting. Lander, WY, October, 2012.

Reed, DE, BE Ewers, E Pendall, RD Kelly, U Norton, **FN Whitehouse**. Mountain pine beetle epidemic changes ecosystem flux controls of lodgepole pine. Ecological Society of America Annual Meeting, Portland, OR, August 2012.

Brooks, PD, HR Barnard, J Biederman, B Borkhuu, SL Edburd, BE Ewers, D Gochis, E Gutmann, AA Harpold, JA Hicke, DJP Moore, E Pendall, **D Reed**, A Somor, PA Troch. Multi-scale observation of hydrologic partitioning following insect-induced tree mortality: Implications for ecosystem water and biogeochemical cycles. Ecological Society of America Annual Meeting, Portland, OR, August 2012.

Frank, JM, WJ Massman, BE Ewers. Linking bark beetle caused hydraulic failure to declining ecosystem fluxes in a high elevation Rock Mountain (Wyoming, USA) forest. Ecological Society of America Annual Meeting, Portland, OR, August 2012.

Ewers BE, DS Mackay, E Pendall, J**M Frank, DE Reed,** WJ Massman, **TL Aston**, **JL Angstmann, K Nathani, B** Mitra. Use of plant hydraulic theory to predict plant controls over mass and energy fluxes in response to changes in soils, elevation and mortality. Ecological Society of America Annual Meeting, Portland, OR, August 2012.

Barnard, HR, A Byers, A Harpold, BE Ewers, D Gochis, P Brooks. Examining the response of lodgepole transpiration to snow melt and summer rainfall in subalpine Colorado, USA. Ecological Society of America Annual Meeting, Portland, OR, August 2012.

Brown, NR, U Norton, E Pendall, BE Ewers, **B Borkhuu**. High levels of soil and litter nitrogen contents after bark beetle-induced lodgepole pine mortality. Ecological Society of America Annual Meeting, Portland, OR, August 2012.

Ewers BE et al. Use of plant hydraulic theory to predict plant controls over mass and energy fluxes in response to changes in species, soils and mortality. American Society of Plant Biology Annual Meeting, Austin, TX, July, 2012.

(Invited) Ewers BE. Simulation modeling of bark beetle effects on stand water budgets. Wyoming Weather Modification Technical Advisory Team Meeting. Saratoga, WY July 2012.

(Invited) Ewers BE. Temporal and Spatial Scaling of Evapotranspiration Using Plant Hydraulic Theory. Penn State. Critical Zone Observatory Distinguished Speaker Series. Mar. 23, 2012

Ewers BE. Impact of Bark Beetle Outbreaks on Precipitation Processing by Forests. Wyoming Weather Modification Technical Advisory Team, Meeting, Cheyenne, WY Jan. 18, 2012.

Frank, J, B Massman, B Ewers. Errors in measured sensible heat flux due to vertical velocity measurements in non-orthogonal sonic anemometers. Front Range Student Ecology Symposium, CSU, Ft. Collins, CO Feb. 22, 2012.

Frank, J, B Massman, BE Ewers. Net ecosystem exchange of carbon dioxide and evapotranspiration response of a high elevation Rocky Mountain (Wyoming, USA) forest to a bark beetle epidemic. UW Program in Ecology Symposium, Feb. 17, 2012.

DE Reed, BE Ewers, E Pendall, RD Kelly. Mountain Pine Beetle epidemic effects on the carbon, water, and energy fluxes of lodgepole pine ecosystems. UW Program in Ecology Symposium, Feb. 17, 2012.

Mackay, DS, BE Ewers, DE Roberts, NG McDowell, E Pendall, **JM Frank, DE Reed**, WJ Massman, B Mitra. A coupled carbon and plant hydraulic model to predict ecosystem carbon and water flux responses to disturbance and environmental change. American Geophysical Union Meeting, San Francisco, CA, Dec. 2011.

Brooks, PD, HR Barnards, JA Biederman, **B Borkhuu**, SL Edburg, BE Ewers, DJ Gochis, ED Gutmann, AA Harpold, JA Hicke, E Pendall, **DE Reed**, AJ Somor, PA Troch. Water, Carbon, and Nutrient Cycling Following Insect-Induced Tree Mortality: How well do plot-scale observations predict ecosystem-scale repsonse. American Geophysical Union Meeting, San Francisco, CA, Dec. 2011.

(Invited) Ewers, BE, E Pendall, D Reed, H Barnard, F Whitehouse, J Frank, W Massman, P Brooks, J Biederman, K Nathan, B Mitra, DS Mackay. Use of plant hydraulic theory to predict ecosystem fluxes across mountainous gradients in environmental controls and insect disturbance. American Geophysical Union Meeting, San Francisco, CA, Dec. 2011.

Frank, JM, WJ Massman, BE Ewers. Net ecosystem exchange of carbon dioxide and evapotranspiration response of a high elevation Rocky Mountain (Wyoming, USA) forest to a bark beetle epidemic. American Geophysical Union Meeting, San Francisco, CA, Dec. 2011.

Norton, U, E Pendall, BE Ewers, **B Borkhuu**. Trace gas emissions from a chronosequence of bark beetle-infested lodgepole pine (Pinus contorta) forest stands. American Geophysical Union Meeting, San Francisco, CA, Dec. 2011.

DE Reed, BE Ewers, E Pendall, RD Kelly. Mountain Pine Beetle epidemic effects on the carbon, water, and energy fluxes of lodgepole pine ecosystems. American Geophysical Union Meeting, San Francisco, CA, Dec. 2011.

Gochis, DJ, ED Gutmann, PD Brooks, DE Reed, BE Ewers, E Pendall, JA Biedermann, AA Harpold, HR Barnard, J Hu. Diagnosing the influence of model structure on the simulation of water, energy and carbon fluxes on bark beetle infested forests. American Geophysical Union Meeting, San Francisco, CA, Dec. 2011.

(Invited) Ewers, BE. Plant Hydraulic Theory and Mountains. Mountain Research Institute, Berkeley, CA, Dec. 2011.

(Invited) Ewers, BE, E Pendall, H Barnard, D Williams, U Norton, **D Reed**, P Brooks, D Gochis, A Harpold, **J Frank**, W Massman, F Whitehouse, **B Borkhuu, J Angstmann.** Impact of Bark Beetle Outbreaks on Forest Ecosystem Processes. Wyoming Environment and Natural Resources Speaker Series, Jackson, WY, Dec. 2011.

(Invited) Ewers, BE, E Pendall, H Barnard, D Williams, U Norton**, D Reed**, P Brooks, D Gochis, A Harpold**, J Frank**, W Massman, **F Whitehouse, B Borkhuu, J Angstmann .** Impact of Bark Beetle Outbreaks on Forest Water Yield. Wyoming Water Development Commission. Cheyenne, WY, Nov. 2011.

(Invited) Ewers, BE, E Pendall, H Barnard, D Williams, U Norton, **D Reed,** P Brooks, D Gochis, A Harpold, **J Frank**, W Massman, **F Whitehouse, B Borkhuu, J Angstmann** . Impact of Bark Beetle Outbreaks on Forest Water Yield. Joint Agriculture Committee of the Wyoming Legislature. Afton, WY, Oct. 2011.

Ewers, BE, E Pendall, U Norton, **D Reed, J Frank, B Borkhuu**, **F Whitehouse, N Brown,** H Barnard, P Brooks, **T Aston, J Angstmann,** W Massman, D Williams, A Harpold, J Biederman, S Edburg, A Meddens, D Gochis, J Hicke. Cascading effects of bark beetles and blue stain fungi on coupled water, C and N cycles. UW Dept. Botany. Sept. 2011.

(Invited) Ewers, BE, E Pendall, H Barnard, D Williams, U Norton, **D King, D Reed**, P Brooks, D Gochis, A Harpold, **J Frank**, W Massman, **F Whitehouse, B Borkhuu**, J Angstmann. The challenge of predicting the interacting effects of weather modification and bark beetles on forest water yield. Wyoming Weather Modification Technical Advertisory Team Meeting. Lander, WY, July 2011.

Borkhuu, B, E Pendall, U Norton, BE Ewers. Effects of mountain pine bark beetle infestation on soil CO2 efflux in lodgepole forests in Southeastern Wyoming. Soil Science Society Western Meeting, Laramie, WY. June 2011.

(Invited) Ewers, BE. Testimony on bark beetle impacts on forest hydrology. Joint meeting of the Select Water Committee of the Wyoming Legislature and the Wyoming Water Development Commission. Cheyenne, WY, June 2011.

Ewers, BE, E Pendall, H Barndard, **F Whitehouse**, **D Reed, J Frank**, P Fornwalt, T Aston, J Angstmann, U Norton, A Harpold, P Brooks. Sap flux measurements quantify the timing of transpiration loss due to fungal xylem occlusion following bark beetle attack and subsequent ecosystem consequences. VIII International Sap Flow Meeting, Volterra, IT, May, 2011.

(Invited) Ewers, BE, E Pendall, H Barnard, D Williams, U Norton, **D Reed,** P Brooks, D Gochis, A Harpold, **J Frank**, W Massman, F Whitehouse, **B Borkhuu,** J Angstmann. Impact of Bark Beetle Outbreaks on Forest Water Yield. Wyoming Water and Environmental Law Conference, Cheyenne, WY, Apr. 2011.

Frank, J, WJ Massman, BE Ewers. Evapotranspiration response of a high elevation Rocky Mountain (Wyoming, USA) forest to a bark beetle epidemic. Bark Beetle-Water Symposium, Boulder, CO 2011.

Harpold, AA, PD Brooks, JA Biederman, A Somor, P Troch, D Gochis, E Gutmann, H Barnard, **D Reed,** E Pendall, BE Ewers. Quantifying the effects of tree dieoff from mountain pine beetles on hydrologic partitioning at the catchment-scale. Bark Beetle-Water Symposium, Boulder, CO 2011.

Gochis, D, E Gutmann, AA Harpold, PD Brooks, JA Biederman, H Barnard, **D Reed**, E Pendall, BE Ewers. Multi-model assessment and verification of bark beetle impacts on land surface-atmosphere energy and water exchanges. Bark Beetle-Water Symposium, Boulder, CO 2011.

Frank J, W Massman, BE Ewers. Response of high elevation rock mountain forest evapotranspiration to a bark beetle epidemic. CSU Hydrology Days, Ft. Collins CO. Feb. 2011.

Reed D, Kelly R, Ewers B, Pendall E. Energy Closure of a Heterogeneous Forest Canopy. Ameriflux Annual Meeting, Feb. 2011

Frank J, W Massman, BE Ewers. Response of high elevation rocky mountain (Wyoming, USA) forest carbon dioxide and water vapor fluxes to a bark beetle epidemic. Ameriflux Annual Meeting, Feb. 2011.

BE Ewers, E Pendall, U Norton, **D Reed, J Franks, T Aston, F Whitehouse**, HR Barnard, PD Brooks, J Angstmann, WJ Massman, DG Williams, AA Harpold, J Biederman, SL Edburg, AJ Meddens, DJ Gochis, JA Hicke. The Rocky Mountain epidemic of bark beetles and blue stain fungi cause cascading effects of coupled water, C and N cycles. AGU, San Francisco, CA, Dec, 2010.

DE Reed, RD Kelly, BE Ewers, E Pendall. The mountain pine beetle epidemic contributes to increased spatial and temporal variablity and decoupling of carbon and water fluxes from lodgepole pine. AGU, San Francisco, CA, Dec, 2010.

DJ Gochis, PD Brooks, AA Harpold, BE Ewers, E Pendall, HR Barnard, **D Reed**, PC Harley, J Hu, J Biederman. Measuring and modeling changes in land-atmosphere exchanges and hydrologic response in forests undergoing insect-driven mortality. AGU, San Francisco, CA, Dec, 2010.

PD Brooks, AA Harpold, AJ Somor, PA Troch, DJ Gochis, BE Ewers, E Pendall, JA Biederman, **D Reed, HR Barnard, F Whitehouse, T Aston, B Borkhuu**. Quantifying the effects of mountain pine beetle infestation on water and biogeochemical cycles at multiple spatial and temporal scales. AGU, San Francisco, CA, Dec, 2010.

BE Ewers (invited) E Pendall, **D Reed, F Whitehouse, J Frank, T Aston, J Angstmann,** D Williams, H Barnard, WJ Massman, U Norton. Impacts of a bark beetle epidemic on forest hydrology. Wyoming Water Forum, Cheyenne, WY, Nov. 2010.

BE Ewers E Pendall, U Norton, **B Borkhu, T Aston, D Reed, J Frank, J Anstmann**, WJ Massman, PD Brooks, DJ Gochis, HR Barnard, D Williams. First and higher order impacts of bark beetles on ecosystem processes of Rocky Mountain Forests. Ecological Society of America Meeting, Pittsburgh, PA, Aug. 2010.

Leveraged Support to this Project.
NSF ESPSCOR. Water in the West. $20 million total grant, $500,000 to Ewers. A major justification for this grant was the lack of correlation between increased water in stands and streams after bark beetle mortality. This finding was primarily funded by this project

NSF ETBC Hydrologic Science. ETBC: Collaborative Research: Quantifying the Effects of Large-Scale Vegetation Change on Coupled Water, Carbon, and Nutrient Cycles: Beetle Kill in Western Montane Forests. CoPI Elise Pendall. $219,261. This NSF funding ran concurrently with this project and the PI took advantage of the synergism to fund many more students than either project alone.

Ag Exp Station and McIntire Stennis. Quantifying the impact of a massive mountain pine beetle outbreak on carbon, water and nitrogen cycling and regeneration of southern Wyoming lodgepole pine forests. CoPIs Elise Pendall and Urszula Norton $60,000. This funding ran concurrently with this project and the PI took advantage of the synergism to fund many more students than either project alone.

Fate of Coalbed Methane Produced Water in Disposal Ponds in the Powder River Basin

Basic Information

Title:	Fate of Coalbed Methane Produced Water in Disposal Ponds in the Powder River Basin
Project Number:	2011WY74B
Start Date:	3/1/2011
End Date:	2/28/2013
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Geochemical Processes, Groundwater, Solute Transport
Descriptors:	
Principal Investigators:	Thijs Kelleners, Katta J Reddy

Publications

There are no publications.

Final Report

FATE OF COALBED METHANE PRODUCED WATER IN DISPOSAL PONDS IN THE POWDER RIVER BASIN

T.J. Kelleners, Associate Professor Soil Physics
K.J. Reddy, Professor of Environmental Quality
R. Drapeau, MS Graduate Student, Soil Science

Department of Ecosystem Science and Management, University of Wyoming

Reporting period: 03/01/2011 – 02/28/2013

1. Abstract

The Powder River basin (PRB) in Wyoming has seen a rapid increase in coalbed methane (CBM) production over the past decade. Product water from the ~20,000 active CBM wells is mostly released in surface ponds. The product water may be high in total dissolved solids, be sodium dominated, and may contain trace elements that are toxic to humans, livestock, and wildlife. The fate of the pond water is generally unknown. Infiltration of pond water could lead to the contamination of shallow groundwater and surface water. Concentration of pond water due to evaporation could lead to unacceptable high trace element concentrations. Previous studies suggest that pond water infiltration reduces with time because of soil dispersion related to the high sodium content of the CBM water. We examined the relationship between soil type, CBM water quality, and infiltration rate for a variety of unlined ponds across the PRB. We were particularly interested in determining the time frame over which the infiltration rate reduces as compared to the total lifetime of the ponds. We completed the analysis for four sites. For two sites we found that infiltration rates were unaffected by the CBM water. For two other sites we did observe a reduction in infiltration rates due to CBM water disposal. This type of information is currently lacking for the PRB and would greatly benefit pond operators, landowners, and agencies in assessing the environmental impact of the ponds (i.e. groundwater contamination versus concentration of pond water constituents). Infiltration experiments conducted in the laboratory will be supplemented with numerical modeling of subsurface water flow and solute transport to assess the practical implications of the measured infiltration rates.

2. Progress

2.1 Objectives

The study examined the relationship between soil type, CBM produced water quality, and infiltration rate for unlined disposal ponds in the PRB. The specific objectives were:

(1) Identify combinations of soil type and CBM water quality that are representative for conditions in the PRB;
(2) Measure saturated soil hydraulic conductivity as a function of time during CBM water infiltration in the laboratory;

(3) Model water flow and solute transport for typical PRB CBM ponds over an assumed 10-year lifetime.

2.2 Methodology

[Completed]
Objective (1): Five representative sites were identified in the PRB for which soil and water samples were collected: Site 1 North of Gillette, WY; Site 2 near Sheridan, WY; Site 3 West of Gillette, WY; Site 4 near Buffalo, WY; and Site 5 near Wright, WY. The original plan to use data from an existing network of water quality measurement sites across the PRB established by the research group of KJ Reddy had to be abandoned because many of the original wells had stopped pumping (the amount of water pumping decreases as the well ages). So instead, five new sites were selected.

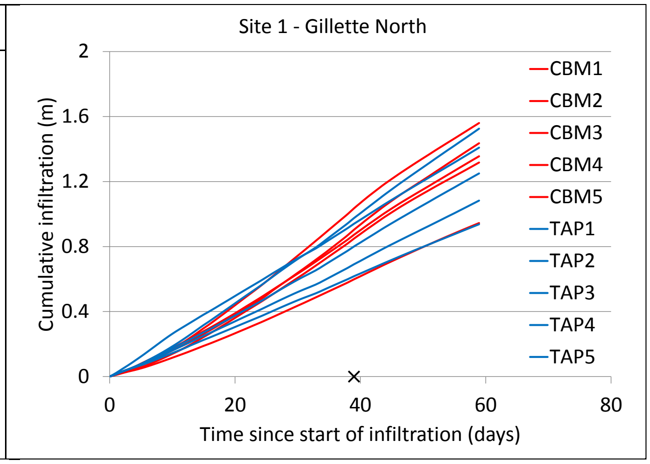
[Mostly completed]
Objective (2): Soil samples were collected from selected sites and taken to the laboratory for the infiltration experiments. The sampled soil was used to represent pre-CBM discharge soil conditions for the pond area. The infiltration experiments were conducted using CBM well water which was collected at the time of soil sampling. The infiltration experiments were conducted in the laboratory by packing the soil in PVC columns with metal screens at the bottom. At the start of the experiment, the columns were wetted from the bottom up with tap water to drive all the air out. Subsequently, well water was applied to the top of the columns at a constant head using a mariotte bottle and outflow quantity and quality was monitored at the bottom of the columns. Outflow quality was measured as Electrical conductivity (EC) and Sodium Adsorption Ratio (SAR) of the water. After about 10 pore volumes were flushed from the columns, the CBM well water was replaced by pristine stream water. The pristine stream water was selected to represent water from rainfall & snow and was used to investigate the impact of non-saline, non-sodic precipitation water on the pond sediments upon cessation of CBM water discharge. Soil water quality inside the columns was analyzed upon completion of the infiltration experiment. The CBM water infiltration results were compared to “baseline” tap water infiltration results for the same soils to more clearly assess the impact of the saline-sodic well water. The “baseline” columns received only tap water (no stream water). For each site 5 columns were infiltrated with CBM / stream water and 5 columns were infiltrated with tap water.

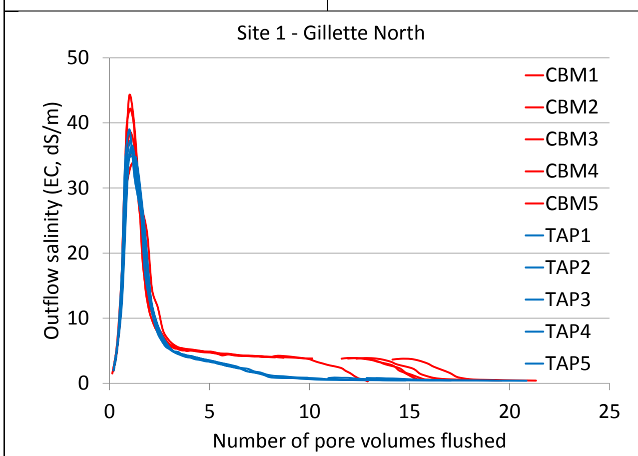
[Yet to be done]
Objective (3): Saturated soil hydraulic conductivity will be calculated from the infiltration data using the Darcy Equation. The practical implications of temporal variations in the saturated hydraulic conductivity of the pond sediments will be studied using the Hydrus-2D model for water flow and solute transport in variably-saturated porous media. The model will be applied in axisymmetric mode to describe a vertical cross section of the pond sediments. A sensitivity analysis will be conducted for a number of idealized pond settings to quantify the effect of reduced hydraulic conductivity on water flow and solute transport over the assumed 10-yr lifetime of the ponds.

2.3 Principal Findings

At the time of writing this report, the laboratory measurements for sites 1-3 were completed, while the measurements for site 4 were being wrapped up. Measurements for Site 5 are anticipated to start once site 4 is completed. The reason for the ongoing laboratory measurements is the long duration of this type of column experiments of up to 100 days. Results for the 3 completed sites are shown below. The results for Site 1, North of Gillette, WY are summarized in Figure 1. The soil type is clay, while the CBM water can be classified as saline, non-sodic. Cumulative infiltration versus time, outflow salinity versus number of pore volumes flushed, and outflow sodicity versus number of pore volumes flushed are shown. The "X" on the "time since start of infiltration" axis (top-right panel) marks the moment when the CBM water was replaced by stream water to see whether the low salinity water would induce soil dispersion. The results for Site 1 show that: (1) On average, infiltration is highest for the CBM water columns; (2) infiltration rates for the CBM and tap water columns remains relatively constant with time; (3) large quantities of salts are flushed from the soil at the onset of infiltration, reflecting the saline nature of the soil; (4) the tap water columns reduce to a lower outflow salinity and sodicity than the CBM water columns; and (5) infiltrating the CBM water columns with good quality stream water does not trigger soil dispersion, judging from the unchanged trend in cumulative infiltration.

Site 1 – Gillette North	
Sand	0 %
Silt	30 %
Clay	70 %
Soil type	Clay
Soil $EC_{1:1}$	10.2 dS m^{-1}
Dry bulk density	1.27 g cm^{-3}
EC CBM water	3.3 dS m^{-1}
SAR CBM water	6.2 $(mmol_c\ l^{-1})^{0.5}$





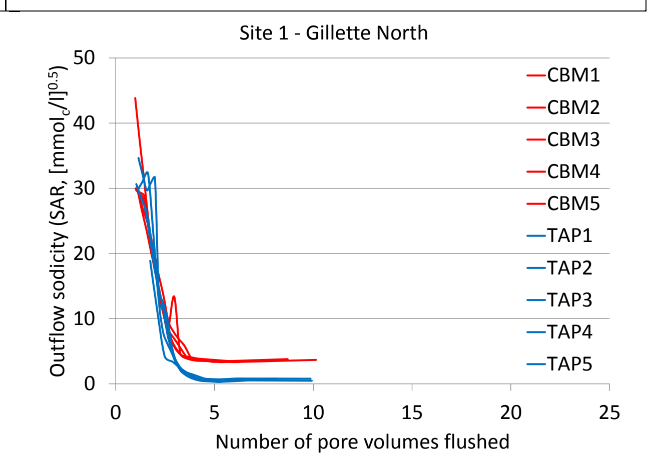
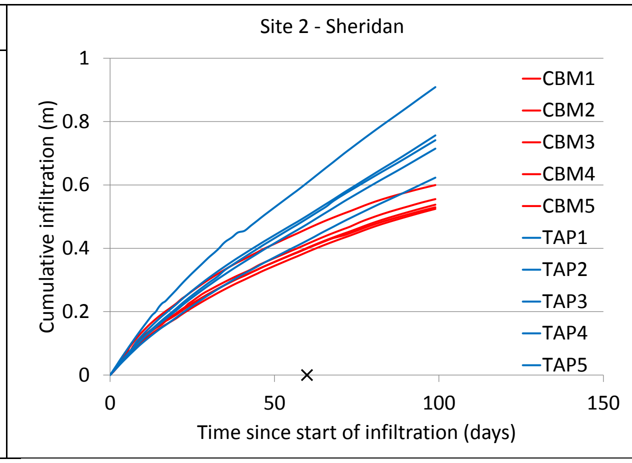


Figure 1Soil & water description, cumulative infiltration, outflow water salinity, and outflow sodicity description for the laboratory soil column experiments for Site 1, North of Gillette, WY.

The results for Site 2 near Sheridan, WY are summarized in Figure 2. The same information is shown as for Site 1. The soil is a clay loam and the CBM water can be classified as moderately saline and highly sodic. The results for Site 2 show that: (1) Infiltration rates decrease with time for both the CBM and tap water treatments; (2) The CBM water columns exhibit a continuous decrease in infiltration rates after CBM water has been replaced by stream water; (3) The tap water columns reduce to a lower outflow salinity and sodicity than the CBM columns; (4) The outflow SAR values remain well below the CBM water SAR values over the course of the entire experiment, possibly indicating that sodium is becoming the dominant cation in the soil solution.

Site 2 – Sheridan	
Sand	22 %
Silt	39 %
Clay	39 %
Soil type	Clay loam
Soil $EC_{1:1}$	0.3 dS m^{-1}
Dry bulk density	1.49 g cm^{-3}
EC CBM water	1.6 dS m^{-1}
SAR CBM water	87.9 $(mmol_c\ l^{-1})^{0.5}$



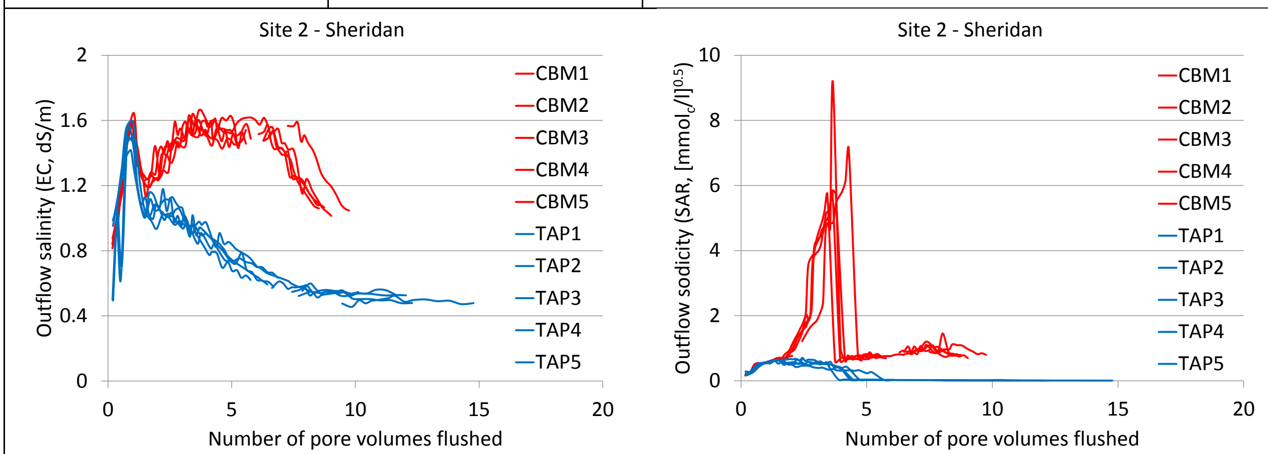
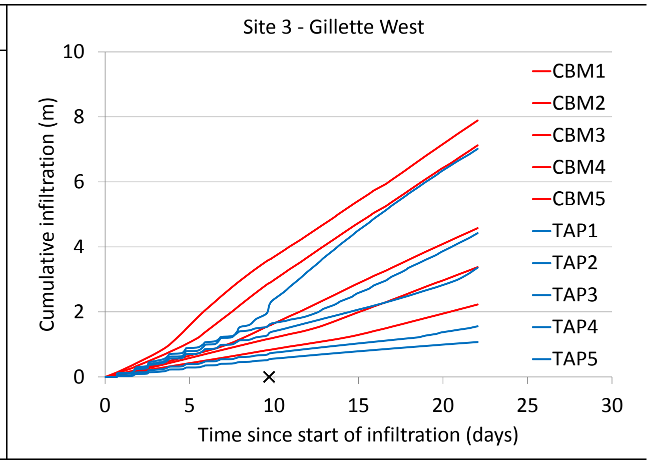


Figure 2Soil & water description, cumulative infiltration, outflow water salinity, and outflow sodicity description for the laboratory soil column experiments for Site 2, Sheridan, WY.

The results for Site 3, West of Gillette, WY are summarized in Figure 3. The soil is a clay loam and the CBM water quality can be classified as saline, non-sodic. The results for Site 3 show that: (1) infiltration rates are higher for CBM water than for tap water and show no decrease with time; (2) leaching of salts by the CBM water is relatively insignificant, compared to Site 1, reflecting the low soil EC; and (3) The introduction of stream water after CBM water results in additional leaching of salts without affecting infiltration rates, indicating no soil dispersion.

Site 3 – Gillette West	
Sand	21 %
Silt	39 %
Clay	40 %
Soil type	Clay loam
Soil $EC_{1:1}$	2.5 dS m^{-1}
Dry bulk density	1.24 g cm^{-3}
EC CBM water	3.4 dS m^{-1}
SAR CBM water	6.3 $(mmol_c\ l^{-1})^{0.5}$



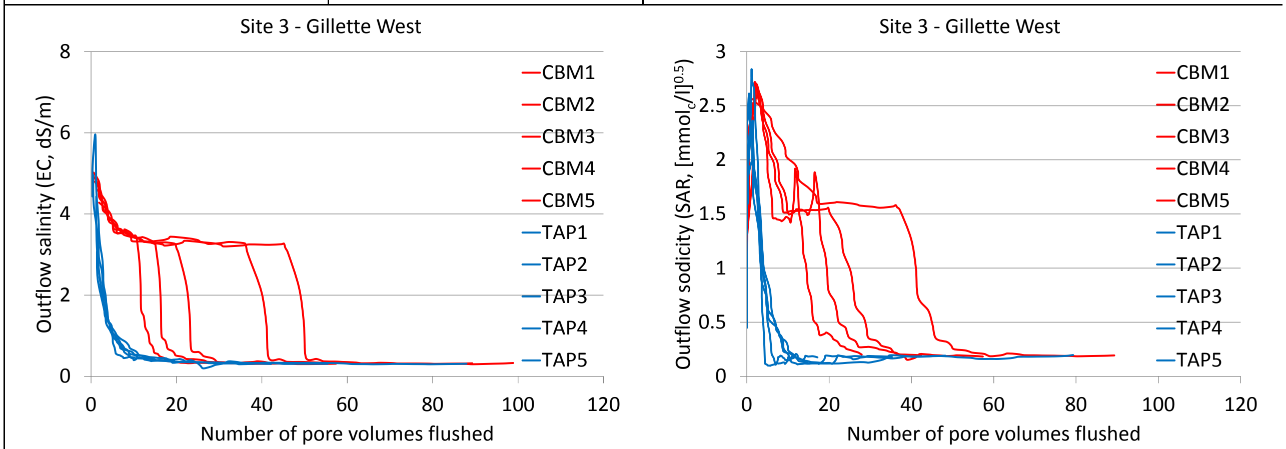


Figure 3Soil & water description, cumulative infiltration, outflow water salinity, and outflow sodicity description for the laboratory soil column experiments for Site 3, West of Gillette, WY.

The preliminary results for Site 4, near Buffalo, WY (not shown) are similar to those for Site 2 (Sheridan), with sodic CBM water having a significant impact on infiltration rates with time.

2.4 Significance

The fate of CBM water in the unlined ponds is not well understood. Both infiltration and evaporation are likely. Infiltration of pond water may lead to contamination of the shallow groundwater and to degradation of streams that are fed by the groundwater. The contamination is caused by the solutes in the pond water and by the mobilization of solutes already present in the soil. Evaporation of pond water may lead to the concentration of trace elements to levels that are toxic for livestock and wildlife that use the pond for drinking water. The infiltration characteristics of the soil determine whether infiltration will be dominant, or, in case of low infiltration rates, evaporation. Previous studies suggest that pond water infiltration reduces with time because of soil dispersion related to the high sodium content of the CBM water. The results from the column infiltration studies for the two Gillette sites seem to contradict this as no drop in infiltration rate with time is observed. In contrast, results for the Sheridan site, and possibly the Buffalo site, do indicate that CBM water sodicity is impacting infiltration rates. Additional column infiltration experiments (Site 5near Wright, WY), will be conducted to provide a more comprehensive picture.

3. Publications

As part of the study, three presentations were given:

Drapeau, R., T.J. Kelleners, and K.J. Reddy. Fate of coalbed natural gas co-produced water in disposal ponds in the Powder River Basin. Oral and poster presentation at the Soil Sci. Soc. Am. Annual Meeting, Oct 21-24, 2012, Cincinnati, OH.

Kelleners, T.J. Water Research Program: Fate of coalbed methane produced water in disposal ponds in the Powder River Basin. Oral presentation for the Wyoming Water Development Commission, Nov 29, 2011, Cheyenne, WY.

Kelleners, T.J. The effects of coal-bed natural gas produced water on infiltration. Oral presentation at the UCOWR/NIWR annual conference, July 11-14, 2011, Boulder, CO.

A journal paper will be drafted and submitted upon completion of the laboratory measurements and the computer modeling. Submission of the paper is anticipated for Fall 2013.

4. Student Support Information

MS student Robert Drapeau was hired for the duration of the 2-year project. The course and research work should result in a MS soil/water resources degree by Fall 2013. Robert attended the Soil Science Society of America Annual meeting in Cincinnati, OH in October 2012 and presented results from the study to a large audience.

5. Awards and achievements

MS student Robert Drapeau has been awarded an energy assistantship by the Office of Academic Affairs of the University of Wyoming.

Instrumentation for Improved Precipitation Measurement in Wintertime Snowstorms

Basic Information

Title:	Instrumentation for Improved Precipitation Measurement in Wintertime Snowstorms
Project Number:	2011WY75B
Start Date:	1/1/2011
End Date:	2/28/2013
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Water Quantity, Climatological Processes, Hydrology
Descriptors:	None
Principal Investigators:	Jefferson Snider

Publication

1. Wolfe, J.P. and J.R.Snider, 2013. Reply to Comments on A Relationship between Reflectivity and Snow Rate for a High-Altitude S-Band Radar , J. Appl. Meteor. Climatol., 52, 730 731.

Improved Precipitation Measurement in Wintertime Snowstorms

Focus Category: WQN, CP, HYDROL

Keywords: Snow Process Research

Final Report

Start Date: 03/01/2011

End Date: 02/28/2013

Principal Investigator: Jefferson Snider, Professor, jsnider@uwyo.edu (307-766-2637)

Abstract-

It is widely acknowledged that precipitation measurements can be biased by an assortment of uncertainties. Measurement of snowfall is especially problematic. Independent of the type of measurement system employed, uncertainty due to wind-induced error is inherent to all snowfall measurements. Also, when using conventional gauges, uncertainty due to loss of material (sublimation and evaporation), and gauge capping, can also occur. Minimization of these uncertainties requires improved snow precipitation sensors. Applications requiring improved precipitation sensors include weather advisory, hydrometeorology and biogeochemistry.

The focus of his research has been an upgraded version the hotplate precipitation sensor manufactured by Yankee Environmental Systems. A hotplate data processing algorithm was developed, calibration studies were conducted, and the hotplate and a conventional precipitation gauge were compared during wintertime field experiments. The algorithm considers all relevant terms in the hotplate's heat budget (sensible, latent and radiative effects). One M.S. student was supported by the project and the upgraded hotplate precipitation sensor is now available for snow precipitation measurements.

Conference Presentation Supported by this WWDC Funding -

Wettlaufer, A., The Hotplate Precipitation Rate Sensor, Young Scientists Symposium, Colorado State University, October, 2012

Thesis Supported by this WWDC Funding -

Wettlaufer, A., Calibration and Operation of a Fully-compensated Hotplate Precipitation Gauge, in progress, thesis defense planned for August, 2013

Publications supported by this WWDC Funding -

Wolfe, J.P., and J.R.Snider, Reply to "Comments on 'A Relationship between Reflectivity and Snow Rate for a High-Altitude S-Band Radar'", J. Appl. Meteor. Climatol., 52, 730–731, 2013, PDF

Publication supported by Previous WWDC Funding-

Wolfe, J.P., and J.R.Snider, A Relationship between Reflectivity and Snow Rate for a High-Altitude S-Band Radar. J. Appl. Meteor. Climatol., 51, 1111–1128, 2012, PDF

Theses supported by Previous WWDC Funding-

Wolfe, J.P., Radar-estimated Upslope Snowfall Rates in Southeastern Wyoming, MS thesis, Dept. of Atmospheric Science, University of Wyoming, 2007

Borkhuu, B., Snowfall at a high-elevation site: A comparison of six measurement techniques, MS thesis, Dept. of Atmospheric Science, University of Wyoming, 2009

Overview -

With funding from this grant we upgraded a hotplate precipitation sensor and developed calibration methodologies and a hotplate data processing algorithm. The hardware upgrade was performed by the company that manufacturers the hotplate (Yankee Environmental Systems). The upgrade provided sensors for the longwave and shortwave radiant fluxes and two additional meteorological sensors (pressure and relative humidity). As we discussed in our grant application, the addition of radiation sensors makes it possible to account for a bias in the hotplate's estimation of precipitation rate. This bias can lead to substantial uncertainty in estimates of the liquid-equivalent accumulation. The accumulation uncertainty is especially problematic during winter in the Rocky Mountains where typically the liquid-equivalent precipitation rate (≤2 mm/hr) is only a factor of five larger than the magnitude of the radiation-induced bias. Further complicating is the fact that the sign of the bias shifts from positive to negative over a 24 hour day-to-night cycle.

Our approach is similar to the instrument development work performed by Borkhuu (2009) but with the distinction that we now have access to the longwave and shortwave radiant fluxes. In addition, this grant supported the development of the data acquisition system we used for data recording.

Algorithm Development and Laboratory Calibration -

During laboratory and field experiments we recorded the data signals output by the hotplate. The most fundamental of these is the hotplate's top-plate power; this was recorded with measurements of temperature, wind speed, and the shortwave and longwave fluxes. Our data processing algorithm assimilates these measurements, applies calibration constants, and outputs the precipitation rate.

The following steady-state energy budget is the basis for our analysis:

$0 =$	Implied Steady-state Balance
$\dot{Q}_{plate}$	Electrical Power Supplied to Top Plate
$-L \cdot K \cdot (T_{hp} - T) \cdot (\alpha \cdot Re^{\beta} + \gamma)$	Outgoing Sensible Heat
$-a \cdot \varepsilon_{hp} \cdot \sigma \cdot T_{hp}^{4}$	Outgoing Longwave Radiant Heat
$+a \cdot \varepsilon_{hp} \cdot (LW + \sigma \cdot T^{4})$	Incoming Longwave Radiant Heat
$+a \cdot (1 - r_{hp}) \cdot SW$	Incoming Shortwave Radiant Heat
$-a \cdot \rho_{\ell} \cdot \xi \cdot E \cdot P$	Precipitation

In this equation we see that there are six terms in the hotplate's energy budget. Most of these are expressed in terms of measurements (e.g., plate power and ambient temperature). We obtained some of the factors by reviewing the heat transfer literature (emissivity and reflectance) and some we evaluated experimentally. In the latter category there are four parameters; these are the hotplate temperature (T_{hp}) and the sensible heat parameters (α, β and γ). These four appear in the sensible heat term; also, T_{hp} appears in the outgoing longwave term. Values for these parameters, and descriptions of how they were evaluated, are provided in Adam Wettluafer's thesis. Because the sensible heat is one of two dominant terms in the heat budget (the other is the top-plate power), its determination, and its dependence on temperature and wind speed is essential for accurate determination of the precipitation rate.

Field Measurements -

During 2012 and 2013 we calibrated and deployed two hotplates; both were upgraded by the manufacturer. Because of the upgrade we have measurements of the longwave and shortwave fluxes which complement the measurements of the top-plate power and temperature. In the sensible heat term we see a temperature difference ($T_{hp} - T$) and a ventilation term $(\alpha \cdot Re^{\beta} + \gamma)$. The latter relates the nondimensional sensible heat - formulated as a Nusselt number (Nu) - to a nondimensional wind speed. The latter is expressed as a Reynolds number (Re).

Two Nu - Re relations are shown in Figure 1. Data used in these plots were recorded in the Sierra Madre Mountains (NCAR hotplate) and at a site located north of the city of Laramie (UWyo hotplate). We see that the shape of the Nu - Re function is different for the two hotplates, and consequently, the fitting coefficients, shown at the top of the graphs, are also different. At the present time, it is not obvious if these differences are instrument-dependent, location-dependent, or a mixture of both effects. Also evident is the occurrence of larger wind speed (larger Re) and the associated larger variability, at the north Laramie site. Ancillary results, not shown here, indicate that Nu - Re function can shift subsequent to repair work conducted by the hotplate manufacturer. Twice during this research, in both 2012 and in 2013, we returned the hotplate to the manufacturer to have them repair failed electronic components. Subsequently, we recalibrated α , β and γ .

In addition to the hotplates, we also worked with conventional precipitation gauges. At the Sierra Madre and Glacier Lakes Ecosystem Experiments Site (GLEES) we have the ETI gauges as comparators. These are maintained by NCAR. At the north Laramie site we worked with a gauge manufactured by Vaisala. The latter is known as the Vaisala Rain Gauge (VRG). We have the four VRGs that were used in the first two years of the Wyoming Weather Modification Pilot Project. These were replaced by ETI gauges. We have made plans to donate the VRGs to the Laramie Junior High School (contact person Heath Brown). All four VRGs were tested in our laboratory; test results are shown in Figures 2. These figures illustrate the VRGs response to the addition of a fixed mass (3.75 g). The mass was not added instantaneously; as a rate the mass addition is equivalent to 1.12 mm/hr precipitation rate. The figures shown some variability in the detection of the mass addition, but for all four VRG's the results are reasonable.

Field testing of one of the VRGs, at the north Laramie site, has not been very encouraging. Pictures of the site is provided in Figure 3. On the left is the UWyo hotplate and on right is one of the VRGs. In March and April of 2013 we recorded four major snow events at this site. The one advantage of operating at the north Laramie site is that line power is more reliable that the power at the GLEES site. As we discuss above, we conducted gauge intercomparison studies at GLESS in 2012.

The VRGs sensitivity to temperature precludes a quantification of the snowfall at the north Laramie site. We have had discussions with Vaisala and they recently agreed to replace the sensor unit in one of the four VRGs. At the present time we are waiting for Vaisala to return the new sensor unit.

Outlook –

The research described here is an ongoing effort. Currently we are focused on writing a journal article with Ms.Bujidmaa Borkhuu and finishing Adam Wettluafer's thesis. The paper will report on the gauge intercomparisons conducted at GLEES, in 2008 and 2012, and will describe Adam's method for calibrating and analyzing the hotplate measurements. Also, we have funding support from NSF (P.I. Bart Geerts) to deploy the UWyo hotplate during a winter precipitation study planned for western New York state in 2014.

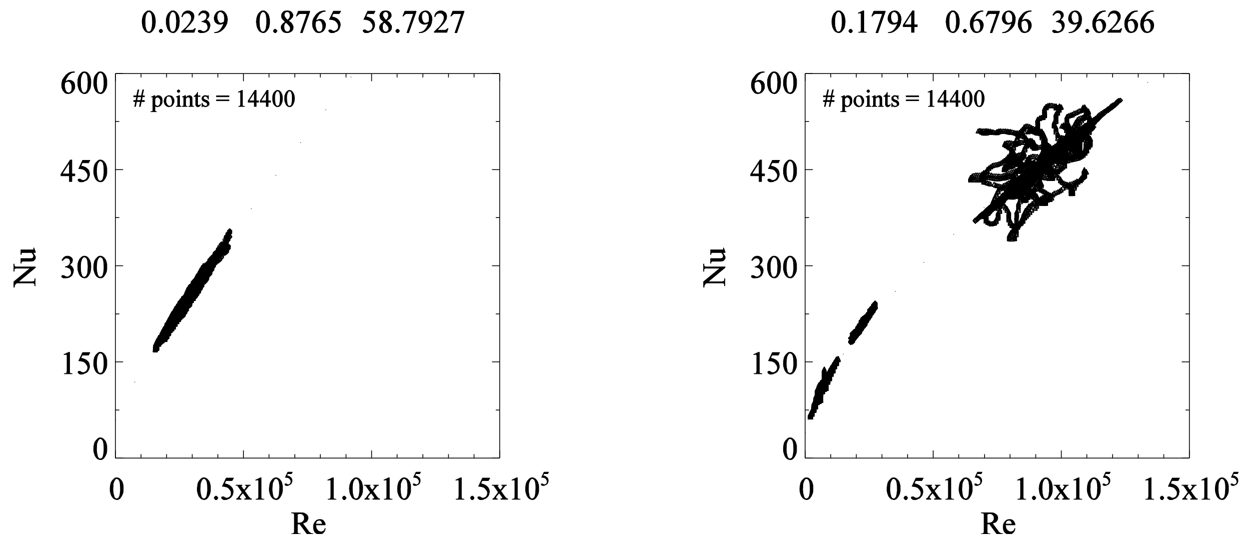


Figure 1 – Nondimensionalized plots of sensible heat (*Nu*) and wind velocity (*Re*) from a hotplate operated in the Sierra Madre Mountains (left panel, NCAR hotplate) and at the north Laramie site (right panel, UWyo hotplate). See text for details.

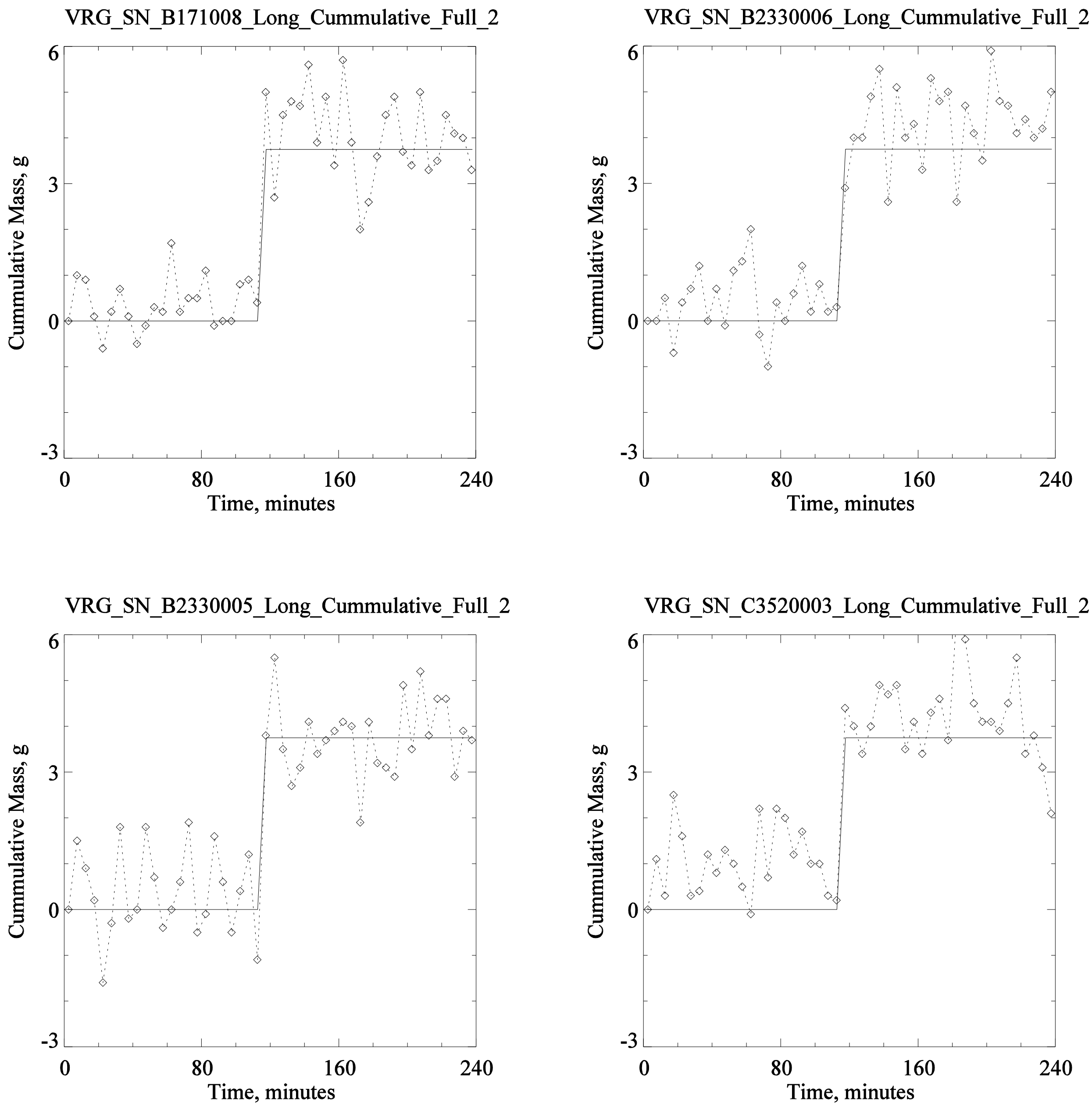


Figure 2 – VRGs response to the addition of a fixed mass (3.75 g) (dotted line connecting diamonds) and the expected response (solid line step function at time ~ 120 minutes). See text for details.

Figure 3 – The UWyo hotplate and a VRG located at the north Laramie site. Measurements were started in early March 2013 and continued into May 2013. See text for details.

Bibliography -

Borkhuu, B., Snowfall at a High Elevation Site: Comparisons of Six Measurement Techniques, M.S. Thesis, Department of Atmospheric Science, University of Wyoming, 2009

A Treatise on Wyoming Water Law

Basic Information

Title:	A Treatise on Wyoming Water Law
Project Number:	2012WY79B
Start Date:	3/1/2012
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	1
Research Category:	Social Sciences
Focus Category:	Law, Institutions, and Policy, None, None
Descriptors:	None
Principal Investigators:	Lawrence MacDonnell

Publications

There are no publications.

A Treatise on Wyoming Water Law
Wyoming Water Research Program Progress Report
Lawrence J. MacDonnell, Principal Investigator
(Annual Report: Year 1 of 2)

Abstract:
This proposal seeks continuing support for student research assistance associated with preparation of a treatise on Wyoming water law. Since the time of Elwood Mead, Wyoming has been a leader in the development of water law in the American West. Wyoming specifically adopted the prior appropriation doctrine in its 1890 Constitution and established a Board of Control and State Engineer to administer water use in the state. The legislature followed up the next year with new legislation putting in place the basic concepts adopted in the Constitution. Significant legislative changes have followed to produce the statutory system now in place in the State. In addition, the Wyoming Supreme Court has decided hundreds of cases involving issues of water law. The State Engineer and the Board of Control have adopted regulations and other guidance. Consequently, Wyoming today operates under a comprehensive set of laws, decisions, and administrative rules. Yet there is no single written source that provides a thorough summary and discussion of this legal system. This project is intended to fill this gap.

Progress
We have just moved into year two of this project. I have completed final drafts of chapters 1 and 2. Chapter 1 provides a historical overview of the development of Wyoming water law, including discussion of important legislative enactments and related court cases. I provided a copy of this chapter to the following reviewers: Pat Tyrrell, Jeff Fassett, Craig Cooper, Anne MacKinnon, John Shields, and John Barnes. I have received helpful comments from several and plan to incorporate some of these comments in my revision. I am just about to send out copies of chapter 2 for review. Chapter 2 represents the heart of the treatise (and the lengthiest chapter) as it provides a summary of all the relevant statutory provisions and their judicial interpretation. We have made some progress already on research for chapter 3, concerning the determination and administration of water rights by the State Engineer and the Board of Control and the process for judicial reviewMay 11, 2013. And we have begun research relating to the Wind River reservation and the law governing uses of water on the reservation—one of the topics of the fourth and final chapter that will also include the law relating uses of interstate rivers.

With project funding, several law students have worked as project research assistants. In addition to funding one full-time student last summer, I have employed five part-time research assistants during this school year. In addition I have hired two students who will work full-time during the summer of 2013.

I was able to draw from this research to prepare and present on March 7, 2013 "Elwood Mead's Vision for Wyoming Water: Then and Now," as this year's President's Speaker for the university. This presentation was recorded and is available on Wyocast.

In sum, we are making good progress in achieving project objectives and expect to be able to publish the results of this research in book form in the next academic year.

Integrated Accelerated Precipitation Softening (APS) - Microfiltration (MF) Assembly and Process Development to Maximize Water Recovery During Energy Production and CO2 Sequestration

Basic Information

Title:	Integrated Accelerated Precipitation Softening (APS) - Microfiltration (MF) Assembly and Process Development to Maximize Water Recovery During Energy Production and CO2 Sequestration
Project Number:	2012WY80B
Start Date:	3/1/2012
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Treatment, Water Supply, Water Use
Descriptors:	None
Principal Investigators:	Jonathan Brant, Dongmei Li

Publications

There are no publications.

Annual Report

Integrated Accelerated Precipitation Softening (APS) – Microfiltration (MF) Assembly and Process Development to Maximize Water Recovery during Energy Production and CO_2 Sequestration

PI's: Jonathan A. Brant, Assistant Professor, Department of Civil and Architectural Engineering, University of Wyoming, Dongmei (Katie) Li, Assistant Professor, Department of Chemical and Petroleum Engineering, University of Wyoming

Project Duration: 03/01/2012 to 02/28/2014

Abstract: The development of Wyoming's energy resources (coal bed methane extraction [CBM], hydraulic fracturing) and carbon dioxide (CO_2) sequestration sites all invariably result in the production of brackish wastewaters. The treatability of these waters varies from relatively simple for CBM water (dissolved solids < 2,000 mg/L) to complex for the water that is displaced during geologic sequestration of CO_2 (dissolved solids > 20,000 mg/L). Reverse osmosis (RO) is a proven desalination process, which requires hydraulic pressures to transport water across semi-permeable membranes. Although RO has been extensively used to treat a variety of source waters, including energy development produced water, managing the concentrate that is produced as a byproduct during RO has persisted as an environmental and economic challenge in maximizing water recovery rate. Here we propose to develop an integrated accelerated precipitation softening (APS)-microfiltration (MF) assembly for reducing the volume of concentrate that must be disposed of when using RO to treat high-salinity, energy activity related waters in Wyoming. The ability of chemical precipitation processes, including APS, to remove scale-forming elements from source waters is established. Conventional softening processes are hindered by the production of fine suspensions of mineral precipitates that require relatively long sedimentation times (1.5-3 hrs) and a residual sludge having a low solids content (2-30%). These issues generate concerns related to the size of softening facilities, solids carry over to downstream membrane processes, and sludge disposal. These concerns hinder the use of APS as a management strategy for RO concentrate. APS processes use calcite crystals to provide a preferential surface area for nucleation and growth to occur, thus accelerating the kinetics of mineral precipitation. As such, the accelerated APS process will allow the removal of $CaCO_3$ as well as other scale forming elements that will be incorporated in the $CaCO_3$ crystals and removed. Built upon the previous findings in the field of treating challenging source waters, the unique contribution of the proposed work lies in the three folds: 1) incorporating MF as a polishing step following precipitation softening and prior to secondary RO process; 2) application of calcite seeds to accelerate the softening process and to improve the treatability of the feed water for the secondary RO system; 3) application of an integrated rather than singular approach for maximizing the recovery/reuse potential of highly saline produced waters. The integrated APS-MF assembly for RO concentrate treatment will provide a superior feed water quality to secondary RO systems that will allow for water recovery ratios to approach, or exceed, 90%.

Nature, scope, and objectives of the project, including a timetable of activities: The *objective of this project* is to build and evaluate the performance of an integrated APS-MF process in order to dramatically improve the treatability of concentrate streams, thus increasing the overall water recovery rate for RO desalination systems. The four specific aims that we are pursuing to attain our objective are as follows: *(1) Build an integrated APS-MF assembly for treating RO concentrate generated during the desalination of produced water*, (2) *Quantify the performance of the integrated APS-MF assembly for primary RO concentrate treatment*, *(3) MF Membrane Material Selection and Testing of the integrated APS assembly treating high-salinity RO concentrate*, *and (4) Build a performance database for selecting desalination processes treating produced waters using experimental data from Aim #2.*

Table 1. Project schedule having a start date of March 1, 2012 and an anticipated completion date of February 28, 2014. The project is currently in Month 9.

Months	**1-2**	**2-4**	**4-6**	**6-8**	**8-10**	**10-12**	**12-14**	**14-16**	**16-18**	**18-20**	**20-22**	**22-24**
Specific Aim #1												
Task 1.1	■											
Task 1.2		■	■									
Task 1.3			■	■	■	■	■	■	■	■	■	■
Specific Aim #2												
Task 2.1							■	■	■	■	■	
Task 2.2								■	■	■	■	
Specific Aim #3												
Task 3.1					■	■	■	■	■			
Specific Aim #4												
Task 4.1									■	■	■	■

Methods, procedures, and facilities: Our research plan is comprised of four specific aims.

Aim #1 –Build an integrated APS-MF assembly for treating RO concentrate generated during the desalination of produced water. At present, there are no integrated APS-MF assemblies for treating the RO concentrate that is generated during the desalination of energy production produced water. Furthermore, data is particularly absent on the performance of ceramic MF membranes in these applications. Therefore, building an integrated APS-MF assembly using ceramic membranes will be the first objective of this work in order to improve the treatability of high-salinity RO concentrate for secondary RO processes. The *approach* will be to operate an APS and ceramic MF process in series using RO concentrate from currently operating seawater and produced water desalination systems in order to evaluate and optimize the performance of the integrated system.

Task 1.1 - Modify existing bench-scale MF system and integrate with accelerated precipitation softening reactor. An existing hollow fiber MF test system will be modified to incorporate an APS process. The APS system includes a 20-L jacketed reaction vessel, digital mixer, and ports for measuring pertinent process parameters. Sludge will be withdrawn from the bottom of the APS reactor, while inlet and outlet ports will be located at prescribed depths from the water surface. The 20-L volume allows for sufficient flexibility in process operation so as to comprehensively assess the impacts of process parameters on membrane performance. The APS system will be operated in a flow through configuration, where raw RO concentrate will be stored in the mixing vessel and metered into the APS reactor. Such configuration was chosen to provide the greatest flexibility for evaluating process performance. Calcite seeds and sodium hydroxide will be dosed into the flow line from the raw water storage tank to the APS reactor. Sludge from the reactor will be collected for analysis. Water from the softening reactor will then be withdrawn and fed to the 5-L jacketed MF feed reservoir.

Task 1.2 – Process Development of the Integrated APS-MF system. Calcium carbonate powder having a particle size of approximately 10 μm will be used as calcite seeds. The size of the calcite seeds will be verified through SEM imaging and dynamic light scattering (DLS) measurements. Calcite seeds may result in significant membrane fouling as their size approaches the nominal membrane pore size, as a result of their ability to penetrate and deposit within the pore. Thus, the seed size that was selected for study in the proposed research is several times larger than the largest nominal membrane pore size to minimize membrane fouling. The RO concentrate will be made to represent a range of energy produced water qualities from around Wyoming. The chemistry/composition of these solutions is based on existing data from the USGS produced water databanks. These waters will be concentrated so as to represent the water leaving a primary RO system. Small-scale APS experiments will be conducted to establish the optimum pH and calcite seed concentration values for the two RO concentrate source waters. Solution pH will first be adjusted using a concentrated sodium hydroxide stock solution. This step will establish the optimum solution pH for initiating $CaCO_3$ precipitation, as well as the NaOH dosage required to achieve the desired pH. Calcite seeds will be injected into the concentrate solution to achieve a desired concentration and the solution will under go rapid mixing for 30-sec followed by mixing at a slower speed. Initial experiments will focus on determining the optimum pH to initiate $CaCO_3$ precipitation, followed by determination of the optimum calcite seed concentration at the previously determined optimum pH value.

Task 1.3 - Performance analysis of the integrated APS-MF system. Integrated system performance experiments will be conducted using the APS-MF test apparatus developed in Task 1.1. The APS system will be operated using the operation parameters determined in Task 1.2. The performance of the APS process will be closely monitored, with respect Ca^{2+} removal, and its operation adjusted as necessary to account for any issues that arise from scaling up the process. Two titanium dioxide tubular ceramic MF membranes, having pore sizes of 0.45 and 1.40 μm, will be evaluated in the initial tests. These tubular membranes have single channels, which will facilitate subsequent characterization of the mineral scale that is expected to form on the membrane surface (Task 3.1). In Task 2.1 we will evaluate the performance of the two process components separately, as well as that of the completely integrated APS-MF system. Performance variables that will be evaluated for the APS and MF processes include: solids retention time, cleaning frequencies, solids loading rate, and treated water quality. Our tests will evaluate Ca^{2+} removal in both the APS slurry as well as that by the MF membrane process. Grab samples will be taken from the APS slurry reactor and from the MF permeate line to measure the Ca^{2+} concentration and to collect samples for detailed water quality analyses.

Aim #2 – Quantify the performance of the integrated APS-MF assembly for primary RO concentrate treatment. Desalination using RO is limited to relatively low feed water recovery rates. Integrated treatment techniques for improving the treatability of RO concentrate are expected to improve the overall recovery rate that may be realized for RO desalination applications. The performance limits and operational challenges associated with secondary RO systems treating effluent from integrated APS-MF processes are currently unknown. The overall objective of this aim is to characterize the performance, and specifically the recovery rate, of a secondary RO desalination process that follows an integrated APS-MF system treating high-salinity primary RO concentrate. Our approach will be to use concentrate from a primary RO system that has been treated using an integrated APS-MF process as feed water for a secondary bench-scale RO system. Flat-sheet RO test cells will be operated in a permeate recycle, or permeate withdraw, configuration to quantify permeate flux and solute rejection as a function of time and feed water concentration factor (CF).

Task 2.1 - Performance analysis of a secondary RO system treating integrated APS-MF effluent. An RO membrane will be identified and selected based on the composition/chemistry of the APS-MF effluent. A suitable spiral wound RO element from which flat-sheet samples will be collected and used in the bench-scale study. The contact angle with water will be measured for the virgin membrane sample using the captive bubble technique. SEM-EDS analysis of virgin membrane samples will also be done as a baseline analysis. The permeability of the virgin membrane will be established by measuring the pure water flux as a function of operating pressure. Baseline tests using untreated RO concentrate from both sources will be done for later comparison to the performance of the RO system treating water that had been subjected to APS-MF treatment. Effluent from the APS-MF bench-scale system will be collected and used as feed water for a bench-scale flat-sheet RO test system.

Task 2.2 - RO membrane autopsy and foulant identification. Membrane samples removed from the bench-scale test unit during Task 2.2 will be subjected to contact angle and SEM-EDS analyses in order to identify the principle membrane foulants. SEM-EDS will be used to identify and characterize any mineral scale or other inorganic fouling that has occurred on the membrane. The distribution of inorganic elements across the membrane surface will be mapped and the structure of the foulant layers imaged in detail. Contact angle with water analysis will be used to assess any changes in membrane hydrophobicity following their operation, which would be indicative of organic fouling.

Aim #3 – MF membrane material selection and testing of the integrated APS assembly treating high-salinity RO concentrate. The range of membrane materials that can be used for the microfiltration in the integrated APS-MF module is very broad. The detailed information of the RO membrane foulants obtained in Task 2.2 will guide us on selecting MF membrane materials that have optimal rejection characteristics for the identified foulants while also demonstrating a high level of fouling resistance. Due to their superior chemical and thermal stability, ceramic and composite membranes will be primarily tested in the MF module.

Task 3.1 - Characterization of mineral scale formed on ceramic membrane elements. Task 3.1 will be done in parallel with Task 1.2. At the completion of each trial the MF membranes will be removed from the test system and analyzed to characterize the type and structure of the mineral scale that has formed. The elemental composition of the mineral scale will be determined using SEM-EDS, while SEM imaging will provide information on the mineral scale structure/morphology. FTIR measurements will be particularly useful for determining what, if any, residual chemical additives are present in the foulant structure. Samples will be removed before and after backwashing at the conclusion of each test to identify the mechanically reversible and irreversible fouling fractions.

Task 3.2 – Identify ceramic membrane candidates that have strong resistance to the membrane fouling characterized in Task 3.1. Based on the fundamental understanding of the MF membrane foulants from different RO concentrate sources (i.e., different produced water chemistries/compositions), various ceramic and composite membrane materials will be tested and evaluated. As explained in more detail in Aim #4, the testing data and evaluation procedure of the membrane candidates will help build a database, which stakeholders can use for their specific water treatment requirements. Of specific importance for the proposed application are the following membrane characteristics: membrane permeability and the ability to recover said permeability following cleaning cycles, specific energy consumption (kWh/1,000 gal of treated water), propensity to lose specific water flux (gal/ft^2 day psig) during operation, particulate/colloidal rejection rate, chemical tolerance, and mechanical robustness.

Aim #4 - Build a performance database for select desalination processes treating produced waters using experimental data from Aim #2. The performance data collected for the APS-MF and primary/secondary RO processes treating the various energy produced waters will be used to construct a database for users to identify promising desalination approaches for managing energy related produced waters. The database (excel based) will allow users to input site specific parameters (water quality/quantity, treatment goals) from which the database will generate a series of treatment scenarios. The database will generate projected finished water characteristics in addition to similar information regarding any residual wastewater streams.

Summary of progress to date: The project is currently in Month 14 of the proposed 24 month long effort (**Table 1**). Efforts to date have centered on modification of the bench-scale APS-MF test unit (Task 1.1) and optimization of the reaction conditions for the precipitation softening process (Task 1.2). While Task 1.1 is complete, Task 1.2 is ongoing (90% complete) in parallel with evaluation of the integrated APS-MF process (Task 1.3). During this time the graduate student on this project (Jennifer Hegarty) has conducted a literature review of produced water treatment technologies and associated produced water qualities in Wyoming. The objective of these efforts was to establish a reasonable range of water chemistries and compositions for use in the APS experiments (Task 1.2) and to catalog the types of produced treatment technologies currently in use in Wyoming as a function of source water quality. From Table 1 work still remains for Task 1.3 and for Aims 2 through 4.

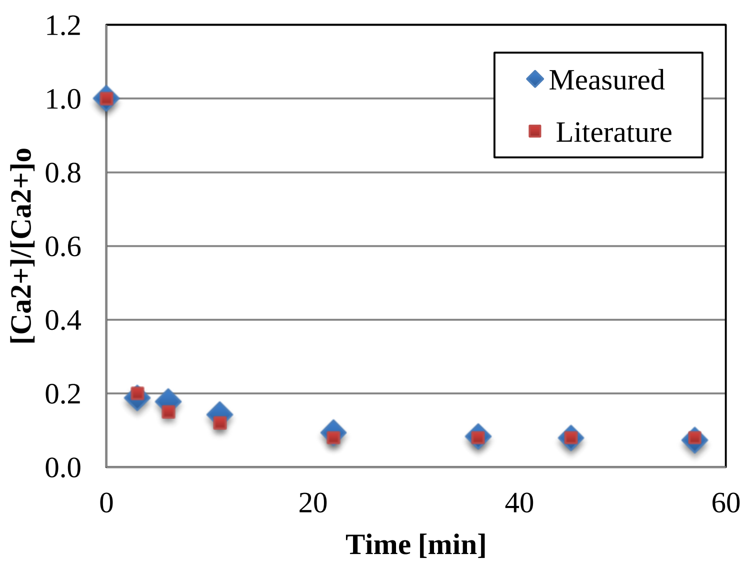


Figure 1. Calcium concentration as a function of time in the decant water following precipitation softening through adjustment of solution pH to 10.5.

The USGS Produced Water Database was surveyed in order to determine minimum, average and maximum values for select water quality parameters for produced water generated in Wyoming. Results from this analysis were used to develop three different test waters for use in the APS and RO experiments (**Table 2**). The three types of test solutions were made to represent a high, medium, or low dissolved solids concentration. The high and low TDS concentrations are based on the first and third quartile for each component and the medium TDS concentration is based on the mean for each component. The quartiles were used instead of the min and max in order to choose a range more representative of the majority of wells in Wyoming. The solution chemistries for the primary RO concentrate streams from the different test waters are being used in the APS and the future APS-MF tests.

Table 2. Total dissolved solids (TDS) concentrations for the starting and concentrated reverse osmosis (RO) process streams. The recovery ratio and concentration factors for the different test solutions are based on known constraints for conventional RO systems.

Sample Designation	Feed TDS, mg/L	Recovery, %	Concentration Factor	Conc. TDS, mg/L
High	17,878	55	2.22	39,730
Medium	6,804	70	3.33	22,679
Low	3,287	75	4.00	13,146

Representative results from preliminary experiments whose purpose was to establish the validity of our experimental approach for the precipitation experiments are given in **Fig. 1**. These tests were done using the same solution chemistry from as reported by another research group doing similar softening tests as those proposed as part of this research project. These results also served as a benchmark comparison for the subsequent APS experiments. From **Fig. 1**, the calcium concentration is reduced to approximately 10% of its initial value following approximately 20 mins after the pH was increased to 10.5. The calcium is precipitating from solution as $CaCO_3$ under these conditions. As evidenced in **Fig. 1** our results are in good agreement with those from the literature.

Additional experiments were done using APS in which calcium concentration in the decant water was measured over time. The purpose of these tests is to establish the optimum $CaCO_3$ seed concentration and to draw performance comparisons with the conventional softening process. Results from the APS experiments are given in **Fig. 2**. From **Fig. 2**, the calcium concentration decreases more rapidly than was observed for those tests in which the solution pH was only adjusted to 10.5 (**Fig. 1**) with no seeds added. A seed concentration of 5 g/L (pH 10.5) provided similar reaction kinetics as higher seed concentrations and was identified as an optimal value for further testing Additionally, the calcium concentration was reduced to 10% of its original value in approximately 5 mins, which is one quarter of the time required with the conventional softening approach.

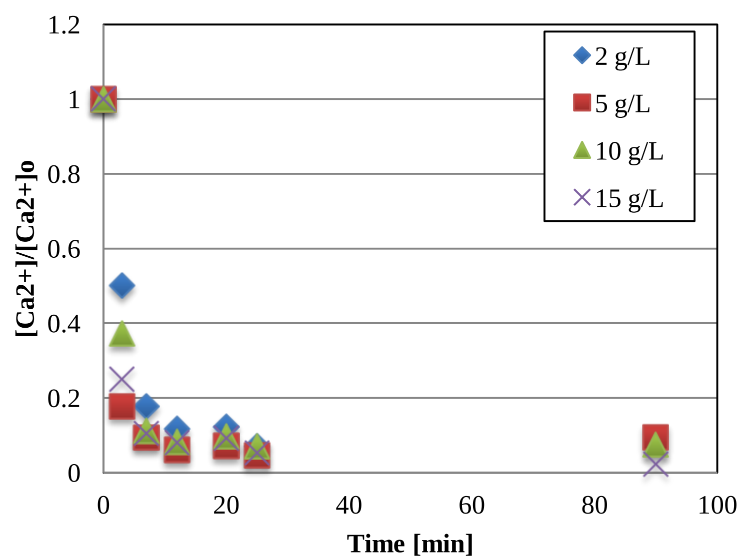


Figure 2. Calcium concentration as a function of time in the decant water following precipitation softening through adjustment of solution pH to 10.5 and the addition of variable concentrations of calcium carbonate ($CaCO_3$) seeds.

Student Support and Involvement: We have successfully recruited one Master of Science graduate student (Jennifer Hegarty) who is majoring in Chemical Engineering and two undergraduate students (Kyle Meyers, Freshman in Chemical Engineering; Weikang Li, Senior in Petroleum Engineering). Jennifer received her B.S. (GPA: 3.77) in May, 2012 from Colorado State University and has been working on the project since June 2012 under the guidance of

Profs. Brant and Li. Jennifer is at the 50% completion mark for her degree, with a schedule graduation date of May 2014. Kyle Meyers (GPA: 3.75) and Weikang Li (GPA: 3.86) both joined the team at the beginning of Fall 2012. All students have been trained on the water chemistry and jar testing procedures for produced water analysis. We plan to keep all three students on the project for the coming year, with Jennifer's research focus on Tasks 2.2 and 3.1, Kyle and Weikang's on Tasks 1.2, 1.3 and 2.1. Weikang will be graduating this month, May 2013. Since Kyle just started in Fall 2012, he plans to graduate in Spring 2016.

Jennifer will be presenting results from her research at the upcoming North American Membrane Society (NAMS) conference that will be held in Boise, ID from June 8 to 12, 2013. Her presentation will be in the form of a poster and will cover her results on the characteristics of CBM produced waters, accelerated precipitation softening (optimum seed concentration for calcium removal), and RO membrane fouling in the presence/absence of the accelerated softening pretreatment. Jennifer has also begun preparation of a manuscript for later submission to the Journal of Membrane Science on her research, specifically the reduction in RO membrane fouling following pretreatment with accelerated precipitation softening.

Multi-frequency Radar and Precipitation Probe Analysis of the Impact of Glaciogenic Cloud Seeding on Snow

Basic Information

Title:	Multi-frequency Radar and Precipitation Probe Analysis of the Impact of Glaciogenic Cloud Seeding on Snow
Project Number:	2012WY81B
Start Date:	3/1/2012
End Date:	2/28/2015
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.

Multi-frequency radar and precipitation probe analysis of the impact of glaciogenic cloud seeding on snow

Year 1 Report
for a three-year (Mar 2012 – Feb 2015)
UW Office of Water Programs
U. S. Geological Survey and the Wyoming Water Development Commission grant
Dr. Bart Geerts, PI
5/1/2013

1. Abstract

This proposal (referred to as Cloud Seeding III) called for the analysis of radar, aircraft, and ground-based datasets collected as part of the ASCII (AgI Seeding Cloud Impact Investigation) campaign over the Medicine Bow mountains (aka the Snowy Range) and the Sierra Madre in Wyoming during the time of glaciogenic cloud seeding conducted as part of the multi-year Wyoming Weather Modification Pilot Project (WWMPP). This pilot project, administered by WWDC and contracted to the National Center for Atmospheric research (NCAR) and Weather Modification Inc (WMI), involves seeding from a series of silver iodide (AgI) generators located in the Snowy Range. Two previous UW Office of Water Programs grants (referred to as Cloud Seeding I and Cloud Seeding II) supported seven research flights over the Snowy Range. Analysis of these data led to a remarkable paper in the *J. Atmos. Sci.* (Geerts et al. 2010), and apparently national recognition in the form of a National Institutes of Water Resources (NIWR) "IMPACT" Award.

2. Objectives and methodology

The key objective is to examine the impact of cloud seeding on radar reflectivity between the AgI generators and the slopes of the target mountain. To do this, we use two radars: the Wyoming Cloud Radar aboard the UW King Air Research Aircraft (UWKA), and two profiling micro-rain radars (MRRs). A composite of reflectivity for seed and no-seed conditions for all downstream flight legs along the wind has been built, using both radars, both upstream of the AgI seed generators ("control") and downwind of the generators ("target"). The next step will be to ascertain that the observed differences in composites are both statistically significant and not attributable to differences in vertical air velocity.

3. Summary of the field work and principal findings

Our ongoing study provides experimental evidence from vertically-pointing airborne radar data, collected on seven flights, that ground-based AgI seeding can significantly increase radar reflectivity within the PBL in shallow orographic snow storms. As reported in Geerts et al. (2010), theory and a comparison between flight-level snow rate and near-flight-level radar reflectivity indicate a ~25% increase in surface snow rate during seeding, notwithstanding slightly stronger updrafts found on average during no-seeding periods. The partitioning of the dataset based on atmospheric stability and proximity to the generators yields physically meaningful patterns and strengthens the evidence. Firstly, the AgI seeding signature is stronger and occurs over a greater depth on the less stable days than on the three more stable days. Secondly, it is stronger for the two legs close to the generators than for the two distant legs (Geerts et al. 2010). This work was supported by a previous UW Office of Water Programs grant, referred to as Cloud Seeding II.

These results have limitations, mainly because just seven storms were sampled and these storms represent a rather narrow region in the spectrum of precipitation systems in terms of stability, wind speed, storm depth and cloud base temperature. While the analysis yields strong evidence for an increase in reflectivity near the surface, the quoted change in snowfall rate (25%) is unlikely to be broadly representative. It appears that PBL turbulence over elevated terrain is important in precipitation growth, both in natural and in seeded conditions, and thus the same results may not be obtained if the precipitation growth primarily occurs in the free troposphere. This work needs to be followed up with a longer field campaign under similar as well as more diverse weather conditions. Such campaign should include ground-based instruments, such as vertically pointing or scanning radars and particle sizing and imaging probes.

Following the review of the *J. Atmos Sci.* paper (Geerts et al. 2010), we wrote a paper dealing with the importance of PBL turbulence on orographic precipitation (Geerts et al. 2011), and another paper further exploring seeded cloud properties with flight-level data (Miao et al. 2012).

The seven flights and follow-up publications, esp. Geerts et al. (2010), have served as a pilot effort for a much larger research project, known as ASCII, funded by the National Science Foundation. This grant is a collaboration between Dr. Geerts' team and several NCAR scientists (Rasmussen, Breed, Xue). The USGS/WWDC-funded field work and data analysis (esp. Geerts et al. 2010, in *J. Atmos. Sci.*) were instrumental in the success of this $569,097 grant entitled "The cloud microphysical effects of ground-based glaciogenic seeding of orographic clouds: new observational and modeling tools to study an old problem" (Aug 2011 – Jul 2014; reference: AGS-1058426). The emphasis of ASCII is on the cloud microphysical effects of glaciogenic seeding in cold orographic clouds, but ASCII examines glaciogenic seeding in the context of natural snow growth processes. The ASCII research grant is the first time in nearly three decades that NSF (or any federal agency) has supported weather modification research.

The first ASCII field phase was conducted in the Sierra Madre between 4 Jan and 4 March 2012, and it deployed the UWKA, a MGAUS sounding system, an automated weather station, and a Doppler on Wheels (DOW) radar, all funded directly by NSF at an additional cost of about $500K. The DOW was positioned on Battle Pass, and often encountered hostile conditions during ASCII. Hidden in the trees about 600 m downwind of the pass, a scaffold was erected to make measurements with an array of instruments characterizing snow at the surface and overhead (Fig. 4b). ASCII-phase 1 involved 17 intensive observation periods, and is regarded a success, notwithstanding several technical challenges and a relatively warm, dry winter.

The second ASCII field phase was conducted in Jan-Feb 2013, and again focused on the Medicine Bow Range. The NSF funding supported 10 UWKA successful research flights. We also deployed a series of snow probes at GLEES (MRR, disdrometer). Both ASCII campaigns are conducted in the context of the WWMPP, which conducts the ground-based glaciogenic seeding. WWMPP alos released soundings for us from Saratoga, funded by this grant.

4. Significance

Our findings are believed to be very significant. Geerts was an invited keynote speaker at the Annual Weather Modification Association meeting in Santa Fe NM in April 2010. At that meeting, Arlen Huggins, a veteran researcher in weather modification, mentioned our work as one of the most significant achievements in glaciogenic seeding efficacy research in the past decade.

Dr. Geerts has been informed that this project was selected along with the Wyoming Institute, for the 2012 National Institutes of Water Resources (NIWR) "IMPACT" Award. At the time of writing, this NIWR Impact Award was not officially presented, but if confirmed, this award confirms the significance of the present work in terms of the greatest potential impact on water supply enhancement. Three equally-weighted criteria have been used to select the winner of this award, i.e. magnitude, timing, and confidence. The award is national, following a regional selection process, and then a selection amongst the 8 NIWR regions nationwide.

5. Peer-reviewed publications

The following peer-reviewed papers directly resulted from the research in this grant and the related :

- Geerts, B. and co-authors, 2013: The AgI Seeding Cloud Impact Investigation (ASCII) campaign 2012: overview and preliminary results. J. Wea. Mod., accepted.
- Yang, Y., B. Geerts, R. Rasmussen, and S. Haimov, 2013: Snow transport patterns in orographic storms as estimated from airborne vertical-plane dual-Doppler radar data. Mon. Wea. Rev., in review.
- Chu, X., B. Geerts and L. Xue, 2013: Cloud-resolving Large Eddy Simulations of the impact of AgI nuclei dispersed from the ground on orographic clouds and precipitation. Part I: observation and model validation. *J. Appl. Meteor. Climat.*, in review.
- Pokharel, B., and co-authors: Case study of the impact of glaciogenic cloud seeding on clouds and snowfall in the ASCII campaign. J. Appl. Meteor. Climat.

The research and publication of the following papers was supported by two previous, related grants from the UW Office of Water programs:

- Geerts, B. and Q. Miao, 2010: Vertically-pointing airborne Doppler radar observations of Kelvin–Helmholtz billows. *Mon. Wea. Rev.*, **138**, 982–986.
- Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010: An airborne profiling radar study of the impact of glaciogenic cloud seeding on snowfall from winter orographic clouds. *J. Atmos. Sci.*, **67**, 3286–3302.
- Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010: The impact of glaciogenic seeding on orographic cloud processes: preliminary results from the Wyoming Weather Modification Pilot Project. *J. Weather Mod.*, **42**, 105-107.
- Geerts, B., Q. Miao, and Y. Yang, 2011: Boundary-layer turbulence and orographic precipitation growth in cold clouds: evidence from profiling airborne radar data. *J. Atmos. Sci.*, **68**, 2344-2365.
- Miao, Q., and B. Geerts, 2013: The impact of ground-based glaciogenic cloud seeding on orographic precipitation: new insights from an airborne down-looking radar. *Advances in Atmospheric Science*, **29**, doi: 10.1007/s00376-012-2128-2.

6. Presentations supported by the Grant

Dr. Geerts and his research group gave oral presentations at a series of meetings in Year 1. These were partly funded by the NSF ASCII grant, partly by the UW Office of Water programs grant. Here is the chronological list:

- Qun Miao presented preliminary ASCII findings at the NCAR Orographic Precipitation and Climate Change workshop on 13-15 March 2012 (http://ral.ucar.edu/hap/events/orographic-precip/).
- Bart Geerts gave an ASCII_12 field campaign overview at the Annual Meeting of the Weather Modification Association, Las Vegas, 25-27 April 2012.
- Yang Yang presented an overview poster at the 2012 National Institutes of Water Resources (NIWR) meeting in Santa Fe in July 2012.
- Binod Pokharel presented an ASCII research update at the WWMPP Technical Advisory Team meeting in Saratoga in August 2012.
- A special session was devoted to ASCII at the American Meteorological Society 15th Conference on Mountain Meteorology (Fig. 1)(http://ams.confex.com/ams/archives.cgi). Note that three oral presentations were given by graduate students funded by this grant and/or by the NSF ASCII grant, namely Binod Pokharel, Xia Chu, and Yang Yang.

3:45 PM-5:15 PM: Thursday, 23 August 2012

16 **Results from recent field campaigns: III**
Location: *Priest Creek C (The Steamboat Grand)*
Sponsor: ***15th Conference on Mountain Meteorology***

Papers:

3:45 PM 16.1 An overview of the ASCII 2012 (AgI Cloud Seeding Impact Investigation) campaign
***Bart Geerts**, University of Wyoming, Laramie, WY; and K. Friedrich, T. Deshler, D. A. R. Kristovich, J. Wurman, L. D. Oolman, S. J. Haimov, Q. Miao, D. W. Breed, R. Rasmussen, and B. A. Boe*

4:00 PM 16.2 Effects of atmospheric conditions and cloud seeding on orographic snowfall characteristics during the Silver Iodide (AgI) Seeding of Clouds Impact Investigation (ASCII) experiment
***Katja Friedrich**, University of Colorado at Boulder, Boulder, CO; and E. A. Kalina, B. Geerts, K. A. Kosiba, and J. M. Wurman*

4:15 PM 16.3 Using airborne vertical-plane dual-Doppler radar to analyze hydrometeor streamline patterns in orographic snow storms
***Yang Yang**, University of Wyoming, Laramie, WY; and B. Geerts*

4:30 PM 16.4 Airborne Cloud Radar and Lidar Observations of Blowing Snow during the ASCII Project: a Possible Natural Cloud Seeding Mechanism
***David A. R. Kristovich**, ISWS, Champaign, IL; and B. Geerts, Q. Miao, L. Stoecker, and J. M. Ritzman*

4:45 PM 16.5 Cold-season precipitation processes in shallow orographic clouds over a continental mountain range: impact of controlled ice nucleus injection
***Binod Pokharel**, University of Wyoming, Laramie, WY; and B. Geerts, Q. Miao, and K. Friedrich*

5:00 PM 16.6 Comparison of model and airborne measurement of AgI plumes from ground-based generators
*Lulin Xue, NCAR, Boulder, CO; and **X. Chu** and B. Geerts*

Fig. 1: List of oral presentations in the ASCII session at the 15th Conference on Mountain Meteorology in Steamboat Springs CO.

- Bart Geerts gave an overview of ASCII_12 and discussed the experimental design for ASCII_13 at the WWMPP Ground School on 14 November 2012 in Laramie.

- Xia Chu presented a poster "Validation of WRF and WRF LES Simulations of the Dispersal of Ground-generated AgI Nuclei" at the 19th AMS Conference on Planned and Inadvertent Weather Modification, Austin, TX, 7-10 January 2013.
- Bart Geerts gave a talk "The ASCII 2012 campaign: overview and early results" at the 19th AMS Conference on Planned and Inadvertent Weather Modification, Austin, TX, 7-10 January 2013.
- Bart Geerts gave a research updates at the WWMPP Technical Advisory Team (TAT) meeting in Cheyenne on 23 January 2013.
- Binod Pokharel gave a talk "Impact of Glaciogenic Seeding on Orographic Clouds in Southeast Wyoming" at the 2013 Annual Meeting of the Weather Modification Association and the North American Interstate Weather Modification Council, San Antonio, TX, 9-11 April 2013.

Media coverage

In Year 1 Geerts' research was covered in the Laramie Boomerang, the Casper Star Tribune, the Wyoming Business Chronicle, and the University of Wyoming News (http://www.uwyo.edu/uw/news/). Geerts was interviewed also on Wyoming Public Radio (Open Spaces), twice, in March 2012 and March 2013. A film crew from Belgium came by in December 2012, and the section on our weather mod research was aired on Canvas, channel VRT (www.canvas.be), in March 2013. We were also part of the Weather Channel's "Hacking the Planet" series in early April 2013. The episode in which we are featured can be viewed at http://youtu.be/rVl_pjEOi9w (this is one of several episodes in the Hacking the Planet series). Note that this is an unlisted and unlinked video, i.e. it is *not* public – the only way to access it is through this link. The reason, of course, is copyright issues.

Upcoming presentations

There is much interest in this work. At this time Bart Geerts has been invited to give 6 talks on weather modification research in Wyoming.

- 6 May 2013: invited talk at SUNY Albany, New York (attendance: ~50)
- 21 May 2013 (tentative date): UW ATSC Departmental seminar – may be later in Spring
- 4 June 2013: invited talk at NCAR, Boulder CO (attendance unknown)
- 13 June 2013: invited talk at the 2013 National Institutes of Water Resources (NIWR) meeting in South Tahoe, CA
- 7 November 2013: invited talk at http://www.cocorahs.org/Content.aspx?page=wxtalk (attendance: ~300)
- Date TBD, AY 2013-14: Faculty Senate Speaker, with presentations in Laramie and Casper (attendance ~50-100)

7. Dissertations/theses

No graduate students partly or entirely funded by this grant have graduated yet, but we are close:

- Ms. Yang Yang (MSc) has been supported by the current and a previous UW Office of Water programs grant; she will defend her thesis on 23 May 2013.
- Ms. Xia Chu (MSc) is supported by the NSF "ASCII" grant. She will defend her thesis on 6 June 2013.

- Mr. Binod Pokharel (PhD) is supported by the NSF "ASCII" grant. He took his Qualifying Exam in Jan 2013, and plans to complete his PhD by May 2015.
- Ms. Xiaoqin Jing started in summer 2012, and is funded by this grant from the UW Office of Water Programs. Her work focuses on DOW observations during ASCII_12. She hopes to defend her thesis in April 2014.
- Dr. Qun Miao, has also been partly supported by this grant. He was essential in the data analysis leading to the *J. Atmos. Sci.* paper (Geerts et al. 2010). He left the group in Jan 2010 to assume a faculty position in Ningbo University in China. His research on this grant was essential to his success assuming a faculty position. Dr. Miao is now on his way to become a leading scientist on weather modification in China. He was a visiting scientist in Jan-Mar 2012 in support of the NSF-supported ASCII field campaign, and will be back in Laramie in June-August 2013, partly funded by this grant. He continuous to work with us from China, as is evident in the list of publications (Section 5).

So while we have been slow graduating professional students supported by this grant, the prospect for graduate student participation and graduation is good.

Decadal Scale Estimates of Forest Water Yield After Bark Beetle Epidemics in Southern Wyoming

Basic Information

Title:	Decadal Scale Estimates of Forest Water Yield After Bark Beetle Epidemics in Southern Wyoming
Project Number:	2012WY82B
Start Date:	3/1/2012
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Surface Water, Water Quantity
Descriptors:	None
Principal Investigators:	Brent E. Ewers, Urszula Norton, Elise Pendall, Ramesh Sivanpillai

Publication

1. Ewers, BE., 2013. Understanding Stomatal Conductance Responses to Long-Term Environmental Changes: A Bayesian Framework that Combines Patterns and Processes. Tree Physiology. 33:119-122.

Annual Report to Wyoming Water Development Commission for the Project:
(Year 1 of 3)

Decadal Scale Estimates of Forest Water Yield After Bark Beetle Epidemics in Southern Wyoming

PIs Brent E Ewers, Elise Pendall, Urszula Norton, Ramesh Sivanpillai

Abstract

The forests in Wyoming are undergoing profound changes in their hydrologic partitioning of precipitation due to an ongoing epidemic of bark beetles. These forests are key components of major river watersheds and could magnify any impacts on downstream users of water. Recent research at the forest stand scale has shown that while the trees die over the first several years of an outbreak, evapotranspiration declines, soil moisture increases, soil nitrogen increases and snowpack increases and melts faster. These changes in forest hydrology strongly suggest that streamflow should increase. However, ongoing streamflow measurements show no increase. This conundrum between stand processes and watershed processes will be directly addressed by this project. Further, the length of time in which hydrological changes at the stand scale will persist is unknown because of lack of knowledge about how these stands will experience succession after bark beetle epidemics. To address these issues we will 1) quantify tree, seedling, sapling and other understory species composition in forest stands to characterize succession and 2) utilize multiple remote sensing tools to improve scaling between well-instrumented forest stands and watersheds. In addition to these two objectives we will synthesize a large amount of prior and ongoing data collection into an explicit data informatics framework. This framework will serve two purposes 1) novel data syntheses can occur in near real-time, enabling model-data fusion to improve predictions of streamflow and 2) rapidly serve data and model results for public and land manager use. This project builds on previous work that quantified and predicted water yield from bark beetle infested stands in the first five years of an outbreak and extends the time frame of predictions out to multi-decades. This work will enable both State and Federal water managers to make crucial predictions of streamflow from infested mountain ranges on time-frames that are relevant to land management decisions.

Objectives

1) Establish a web service for public and water management use that will provide direct access to data and model predictions

2) Predict the impact of forest succession from lodgepole and spruce-fir forests after bark beetle mortality on forest water yield and nitrogen loss from stands

3) Use ongoing stand and catchment scale measurements with remote sensing tools and mechanistic models to estimate bark beetle impacts on water yield at the mountain range scale

Methodology

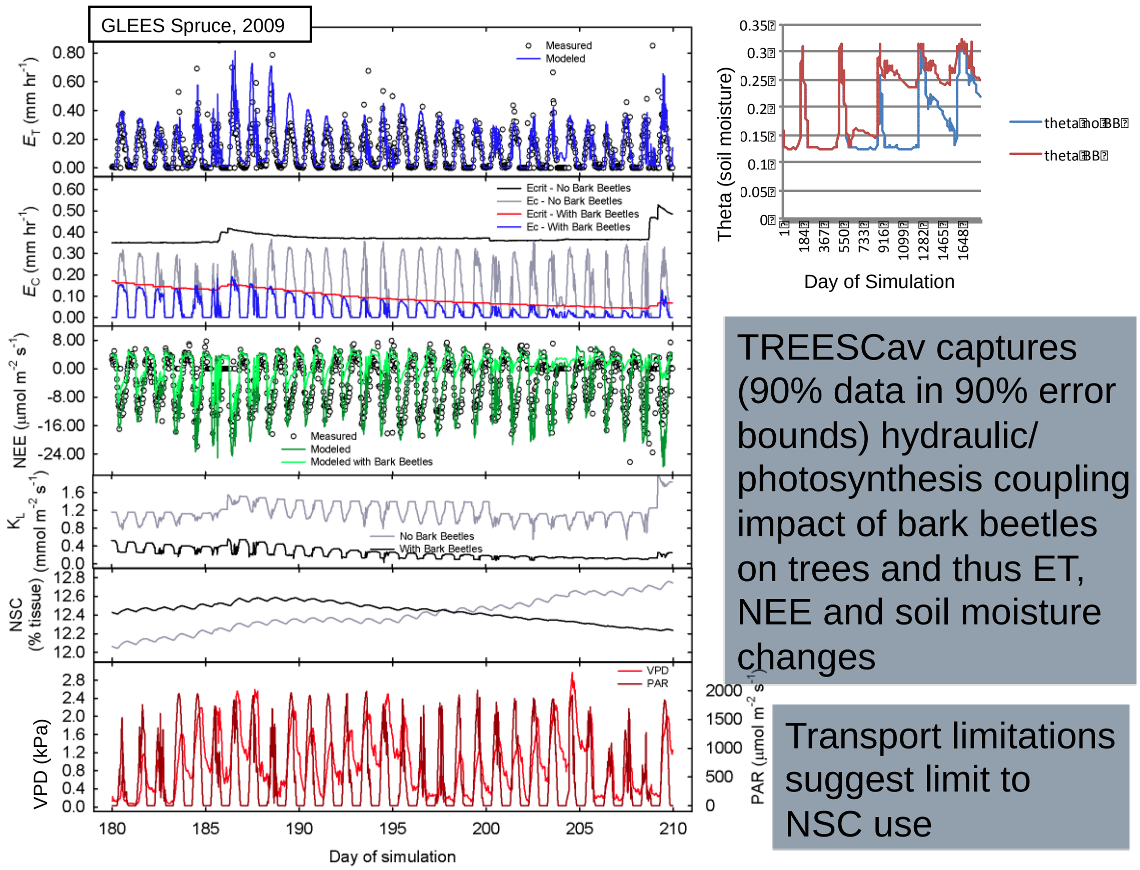
We have adopted the Terrestrial Regional Ecosystem Exchange Simulator-Cavitation (TREESCav) model for all the simulations for this project. The TREESCav model has the appropriate tree hydraulic and photosynthesis mechanisms to simulate bark beetle attacks. The model also has a full water budget including snow melt, sublimation, interception, soil moisture, drainage, tree transpiration and evaporation. The model includes Bayesian model-data fusion so that parameterization rigorously use data. The hydrology community has begun to recognize that simulation of water budgets from vegetated watersheds must include carbon and nitrogen cycles for mechanistic and thus predictive understanding. Such an approach is necessary when projecting forest changes after a disturbance because carbon and nitrogen cycling co-limit forest production along with water. Thus, we have implemented new algorithms of soil carbon and nitrogen processing that can be compared to soil measurements of both processes from a recently finished NSF grant. This project will supply some ongoing measurements of soil carbon and nitrogen pools and fluxes to constrain TREESCav as succession continues.

Our remote sensing approach utilizes Landsat data as an appropriate compromise between spatial and temporal resolution based on preliminary analyses comparing the data to MODIS and Aerocam.

The testing of both the TREESCav model and remote sensing data sets requires multiple data sets interacting at various temporal and spatial scales. To facilitate these comparisons and prepare the data for public sharing, we have adopted Structured Query Language (SQL) approaches. We have implemented SQL databases for all of the vegetation data from the Chimney Park and GLEES research sites which was funded by a grant from this agency that ended in Feb. 2013 (see final report for details). The database for the stand level fluxes and water budgets are still under development as part of this project.

Principal Findings (Cited Papers are in Publications Section)

All three of our objectives require successful testing of the TREESCav models against the bark beetle mortality datasets from the Chimney Park and GLEES research sites. The Bayesian approach to model parameterization via fusion with data is superior for processes that have uncertainty in both the processes and data (Ewers et al 2013). With this conceptual framework in place, we have tested the model against tree transpiration, evapotranspiration, tree hydraulic and tree nonstructural carbohydrates (Figure 1). The model has been very successful in simultaneously simulating all of these processes. Our Bayesian model-data fusion analyses now show that the model is simulating the data as best as possible given the uncertainties in the data itself. The effort required to obtain this results has been significant in both coding and processing time. We have also tested the model against soil fluxes of carbon dioxide. We were only able to simulate these fluxes successfully when appropriate root and microbial response to soil moisture and nitrogen were included showing the link to stand water budgets and water quality. The net outcome is that TREESCav provides realistic simulations of soil moisture (Figure 1 subset). We are exploring use of the supercomputing resources from UW and NCAR to increase the rate of model analyses. We will finish off this phase of model analysis at the stand scale over the summer of 2013 and submit two manuscripts.



Once the stand scale analyses are complete, we will run the model at the watershed and mountain range scale using Landsat data sets tested against ground data. The Landsat analyses are funded by the Wyoming Weather Modification Project. Ongoing analyses of this data have shown that dead trees are well correlated to several individual spectral bands and indices. However, no spectral analyses have been able to distinguish between spruce/fir and lodgepole pine dead trees so we are adding ancillary data on slope, aspect and elevation to produce final maps. The stand-scale version of TREESCav will then be run at the watershed and landscape/mountain range scale using these final maps. We aim to have preliminary results for these larger scale analyses in time for the AGU meetings in Dec. 2013.

Simulating the impact of tree mortality at decadal scales will require continued refinement of the soil carbon and nitrogen processes in TREESCav. We know have data from 3-4 years of recovery in some stands which shows a dramatic increase in understory vegetation including tree saplings and seedlings as well as increased nitrogen in soils. Our preliminary analyses show that TREESCav misses these vegetation and thus hydrology dynamics unless soil nitrogen processes are appropriately captured. We aim to be running these analyses with presentable results by Summer 2014.

Significance
Many studies over the past 5 years have documented increased mortality of forests globally. However, none of these studies have truly mechanistic connections between tree mortality and larger scale consequences such as water yield and quality. Our study is making these connections by rigorously testing a simulation model with stand data (Figure 1) from two different forests in Wyoming experiencing mortality from bark beetles. By starting with the stand-scale of data and incorporating carbon and nitrogen cycling, we will have much more confidence when we infer changes at larger spatial scales in watersheds and landscapes/mountain ranges and longer temporal scales as the forests recover from the disturbance.

While there are still some UW IT issues to work out (our group is interacting with IT on a weekly basis now), our serving of data from this project will enable policy implications to occur faster. We are using leveraged funds from the WyCEHG (see leveraged funding below) project to establish radio-link high speed internet access which will then be funneled to the web server for near real time flux data from the GLEES and Chimney Park sites.

Students/Post-Docs Supported
Bujidma Borkhuu-ongoing PhD student, main responsibilities are soil measurements and assistance with atmospheric measurements. Receives partial funding from this project.

Andrew King-ongoing MS student, main responsibilities are remote sensing image analysis and comparison to vegetation databases established through this project. Receives partial funding from this project.

Nick Brown-ongoing MS student, main responsibilies are soil measurements of nitrogen and carbon cycles. Receives partial funding from this project.

John Frank- ongoing PhD student, main responsibilities are all of the flux measurements from the spruce and fir bark beetle site (note: John Frank is a full time employee of the USFS RM Exp St in Ft. Collins, and does not receive any salary support from this project). Support from this project is used for field visits and site maintenance through a USFS subcontract.

David Reed-ongoing PhD Student, main responsibilities are the atmospheric and streamflow measurements. Receives partial funding from this project.

Scott Peckham-ongoing post-doctoral scientist, main responsibilities are coding modifications to the TREES model and model-data fusion analyses as well as supervision of the Chimney Park lodgeople pine site. Receives full support from this project.

Publications (*Students and Post-Docs are italicized*)

Ewers, BE. 2013. Understanding stomatal conductance responses to long-term environmental changes: A Bayesian framework that combines patterns and processes. Tree Physiology. 33:119-122

Presentations (*Students and Post-Docs are bolded*)

(Invited) Ewers BE. Hydraulic Limitations Help Explain the Behavior of Plants: from clocks to mortality to ghosts. Department of Biology, U. of New Mexico, February, 2013

(Invited) Ewers BE. Hydraulic Limitations Help Explain the Behavior of Plants: from clocks to mortality to ghosts. Department of Biology, Los Alamos National Labs, February, 2013

(Invited) Ewers BE. Impact of Fire and Insect Disturbance on Water Cycling in Ecosystems. Land Managers of the Laramie District of the Medicine Bow National Forest. February 2013

(Invited) Ewers BE. Surprising effects of bark beetle-induced mortality on snowpacks and water yield. Wyoming Weather Modification Technical Advisory Team Meeting, Cheyenne, WY January, 2013.

(Invited) Ewers BE. Impact of bark beetle outbreaks on forest water yield. Wyoming Association of Conservation Districts. Casper, WY, December, 2012.

P.D. Brooks; A.A. Harpold; J.A. Biederman; M.E. Litvak; P.D.Broxton; D. Gochis; N.P. Molotch; P.A. Troch; B.E. Ewers. Insects, firests, and climate change: implications for snow cover, water resources and ecosystem recovery in Western North America. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012.

Ewers, BE, DS Mackay, C Guadagno, **SD Peckham**, E Pendall, B Borkhuu, **T Aston**, **JM Frank**, WJ Massman, **DE Reed**, Y Yarkhunova, C Weinig. Nonstructural carbon dynamics are best predicted by the combination of photosynthesis and plant hydraulics during both bark beetle induced mortality and herbaceous plant response to drought. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012.

King A, BE Ewers, R Sivanpillai, E Pendall. Testing remote sensing estimates of bark beetle induced mortality in lodgepole pine and Engelmann spruce with ground data. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012.

Peckham, SD, BE Ewers, DS Mackay**, JM Frank**, WJ Massman, MG Ryan, H Scott, E Pendall. Modeling net ecosystem exchange of carbon dioxide in a beetle-attacked subalpine forest using a data-constrained ecosystem model. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012.

Mackay, DS, BE Ewers, **DE Reed**, E Pendall, NG McDowell. Plant hydraulic controls over ecosystem responses to climate-enhanced disturbances. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012.

(Invited) Ewers BE. Impact of bark beetle outbreaks on forest water yield. Wyoming Water Development Commission. Cheyenne, WY, November, 2012.

(Invited) Ewers BE. Impact of bark beetle outbreaks on forest water yield. Joint meeting of the Wyoming Water Development Commission and the Select Water Subcommittee of the Wyoming Legislature. Casper, WY, November, 2012.

(Invited) Ewers BE. Impact of bark beetle outbreaks on forest water yield. Wyoming Water Association Annual Meeting. Lander, WY, October, 2012.

Reed, DE, BE Ewers, E Pendall, RD Kelly, U Norton, **FN Whitehouse**. Mountain pine beetle epidemic changes ecosystem flux controls of lodgepole pine. Ecological Society of America Annual Meeting, Portland, OR, August 2012.

Brooks, PD, HR Barnard, J Biederman, B Borkhuu, SL Edburd, BE Ewers, D Gochis, E Gutmann, AA Harpold, JA Hicke, DJP Moore, E Pendall, **D Reed**, A Somor, PA Troch. Multi-scale observation of hydrologic partitioning following insect-induced tree mortality: Implications for ecosystem water and biogeochemical cycles. Ecological Society of America Annual Meeting, Portland, OR, August 2012.

Frank, JM, WJ Massman, BE Ewers. Linking bark beetle caused hydraulic failure to declining ecosystem fluxes in a high elevation Rock Mountain (Wyoming, USA) forest. Ecological Society of America Annual Meeting, Portland, OR, August 2012.

Ewers BE, DS Mackay, E Pendall, J**M Frank, DE Reed,** WJ Massman, **TL Aston**, **JL Angstmann, K Nathani, B** Mitra. Use of plant hydraulic theory to predict plant controls over mass and energy fluxes in response to changes in soils, elevation and mortality. Ecological Society of America Annual Meeting, Portland, OR, August 2012.

Barnard, HR, A Byers, A Harpold, BE Ewers, D Gochis, P Brooks. Examining the response of lodgepole transpiration to snow melt and summer rainfall in subalpine Colorado, USA. Ecological Society of America Annual Meeting, Portland, OR, August 2012.

Brown, NR, U Norton, E Pendall, BE Ewers, **B Borkhuu**. High levels of soil and litter nitrogen contents after bark beetle-induced lodgepole pine mortality. Ecological Society of America Annual Meeting, Portland, OR, August 2012.

Ewers BE et al. Use of plant hydraulic theory to predict plant controls over mass and energy fluxes in response to changes in species, soils and mortality. American Society of Plant Biology Annual Meeting, Austin, TX, July, 2012.

(Invited) Ewers BE. Simulation modeling of bark beetle effects on stand water budgets. Wyoming Weather Modification Technical Advisory Team Meeting. Saratoga, WY July 2012.

Leveraged Support to this Project.

NSF ESPSCOR. Water in the West. $20 million total grant, $500,000 to Ewers. A major justification for this grant was the lack of correlation between increased water in stands and streams after bark beetle mortality. The TREES model funded by this project will now be tested against other, less biologically sophisticated hydrology models. This grant establishes the Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG).

NSF ETBC Hydrologic Science. ETBC: Collaborative Research: Quantifying the Effects of Large-Scale Vegetation Change on Coupled Water, Carbon, and Nutrient Cycles: Beetle Kill in Western Montane Forests. CoPI Elise Pendall. $219,261. This NSF funding provided partial funding for several of the data sets used to test TREES.

Ag Exp Station and McIntire Stennis. Quantifying the impact of a massive mountain pine beetle outbreak on carbon, water and nitrogen cycling and regeneration of southern Wyoming lodgepole pine forests. CoPIs Elise Pendall and Urszula Norton $60,000. This grant provided partial funding for several of the data sets used to test TREES.

Information Transfer Program Introduction

Information dissemination efforts included reports and presentations by the Director to State and Federal entities and the private sector. The Director reports annually to the Wyoming Water Development Commission and to the Select Water Committee (of the Wyoming Legislature). Presentations were given throughout the state concerning the research program and project results. The Director serves as the University of Wyoming Advisor to the Wyoming Water Development Commission and attends their monthly meetings. This provides a means for coordinating between University researchers and Agency personnel. The Director also serves as an advisor to the Wyoming Water Association (www.wyomingwater.org) and regularly attends meetings of the Wyoming State Water Forum.

Publications and other information dissemination efforts were reported by the PIs of the projects funded under this program. 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 committee meeting. Presentations discussing interim results are made by PIs of continuing projects at the fall/winter committee meeting. PIs are encouraged to publish in peer reviewed journals as well as participate in state-wide water related meetings and conferences. Publications are listed in the individual research reports.

Director FY12 information dissemination activities are listed in the following paragraph:

DIRECTOR SERVICE AND PRESENTATIONS: (1) Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., January 3, 2012; (2) Wyoming Water Development Commission Meeting, Presentation on recommendation for FY2012 WRP Annual funding and OWP Biennium funding. Cheyenne, WY., January 11, 2012; (3) Wyoming Legislative Select Water Committee, Presentation on WRP projects and recommendation for FY2012 WRP Annual funding and OWP Biennium funding. State Capital, Cheyenne, WY., January 12, 2012; (4) Wyoming Water Association Board Meeting, Legislative Review, (Advisor), Cheyenne, WY., January 12, 2012; (5) Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., February 7, 2012; (6) The National Institutes for Water Resources annual meetings. Washington, DC., February 13-15, 2012; (7) Wyoming State Legislature – House Agriculture Committee. Wyoming Water Development Commission (Advisor), Omnibus Water Plan. State Capital Bld., Cheyenne, WY., January 16, 2012; (8) AGU Chapman Conference –Remote Sensing of the Terrestrial Water Cycle. Kona, HI., February 20-23, 2012; (9) Project Coordination meeting with University of Tennessee and University of Wyoming, Hydrology modeling from Weather Modification. Laramie, WY., February 29, 2012; (10) Wyoming State Legislature – Senate Agriculture Committee. Wyoming Water Development Commission (Advisor), Omnibus Water Plan. State Capital Bld., Cheyenne, WY., January 28, 2012; (11) Abandoned research site coordination on the Snowy Range, WY., with the US Forest Service and the Wyoming Conservation Corp. Laramie, WY., March 2, 2012; (12) Water-based ecosystem services—Wind River Glaciers, project coordination with Montana State Univ. Laramie, WY., March 5, 2012; (13) Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., March 6, 2012; (14) Wyoming Water Development Commission/Select Water Committee Meeting. Cheyenne, WY., March 7-9, 2012; (16) Interview with Craighead Institute and Ruckelshaus Institute for Wyoming Water Resources Film Project. Laramie, WY., April 12, 2012; (17) 10th Annual Conference – Wyoming Water Law, with CLE International. Cheyenne, WY., April 19-20, 2012; (18) North American Weather Modification Council – Annual Meeting, Presentation on Wyoming Water Research Program – Weather Modification Project. Las Vegas, NV., April 24, 2012; (19) Weather Modification Association -- Annual Conference. Las Vegas, NV., April 25-27, 2012; (20) Wyoming Weather Modification pilot program team meeting. Las Vegas, NV., April 26, 2012; (21) Wyoming Water Forum, Presentation on Water Research Program final project reports. Cheyenne, WY., May 1, 2012; (22) Wyoming Water Development Commission Meeting. Cheyenne, WY., May 11, 2012; (23) Mountain West Water Institute – Waters of the West Workshop. Idaho Falls, ID., May 15-16, 2012; (24) Universities Council On Water Resources/ National Institutes for Water Resources Annual

Conference, Managing Water, Energy, & Food In An Uncertain World. Santa Fe, NM., July 17-19, 2012; (25) UW Water Research Program. WRP Priority and Selection Committee meeting to select research priorities and review final project reports. Cheyenne, WY., July 26, 2012; (26) Wyoming Water Development Commission/Select Water Committee joint workshop. Riverton, WY., August 15, 2012; (27) Wyoming Water Development Commission/Select Water Committee joint meeting/summer tour. Riverton, WY., August 16-17, 2012; (28) Wyoming Center for Environmental Hydrology and Geophysics – Strategic Planning Meeting. Laramie, WY., September 17–18, 2012; (29) Wyoming Water Association Board meeting (Advisor), Lander, WY., October 23, 2012; (30) Co-Sponsor Wyoming Water Association Annual Meeting & Educational Seminar, University of Wyoming Water Research Initiatives. Lander, WY., October 24-26, 2012; (31) Wyoming Water Development Commission/Select Water Committee joint workshop. Presentation on the UW Office of Water Programs and Water Research Program. Casper, WY., November 7-9, 2012; (32) UW Water Research Program Meeting. WRP Priority and Selection Committee to select research projects. Cheyenne, WY., November 29, 2012; (33) UW Ag Summit, presentation on the Office of Water Programs/Wyoming Water Research Program, Laramie, WY., December 1, 2012; (34) AGU Fall Meeting, Poster Presentation Use of Remote Sensed Imagery to Evaluate Land Cover Change: North Platte River Basin. San Francisco, CA., December 3-7, 2012; (35) Wyoming Association of Conservation Districts Annual Conference. Lander, WY., December 12, 2012; (37) Wyoming Water Development Commission Meetings/Workshop, Presentation on recommendation for FY2013 WRP Annual funding. Cheyenne, WY., December 12-13, 2012; (38) Wyoming Water Forum, Presentation on Water Research Program update. Cheyenne, WY., January 8, 2013; (39) Wyoming Water Association Board Meeting, Legislative Review, (Advisor), Cheyenne, WY., January 10, 2013; (40) Wyoming Legislative Select Water Committee, Presentation on WRP projects and recommendation for FY2013 WRP Annual funding. State Capital, Cheyenne, WY., January 14, 2013; (41) Wyoming State Legislature – House Agriculture Committee. Wyoming Water Development Commission (Advisor), Omnibus Water Plan. State Capital Bld., Cheyenne, WY., January 15, 2013; (42) Wyoming Water Association Board Meeting, Legislative Review, (Advisor), Cheyenne, WY., January 16, 2013; (43) Wyoming State Legislature – House Agriculture Committee. Wyoming Water Development Commission (Advisor), Omnibus Water Plan. State Capital Bld., Cheyenne, WY., January 17, 2013; (44) Wyoming Water Association Board Meeting, Legislative Review, (Advisor), Cheyenne, WY., January 24, 2013; (45) The National Institutes for Water Resources (NIWR) annual meetings. Washington, DC., February 11-13, 2013; (46) Project Coordination meeting with University of Alabama and University of Wyoming, Hydrology modeling from Weather Modification. Laramie, WY., February 25, 2013.

FY12 information dissemination activities reported by research project PIs are listed, by project, in the following paragraphs:

Project 2010WY54B, IS THE MUDDY CREEK FOOD WEB AFFECTED BY COALBED NATURAL GAS INPUTS?, information transfer activities: (1) Tronstad, L.M. and W. Estes-Zumpf. 2012. Trace elements in the Muddy Creek food web prior to most coalbed natural gas development. Wyoming Landscape Conservation Initiative, Rock Springs, Wyoming; (2) Tronstad, L.M. and W. Estes-Zumpf. 2012. Are trace elements bioaccumulating in the Muddy Creek food web prior to most coalbed natural gas development? Zoology Brown Bag Seminar, University of Wyoming, Laramie, Wyoming.

Project 2010WY56B, ENHANCING STREAM FLOWS IN WYOMING, information transfer activity: (1) MacDonnell, Lawrence J., Water Rights Sales and Transfers, Presentation at CLE on March 6 in Casper (with copy of the final report in the conference materials).

Project 2010WY60B, MULTI-CENTURY DROUGHTS IN WYOMINGS HEADWATERS: EVIDENCE FROM LAKE SEDIMENTS, information transfer activities: (1) Fredrickson, J., 2012. Hydroclimatic variability in Wyoming headwaters. Masters defense, UW Geography, May 15, 2012; (2) Fredrickson, J. and Shinker, J.J., 2012. Hydroclimatic variability and drought in Wyoming headwater regions. Annual meeting of the Association of American Geographers, New York City; (3) Heyer, J., Fredrickson, J. and Shinker, J.J., 2012. Climate, drought and low stream flow in the headwaters of the North Platte River. Annual meeting of the Association of American Geographers, New York City; (4) Serravezza, M. and Shuman, B., 2012. Millennial-scale hydrologic fluctuations during the Holocene in the Bighorn Basin, northern Wyoming. Poster presentation, American Quaternary Association, Duluth, MN; (5) Shuman, B., 2012. A Mid-Holocene Regime Shift in Mid-Latitude North Hemisphere: Pollen and Lake-Level Datasets. NSF/NCAR SynTrace Climate Model Workshop, Providence RI; (6) Shuman, B., 2012. Patterns and Impacts of millennial-scale hydroclimatic change in North American during the Holocene. American Geophysical Union Fall meeting, San Francisco.

Project 2010WY61B, IMPACT OF BARK BEETLE OUTBREAKS ON FOREST WATER YIELD IN SOUTHERN WYOMING, information transfer activities: (1) (Invited) Ewers BE. Hydraulic Limitations Help Explain the Behavior of Plants: from clocks to mortality to ghosts. Department of Biology, Los Alamos National Labs, February, 2013; (2) (Invited) Ewers BE. Surprising effects of bark beetle-induced mortality on snowpacks and water yield. Wyoming Weather Modification Technical Advisory Team Meeting, Cheyenne, WY January, 2013; (3) P.D. Brooks; A.A. Harpold; J.A. Biederman; M.E. Litvak; P.D.Broxton; D. Gochis; N.P. Molotch; P.A. Troch; B.E. Ewers. Insects, firests, and climate change: implications for snow cover, water resources and ecosystem recovery in Western North America. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012; (4) King A, BE Ewers, R Sivanpillai, E Pendall. Testing remote sensing estimates of bark beetle induced mortality in lodgepole pine and Engelmann spruce with ground data. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012; (5) Mackay, DS, BE Ewers, DE Reed, E Pendall, NG McDowell. Plant hydraulic controls over ecosystem responses to climate-enhanced disturbances. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012; (6) (Invited) Ewers BE. Impact of bark beetle outbreaks on forest water yield. Joint meeting of the Wyoming Water Development Commission and the Select Water Subcommittee of the Wyoming Legislature. Casper, WY, November, 2012; (7) Reed, DE, BE Ewers, E Pendall, RD Kelly, U Norton, FN Whitehouse. Mountain pine beetle epidemic changes ecosystem flux controls of lodgepole pine. Ecological Society of America Annual Meeting, Portland, OR, August 2012; (8) Frank, JM, WJ Massman, BE Ewers. Linking bark beetle caused hydraulic failure to declining ecosystem fluxes in a high elevation Rock Mountain (Wyoming, USA) forest. Ecological Society of America Annual Meeting, Portland, OR, August 2012; (9) Barnard, HR, A Byers, A Harpold, BE Ewers, D Gochis, P Brooks. Examining the response of lodgepole transpiration to snow melt and summer rainfall in subalpine Colorado, USA. Ecological Society of America Annual Meeting, Portland, OR, August 2012; (10) Ewers BE et al. Use of plant hydraulic theory to predict plant controls over mass and energy fluxes in response to changes in species, soils and mortality. American Society of Plant Biology Annual Meeting, Austin, TX, July, 2012; (11) (Invited) Ewers BE. Temporal and Spatial Scaling of Evapotranspiration Using Plant Hydraulic Theory. Penn State. Critical Zone Observatory Distinguished Speaker Series. Mar. 23, 2012.

Project 2011WY74B, FATE OF COALBED METHANE PRODUCED WATER IN DISPOSAL PONDS IN THE POWDER RIVER BASIN, information transfer activity: (1) Drapeau, R., T.J. Kelleners, and K.J. Reddy. Fate of coalbed natural gas co-produced water in disposal ponds in the Powder River Basin. Oral and poster presentation at the Soil Sci. Soc. Am. Annual Meeting, Oct 21-24, 2012, Cincinnati, OH.

Project 2011WY75B, IMPROVED PRECIPITATION MEASUREMENT IN WINTERTIME SNOWSTORMS, information transfer activity: (1) Wettlaufer, A., The Hotplate Precipitation Rate Sensor, Young Scientists Symposium, Colorado State University, October, 2012.

Project 2012WY79B, TREATISE ON WYOMING WATER LAW, information transfer activities: (1) MacDonnell, Lawrence J., Elwood Meads vision for Wyoming Water: Then and Now, University of Wyoming Presidents Speaker Series, March 7, 2013, College of Law, UW. Presentation was recorded and is available on Wyocast.

Project 2012WY81B, MULTI-FREQUENCY RADAR AND PRECIPITATION PROBE ANALYSIS OF THE IMPACT OF GLACIOGENIC CLOUD SEEDING ON SNOW, Dr. Geerts and his research group gave oral presentations at a series of meetings in Year 1. These were partly funded by the NSF ASCII grant, partly by the UW Office of Water programs grant. (1) Qun Miao presented preliminary ASCII findings at the NCAR Orographic Precipitation and Climate Change workshop on 13-15 March 2012 (http://ral.ucar.edu/hap/events/orographic-precip/); (2) Bart Geerts gave an ASCII_12 field campaign overview at the Annual Meeting of the Weather Modification Association, Las Vegas, 25-27 April 2012; (3) Yang Yang presented an overview poster at the 2012 National Institutes of Water Resources (NIWR) meeting in Santa Fe in July 2012; (4) Binod Pokharel presented an ASCII research update at the WWMPP Technical Advisory Team meeting in Saratoga in August 2012; (5) A special session was devoted to ASCII at the American Meteorological Society 15th Conference on Mountain Meteorology (Fig. 1)(http://ams.confex.com/ams/archives.cgi). Three oral presentations were given by graduate students funded by this grant and/or by the NSF ASCII grant, namely Binod Pokharel, Xia Chu, and Yang Yang; (6) Bart Geerts gave an overview of ASCII_12 and discussed the experimental design for ASCII_13 at the WWMPP Ground School on 14 November 2012 in Laramie; (7) Xia Chu presented a poster Validation of WRF and WRF LES Simulations of the Dispersal of Ground-generated AgI Nuclei at the 19th AMS Conference on Planned and Inadvertent Weather Modification, Austin, TX, 7-10 January 2013; (8) Bart Geerts gave a talk The ASCII 2012 campaign: overview and early results at the 19th AMS Conference on Planned and Inadvertent Weather Modification, Austin, TX, 7-10 January 2013; (9) Bart Geerts gave a research updates at the WWMPP Technical Advisory Team (TAT) meeting in Cheyenne on 23 January 2013; (10) Geerts research was covered in the Laramie Boomerang, the Casper Star Tribune, the Wyoming Business Chronicle, and the University of Wyoming News (http://www.uwyo.edu/uw/news/); (11) Geerts was interviewed on Wyoming Public Radio (Open Spaces), twice, in March 2012 and March 2013; (12) A film crew from Belgium came by in December 2012, and the section on our weather mod research was aired on Canvas, channel VRT (www.canvas.be), in March 2013; (13) We were also part of the Weather Channels Hacking the Planet series in early April 2013. The episode in which we are featured can be viewed at http://youtu.be/rVl_pjEOi9w (this is one of several episodes in the Hacking the Planet series). Note that this is an unlisted and unlinked video, i.e. it is not public – the only way to access it is through this link. The reason, of course, is copyright issues.

Project 2012WY82B, DECADAL SCALE ESTIMATES OF FOREST WATER YIELD AFTER BARK BEETLE EPIDEMICS IN SOUTHERN WYOMING, information transfer activities: (1) (Invited) Ewers BE. Hydraulic Limitations Help Explain the Behavior of Plants: from clocks to mortality to ghosts. Department of Biology, U. of New Mexico, February, 2013; (2) (Invited) Ewers BE. Impact of Fire and Insect Disturbance on Water Cycling in Ecosystems. Land Managers of the Laramie District of the Medicine Bow National Forest. February 2013; (3) (Invited) Ewers BE. Impact of bark beetle outbreaks on forest water yield. Wyoming Association of Conservation Districts. Casper, WY, December, 2012; (4) Ewers, BE, DS Mackay, C Guadagno, SD Peckham, E Pendall, B Borkhuu, T Aston, JM Frank, WJ Massman, DE Reed, Y Yarkhunova, C Weinig. Nonstructural carbon dynamics are best predicted by the combination of photosynthesis and plant hydraulics during both bark beetle induced mortality and herbaceous plant response to drought. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012; (5) Peckham, SD, BE Ewers, DS Mackay, JM Frank, WJ Massman, MG Ryan, H Scott, E Pendall. Modeling net ecosystem exchange of carbon dioxide in a beetle-attacked subalpine forest using a data-constrained ecosystem model. American Geophysical Union Meeting, San Francisco, CA, Dec. 2012; (6) (Invited) Ewers BE. Impact of bark beetle outbreaks on forest water yield. Wyoming Water Development Commission. Cheyenne, WY, November, 2012; (7) (Invited) Ewers BE. Impact of bark beetle outbreaks on forest water yield. Wyoming Water Association Annual Meeting. Lander, WY, October, 2012; (8) Brooks, PD, HR Barnard, J Biederman, B Borkhuu, SL Edburd, BE Ewers, D Gochis, E Gutmann, AA Harpold, JA Hicke, DJP Moore, E Pendall, D Reed, A Somor, PA Troch. Multi-scale observation of hydrologic partitioning following insect-induced tree mortality: Implications for ecosystem water and biogeochemical cycles. Ecological Society of America Annual Meeting, Portland, OR, August 2012; (9) Ewers BE, DS Mackay, E Pendall, JM Frank, DE Reed, WJ

Massman, TL Aston, JL Angstmann, K Nathani, B Mitra. Use of plant hydraulic theory to predict plant controls over mass and energy fluxes in response to changes in soils, elevation and mortality. Ecological Society of America Annual Meeting, Portland, OR, August 2012; (10) Brown, NR, U Norton, E Pendall, BE Ewers, B Borkhuu. High levels of soil and litter nitrogen contents after bark beetle-induced lodgepole pine mortality. Ecological Society of America Annual Meeting, Portland, OR, August 2012; (11) (Invited) Ewers BE. Simulation modeling of bark beetle effects on stand water budgets. Wyoming Weather Modification Technical Advisory Team Meeting. Saratoga, WY July 2012.

USGS Summer Intern Program

None.

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	7	0	0	0	7
Masters	11	0	0	0	11
Ph.D.	11	0	0	0	11
Post-Doc.	2	0	0	0	2
Total	31	0	0	0	31

Notable Awards and Achievements

Project 35 (2010WY61B), IMPACT OF BARK BEETLE OUTBREAKS ON FOREST WATER YIELD IN SOUTHERN WYOMING, Ewers, 3/1/2010 thru 2/28/2013 and Project 41 (2012WY82B), DECADAL SCALE ESTIMATES OF FOREST WATER YIELD AFTER BARK BEETLE EPIDEMICS IN SOUTHERN WYOMING, Ewers, 3/1/2012 thru 2/28/2015.

Significant leveraged support for the above two projects is described in the following three paragraphs:

NSF ESPSCOR. Water in the West. $20 million total grant, $500,000 to Ewers. A major justification for this grant was the lack of correlation between increased water in stands and streams after bark beetle mortality. The TREES model funded by this project will now be tested against other, less biologically sophisticated hydrology models. This grant establishes the Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG).

NSF ETBC Hydrologic Science. ETBC: Collaborative Research: Quantifying the Effects of Large-Scale Vegetation Change on Coupled Water, Carbon, and Nutrient Cycles: Beetle Kill in Western Montane Forests. CoPI Elise Pendall. $219,261. This NSF funding provided partial funding for several of the data sets used to test TREES.

Ag Exp Station and McIntire Stennis. Quantifying the impact of a massive mountain pine beetle outbreak on carbon, water and nitrogen cycling and regeneration of southern Wyoming lodgepole pine forests. CoPIs Elise Pendall and Urszula Norton $60,000. This grant provided partial funding for several of the data sets used to test TREES.

Project 2010WY60B, MULTI-CENTURY DROUGHTS IN WYOMINGS HEADWATERS: EVIDENCE FROM LAKE SEDIMENTS, Shuman, 3/1/2010 thru 2/28/2013.

Results from the above listed project helped to motivate UW's successful NSF EPSCoR proposal, Water in a Changing West: The Wyoming Center for Environmental Hydrology and Geophysics (WYCEHG), which is providing $20 million over five years to enhance hydrologic research in Wyoming. One of the core WYCEHG science teams is focusing on paleohydrology using the methods applied and refined in this WWRP grant. In particular, the WYCEHG project will examine how hydrologic connectivity (e.g., via deep groundwater transfer) within watersheds influences sensitivity of water resources to changes in temperature.

Publications from Prior Years

1. 2006WY33B ("Precipitation Measurement and Growth Mechanisms in Orographic Wyoming Snowstorms") - Articles in Refereed Scientific Journals - Wolfe, J.P., and J.R.Snider, A Relationship between Reflectivity and Snow Rate for a High-Altitude S-Band Radar. J. Appl. Meteor. Climatol., 51, 1111 1128, 2012.
2. 2006WY33B ("Precipitation Measurement and Growth Mechanisms in Orographic Wyoming Snowstorms") - Dissertations - Wolfe, J.P., 2007. Radar-estimated Upslope Snowfall Rates in Southeastern Wyoming, MS thesis, Dept. of Atmospheric Science, University of Wyoming.
3. 2006WY33B ("Precipitation Measurement and Growth Mechanisms in Orographic Wyoming Snowstorms") - Dissertations - Borkhuu, B., 2009. Snowfall at a high-elevation site: A comparison of six measurement techniques, MS thesis, Dept. of Atmospheric Science, University of Wyoming.
4. 2009WY46B ("Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming II: Further Airborne Cloud Radar and Lidar Measurements") - Articles in Refereed Scientific Journals - Miao, Q., and B. Geerts, 2013. The impact of ground-based glaciogenic cloud seeding on orographic precipitation: new insights from an airborne down-looking radar. Advances in Atmospheric Science, 29, doi: 10.1007/s00376-012-2128-2.
5. 2007WY37B ("Tracing Glacial Ice and Snow Meltwater with Isotopes") - Articles in Refereed Scientific Journals - Cable, J.M., K. Ogle, and D.G. Williams, 2011. Contribution of glacier meltwater to streamflow in the Wind River Range, Wyoming: inferred vai a Bayesian mixing model applied to isotopic measurements, Hydrological Processes, Vol. 25, Issue 14, pgs 2228-2236. Article first published online : 9 FEB 2011, DOI: 10.1002/hyp.7982