

**State of Washington Water Research Center
Annual Technical Report
FY 2013**

Introduction

Since its inception in 1964, the overarching strategic mission of the State of Washington Water Research Center (SWWRC) has been to: i) facilitate, coordinate, conduct, and administer water-related research important to the State of Washington and the region, ii) educate and train engineers, scientists, and other professionals through participation in research and outreach projects, and iii) disseminate information on water-related issues through technical publications, newsletters, reports, sponsorship of seminars, workshops, conferences as well as other outreach and educational activities. While specific emphasis areas have evolved over time, with the competition for water resources continuing to grow, this mission is still vital to the State of Washington today.

The SWWRC has developed a multi-faceted, interdisciplinary approach to accomplish these goals. To promote multidisciplinary research and outreach, the SWWRC has been organized into five program areas: Watershed Management, Groundwater Systems, Environmental Limnology, Vadose Zone Processes, and Outreach and Education. These programs have helped prepare several multidisciplinary research proposals and provide better links between faculty and the SWWRC. The SWWRC is also heavily involved in international research and education activities.

Important lessons learned from the research and outreach components are disseminated to faculty and stakeholders and used by the Director to shape and enhance the education goals. Research projects are also used as a mechanism to fund graduate and undergraduate students as training the next generation of water professionals is an essential role for universities to fill. The SWWRC has continued its extensive efforts to reach out to agencies, organizations, and faculty throughout the State. Activities include presentations to watershed groups, discussions with state agencies, participation in regional water quality meetings, and personal contacts.

It is within this overall context that the USGS-funded project activities reported in this document contribute. These include the internally funded projects as well as the national proposals awarded to the SWWRC. These projects provide a solid core to the diverse efforts of the SWWRC. Water quantity and quality issues continue to be a major concern in the State of Washington due to the endangered species act, population growth, industrial requirements, and agricultural activities. Emerging issues such as water resources management in the face of global warming, water reuse, energy-related water quantity and quality considerations, ecological water demands, the potential renegotiation of the Columbia River Treaty between the US and Canada, and storage

As it enters its 50th year this reporting period, the SWWRC is in transition. The previous Director stepped down during the summer of 2013 to take a position at the University of Utah. The new administration, including a Director and Associate Director began their appointments on March 1, 2014, just after this reporting period, although this new administration has stepped in to satisfy the NIWR reporting and application requirements as well as other needs of the SWWRC in the interim. Three colleges at Washington State University have committed additional resources committed to the Center by, including funds to support a new Associate Director position and one-half FTE for a clinical assistant professor to help focus the Center's research programs. We are in the process of developing a new strategic plan to further strengthen the productivity, relevance, and visibility in the State of Washington and the Pacific Northwest.

Research Program Introduction

In accordance with its mission, the SWWRC facilitates, coordinates, conducts, and administers water-related research important to the State of Washington and the region. Research priorities within the 104(b) program for the State of Washington are established by a Joint Scientific Committee which includes representatives from water resource professionals at state agencies, universities, and the local USGS office. The SWWRC supports competitively awarded internal (within the State of Washington) grants involving water projects evaluated by the Joint Scientific Committee. The SWWRC also actively seeks multidisciplinary research at local, state, and national levels. Meetings between stakeholder groups, potential funding agencies, and research faculty are arranged as opportunities arise. Faculty are notified of any opportunities for individual or collaborative endeavors. The SWWRC also submits proposals to various local, state, and federal agencies on its own behalf.

During FY 2013, three locally-relevant research projects were selected for funding by the Center: (1) Black Carbon and Dust Deposition on South Cascade Glacier Since 1750 AD: Implications for the Timing and Availability of Water Resources in Washington State, awarded to Susan Kaspari, Assistant Professor, Central Washington University, (2) Arsenic Fate Following In-Situ Sulfate Reduction: Assessing the Sustainability of a Promising Groundwater Remediation Strategy, awarded to Rebecca Neumann, Assistant Professor, University of Washington and (3) An Integrated Engineering and Economic Analysis of the Columbia River Treaty Renegotiation using Game Theory, awarded to Michael Brady, Assistant Professor, Washington State University. These projects were competitively awarded based on review and recommendation by the SWWRC's Joint Scientific Board. As described below, these projects address important state issues but are also relevant to national interests.

Black Carbon and Dust Deposition on South Cascade Glacier Since 1750 AD: Implications for the Timing and Availability of Water Resources in Washington State

Basic Information

Title:	Black Carbon and Dust Deposition on South Cascade Glacier Since 1750 AD: Implications for the Timing and Availability of Water Resources in Washington State
Project Number:	2013WA372B
Start Date:	3/1/2013
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	Washington 4
Research Category:	Climate and Hydrologic Processes
Focus Category:	Climatological Processes, Water Quantity, Geochemical Processes
Descriptors:	None
Principal Investigators:	Susan Kaspari, Carey Alice Gazis

Publications

There are no publications.

BLACK CARBON AND DUST DEPOSITION ON SOUTH CASCADE GLACIER SINCE 1900 AD: IMPLICATIONS FOR THE TIMING AND AVAILABILITY OF WATER RESOURCES IN WASHINGTON STATE

Annual Report: May 19, 2014
PI Susan Kaspari, Central Washington University

Abstract

Seasonal snowpack and glaciers provide an important source of water in Washington State, but in recent decades they have undergone substantial decline. Warming temperatures are commonly identified as the dominant cause of this decline, but the deposition of light absorbing impurities (LAI) onto snow and glacier surfaces can be an even larger driver of melt. LAI include black carbon (BC) produced by the incomplete combustion of fossil and biofuels, and dust emissions from desert regions and land use change. When deposited on highly reflective snow and glacier ice, LAI cause darkening of the surface, resulting in greater absorption of solar energy, heating of the snow/ice, and accelerated snow and glacier melt. We analyzed an ice core from South Cascade Glacier in the North Cascades of Washington State to assess variations in LAI deposited on snow and glacier surfaces since 1900 AD, and the associated implications on melt and the availability of water resources. The BC record is 75% complete, and the preliminary record indicates low background BC concentrations in the early 20th century, followed by approximately a magnitude increase in peak and background concentrations, and a subsequent reduction in BC at the top of the record. Concentrated BC layers in excess of 100 ng/g likely resulted from BC deposition from forest fire events. Once the dust analyses and dating are complete, we will be able to: determine the timing of LAI deposition on the glacier; assess the relative absorption of solar energy from dust versus BC; and evaluate the role of LAI in reducing glacier albedo in the context of glacier melt and water resources.

I. PROBLEM AND RESEARCH OBJECTIVES

Importance of snow and glacier melt

The seasonal snowpack and mountain glaciers play an important role in the earth system by modulating climate and providing a major source of water resources. More than one-sixth of the global population relies on melt water from snow packs and glaciers for their water supply, and in the Western United States melt water from mountain regions accounts for more than 70% of annual stream flow [Barnett *et al.*, 2005].

In the Cascade Mountains of Washington State, most of the annual precipitation falls during the winter-spring and is stored in the snowpack [Elsner *et al.*, 2010; Vano *et al.*, 2010]. The majority of runoff is derived from the melting snowpack, transferring water from the relatively wet winter season to the typically dry summers [Mote *et al.*, 2005]. The timing and availability of water resources is thus strongly related to the duration of mountain snow cover.

Glacier melt water also provides essential water resources in Washington, particularly for watersheds that have a large concentration of glaciers. In some watersheds glacier melt water can account for nearly 50% of the May-September runoff (Fig. 1). Glacier melt variable from year to year, with glacier melt contributing a greater amount of water during years when the snow pack minimal. Glaciers thus provide an important water resource that can act as buffer during drought years [Riedel and Larrabee, 2011].

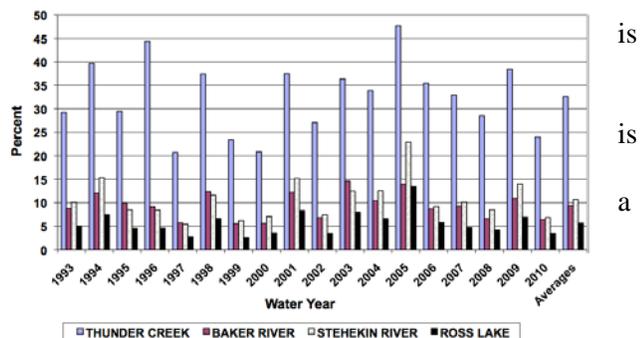


Fig. 1. Contribution of glacier runoff to in-stream flows in %. Riedel and Larrabee [2011].

Reduction in seasonal snowpack and glacier retreat in the Cascade Mountains

Observations show a global-scale decline of seasonal snow cover extent and duration, and mountain glaciers are shrinking [IPCC, 2007]. Spring snowpack levels (snow water equivalent and spatial extent) in the Western United States have declined considerably since the 1950s. The largest decreases occur where winter temperatures are mild, with the Cascade Mountains having experienced some of the largest decreases. Previous studies suggest that climate change, particularly warming, is the dominant factor inducing earlier snowmelted runoff [Mote *et al.*, 2005]. Regions with maritime climates, which have snow season temperatures in the range -5°C to 5°C , are particularly susceptible to warming. Because these regions lie close to 0°C , a slight warming can accelerate the melting rate of the snow pack, and change precipitation from falling in the form of rain rather than snow, preventing water from being stored in the snowpack. This in turn affects the timing and magnitude of water resources available during the comparatively dry summer months. Similar to the snowpack decline, glaciers in Washington State are also retreating (Fig. 2). For example, in the North Cascades, glacier area is estimated to have declined $\sim 40\%$ over the past 150 years [Riedel and Larrabee, 2011].

Accelerated snow and ice melt due to the presence of light absorbing impurities (LAI)

While warming temperatures are a well-recognized factor leading to reduction in snowpack and glacier retreat, another cause of accelerated melt is the deposition of LAI onto snow and glacier surfaces. Net solar radiation is the most important component of the surface energy budget for mid-latitude glaciers and snowpack, with albedo (i.e., reflectivity) dominating the amount of energy available for warming and melt [Anslow *et al.*, 2008; Oerlemans, 2000; Painter *et al.*, 2007]. When LAI are present, the albedo of snow and glacier surfaces is reduced (Fig. 3) [Conway *et al.*, 1996; Warren and Wiscombe, 1980], resulting in greater absorption of solar energy and accelerated snow and ice melt [Flanner *et al.*, 2009; Hansen and Nazarenko, 2004; Ramanathan and Carmichael, 2008]. For snowpack and glaciers with substantial deposition of LAI, these impurities are more important than temperature in driving melt [Skiles *et al.*, 2012].

LAI include black carbon (BC, often referred to as soot), dust, volcanic ash and colored organic material, with BC and dust being the most effective at reducing albedo [Warren and Wiscombe, 1980]. BC and dust are emitted into the atmosphere from both natural and anthropogenic sources. BC is emitted by incomplete combustion of biomass, coal and diesel fuels [Bond *et al.*, 2004], while dust is emitted from desert regions and human activities including agriculture, overgrazing, deforestation and construction [Tegen *et al.*, 2004].

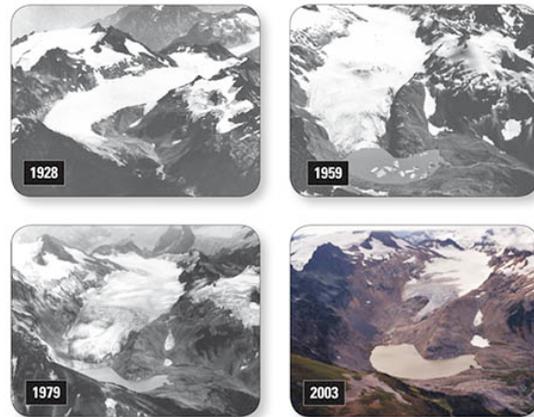


Fig. 2. Retreat of the South Cascade Glacier in Washington State from 1928 (top left) to 2003 (bottom right). USGS.

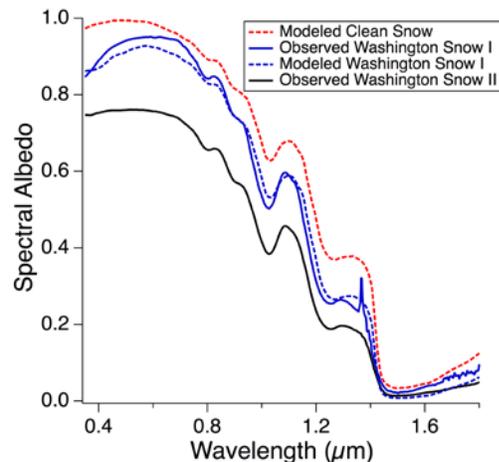


Fig. 3. Observed and SNICAR modeled snow spectral albedo for clean and observed snow in Washington State corresponding to $130 \mu\text{g/L}$ BC and 62 mg/L dust [Kaspari *et al.*, 2012]

The atmospheric residence time of BC and dust is short (days to two weeks), resulting in regional variations these LAI in the atmosphere and snow/ice. BC emissions have increased globally in recent decades, but emission trends vary regionally (Fig. 4). An increase in dust emissions has been documented in the western US since the 19th century associated with western settlement and increased livestock grazing [Neff *et al.*, 2008]. LAI deposited on snow and glaciers in Washington State have larger potential to accelerate melt than in many other regions because the snowpack is near 0°C, thus minimal energy needs to be added to the snowpack to result in melt. Our recent research in Washington State has documented BC and dust concentrations in snow at high enough concentrations to reduce albedo in excess of 20%, which can substantially accelerate snow and glacier melt (Fig. 3) [Delaney *et al.*, 2012; Kaspari *et al.*, 2012]. However, currently it is not known how much of the LAI are from natural vs. anthropogenic sources, nor how deposition of LAI change over time.

Research objectives

The objectives of this project are to analyze the South Cascade Ice Core retrieved from the North Cascades of Washington State for BC and dust. This record enables us to assess changes in the frequency and magnitude of LAI deposited onto snow/glaciers in the region since ~1900 AD, and the associated impacts on albedo and melt. Furthermore, the ice core record is being used to differentiate the sources of the LAI (e.g., from forest fires and background dust levels) versus anthropogenic sources (e.g. fossil fuel burning, land use change).

II. METHODOLOGY

Ice core processing

The 158 m long South Cascade Ice Core was drilled in 1994, and has been archived at the National Ice Core Laboratory (NICL) in Denver, CO. In June 2013 Kaspari, Central Washington University MS student Dan Pittenger, University of Colorado undergraduate students Nicholas Story and Garrett Rue, University of S. California postdoctoral researcher Nik Buenning, and three NICL employees processed the ice core. This included: imaging the ice core to identify LAI layers; making longitudinal cuts to the ice core (outer sections were used for total impurity mass measurements, while inner sections were used for BC, trace element, isotope, ²¹⁰Pb and tritium measurements). The longitudinal sections of the ice core were sampled at 7-10 cm resolution, resulting in a total of 1989 samples. The ice sections were bagged in whirlpak bags, and stored frozen at NICL until shipped to Central Washington University for analyses. Additional samples were sent to University of S. California for stable isotope analysis by postdoctoral researcher Nik Buenning, and to the Paul Scherrer Institut in Switzerland for ²¹⁰Pb measurements. The work conducted by University of S. California and the Paul Scherrer Institut is being conducted with no cost to the USGS grant.

Ice core dating

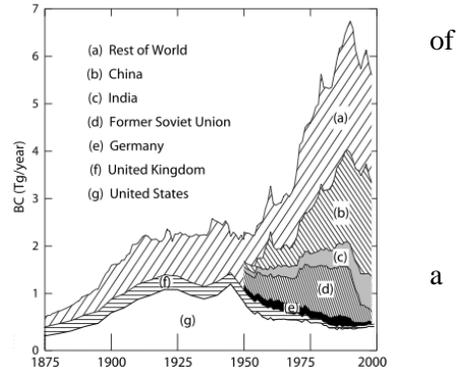


Fig. 4. Estimated fossil fuel BC emissions. Novakov *et al.* [2003].



Figure 5: MS student Dan Pittenger identifies a dust layer in a section of the South Cascade ice core.

The ice core is being dated using a combination of ^{210}Pb dating, glacial flow modeling, tritium dating, and glacial mass balance records. ^{210}Pb dating indicates the bottom age of the ice core is 1916 \pm 18 AD (Fig. 6). Soon the stable isotope analyses will be complete, after which the remaining sample water will be sent to the National Isotope Centre in New Zealand to identify the 1963 tritium peak associated with atmospheric hydrogen bomb testing [Morgenstern and Taylor, 2009]. Below 1963, we will use a glacial flow model [Nye, 1952] to further constrain the age of the bottom half of the core. The upper section will be constrained by a combination of annual layer counting and mass balance data provided by the United States Geological Survey.

Black carbon analyses

The ice samples for BC analyses were rinsed with MQ water to remove any potentially decontaminated ice, and stored frozen in acid pre-cleaned polypropylene vials. The samples were melted just prior to analysis, sonicated for 20 minutes, and stirred with a magnetic stirrer during analysis. The liquid sample is pumped using a peristaltic pump, nebulized using a CETAC U-5000 AT+ ultrasonic nebulizer, and the resultant dry aerosol is coupled to the sample inlet on a Single Particle Soot Photometer (SP2). The SP2 uses laser-induced incandescence to determine the mass of refractory BC in individual particles (Schwarz et al., 2006; Stephens et al., 2003). Monitoring of liquid sample flow rate pumped into the nebulizer, fraction of liquid sample nebulized and purge airflow rate allows BC mass concentrations in the liquid sample to be determined. Because BC is not nebulized with 100% efficiency, Aquadag standards were used to correct the measured BC concentrations. Nebulization efficiency for the CETAC nebulizer drops at particle sizes greater than 500nm (Schwarz et al., 2012, results confirmed in our laboratory). The concentrations reported herein predominantly represent the mass of BC particles 500 nm and smaller, which corresponds to the size range where the mass absorption cross section of BC particles is greater relative to larger particles, meaning that smaller BC particles absorb light and reduce albedo more efficiently (Schwarz et al., 2013).

Dust analyses

Once the BC analyses are complete, the samples will be analyzed for trace elements via Inductively Coupled Mass Spectrometry. In the meantime, an outer latitudinal section of the ice core is being sampled for total impurity mass, which is a proxy for dust concentrations. For this measurement the ice core is being sampled at \sim 20-100 cm resolution, rinsed with MQ water, sonicated, and filtered through pre-weighed 0.45 μm Millipore filters using a vacuum pump. The filters are dried in a laminar flow hood and re-weighed to provide a record of impurity mass. Additionally, optical differences in the impurities trapped on the filters will provide information in changes in impurity deposition over time.

III PRINCIPLE FINDINGS AND SIGNIFICANCE

Due to federal sequestration measures the funding for this project was reduced to 60% of the initial budget. Due to the smaller budget, we were not able to work on the project during summer 2013 with the exception of processing the ice core at NICL in June 2013. As a result, the proposed work has not been completed on the timeline initially proposed, and some work had to be eliminated (mainly measuring elemental carbon with the Sunset analyzer to facilitate method

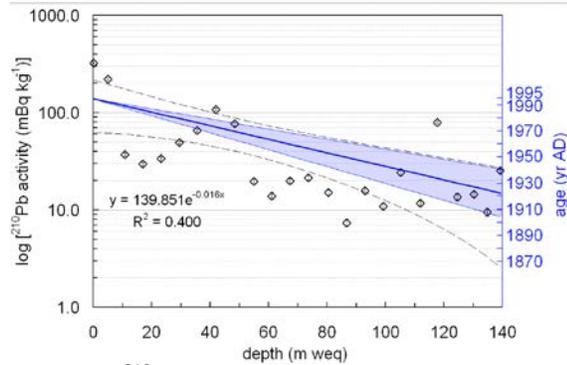


Figure 6: ^{210}Pb dating on the South Cascade ice core, dating the bottom of the core to 1916 \pm 18 years. Depth is in meters water equivalent.

intercomparison). We have been granted a no-cost extension through the end of June 2014, and acquired some additional funds from other sources to help conduct the research. Thus the proposed project will largely be completed, but on a delayed schedule from what was initially proposed. Below we present the results of this research up to May 2014.

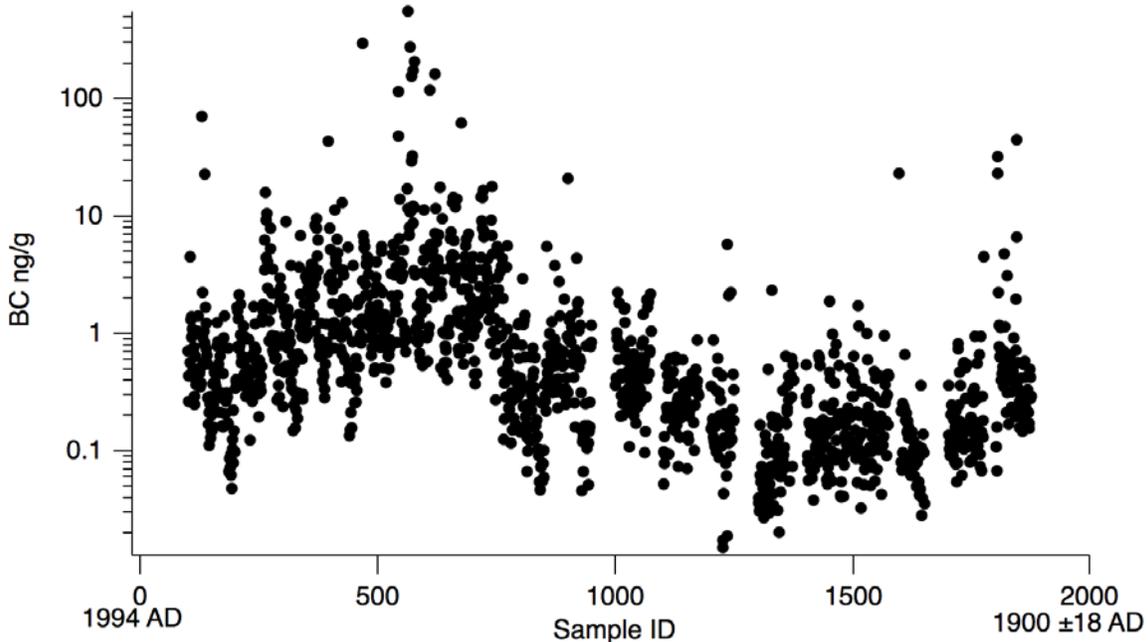


Figure 7: Preliminary BC data from the South Cascade Ice Core. 1994 AD marks the top of the record, and 1900 \pm 18 AD marks the bottom of the record based on ^{210}Pb dating.

BC record

The South Cascade ice core BC record is 75% complete. Based on the preliminary data (Figure 7) there are several notable findings:

1. There is a clear trend to the record, with BC concentrations relatively low in the oldest part of the record (samples 1000-1989), approximately a magnitude higher for samples ~300-700, and a return to lower concentrations for the most recent portion of the record.
2. The period of high BC concentrations (samples ~300-700) is evident in the maximum and background concentrations, suggesting a period of continuously higher BC concentrations in the atmosphere during this time. Once dated, this record will be very valuable in reconstructing past atmospheric concentrations of BC.
3. BC concentrations were measured in high enough concentrations to result in a marked reduction in the glacier albedo, particularly during the period of time when BC is elevated (samples ~300-700) and BC concentrations are in excess of 100 ng/g. Lower glacial albedo causes greater energy absorption, which causes melt.
4. Based on visual observations of a thin black layer in the ice core, the source of many of the high BC concentrations layers is likely from forest fires.

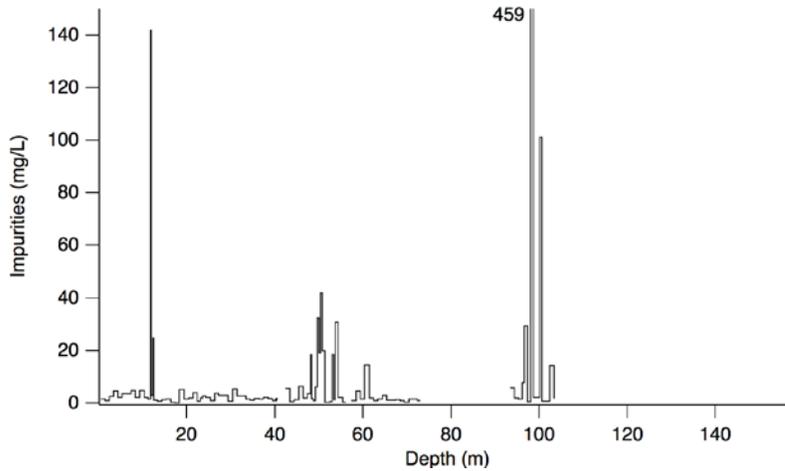


Figure 8: Preliminary gravimetric impurity data from the South Cascade ice core.

Impurity record

The gravimetric impurity record is 50% complete (Figure 9). Based on the preliminary record, it appears that background concentration of impurities deposited on the glacier is ~4 mg/L, punctuated by periods with high impurity concentrations. Visual inspection of the filters used to capture the impurity mass indicates that the composition of the impurities changes over time (Figure 9). The record will need to be completed and compared to the BC record to inform our interpretation of LAI deposited on South Cascade glacier.



Figure 9: Filters showing optical differences in impurities deposited on South Cascade Glacier (bottom, including ice core depths), and black and white Spectralon color standards (top).

Further work

We are completing the BC and gravimetric impurity analyses on the South Cascade ice. Additional work that needs to be completed includes:

1. Dating the ice core. The stable isotope analyses (not supported by this grant) are nearly complete, and remaining sample volume will be sent to New Zealand for tritium analysis. We will integrate the tritium and ²¹⁰Pb data into a glacier flow model to date the ice core record.
2. Conduct ICPMS analysis on select high impurity samples. The iron and BC data will be used to assess the relative absorption of solar energy from dust versus BC.
3. Calculate historic albedo reductions using the Snow, Ice, and Aerosol Radiation (SNICAR) model (Flanner et al., 2007). The modeled albedo reductions will enable energy balance calculations to be made (Ricchiuzzi et al., 1998) to assess the role that LAI have played in 20th century glacial melt and the availability of water resources.

LIST OF STUDENTS SUPPORTED

- Dan Pittenger, Central Washington University MS student. Pittenger participated in processing the ice core at NICL, and is conducting the BC measurements under Kaspari's advisement. This project is the basis for Pittenger's MS theses.
- University of Colorado undergraduate students Nicholas Story and Garrett Rue assisted in processing the ice core at NICL for one week in June 2013.
- Three Central Washington University undergraduate students (Katarina Wells, Curtis Reid, and Beck Luchansky) conducted the gravimetric impurity analyses. The research supplies and their time were supported by Central Washington University.

PRESENTATIONS

An abstract including results from this study has been submitted to the Pacific Northwest Climate Conference to be held in Seattle, WA in September 2014. Additionally the results of this research will be presented by Pittenger and Kaspari at the American Geophysical Union fall meeting in December 2014.

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Arsenic Fate Following In-Situ Sulfate Reduction: Assessing the Sustainability of a Promising Groundwater Remediation Strategy

Basic Information

Title:	Arsenic Fate Following In-Situ Sulfate Reduction: Assessing the Sustainability of a Promising Groundwater Remediation Strategy
Project Number:	2013WA374B
Start Date:	3/1/2013
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	WA-007
Research Category:	Water Quality
Focus Category:	Water Quality, Hydrogeochemistry, Treatment
Descriptors:	None
Principal Investigators:	Rebecca B. Neumann, Jennifer A. Jay

Publications

1. Pracht, Lara E., Brett T. Beaulieu, Benjamin D. Kocar and Rebecca B. Neumann, in progress, Arsenic Sequestration Mechanisms from Field Application of Induced Sulfate Reduction With and Without Zero-Valent Iron. In progress for a refereed scientific journal.
2. Pracht, Lara E., in progress, Subsurface Mechanisms that Release and Sequester Arsenic in Aquifer Sediments. Ph.D. Dissertation, Civil and Environmental Engineering, University of Washington, Seattle, WA.

Arsenic Fate Following In-Situ Sulfate Reduction: Assessing the Sustainability of a Promising Groundwater Remediation Strategy

PROBLEM & RESEARCH OBJECTIVE

Arsenic contaminated groundwater is a global problem, negatively impacting the health of millions of people worldwide who rely on groundwater for drinking and irrigation purposes — including those who live in Washington State. A country-wide survey conducted in 2006 documented Pierce and King county as having a high risk of arsenic exposure through untreated groundwater consumption [Twarakavi and Kaluarachchi, 2006], while a state-wide survey of 107 Washington homes found 91% with detectable levels of arsenic in their water [Nielsen et al., 2010]. Chronic consumption of arsenic results in skin lesions, skin cancer, bladder cancer, and lung cancer, and has been shown to increase the rate of morbidity by 9–68% [Argos et al., 2010]. While some of the groundwater arsenic in Washington State is of geologic origin (i.e., mobilized off aquifer sediments) [Murcott, 2012], much of it is due to past industrial [Paul et al., 1996], mining [Peplow and Edmonds, 2004], and disposal [Beaulieu and Ramirez, 2013] activities.

Given the prevalence and negative health consequences of arsenic-contaminated groundwater, it is important —at both the global and local scale— to develop robust and sustainable groundwater arsenic remediation strategies. *In-situ* arsenic removal from groundwater by induced microbial sulfate reduction, either with or without the addition of zero-valent iron (ZVI), is a promising remediation strategy. It works by injecting the appropriate microbial substrates (e.g., sulfate, carbon sources, ZVI) into the subsurface, creating biogeochemical conditions that favor the formation of minerals that incorporate arsenic during precipitation or create surfaces upon which arsenic adsorbs. Such minerals include arsenic-bearing iron sulfides, arsenic sulfides, and, when ZVI is used, iron (oxy)hydroxides [O'Day et al., 2004; Lien and Wilkin, 2005]. While numerous laboratory studies have documented the ability of induced sulfate reduction to remove arsenic from solution, adoption of the technique remains low, reflecting the sparse number of field-based applications [Benner et al., 2002; Saunders et al., 2008; Wilkin et al., 2009; Beaulieu and Ramirez, 2013] and a deficiency of direct evidence regarding the arsenic sequestration mechanisms.

The objective of the proposed project was to advance understanding of the long-term sustainability of arsenic removal from groundwater following field-scale application of induced microbial sulfate reduction with and without ZVI. Washington State has one of the few field applications of induced microbial sulfate reduction. The WA Department of Ecology has overseen application of the technique (with and without ZVI) as permeable reactive barriers (PRBs) at the B&L Woodwaste site to remediate the leading edges of a groundwater arsenic plume emanating from a former woodwaste landfill near Tacoma [Beaulieu and Ramirez, 2013]. From the mid-1970s until the early 1980s, the unlined landfill received woodwaste that was contaminated with slag from the former Asarco smelter in Ruston. The Asarco slag contained up to 2% arsenic, and biogeochemical conditions formed within the base of the landfill resulted in a redox-driven release of arsenic that created a large groundwater arsenic plume with current concentrations reaching ~5,000 micrograms per liter ($\mu\text{g/L}$), or 1000x the site's background concentration of 5 $\mu\text{g/L}$. The plume endangers Hylebos Creek, a salmon-bearing waterway, and is considered a threat to human health and the environment by the Washington Department of Ecology. The applied remediation strategy with ZVI has decreased arsenic concentrations within the PRBs by 66–96%, and has maintained low arsenic concentrations over a period of ~ 2 years

(Figure 1). The remediation strategy without ZVI has had more limited success. In this treatment concentrations initially decreased but then increased again (Figure 2).

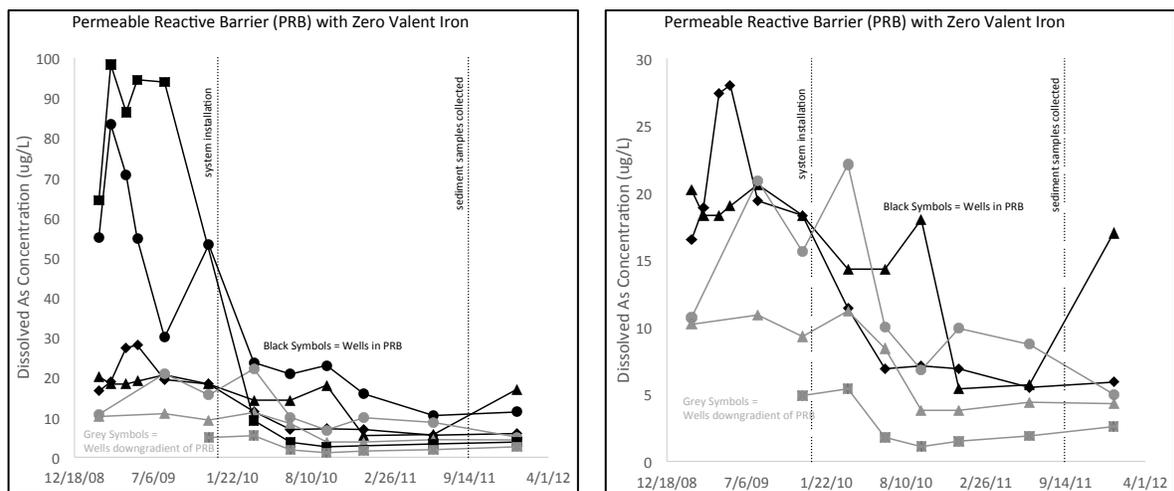


Figure 1: Arsenic concentrations in groundwater in (black symbols) and downgradient (grey symbols) of permeable reactive barrier (PRB) treated with induced sulfate reduction that included zero-valent iron. The plot on the left includes all sampled wells. The plot on the right includes only the wells with lower initial arsenic concentrations (<30 ug/L). The time points corresponding to treatment initiation (i.e., injection of treatment substrates into subsurface) and sediment sample collection for this study are marked in both plots. The plots are modified from Beaulieu and Ramirez [2013].

To achieve our objective, we worked to characterize the arsenic sequestration mechanism within the PRB's treated both with and without ZVI. Ultimately, we wanted to answer the following two questions:

- Is arsenic co-precipitated with minerals and/or adsorbed onto mineral surfaces in the two PRBs?
- What minerals are involved in removing arsenic from solution in the two PRBs?

The arsenic sequestration mechanisms occurring during induced sulfate reduction will dictate the success and long-term stability of the treatment. For example, arsenic incorporated into minerals is generally less mobile than that adsorbed onto mineral surfaces, and arsenic associated with sulfide minerals is likely less mobile than that associated with iron (oxy)hydroxides due to the prevalence of iron-reducing conditions within natural groundwater that can promote reductive dissolution of iron (oxy)hydroxides [Han et al., 2011].

METHODOLOGY

We used x-ray adsorption spectroscopy and x-ray fluorescence to help identify the mechanisms involved with arsenic sequestration in the two PRBs. Below we discuss our

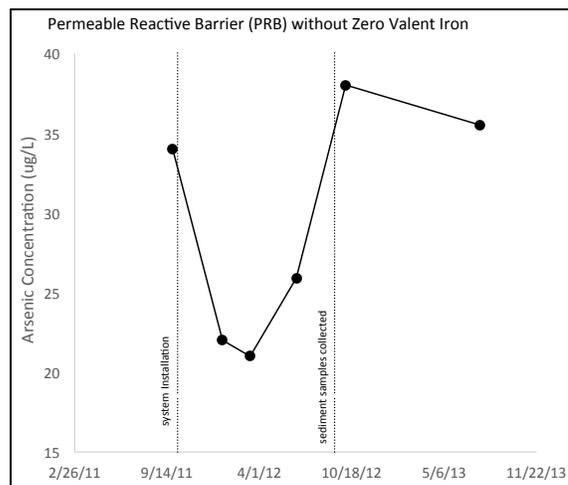


Figure 2: Arsenic concentrations in permeable reactive barrier treated with induced sulfate reduction that did not include zero-valent iron. Plot is modified from Floyd[Snider and AMEC [2013].

methods for collecting aquifer sediment from both PRBs, preparing the sediment for these analyses and conducting these analyses.

Sample Collection and Storage. Aquifer sediment samples were collected from the B&L Woodwaste site on September 11, 2012. Samples were collected using a direct-push drill rig at locations where induced sulfate reduction was stimulated without ZVI and with ZVI iron. Sediment was collected from depths where dissolved arsenic concentrations and hydraulic conductivity were highest, which corresponded to depths of 13.5 to 16.5 feet for the non-ZVI location, and 17 to 20 feet for the ZVI location. Samples were collected in plastic core liners and capped. Cores were put, along with oxygen-scavenging sachets (GasPak, BD Diagnostic Systems), into gas-impermeable bags that were heat-sealed in the field. Cores were stored in a cooler with dry ice. After transport back to the lab, samples were stored in the freezer.

Preparation of Aquifer Materials. One three-foot long core from each collection location (i.e., location with ZVI and without ZVI) was thawed inside an anaerobic glove box. Each core was dried inside the glove box and homogenized with an acid-washed plastic spoon in an acid-washed and furnace (550 °C for 4 hours) glass bowl. Dried samples were sieved with a plastic #200 sieve (Model SV-165#200, Gilson Company, Inc., Lewis Center, OH) to isolate the fine fraction. The sieving step was done to concentrate the arsenic and achieve a stronger XAS signal. The sample was spread out as a single layer onto a piece of Kapton tape and sealed with additional Kapton tape to keep the sample anoxic during analysis (Figure 3). Samples were then sealed into a gas-impermeable ESCAL bag with an oxygen-scavenging sachet for transport to the synchrotron beamline.

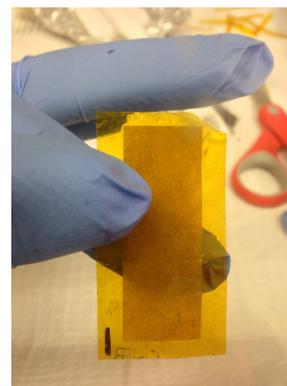


Figure 3: Aquifer sediment sample spread onto Kapton tape in preparation for synchrotron analysis.

Synchrotron Measurements. We obtained direct evidence of arsenic sequestration mechanisms using microscale x-ray fluorescence (μ XRF) and x-ray absorption (μ XAS) capabilities at the Stanford Synchrotron Radiation Lightsource Beamline 2-3 in Menlo Park, CA. Using μ XRF, we created fluorescence element composition maps, and using μ XAS we collected XANES (X-ray absorption near edge structure) spectra from micron-scale points of interest within the samples to determine solid phase speciation and local coordination of arsenic [Newville, 2004]. XANES is sensitive to formal oxidation state and coordination chemistry.

μ XRF: Micro-x-ray fluorescence was used to create spatial maps of element locations and relative concentrations. Analyzed elements included: arsenic, iron, sulfur, silicon, phosphorous, chloride, potassium, calcium, titanium, chromium, manganese, nickel, copper and zinc. The mapped domain was a square with sides ranging between 50 and 2000 μ m. In a majority of cases, the maps were composed of pixels (step size) of 1 μ m², obtained with a dwell time of 30ms. All data were analyzed using the Microprobe Analysis Toolkit software (Samuel Webb, SSRL).

μ XAS: Micro-XAS scans were collected for arsenic and iron. The spatial element maps generated by μ XRF were used to determine ideal locations for μ XAS analysis. The low concentrations of arsenic in the soil (low relative to the instrument's detection ability) required that μ XAS data be collected from "hotspots" of arsenic. Once these hotspot locations were determined, between 6-7 scans were generated for arsenic and 2-6 scans were generated for iron. Arsenic scans were collected from an energy of 11640 to 11900 eV, sufficiently surrounding the arsenic K-edge (11867 eV). Iron scans were collected from an energy of 7090 to 7160 eV, surrounding the iron K-edge (7111 eV). All data were calibrated by shifting energies a constant value, as determined by the adjustment required to align scans of iron and arsenate

foil standards to their known k-edges. All data were analyzed using the SIXPack software (Samuel Webb, SSRL).

PRINCIPLE FINDINGS AND SIGNIFICANCE

Results in this report are preliminary. We are continuing to collect and analyze data related to our research questions.

X-ray Fluorescence and X-ray Absorbance Data. Figures 4–9 below present arsenic, iron and sulfur XRF data and Figures 10 present XAS (XANES) data for arsenic. We are still analyzing and interpreting the iron XANES data. We use a sample identifier of “NZ” to indicate the sample came from the location without ZVI and an identifier of “Z” to indicate it came from the location with ZVI iron. Within the NZ or Z sample (see Figure 3 for a representative picture of the samples), XRF maps were collected for 1000 to 2000- μm square domains. Each of these mapped domains is indicated with a number (e.g., NZ1 represents the first $\sim 1000\text{-}\mu\text{m}$ wide domain targeted in the NZ sample, NZ2 represents the second target domain in the NZ sample). Within these $\sim 1000\text{-}\mu\text{m}$ domains, even smaller areas (100 to 200 μm -wide) were targeted for $\mu\text{-XRF}$ and $\mu\text{-XAS}$ (XANES) analyses. The locations of these sub-domains within the larger domain are indicated with a square and identified with a letter (e.g., NZ2a indicates data from the box labeled “a” within the larger NZ2 domain). Within the smaller domain (e.g., NZ2a), the location of XANES scans, if collected, is marked.

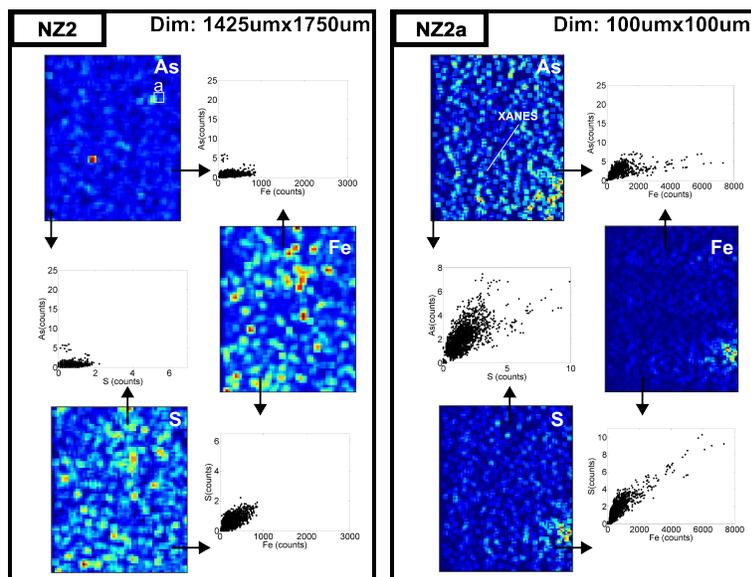


Figure 4: XRF data and spatial correlations for arsenic, iron and sulfur within NZ2, a $1425\ \mu\text{m} \times 1750\ \mu\text{m}$ area targeted in the sample collected from the PRB where ZVI was not used. NZ2a is a $100\ \mu\text{m} \times 100\ \mu\text{m}$ domain within NZ2, and an arsenic XANES scan was collected from NZ2a. Arsenic, iron and sulfur are spatially correlated in NZ2a.

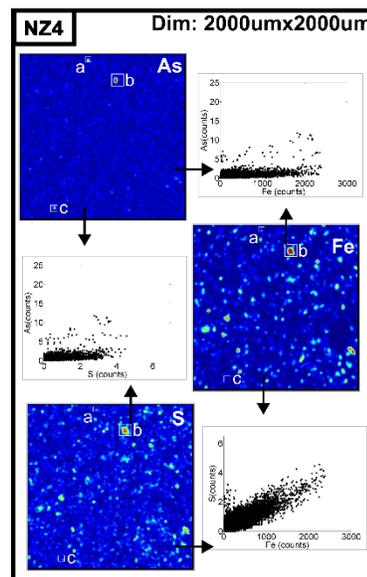


Figure 5: XRF data and spatial correlations for arsenic, iron and sulfur within NZ4, a $2000\ \mu\text{m} \times 2000\ \mu\text{m}$ area targeted in the sample collected from the PRB where ZVI was not used. Corresponding data for arsenic hot spots identified as areas a, b, c in the maps are presented in Figure 6.

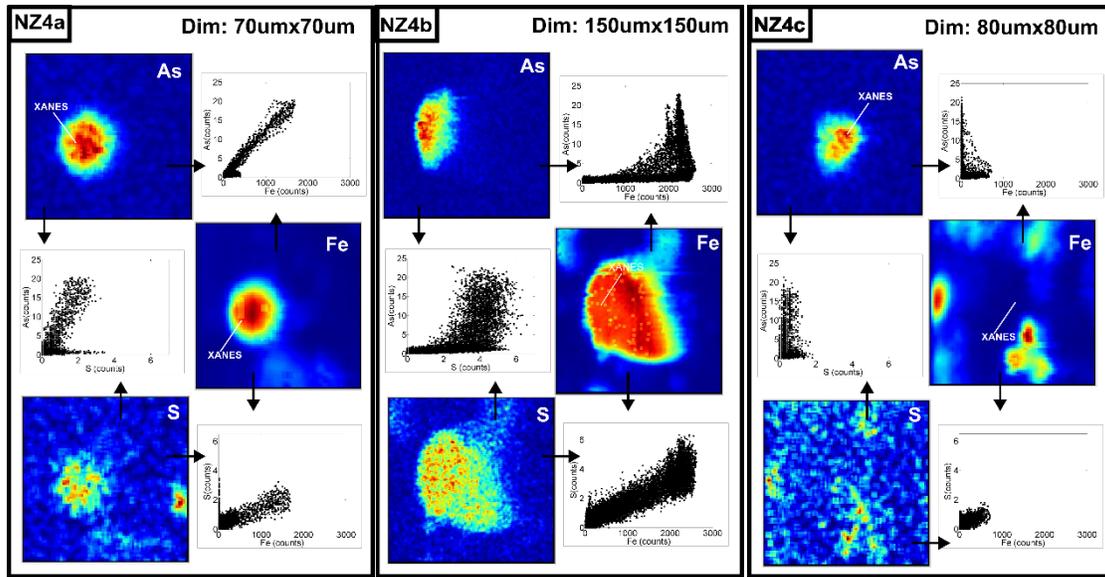


Figure 6: XRF data and spatial correlations for arsenic, iron and sulfur for arsenic hotspots a, b, and c identified within NZ4 (see Figure 5). Arsenic and iron XANES scans were collected for NZ4a and NZ4c. An iron XANES was collected for NZ4b. Arsenic, iron and sulfur are spatially correlated in NZ4a. In NZ4b, iron and sulfur are spatially correlated, and arsenic is associated with only a portion of the iron and sulfur hotspot. In NZ4c, arsenic and iron are correlated but arsenic appears uncorrelated with both of these elements.

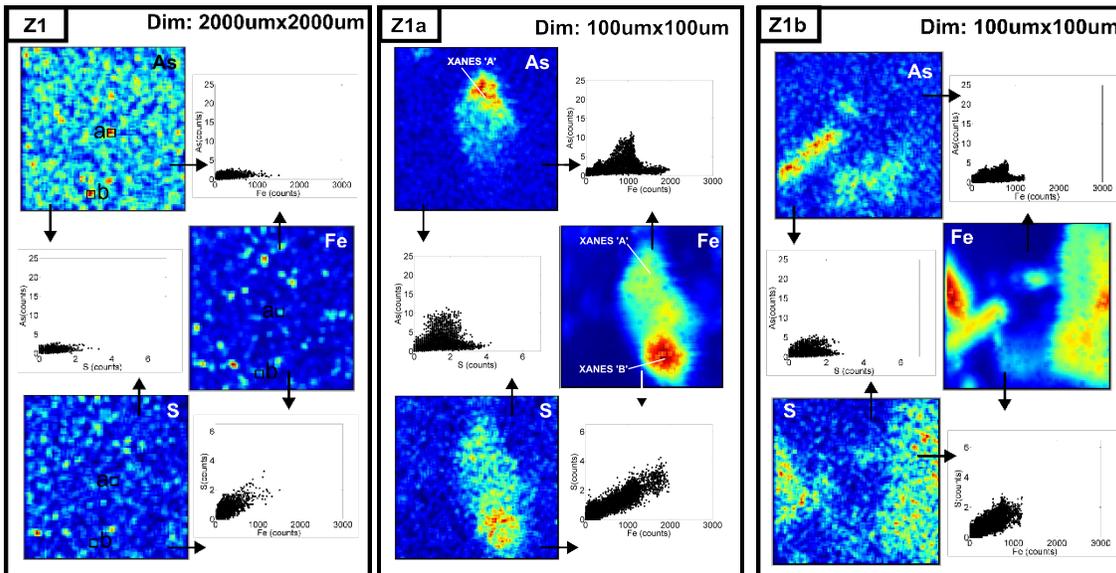


Figure 7: XRF data and spatial correlations for arsenic, iron and sulfur within Z1, a 2000 μm x 2000 μm area targeted in the sample collected from the PRB where ZVI was used. Z1a is a 100 μm x 100 μm domain within Z1; an arsenic XANES scan and two iron XANES scans were collected from Z1a. Z1b is a 100 μm x 100 μm domain within Z1; no XANES scans were collected from Z1b. In both Z1a and Z1b, iron and sulfur are spatially correlated. Arsenic appears correlated with both of these elements only at lower concentrations.

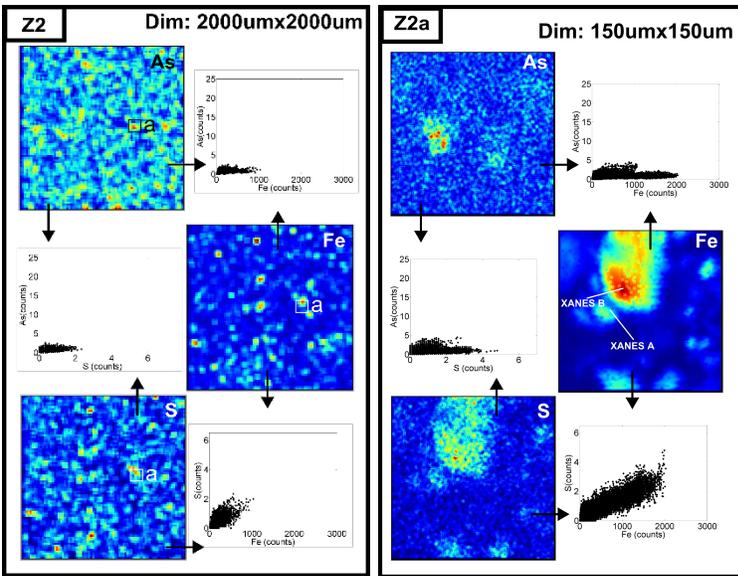


Figure 8: XRF data and spatial correlations for arsenic, iron and sulfur within Z2, a 2000 μm x 2000 μm area targeted in the sample collected from the PRB where ZVI was used. Z2a is a 150 μm x 150 μm domain within Z2; two iron XANES scans were collected from Z2a. Iron and sulfur are spatially correlated in Z2a, and arsenic appears correlated with both of these elements only at lower concentrations.

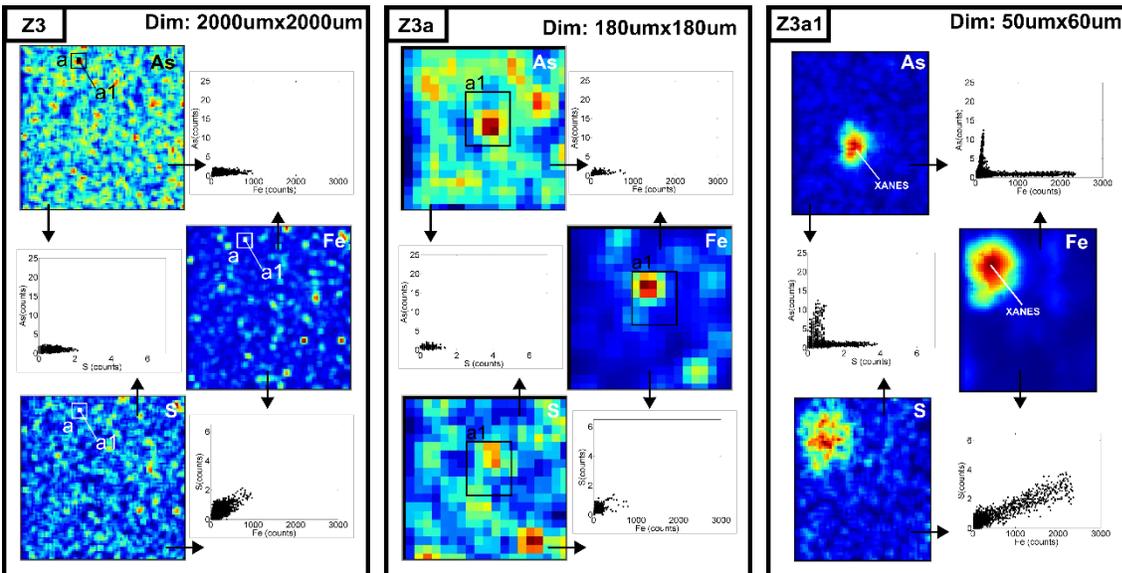


Figure 9: XRF data and spatial correlations for arsenic, iron and sulfur within Z3, a 2000 μm x 2000 μm area targeted in the sample collected from the PRB where ZVI was used. Z3a is a 180 μm x 180 μm domain within Z3. Z3a1 is 50 μm x 60 μm domain within Z3a; an arsenic and iron XANES scans were collected from Z3a1. Iron and sulfur are spatially correlated in Z3a1. Arsenic appears correlated with both of these elements only at lower concentrations.

Preliminary Interpretation. The data presented in Figures 4–10 suggest multiple arsenic sequestrations mechanisms are operating in both treatment locations. The Z0 XANES scan (Figure 10) indicates that before the application of induced sulfate reduction, arsenic was present in the aquifer sediment as arsenite and arsenate. This speciation could represent arsenite and arsenate sorbed to the aquifer sediment, or could represent arsenite and arsenate minerals. For example, enargite (Cu_3AsS_4) has a similar K-edge energy as sorbed arsenite [Beak and Wilkin, 2009]; though, low sulfide concentrations at the site [Beaulieu and Ramirez, 2013] suggest it is unlikely that enargite existed previous to treatment. Similarly, scrodite ($\text{FeAsO}_4 \cdot 2\text{H}_2\text{O}$) has a K-edge energy close to that of sorbed arsenate [Beak and Wilkin, 2009]. Naturally occurring arsenate minerals are not uncommon, and are often classified with phosphate minerals. Given the co-occurrence of arsenate with more reduced arsenic-sulfide species in the aquifer sediment after treatment (Figure 10, NZ4a), we suspect that the arsenate in sample Z0 existed as a mineral phase rather than a more easily transformed sorbed species. Our preliminary interpretation is that previous to treatment, arsenite, which is the predominate arsenic species dissolved in groundwater [Beaulieu and Ramirez, 2013], was sorbed onto the aquifer sediment, while arsenate was precipitated as a mineral or co-precipitated into a mineral phase. We plan to check this interpretation with equilibrium geochemical modeling for the site given measured groundwater chemistry.

After treatment with induced sulfate reduction, in the aquifer location treated without including ZVI, arsenic existed as arsenate (Figure 10, NZ4a, NZ4c) and as As(III) in or on sulfide phases (Figure 10, NZ2 and NZ4a). Arsenic did not exist as As(0) (e.g., arsenopyrite, Figure 10). The spots with sulfide-As(III) phases demonstrated high spatial correlation between arsenic, iron and sulfur (Figure 4 and 6, NZ2 and NZ4a). This spatial correlation suggests the involvement of iron-sulfide phases, for example disordered mackinawite and/or amorphous FeS. A similar spatial correlation between arsenic, iron and sulfur existed for most of the NZ spots (Figure 4 and 6, NZ2a, NZ4a, and NZ2b). However, one spot, NZ4c with an arsenate XANES scan (Figure 10), was not spatially correlated with either iron or sulfur. Calcium was the only tested element that was spatially correlated with arsenic at this spot (Figure 11), suggesting the presence of a calcium-arsenate mineral [Zhu et al., 2006]. Our preliminary interpretation of these data is that induced sulfate reduction performed without ZVI resulted in As(III) associating with iron-sulfide phases, but that the treatment did not alter conditions

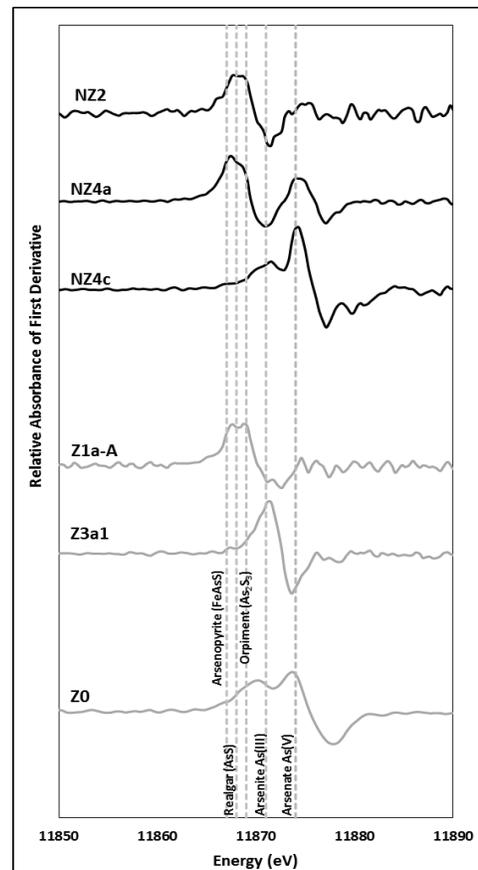


Figure 10: Normalized first derivative of arsenic XANES data collected from locations identified in XRF images above (see Figures 4–9). Z and NZ indicate the samples collected from the location where ZVI was and was not used, respectively. Z0 is a scan measured by Brett Beaulieu for sediment collected at the Z location before application of induced sulfate reduction. Dotted vertical lines indicate K-edge values for arsenic standards published in the literature [Wilkin 2006; Beak & Wilkin 2009; Kocar et al. 2010; Onstott et al. 2011].

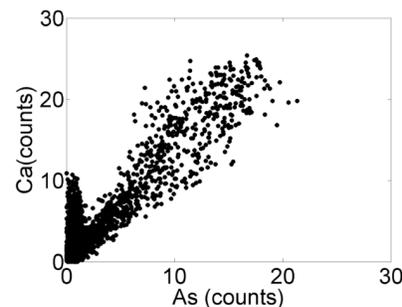


Figure 11: Spatial correlation between arsenic and calcium for NZ4c.

in the aquifer enough to reduce arsenate that was potentially precipitated in a mineral phase.

After treatment with induced sulfate reduction, in the aquifer location treated with the inclusion of ZVI, arsenic existed as arsenite and as As(III) in or on sulfide phases (Figure 10, Z1a-A and Z3a1). In all of the tested spots from this location, arsenic demonstrated a spatial correlation with iron and sulfur, but only for low and mid-range concentrations (Z1a, Z1b, Z2a, Z3a1, Figure 7, 8 and 9); arsenic was not associated with the highest iron and sulfur concentrations. This pattern was particularly dramatic for Z3a1, where arsenic was spatially correlated with only low concentrations of iron and sulfur. At this spot, arsenic was speciated as arsenite (Figure 10). We suspect that at this spot (Z3a1), arsenite was sorbed to the aquifer sediment. In other spots, we suspect As(III) was sorbed onto or precipitated in iron-sulfide minerals.

Significance. While numerous laboratory studies have documented the ability of induced sulfate reduction to remove arsenic from solution, there have been few field-based applications. Our data provide evidence of the sequestration mechanisms involved with the technique applied for field-scale remediation of arsenic in groundwater. Our results will help inform future cleanup and monitoring strategies at the B&L Woodwaste site, and will help improve understanding of the stability and performance of induced sulfate reduction applied in field conditions, with and without the inclusion of ZVI.

In laboratory test of induced sulfate reduction, arsenic has been removed from groundwater by adsorbing onto the surface of freshly formed, kinetically favored, amorphous iron monosulfide phases (e.g., disordered mackinawite and amorphous FeS). This process is thought to precede incorporation of sorbed arsenic into the crystal structure of thermodynamically favored, but slower forming, authigenic iron sulfides, such as pyrite (FeS₂) [Saunders et al., 2008; Teclu et al., 2008] and arsenic sulfide realgar (AsS) [O'Day et al., 2004; Gallegos et al., 2008]. The eventual formation of crystalline arsenic-sulfide minerals, such as arsenian pyrite, is often the goal of induce sulfate reduction schemes [Saunders et al., 2008; Beaulieu and Ramirez, 2013]. Our data, from a field application of induced sulfate reduction, appear consistent with previous laboratory studies. At both of our locations, arsenic was associated with iron-sulfide phases, like mackinawite and amorphous FeS, but was not yet incorporated into pyrite. The arsenic XANES scans suggest that realgar was potentially formed in some instances (Figure 10).

Considerable research has shown that ZVI coupled with sulfate reduction in permeable reactive barriers (PRBs) provides a source of reductants (iron(II) and H₂ gas), which improves arsenic removal efficiency [Zhang, 2003; Wilkin et al., 2009]. Spectroscopic analysis indicates that treatment of arsenic-impacted water with ZVI can result in a mixture of arsenic removal pathways including incorporation into both iron sulfides and iron (oxy)hydroxides [Beak and Wilkin, 2009]. At our site, treatment without the inclusion of ZVI was not effective at removing arsenic from groundwater (Figure 2); dissolved arsenic concentrations initially decreased but then rebounded. In contrast, treatment with the inclusion of ZVI successfully removed dissolved arsenic from groundwater over a multi-year period (Figure 1). Our data suggest that without ZVI, the aquifer did not have enough reducing power to stably sequester arsenic into the solid phase. This potential lack of reducing power is demonstrated by the presence of arsenate in the initial aquifer sample (Z0, Figure 10) and in the sample treated without ZVI (NZ4a and NZ4c, Figure 10), but not in the sample treated with ZVI (Z1a-A and Z2a1, Figure 10).

We plan to check the consistency of our preliminary interpretations with the iron XANES data, which we are currently analyzing.

STUDENTS SUPPORTED

Lara E. Pracht was supported by the USGS SWWRC Grant. She is a Ph.D. student advised by Dr. Neumann, and was the top graduate applicant to CEE at University of Washington in 2010, receiving the department's Valle Scholarship and the UW Graduate School's ARCS Fellowship. Her thesis is focused on understanding arsenic mobilization from and sequestration into aquifer sediments, both in WA State and SE Asia. This research effort will form a chapter of her Ph.D. thesis.

PUBLICATIONS

Pracht, Lara E., Brett T. Beaulieu, and Rebecca B. Neumann, 2013, Arsenic fate following in-situ sulfate reduction: assessing the sustainability of a promising groundwater remediation strategy, in 2013 ASA, CSSA, and SSSA International Annual Meetings — Water, Food, Energy & Innovation for a Sustainable World, Tampa, FL, Nov. 3–6, 2013.

Beaulieu, Brett T., Lara E. Pracht, Rebecca B. Neumann, 2014, In-situ groundwater arsenic remediation: what can monitoring and micro-X-ray absorption spectroscopy (μ XAS) tell us about treatment stability?, in Association of Environmental and Engineering Geologists, Washington Section, January AEG Meeting, Seattle, Washington, Jan. 16, 2014.

Floyd|Snider and AMEC, 2013, Phase 2 In-situ Pilot Study Monitoring Report for B&L Woodwaste Site, Pierce County Washington, prepared for B&L Custodial Trust.

Note: data collected as part of this research effort were included in this report.

The following publications related to this funded work are in progress:

Pracht, Lara E., Brett T. Beaulieu, Benjamin D. Kocar and Rebecca B. Neumann, *in progress*, Arsenic Sequestration Mechanisms from Field Application of Induced Sulfate Reduction With and Without Zero-Valent Iron. *In progress for a refereed scientific journal*.

Pracht, Lara E., *in progress*, Subsurface Mechanisms that Release and Sequester Arsenic in Aquifer Sediments. Ph.D. Dissertation, Civil and Environmental Engineering, University of Washington, Seattle, WA.

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An Integrated Engineering and Economic Analysis of the Columbia River Treaty Renegotiation using Game Theory

Basic Information

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Project Number:	2013WA378B
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End Date:	2/28/2014
Funding Source:	104B
Congressional District:	5
Research Category:	Social Sciences
Focus Category:	Law, Institutions, and Policy, Economics, Water Use
Descriptors:	None
Principal Investigators:	Michael Brady, Jennifer Adam, Jonathan Yoder

Publication

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Project Title: An Integrated Engineering and Economic Analysis of the Columbia River Treaty Renegotiation using Game Theory

Principal Investigator: Michael Brady

Project Duration: 3/1/2013-3/1/2014

Projective Objectives

The Columbia River Treaty (CRT), signed between Canada and the United States, has been in effect since 1964. Three dams were constructed in Canada to meet these goals (Mica, Duncan, and Keenleyside). Canada took a lump sum payment for 30 years of their share of the hydropower from the U.S. to pay for dam construction. The existing treaty focuses on the management of dam operations for flood control and hydropower generation. This reflected the costs of floods in places like Portland, Oregon in 1948, and the growth in manufacturing in energy intensive industries in the region like aircraft manufacturing. Irrigated agriculture was also spreading quickly following the Columbia Basin Project.

Either country can exit or initiate renegotiation starting in 2024 with a ten year advance notice, and both countries are in the process of reviewing options. There is a great deal of uncertainty over the future of the CRT because of the changes in the regional economies within the CRB over the last 50 years. The population of Washington grew from 2.3 million in 1950 to about 7 million currently. The regional economy has diversified significantly from heavy industries like manufacturing and natural resource extraction (e.g. timber). Seattle's economy now focuses on software, information technology, and services. Firms such as Amazon, Microsoft, and Costco are all headquartered in the area. The environmental amenities provided by the region's ecosystems plays an important part in the ability of these firms to recruit the most talented workers from other parts of the country. This has resulted in increased pressure to manage lakes and rivers in a way that enhances ecosystem health. The rehabilitation of fish runs and reservoirs for boating, for example, is often at odds with flood control and hydropower. Drawing down reservoirs in the winter allows for additional storage capacity in the spring if it is needed to prevent flooding. However, lower river levels impede fish passage, and low lake levels can persist into the mid-summer if snowmelt is late which hurts boating recreation. Tribes have also become more politically active in asserting their rights over fisheries and water. Climate change is also expected to impact dam operations by reducing winter snowpack and increasing spring rainfall. This amounts to a loss in natural water storage that provides in-stream flow at periods of peak demand that would need to be replaced with man-made storage if objectives are to be met in the future. Water scarcity problems have also grown in Eastern Washington where irrigated agriculture is the primary economic driver for many parts of the state. Managing dams for flood control and hydropower does move the hydrograph from spring to summer to the benefit of irrigators. However, winter drawdown of reservoirs can reduce in-stream flows in summer if late winter snow and spring rain is less than expected. Energy generation has also changed due to the large scale deployment of wind power generators throughout the region.

The dimensionality of the problem of managing dams and reservoirs on the Columbia River from the headwaters in Canada out to the Pacific Ocean between Oregon and Washington has increased substantially since the Columbia River Treaty was signed due to changes in the regional economy. There are now a number of stakeholder groups with a strong interest in changing how the system is managed in both Canada and the U.S. With this many dimensions to management it becomes difficult to account for all the costs and benefits to changes in management to either country. A systematic approach is

required to quantify impacts from changing management and to understand how potential changes may cause abandonment of the current treaty or a willingness to renegotiate.

To this end, we develop an integrated engineering and economic analysis of the renegotiation of the Columbia River Treaty using a game theoretic bargaining framework. The economic portion will consist of an accounting of costs and benefits associated with different reservoir management regimes and an analysis of treaty negotiation within a game theoretic bargaining framework. The engineering analysis will consist of the use of reservoir model to simulate the impact of different reservoir management regimes on various outcomes including flood control, hydropower generation, irrigation, and recreation.

The development of game theory revolutionized the analysis of strategic interactions. Since its founding in the mid-20th Century it has become a foundational tool in economics and political science for understanding decision making in a wide range of contexts that involve strategic behavior, including a number of trans-boundary water agreements. Game theory accounts for the fact that parties give priority to their own objectives, and also recognize that others do the same and take that fact into account. This often does not result in the best system-wide outcome (Madani, 2010). By taking an integrated engineering-economic approach, we can more accurately account for the impact of changes in policy on the hydrological system and those who benefit from it. *Analyzing the CRT using the tools of game theory in an integrated engineering-economic study will identify an agreement that (1) both countries are likely to agree to, (2) that will leave both countries better off compared to the current agreement or to a withdrawal from the treaty, and (3) will be based on realistic estimates of the impact of changes in dam operations on the hydrograph of the Columbia River.* The logic model below shows how the different components of the study fit together to provide scientifically objective research aimed at maximizing the societal benefits generated by the Columbia River system in Canada and the USA.

1. Objectives

- Provide an accurate accounting of the costs and benefits to the USA and Canada that would result from changing reservoir operation objectives from current objectives to likely alternative(s).
- Construct a realistic game theoretic model of the renegotiation of the Columbia River Treaty.
- Using game theoretic equilibrium concepts, answer the following questions:
 - Is either country likely to withdraw without renegotiation from the current agreement?
 - Is there is an agreement structure that leaves both countries better off compared to the current treaty?
 - How can the negotiation process be designed to increase the chance of maximizing societal benefits from the Columbia River system in both countries?

While the environment within which this treaty operates is complex, the small number of treaty participants lends itself well to an analysis of country-specific objectives, potential strategies,

and their payoffs. As such, a game-theoretic modeling approach provides a promising framework for understanding potential outcomes.

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Background on Game Theory's Relevance to Resource Allocation Problems

For modeling the allocation of water resources, a typical socio-economic approach is to rely on optimization models that focus on strategies like transferable water rights (water markets) as a way to maximize social welfare. This approach is well-suited to situations where a single entity has primary authority over water resources. For example, in Washington the Washington Department of Ecology is the primary regulatory agency that oversees water issues in the state. They are not forced to reach agreements with other entities like the Washington State Department of Agriculture. This approach breaks down when there are two or more entities that have legal authority over different parts of a system where one is not subservient to the other. When this is the case a game-theoretic approach is preferable. An optimization will not account for the fact that Canada holds most of the storage capacity on the Columbia River while most of the benefits from flood control, hydropower, and irrigation are accrued in the USA.

Bargaining models have been used to analyze trans-boundary negotiations over water resources since the 1960s. Game theory provides a systematic framework for taking account of biophysical and socio-economic conditions of each country when trying to identify solutions to complex resource allocation problems. Bogardi and Szidarovsky (1976) showed how to find equilibrium solutions for water management aimed at addressing a range of problems including environmental protection, irrigation systems, water quality management, and multi-purpose water management systems. The World Bank has argued for a greater use of game theory to improve trans-boundary water agreements because this approach helps determine when an agreement is likely to emerge and signals how negotiations can be designed to improve the process (World Bank Policy Research Working Paper No. 3641). Game theory has been used to study conflict resolution over trans-boundary water resources across the globe including India (Rogers, 1969; Kilgour and Dinar, 2001), the Great Lakes (Becker and Easter 1995), Mexico and the USA (Fisvold and Caswell, 2000), the Middle East (Kucukmehmetoglu and Guldmen, 2004; Madani and Hipel, 2007), Africa (Wu and Whittington, 2006; Elimam, 2008), and Central Asia

(Sheikhmohammady and Madani, 2008).

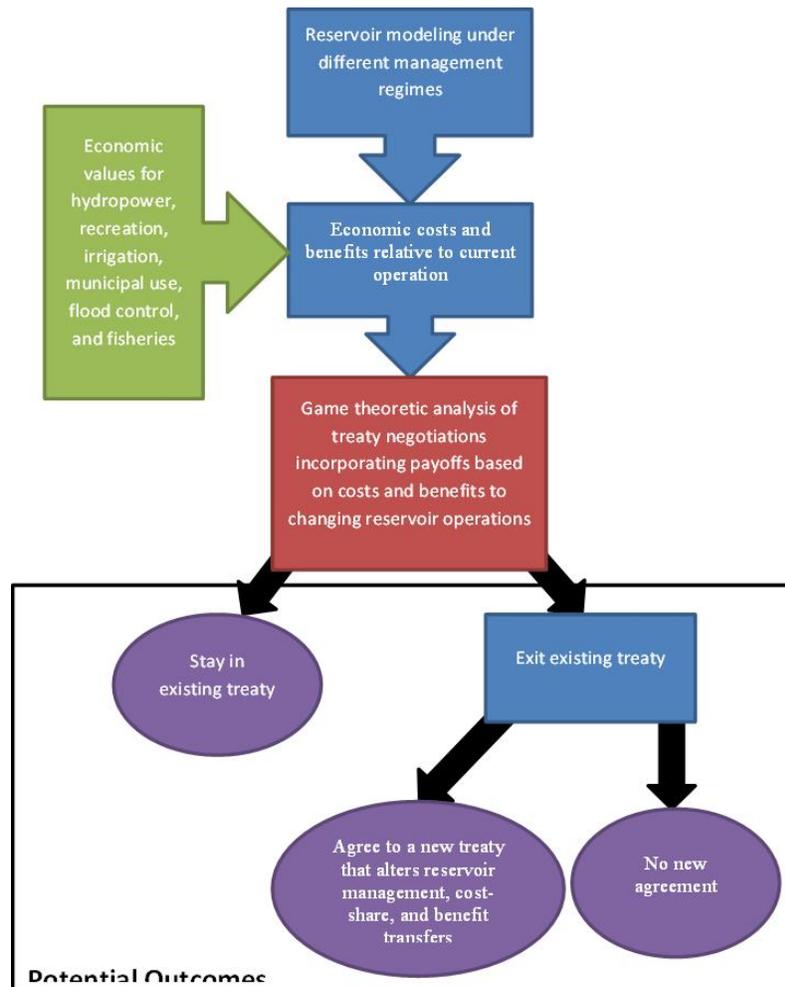


Figure 1. Logic model for the research that connects the reservoir modeling to economic costs and benefits that are then analyzed using game theory to identify the potential for withdrawal and renegotiation of the existing treaty.

The most well-known game theory example is the Prisoner's Dilemma (PD), which captures some of the characteristics of trans-boundary water negotiations and can be used to demonstrate the usefulness of the approach. The lesson from the PD is that the best strategy for each individual does not result in the best possible outcome, where the best outcome refers to the payoffs that could be reached if cooperation was possible. Consider a crime committed jointly by two people that are subsequently held for questioning. The partners in crime get a light sentence if neither confesses. Both are offered plea deals so that if they confess and indict their partner they are freed and their partner serves the longest possible prison sentence. If both confess then they do not need either plea deal and each serves a medium length prison sentence. A dominant strategy exists where one person is better off pursuing a particular strategy no matter what the other person does. The PD game is shown below in Figure 2 in

matrix form where the values represent length of prison term. It can be shown that each suspect has a dominant strategy. Suspect 1 is better off confessing no matter which strategy Suspect 2 takes because $0 < 1$ and $6 < 10$. The same holds for Suspect 2 given Suspect 1's actions. Therefore, both suspects confess and get six years in prison even though they would have been better off if they could have coordinated and not confessed.

Figure 2. Prisoner's Dilemma Payoff Matrix

		Suspect 2	
		Don't Confess	Confess
Suspect 1	Don't Confess	1, 1	10, 0
	Confess	0, 10	6, 6

Values are prison terms in years (Player 1, Player 2).

While the PD is a highly stylized game it shows that the best strategy for one party depends on the best strategy for the other party, and vice versa. It also shows in a very simple example why system-wide optimal outcomes, or pareto-optimal outcomes, are often not achieved. This can be due to barriers to coordination, such as is the case when agreements cannot be enforced, or to political or legal constraints that can eliminate many solutions. For example, many developing countries have argued that fairness dictates that richer countries bare all the costs of climate change mitigation because they are responsible for a majority of emissions in the last 200 years. Also, the Reagan Administration stipulated that Mexico and the USA split costs of water treatment facilities for border towns 50/50, which prevented the ability of the two countries to reach an agreement that would allow the facilities to be built (Frisvold and Caswell, 2000).

The negotiation of the CRT fits well into a game theoretic framework because the costs and benefits of pursuing various objectives are not evenly shared by Canada and the USA without some compensation. Also, the fact that both are sovereign nations means that there are political barriers to cooperation because there is no unified actor that has ultimate say over decisions. Another challenge is that stakeholder groups in both countries often seek to restrict the policy space to exclude strategies that are counter to their interest. Game theory provides a mathematically rigorous framework for organizing and accounting for how all these factors influence negotiations. Most importantly, game theory is not simply a *descriptive* tool for explaining why two parties fail to reach an agreement that leave both better off. Instead, game theory is a *prescriptive* tool that can be invaluable for identifying mutually beneficial outcomes in complex multi-dimensional bargaining situations. Game theory also helps identify what obstacles may prevent reaching a mutually beneficial agreement, and also aids in improving negotiations by ruling out agreements that are not feasible.

2. Modeling of Streamflow Routing and Reservoir Operations

Modeling of streamflow routing and reservoir operations is accomplished by using a suite of models. The variable infiltration capacity (VIC) hydrologic model sums the runoff and baseflow contributions from each grid-cell included in the area of study. These contributions are routed downstream using linearized St. Venant's equations (Lohmann et al. 1996; 1998).

Monthly routed streamflow is then an output of VIC into the Columbia River Simulation Model (ColSim). ColSim accounts for physical characteristics of the CRB water management system such as type of reservoir (storage or run-of-river), diversions, and return flows. ColSim can also model reservoir operating policies (Hamlet and Lettenmaier 1999). These are rule curves that are a function of objectives including flood control, hydropower, in-stream flow targets, out-of-stream withdrawals for agricultural and municipal uses, and recreation. ColSim is well-suited to analyzing the impacts of changes in the weights placed on objectives of dam operations, which is the focus of this study.

The third component to the engineering modeling is HEC-ResSIM, which provides information on power generation and reservoir storage. While ColSim captures changes in operation at a system-wide level, HEC-ResSIM provides a more detailed summary of the relationship between reservoir storage and power generation. Also, HEC-ResSIM employs a graphical user interface that allows the user to define rule-based operations. VIC provides information on streamflows. Rules are based on within-year forecasts of volume from April to August.

Simulating future hydrological flows account for climate change given the multi-decadal lifespan of most trans-boundary water agreements. Future temperature and precipitation conditions are from the Hadley Centre's HadCM3 general circulation model. We will use the B1 emission scenario. Climate scenarios are incorporated via the baseflow estimates in VIC. There is a very large of potential reservoir management regimes that could be employed. The cost of simulating each regime is significant so only a limited number of runs can be handled

3. Economic Impact of Changes in Reservoir Modeling

The streamflow routing and reservoir operations modeling quantifies the impact of changes in dam operations on the outcomes of interest. In this study the outcomes we will focus on are floods, hydropower generation, out-of-stream uses including irrigation and municipal demand, recreation, and fish habitat. Given the limited scope of the proposal, economic values associated with each use will be derived from existing estimates. The scope will also prohibit considering general equilibrium impacts that account for the effect of a change in one sector on the output of all other sectors. Future values will be forecasted based on expected changes in the regional economy and climate.

4. Game Theoretic Analysis

The bargaining analysis between the USA and Canada is based on the payoffs that each receives under different agreements that are defined by reservoir management objectives and transfers between them. The current agreement is defined by reservoir management that seeks to reduce the chance of floods and also maximize hydropower generation. To compensate Canada

for storage operations on their dams 50% of the value of potential hydropower generation is awarded. This defines the current “no change” scenario. While defining the full set of alternatives is part of the research project the option of “no treaty” will be included. Solutions to game theory problems depend critically on payoffs under no cooperation. The “no treaty” scenario assumes that both Canada and the USA manage their dam operations to their own interests recognizing that the other will do the same.

The type of game that is the best fit for the CRT negotiations is a **cooperative game** because a treaty allows for enforcement of binding agreements. Costly enforcement of agreements can make the assumption of a cooperative game problematic. However, dam operations are fairly transparent and legal costs are likely to be relatively low compared. It is also fitting to assume that any treaty is binding given the durability of the existing treaty despite controversy over the equity and efficiency of the arrangement.

For comparison, a coordination game is relevant when two parties are attempting to agree to non-binding actions like in the case of the Kyoto Protocol to address climate change. A cooperative game structure is also designed to consider whether some constraint will prevent the two parties from reaching a binding agreement. In the case of the CRT there are potentially a number of such constraints. Tribes have become much more active in seeking to exert their fisheries rights since the first treaty was negotiated. Setting a minimum standard on in-stream flows at certain times of the year to maintain fish runs reduces the number of pathways to an agreement. There are many other examples of how domestic law can constrain the treaty choice set.

Following similar studies, the bargaining process will be modeled as a **sequential game** which reflects the realities of the political process. In a sequential game one party makes an offer and the other either accepts or rejects and can then make a counteroffer. Another benefit of the sequential game structure is that it has been shown that the outcome is approximated by the Nash solution (Binmore et al., 1986). The **Nash solution** (Nash 1953) maximizes the product $N = [u_m - u_m^*][u_n - u_n^*]$ where u_m and u_n^* are the payoffs, as a function of terms being bargained over, to country m under an agreement and with no agreement, respectively. The Nash solution to a cooperative game is pareto-efficient which guarantees that there is no other agreement that could make one party better off without making the other worse off. This requirement lends the model results credibility that countries are (1) likely to be agree to the conditions, and (2) will not prefer some other agreement more. The assumption of **full information** can also be made given the history of information sharing under the existing treaty about the benefits to each country from different outcomes.

A complex part of modeling the negotiations will be to look at how stakeholder groups in each country are likely to form coalitions to politically pressure for particular standards. Coalition formation is always an important part of modeling cooperative games. Constructing a model of stakeholder influence will be part of the initial economic analysis that is aimed at reducing the number of feasible treaties that will be the basis of the reservoir model runs. This part of the game will also be an important part of the final game theoretic analysis that incorporates payoffs based on the reservoir model runs.

Status of Work

This project has received a no-cost extension to complete this work. Work to date includes:

- Reviewed existing reports analyzing the benefits and costs of the Treaty to existing parties.
- Collected data on the positions of stakeholder groups in the US and Canada in regards to staying in the existing Treaty or renegotiating a new Treaty based on discussions at public meetings.
- Collected data on historical hydropower production and value.
- Developed a game theoretic model to analyze the “Canadian Entitlement” relative to a predicted equilibrium outcome from a negotiating process in terms of the distribution of benefits and costs.

Remaining Work

- Additional time is needed to integrate the economic modeling with the reservoir modeling (ColSim) needed to analyze the effect of changes in dam operations with in-stream flows at different points in the year.
- A more complete analysis of the incentives of all stakeholder groups not active in the negotiation of the original treaty are needed including tribes, agriculture, and recreation.

Outputs

The work modeling done to date is being presented at the 2014 UCOWR-NIWR-CUAHSI Conference on “Water Systems, Science, and Society Under Global Change held June 18-20 at Tufts University, Medford, MA.

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Information Transfer Program Introduction

Public Outreach and Education are critically important components of the State of Washington Water Research Center mission. As agency and stakeholders struggle to comprehend important decisions facing water resources, it is essential that they receive unbiased scientific information. The primary outreach goal is to facilitate information exchange by providing opportunities for combining the academic work of research universities in the state with potential users and water stakeholders. The education goal is typically achieved through faculty and student involvement in public presentations and gatherings to promote and build better two-way understanding of water issues and possible solutions and provide unique educational experiences for tomorrow's water resources professionals. These processes occur through a variety of activities, formal and informal, that raise the visibility of university research results throughout the Pacific Northwest. Federal, state and local agencies, non-governmental organizations, watershed groups, and concerned citizens are in need of interpreted science that can be applied to solving the regions' water problems. The SWWRC makes substantial efforts to facilitate this process. The items described in the following Information Transfer Report constitute the core of the technology transfer activities.

USGS Summer Intern Program

None.

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	5	0	0	0	5
Masters	1	0	0	0	1
Ph.D.	2	0	0	0	2
Post-Doc.	0	0	0	0	0
Total	8	0	0	0	8

Notable Awards and Achievements

Publications from Prior Years

1. 2009WA264B ("Understanding Controls on Cyanobacteria Blooms: Vancouver Lake as a Model System") - Articles in Refereed Scientific Journals - Lee T, Rollwagen-Bollens G, Bollens, S. (in review). The Influence of Water Quality Variables on cyanobacteria blooms and phytoplankton community composition in a shallow temperate lake. *Lake and Reservoir Management*.
2. 2010WA308B ("Water Quality Parameters Controlling the Photodegradation of Herbicides in Surface Waters in the Columbia Basin, Washington") - Articles in Refereed Scientific Journals - Furman, O., Miao Yu, A.L. Teel, and R.J. Watts. 2013. Water Quality Parameters Controlling the Photodegradation of Two Herbicides in Surface Waters of the Columbia Basin, Washington. *Chemosphere* 43: 1734–1741
3. 2010WA317B ("Understanding the Vulnerability of Columbia Basin Irrigated Agriculture to Predicted Climate Changes using a Coupled Hydrological-crop Model") - Conference Proceedings - Barber, M.E., J.C. Adam, K. Rajagopalan, G. Yorgey, and R. Mahler, 2013. Impacts of Climate and Municipal Water Demand Changes on Ecological Flows in the Columbia River Basin, USA, *Ecosystems and Sustainable Development IX, WIT Transactions on Ecology and the Environment*, 175, ISSN 1743-3541, Bucharest, Romania, June 2013.
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6. 2010WA317B ("Understanding the Vulnerability of Columbia Basin Irrigated Agriculture to Predicted Climate Changes using a Coupled Hydrological-crop Model") - Articles in Refereed Scientific Journals - Liu, M., J.C. Adam, and A.F. Hamlet, 2013. Spatial-temporal variations of evapotranspiration and runoff/precipitation ratios responding to the changing climate in the Pacific Northwest during 1921-2006, *Journal of Geophysical Research: Atmospheres*, doi: 10.1029/2012JD018400.