Wyoming Water Research Program
Annual Technical Report
FY 2008
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 agencies involved in water related activities in the State, 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, which was approved by the 2002 Wyoming Legislature, to identify water related research needs, coordinate research activities, administrate 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 research and education. Another goal of the program is to promote coordination between the University, State, and Federal agency personnel. The WRP provides interaction from all the groups involved rather than being solely a University of Wyoming research program.

In conjunction with the WRP, an Office of Water Programs 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 Wyoming Water Research Program (WRP) is a cooperative Federal, State, and University effort. All activities reported herein are in response to the NIWR program, with matching funds provided by the Wyoming Water Development Commission and the University of Wyoming. While the WRP is physically housed in the Civil and Architectural Engineering Department, the 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 and select projects for funding. The Director coordinates all activities.

Reports for nine research projects are given herein. The reports consist of three final reports and six reports for continuing projects. In addition to the continuing projects, the Wyoming Institute is currently supporting three new research projects which were initiated March 2009. The three new projects are listed below, but annual reports are not included herein. The three new projects were selected by the Institute Advisory Committee based upon peer reviews and subsequent ranking by the Advisory Committee of proposals received in response to the Institute FY09 RFP.


New Projects (as of March 2009) are: (1) Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming II: Further Airborne Cloud Radar and Lidar Measurements, Bart Geerts, Dept of Atmospheric Science, UW, Mar 09 thru Feb 12; (2) Effects of Warm CBM Product Water Discharge on Winter Fluvial and Ice Processes in the Powder River Basin, Robert Ettema, Engineering and Applied Science, and Edward Kempema, Dept of Geology and Geophysics, UW, Mar 09 thru Feb 11; and (3) Characterization of Algal Blooms Affecting Wyoming Irrigation Infrastructure: Microbiological Groundwork for Effective Management, Naomi Ward, and Blaire Steven, Dept of Molecular Biology, UW, Mar 09 thru Feb 11.
Real-Time Monitoring of E. Coli Contamination in Wyoming

Basic Information

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Publication


Real-Time Monitoring of E. Coli Contamination in Wyoming Surface Waters
Dr. Paul E. Johnson
Year 3 Report

Abstract
This project shows the feasibility of economical, simultaneous, real-time detection of individual *Escherichia coli* and their viability in surface waters. The Clean Water Act requires states to monitor surface waters for fecal coliforms or specifically for *E. coli*. Fecal coliform monitoring is an indicator of the sanitary quality of the water and can determine the extent of fecal contamination in the water from warm-blooded animals. A low-cost, portable, highly sensitive, self-contained single cell detection prototype for *E. coli* enumeration was developed for rapid monitoring of surface waters, including streams, rivers, and lakes. With USGS/WWDC funding, the P-I and his team have demonstrated and significantly improved an innovative technique for detection of pathogenic microorganisms in surface water, economically and in real time. This technology is based on LED-induced fluorescence of antibody- and DNA labeled cells. The project demonstrated the detection of individual *E. coli* simultaneously in two wavebands in order to detect and determine viability of individual microorganisms. The suspended bacteria are stained using both an immunofluorescent antibody and a fluorescent cell viability label. The resulting aqueous sample is passed as a stream in front of an LED, which excites the fluorescent labels (Figures 1 and 2). The resulting fluorescence is measured with a CCD or CMOS imager using an innovative integration scheme (called Fountain Flow), giving a dramatically higher signal-to-noise ratio than conventional techniques. In addition, we are investigating the extension of the fountain flow technology to imaging, to provide increased discrimination capability among *E. coli*, other biological particles, and small geological particles.

Objectives
The major tasks of this 3-year project were to: 1.) fabricate and test a two-color, LED-illuminated detection system in order to simultaneously detect and determine the viability of *E. coli*, 2.) perform laboratory measurements on quantified *E. coli* samples to determine the detection efficiency and sensitivity of the two-color monitoring system, 3.) enumerate *E. coli* in stream and lake water samples using both our proposed method and the standard method currently recommended by the US Environmental Protection Agency, and 4.) determine the feasibility of a rare-cell, fountain flow imaging system based on an extension of our current technology, and 4.) fabricate and test a prototype fountain flow imaging system for proof of concept.

Progress
We completed and tested improvements on a low-cost, portable, highly sensitive, self-contained single-cell detection system for *E. coli* in surface waters, which greatly exceeds the current testing procedures in both speed and reliability. The goal of this project was the development of 1) a low-cost, rapid (<< 1 hour test), sensitive (< 5 cells/ml), portable, easy to use system for *E. coli* detection in raw surface water. Our objectives were to: 1) develop and test a system for simultaneous detection and viability testing of *E. coli* and 2) develop and test a proof-of-concept prototype for multi-spectral high resolution FF imaging. We completed the first objective, and the second is still being pursued, although limited funding precludes us finishing that in a timely way. This proof of concept will allow for the design and fabrication of a remote monitoring system that will automatically screen water in real time. Alternative methods necessitate the shipping of bulk water samples or concentrates to laboratories and labor-intensive screening technologies, which may include bulk water concentration, incubation, and culturing. These factors combine to impede overall routine monitoring for fecal coliforms in the field and preclude widespread, routine screening of surface waters.

Over the three-years of funding, we have:
• successfully fabricated a two-color detection system for detection of microorganisms,
• continued successful proof of concept experiments for a fountain flow (FF) imaging system, using a syringe pump to consistently stop fluorescent beads in the focal plane of the FFC,
• collected data on the two-color detection of amoebae in natural river water for a manuscript to be submitted this year,
• published a paper on the detection of E. coli in water to the journal Cytometry,
• published a paper on the detection of amoebae in natural river water using LED illumination, against a background of organic detritus, in the Journal of Applied Microbiology, and
• have pending patent applications for the software control of Fountain Flow and for cell sorting using Fountain Flow Cytometry. The latter allows for the separation of rare cells from a large volume of water, so that species identification can then be made using other techniques, such as PCR.

The paper that we have written and are about to submit to JAM concerns the use of Fountain Flow Cytometry (FFC) for detection of protozoa and bacteria in raw water with a two-color LED-illuminated FFC system. The system was tested with a flow throughput of 10 ml/minute and amoebae concentrations of 0.06 to 3 amoebae/ml. Two dyes were used, Chemchrom V6, a viability dye, and an R-Phycoerytherin immunolabel. Detections were made in two colors, simultaneously using two cameras and two LED illuminators. Water samples for the Tech River (France) were sampled and tested for background autofluorescence from organic and non-organic material. These experiments show that two-color simultaneous measurements allow us to successfully separate living amoebae at 0.5 to 4 amoebae/ml from background detritus and that we will be able to separate E. coli detections from background detritus. Our final experiment in this series, this summer and fall, will be to improve our detections by using RPE-CY7.

Figure 1. Schematic diagram of an LED-illuminated epifluorescent Fountain Flow Cytometer. A sample of fluorescently tagged cells flows through the flow cell toward the CMOS camera and fore-optics. The cells are illuminated in the focal plane by an LED. When the cell(s) pass through the CMOS camera focal plane they are imaged by the camera and lens assembly through the transparent flow cell window, and a filter that isolates the wavelength of fluorescence emission. The fluid in which the cells are suspended then passes by the window and out the flow cell drain tube.
**Figure 2.** The Fountain Flow™ Cytometer aluminum flow manifold as used in the device shown in Figure 1 (from Johnson et al., 2006). **Upper Panel:** The sample enters the flow block through a Tygon tube connected to a stainless steel tube and exits through a stainless steel tube. Two holes have been drilled into the aluminum flow block: an entrance hole and an exit hole. As the sample flows up the internal entrance hole, it passes through the focal plane of the CCD/CMOS camera. A Teflon tape gasket is sandwiched between the aluminum flow block and a circular window, and tightly held with a screw-on brass cap. The gasket is cut to form a channel through which the fluid is diverted into the exit hole. **Lower Panel:** A photograph of a working flow block with attached tubing.

**Student Support**

During this three-year project, the P-I employed one former undergraduate Pre-Med student, Chris Havens (BS graduate 2006), one geology student, Joseph Johnson (provisional graduate student), and one pharmacy graduate student, Anthony Deromedi in this research. The interaction among personnel of varying backgrounds has provided a highly educational experience for everyone in research biodetection technology.

**Publications in Preparation and Patents**

**Publications in Preparation**


**Patents Pending**


**Patent Granted**

1. Apparatus and methods for high throughput analysis of samples in a translucent flowing liquid, P.E. Johnson.
Presentations (2005-2008)
All presentations listed were invited.
2005 Cytometry Development Workshop, Asilomar, California
1. High-Throughput-Axial Imaging Flow Cytometry with LED illumination
2. Imaging Flow Cytometry
2006 Cytometry Development Workshop, Asilomar
1. High-Throughput-Axial Imaging Flow Cytometry with LED illumination
2. Imaging Flow Cytometry
2006 Select Water Committee Meeting, Wyoming State Senate
1. Detection of Pathogenic Organisms in Wyoming Surface Water
2007 Cytometry Development Workshop, Asilomar
1. Fountain Flow cytometry of microorganisms in complex matrices (milk & blood)
2. Cytometry of ultra-large multi-cellular organisms
Precipitation Measurement and Growth Mechanisms in Orographic Wyoming Snowstorms

Basic Information

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Publication
Abstract –

We review activities supported by our WWDC/USGS grant. The first is Jonathan Wolfe’s assessment of data from the Cheyenne National Weather Service Radar, combined with surface measurement of snowrate, and his parameterization of a radar reflectivity / snowrate relationship. Wolfe’s thesis was completed in 2007. The second is Binod Pokharel’s study of airflow and cloud processes inferred using Wyoming King Air and Wyoming Cloud Radar measurements made in orographic clouds formed over the Medicine Bow Mountains. Pokharel’s thesis was completed in 2009. The third is Bujidmaa Borkhuu’s study of snowfall measurement made at the Glacier Lakes Environmental Experimental Site during the winters of 2007 and 2008. This work entails a comparison of snow accumulations made at one of the sites being used to evaluate the efficacy of the Wyoming Weather Modification Pilot Project. Borkhuu’s thesis defense is planned for July 2009. Each of the theses presents significant findings; all three are being advanced to the level necessary for submission to a peer-review journal.

Proposal Objectives –

1) Contrast precipitation development in storms moving in from the west against those coming from the Great Plains.

With funding from WWDC, USGS and NASA seven University of Wyoming King Air flights were conducted in snowstorms with low-level westerly flow over the mountain ranges west of Laramie, and one flight in an “upslope” snowstorm over the Laramie Range, in which the low-level flow had an easterly component. The flight operations were conducted in January and February 2006. Profiles of Wyoming Cloud Radar reflectivity and Doppler velocity were collected on all flights. Storms of both types (low-level westerly and easterly flow) reveal strong turbulence in the lowest 500-1000 m above the ground along the slopes upwind of the crest. This boundary-layer turbulence is important in orographic precipitation generation; we are preparing a manuscript which reports that finding. In the one “upslope” storm we sampled, there was considerable wind shear in the layer between 1-2 km above ground level (AGL). This shear produced far less turbulence than inferred from analysis of the Doppler radar data acquired at lower altitude, suggesting that turbulence associated with snow generation occurred relatively close to the ground. Also with support from WWDC, USGS and NASA J.Wolfe collected Hotplate snowrate data on the ground, in both low-level westerly flow regimes, at the Glacier Lakes Environmental Experiment Site (GLEES) in the Medicine Bow Mountains, and in low-level easterly storms at a site east of the Laramie Range crest, near Cheyenne. A fair comparison of snowrate characteristics of the two storm types was not possible because of inaccurate measurements at the GLEES. The thesis work of J.Wolfe and B.Borkhuu address this inaccuracy, and is discussed below.
2) Acquire data by conducting flight transects across the Laramie Range and the Medicine Bow Mountains and to study how cloud depth, horizontal and vertical wind speed, thermal stability and properties of the aerosol ingested by winter orographic storms influence snow formation.

In the four WWDC/USGS/NASA cases analyzed by B. Pokharel in his thesis, a diverse combination of cloud depth and thermal stability was documented. This diversity, and the limited number of cases (B. Pokharel only analyzed cases which had aerosol measurements made up and downwind of the Medicine Bow Mountains), prohibits a climatological assessment. Consistency does emerge from Pokharel’s analysis of the horizontal and vertical wind fields derived from the Doppler-capability of the Wyoming Cloud Radar. Specifically, Pokharel documents low-level vertical shear of the horizontal wind and localized regions of ascending air in association with ridges that run perpendicular to the prevailing (westerly) wind direction. Pokharel concludes that assessments of airflow through orographic clouds, based on conventional measurements of the wind magnitude and wind direction, can only provide rough estimates of time available for precipitation particle growth. In contrast, the two-dimensional wind field available from the Wyoming Cloud Radar was promoted as a better product for evaluating precipitation processes in orographic clouds and for developing understanding of the efficacy of cloud seeding. In spite of this new application for the Wyoming Cloud Radar, it has its own limitations. Details are discussed in the thesis of B. Pokharel and in a manuscript we are preparing for journal submission.

3) Refine the Z_e-to-S parameterization applied to Weather Surveillance Radar measurements of Z_e acquired in shallow winter upslope snow storms.

This aspect of the study was conducted by J. Wolfe. His analysis reveals that the reflectivity-to-snowrate (Z_e-to-S) parameterization is temperature dependent, in a manner consistent with the combined action of ice nucleation and snowflake aggregation on snowflake concentration. Data was collected over the temperature range -20 °C to 0 °C. Wolfe’s temperature-dependent Z_e-to-S parameterization was found to produce snowrates that agreed well with those derived using the parameterization of Super and Holroyd (1998). This finding is significant because it indicates consistency among the data set utilized in the Wolfe thesis and by Super and Holroyd (1998). The result also points to a physical limitation in the use of radar measurements of reflectivity, or radar reflectivity combined with temperature, for making snowrate estimates. These limitations are discussed in more detail below. The significant advantage of radar-derived snowrates, versus those made with precipitation gauges, is that the radar-derived values are available for a broad area, extending out to as far as 100 km from the radar.

4) Intercompare snowrate measurements from two Hotplates to infer Hotplate measurement uncertainties.

In our Year-1 report we presented our decision to not collaborate with NCAR in this proposed intercomparison. Rather, we elected to calibrate our Hotplate sensor versus an accurate lab-based precipitation reference standard. In addition, the response of our Hotplate sensor to ventilation was also evaluated in the laboratory. Both of these effects were incorporated into the Wyoming Hotplate algorithm developed by thesis candidate B. Borkhuu. We elected this path after consultation with Dr. Roy Rasmussen, co-inventor of the Hotplate, and after obtaining legal permission to access the proprietary data necessary for developing the Wyoming Hotplate algorithm.
5) Evaluate consistency among Hotplate and Snotel snow accumulation measurements. These results are in the B. Borkhuu thesis. She concludes that the Snotel measurements (made at the Brooklyn Lake NRCS site) are positively biased due to registration of wind-resuspended ice particles. As is discussed below, this positive bias may be as large as a factor of two.

6) Quantify orographic precipitation enhancement, in the Medicine Bow Mountains, over time intervals shorter than that measurable by Snotel. It is our opinion that bias associated with snowrate measurement is profound and underappreciated, and that these complexities limit our ability to interpret snowrate measurements made at the GLEES. Having said this, we also recognize that a range of time response is available in the set of sensors operated at the GLEES (weekly to minute) and that there is merit to doing an examination of measurements from the fast-response snowrate sensors, especially after making an attempt to correct for snowrate bias. This analysis may be especially informative during study days that were modulated by cloud seeding. We have not attempted such an analysis, but will make the data available if a request is made.
Jon Wolfe Vitae –
Master of Science, Dept. of Atmospheric Science, University of Wyoming, May, 2007
Current Employment: National Weather Service, Portland, OR

Wolfe Manuscript Title and Abstract –
A Temperature Dependent Reflectivity/Snowrate Relationship for S-Band Radar
Jonathan P. Wolfe, Jefferson R. Snider and Bart Geerts

Weather radar offers a practical way of estimating snowfall rate with high spatial and
temporal resolution. Such remotely-sensed snowrates are useful for weather advisory and
hydrometeorology. In either application a relationship between equivalent radar reflectivity
\( Z_e \) and water equivalent snowrate \( S \) is needed. In the Rayleigh scattering regime (radar
wavelength much larger than snowflake diameter), the leading coefficient in the relationship
\( Z_e = \alpha \cdot S^\beta \) can be shown to vary with temperature-dependent properties of the snowflake size
distribution. We describe measurements, and a statistical analysis, leading to a temperature
dependence for \( \alpha \) which can be applied to wintertime upslope storms occurring in southeastern
Wyoming. This documented temperature-dependence for \( \alpha \) is suggestive of the combined
action primary ice nucleation and snowflake aggregation.
24 hr Snow Water Equivalent Accumulation Comparisons

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Values of the Hotplate and radar-derived snowrate on March 8, 2006. For the radar-derived snowrates a radar reflectivity acquired at tilt angles 0.5° and 1.5° and the parameterization developed in Jon Wolfe’s thesis were used. Radar reflectivities were acquired along the 299° radial connecting the Cheyenne National Weather Service Radar and the surface site where the Hotplate was located (25 km northwest of Cheyenne). The time lag apparent at ~15:00 and at ~17:00 UTC with maximum snowrate observed at 1.5°, next at 0.5° and finally at the Hotplate is attributed to the time it takes for snowflakes (fall speed ~ 1 m/s) to fall the 800 meter distance from the top of the 1.5° radar volume to the Hotplate. The plot also demonstrates that the radar is a more sensitive detector of snow. It is also possible that this discrepancy is due to negative bias in the Hotplate’s assessment of snowrate. This figure is from a manuscript in preparation for journal submission.

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a Coordinated Universal Time

b Data from the precipitation gauge operated at the Cheyenne, WY National Weather Service Office

c Based on the temperature-dependent $Z_r$-to-$S$ parameterization derived in Jon Wolfe’s thesis

d Based on the parameterization derived by Super and Holroyd (1998)
Binod Pokharel Vitae –
Master of Science, Dept. of Atmospheric Science, University of Wyoming, May, 2009
Current Employment: Dept. of Atmospheric Science, Research Scientist, University of Wyoming

Pokharel Thesis Title and Abstract –
The Removal of Ultrafine Nuclei in Mountain Wave Clouds

The smallest detectable atmospheric aerosol particles - ultrafine nuclei (UFN) with diameter between 0.003 and 0.015 \( \mu \text{m} \) - were studied in association with mountain wave clouds formed over the Medicine Bow Mountains located in southeastern Wyoming. Aircraft measurements of the UFN were made upwind and downwind of the cloud and used to estimate the in-cloud removal of those particles. Also, an airborne Doppler cloud radar was used to measure the horizontal and vertical components of the wind. The study was conducted on four days: January 18, 2006, January 26, 2006, January 31, 2006 and February 2, 2006.

In model simulations, an air parcel trajectory obtained from the radar wind field and a cloud parcel model were used to simulate UFN removal in the cloud. The trajectory/parcel model was initialized with the measurements made upwind of the cloud and was validated with cloud property measurements made near the top of the trajectory and with measured values of the UFN removal.

The model simulates the time-dependent size distributions of cloud condensation nuclei, cloud droplets, and ice particles. Based on the model, and its comparison to the observations, four conclusions are reached: 1) Approximately 50% of the UFN entering the cloud are removed during in-cloud transport, 2) the UFN are too small to initiate cloud droplet formation, 3) the removal of the UFN is dominated by their Brownian attachment to cloud droplets, and 4) the Brownian attachment of the UFN to ice particles contributes less than 10% to their removal.
Wyoming Cloud Radar measurements made on 20060118 over the Medicine Bow Mountains. Top panel is the field of radar reflectivity (expressed as decibels, $\text{dBZe} = 10\log_{10}(Z_e)$), the middle panel is the field of vertical-component Doppler velocity, and the bottom panel is the field of horizontal-component Doppler velocity (only available below the aircraft). Values presented in the middle panel were increased by 1.4 m s$^{-1}$ to account the contribution of the particle fall speed to the vertical-component Doppler velocity. The top and middle panels show the flight track of the King Air at 4300 m, and all the three panels show the derived air parcel trajectory. The air parcel trajectory for this case, and trajectories derived for three other study days, were the basis for B.Pokharel’s calculation of conditions experienced by an air parcel moving through the orographic cloud. The trajectory/parcel model is the basis for B.Pokharel’s assessment of ultrafine aerosol particle scavenging due to their Brownian attachment to cloud droplets and ice crystals.
Bujidmaa Borkhuu Vitae –
Master of Science, Dept. of Atmospheric Science, University of Wyoming, August, 2009

Borkhuu Thesis Abstract –
Snowfall at a High-elevation Site: A Comparison of Six Measurement Techniques

Diminishing annual snowpack in Rocky Mountain region is causing concern for water resource management and motivating improved techniques for wintertime (snow) precipitation measurement. At many high elevation sites in the Rocky Mountains the measurement of snow precipitation is confounded by wind. For example, at forested gauge sites both negative and positive wind-bias can occur, 1) due to the shadowing of a precipitation gage by trees (negative bias) and 2) due to the capture of wind-resuspended ice particles (positive bias). This work presents an analysis of data from six precipitation measurement systems operated near the forested Glacier Lakes Environmental Experiment Site (GLEES) located in the Medicine Bow Mountains of southeastern Wyoming. There are two objectives of the research: 1) to analyze the data sets for evidence of bias and 2) to recommend which of the systems is least affected by bias. The study demonstrates that gauge precipitation measurements made by the National Atmospheric Deposition Program at the GLEES are positively biased. The degree of this bias is a factor of two. Further, snowfall measurements made with the Yankee Environmental Systems Hotplate, and a comparison of that data to measurements made with three other measurement systems, show that all of the three (SNOTEL pillow, SNOTEL gauge and Vaisala VRG gauge) are biased positive relative to the Hotplate. Because the Hotplate measurement was made on a 30 meter tower, above the gauges, and also above the top of the forest canopy, this result indicates that a significant component of the accumulation recorded by surface gauges may be attributable to the inadvertent measurement of wind-resuspended ice particles.
Comparison of weekly precipitation from the two sensors (gauge and sample volume) operated at the GLEES site by the National Atmospheric Deposition Program (NADP). Precipitation amounts less than 0.1 mm/week are eliminated from the analysis. Left panel is a comparison for winter months (December, January and February) and the right panel is the comparison for summer months (June, July and August). The poor agreement during winter is attributed to registration of wind-resuspended ice crystals by the NADP gauge.

Accumulation from the six sensors at the GLEES starting on 23 March 2008. The decrease of Snotel pillow accumulation at day 21 is because of snowpack melting - daily-averaged temperature in excess of 0 °C. Prior to day 21 the daily-averaged temperature was significantly smaller (~ -10 °C) and registration of wind-resuspended ice crystals by gauges other than the Hotplate is thought to explain the discrepancy in accumulation. The Hotplate was operated on a 30 m tower, 5 m above the tree tops and 30 m above the VRG gauge.
Published Conference Presentations –

Conference Presentations with Abstracts –
Pokharel, B., J.R.Snider and D.Leon, Trajectories and microphysics within wintertime mountain wave clouds: Implications for the aerosol size distribution, 15th International Conference on Clouds and Precipitation, Cancun, Mexico, 2008
Geerts, B., Detailed vertical structure of orographic precipitation development in cold clouds. Oral presentation at the 16th Conf. on Mountain Meteorology, American Meteorological Society, Santa Fe, NM, August 2006
Wolfe, J., and J. Snider, Validation of radar-estimated upslope snowfall in Southeastern Wyoming, 32nd Conference on Radar Meteorology, Albuquerque, NM, October 2005

Presentations without Abstract –
McIntyre, H., NASA06 observations of orographic precipitation types over the Snowy Range under different stability and flow regimes, UW-NCAR RAL workshop in Boulder, CO, September 6, 2006
Snider, J.R., Aerosol scavenging in winter orographic clouds, presented at the Wyoming-NCAR RAL workshop in Boulder, CO, September 6, 2006
Students Supported by the Grant -
Borkhuu, B., Snowfall at a high-elevation site: A comparison of six measurement techniques, MS thesis, Dept. of Atmospheric Science, University of Wyoming, 2009
Casey, G., A comparison of observed vs. predicted snowfall amounts over the mountains of Southeastern Wyoming in Jan-Feb 2006. An undergraduate research term paper, Dept. of Atmospheric Science, University of Wyoming, 2006

Funding that was Complimentary to this WWDC/USGS Grant –
Grants from NASA and DEPSECOR were used to support two students (Wolfe and Pokharel) who are conducting analyses of the WWDC/USGS data set as part of their MS thesis research.

References –
Tracing Glacial Ice and Snow Meltwater with Isotopes

Basic Information

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<td>David Williams</td>
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Publication

Tracing glacial ice and snow meltwater with isotopes
Principal Investigator – David G. Williams
Co-Principal Investigators – Jessica Cable, Kiona Ogle
Final Project Report

Abstract
This report describes accomplishments for the two-year project investigating temporal dynamics of glacial ice and snow meltwater, rainfall and baseflow contributions to streamflow of Dinwoody Creek in the Wind River Range of western Wyoming. The primary objectives were to 1) characterize diurnal, seasonal and interannual variation in the isotopic composition of water in Dinwoody Creek, 2) quantify the contribution of baseflow and surface runoff to stream discharge using isotopic methods, and 3) partition the surface runoff component of stream discharge into that derived from glacial melt, snowmelt, and summer precipitation. This project involved a collaboration among the University of Wyoming Stable Isotope Facility, directed by the project PI (Williams), Dr. Jessica Cable of the Department of Botany and Dr. Kiona Ogle of the Departments of Botany and Statistics. Dr. Cable led the field and laboratory studies and statistical modeling and will be the primary author of a forthcoming journal article describing the findings from this project to be submitted in June 2009 to Hydrological Processes. Dr. Cable was supported part time as a postdoctoral student on this project and was mentored by Drs. Williams and Ogle. Dr. Ogle provided valuable leadership on the statistical modeling used to partition streamflow and quantify the contribution of glacier meltwater.

We estimated the fractional contribution of glacier meltwater to flow in Dinwoody Creek on seasonal and interannual time scales. The stable isotope composition of water (oxygen-18 and deuterium) from the Dinwoody Creek watershed and glacier system was determined on a temporally intensive scale in 2007 and 2008. Field sampling of the primary contributors to streamflow, namely snow melt, glacier melt, rain, and baseflow, were collected during the summers of 2007 and 2008. Stream samples were collected every 48 h over the entire melt season from mid-April to late October using an automated stream sampler placed beside an unimpaired USGS gauging station low in the watershed. The data were analyzed with a hierarchical Bayesian framework that allowed integration of temporal and spatial autocorrelation in the isotope data. Glacial melt contributed a significantly large proportion to streamflow in a low flow year (2007) and when streamflow was low during a high flow year (early and late summer 2008). In 2008, a large and persistent snowpack and associated melt dominated streamflow in the middle of the summer. Summer rainfall had minimal contribution to streamflow. Our findings strongly support the assertion that loss of alpine glaciers in the Wind River Range with climate warming will substantially reduce streamflow, but only during periods when snowmelt contributions are low.

Overview and Significance
Widespread glacier recession has been occurring over the past half century and has accelerated since the early 1990’s in conjunction with the post 1970’s warming trend (Kundzewicz et al. 2007). Continued decline of glacier mass will result in a transient increase in river discharge (Aizen et al. 1997, Kundzewicz et al. 2007). It is estimated that 1/6th of the global population derives much of their water from glacier and snow-fed watersheds (Barnett et al. 2005, Kundzewicz et al. 2007). For example, glacier meltwater contributes to nearly 70% of the Ganges discharge, which supports a large human population (Singh et al. 1997, Singe and Jain...
The impacts of glacier shrinkage on social, economic, and ecological systems are multi-faceted because the surge of glacier meltwater into rivers will be transient (e.g., Kundzewicz et al. 2007). For the systems depending on the glacier-fed late summer water supply, the post-surge decline in glacier meltwater may be detrimental (Mark et al. 2003, Singh and Bengtsson 2004, Barnett et al. 2005). In conjunction with glacier shrinkage, many of these systems will suffer from altered precipitation regimes, drought, and reduced snowpack, further exacerbating the effects of climate change on water supply (Barnett et al. 2005, Kundzewicz et al. 2007, Stewart 2009). The loss of mountain glaciers in the western U.S., particularly Wyoming, may exacerbate the drought situation faced by water resource planners concerned with allocating water for agricultural and municipal use. The contribution of glacier meltwater to stream discharge in Wyoming is not well quantified.

Stable isotope composition (deuterium [δD] and oxygen 18 [δ18O]) of water have successfully been used as naturally occurring hydrologic tracers to constrain estimates of the contributions of different water sources to stream flow, including snowmelt, glacier meltwater, and groundwater baseflow (Behrens et al. 1971, 1979; Dinçer et al. 1970; Martinec et al. 1974; Rodhe 1981, Hooper and Shoemaker 1986, Obradovic and Sklash 1986, Maulé and Stein 1990). Although there have been a number of important hydrological investigations in Wyoming that have employed isotope tracers (e.g., Schuster et al. 2000, Coplen and Kendall 2000, Naftz et al. 2002, Frost et al. 2002, Frost and Toner 2004, Benjamin et al. 2004), the use of isotopic tracers in studies to identify contributions of rain, snowmelt, groundwater baseflow, and glacier meltwater to stream flow in alpine catchments has received little attention. Potential effects of climate variability, loss of alpine glaciers, and forest disturbances on stream flow are highly uncertain. Stable isotope tracers combined with Bayesian analysis techniques can play a prominent role in reducing this uncertainty. In this study, we used isotopic tracers to distinguish sources of stream discharge in Dinwoody Creek in the Wind River Range by partitioning stream flow into that derived from baseflow, glacier melt, snowmelt, and summer precipitation. We analyzed the data in a hierarchical Bayesian framework, thereby fully accounting for uncertainty and incorporating temporal and distance autocorrelation.

Objectives
The principal scientific objective of this work was to evaluate isotopic tracers at natural abundances for their ability to distinguish sources of flow in a glacier-fed stream. Specific objectives were to:
1. Characterize seasonal and interannual variation in isotopic composition of a glacier fed stream in the Wind River Range;
2. Quantify the contribution of baseflow and surface runoff to stream discharge using isotopic methods; and
3. Partition the surface runoff component of stream discharge into that derived from glacial melt, snowmelt, and summer precipitation.

Methodology
Using Stable Isotopes for Hydrograph Partitioning. Isotopic tracers are useful for constraining estimates of source contributions to stream flow and are easily employed in remote field locations. Isotopic measurements can be coupled with stream flow measurements to partition the contributions of different sources. Hydrograph separation using isotope tracers is based on mass conservation for water and tracer (Genereux and Hooper 1998). Successful
hydrograph or stream flow separation using isotopes requires that: (1) the isotopic content of the contributors significantly differs from that of the primary glacier-fed river; (2) the contributing sources maintain a constant isotopic content; (3) vadose water does not contribute significantly to stream flow; (4) surface storage contributes minimally to stream flow after a precipitation event occurs.

The first of these requirements is obvious, and the latter requirements to some degree can be dealt with by appropriately sampling the sources of stream flow with enough frequency to either account for this variation or ignore it. Additional isotopic tracers can be included during periods when more than one source contributes to stream flow (e.g., glacier melt and snowmelt). For instance, $\delta D$ and $\delta^{18}O$ together can be measured if the two sources isotopically differ; then partitioning of these sources can be accomplished by examining the isotope data in dual-isotope space.

Alpine glaciers are complex water storage compartments that to some degree behave isotopically like a well mixed lake. Because the current year’s snowmelt and summer rain can be trapped within the glacier in fissures to be frozen during winter, the melting of the glacier can release water that has been added from recent inputs together with water stored for decades to centuries. Therefore, it is difficult to predict how the isotopic composition of glacier melt water will differ from the current year’s snowmelt or rainfall. However, if one assumes that the glacier mass is an integrator, then melt water from the glacier may be attenuated isotopically relative to seasonal and interannual isotopic variations in meteoric waters. For that reason alone, glacier melt water can be distinguished isotopically from the current year’s meteoric inputs. The $\delta D$ and $\delta^{18}O$ compositions of precipitation co-vary but their correlation can be affected by evaporation, sublimation, re-melting, and exchange with atmospheric vapor. The offset due to these fractionation processes can easily be detected in the deuterium excess value of the water sample. Because these processes are likely to play a role in glacier melt and accumulation, both $\delta D$ and $\delta^{18}O$ should be measured as together they may reveal unique signatures of different source waters contributing to stream flow in a snowmelt driven catchment.

Field Sampling of Water.
This study was conducted in 2007 and 2008 on Dinwoody Creek, a primary tributary of the Wind River Range fed principally by Dinwoody Glacier (Figure 1). To capture temporal variation in the isotopic composition of Dinwoody Creek, a 24 bottle stream sampler (Teledyne Isco, Inc, Lincoln, NE) was installed beside an unimpaired USGS gauging station (# 06221400, 1981m asl) to collect stream water samples every 2 days at daily peak flow (~ 3 pm) from mid-spring just prior to the onset of snowmelt to late fall. A sample was collected by hand in mid-winter when streamflow was dominated by baseflow. Mineral oil was added to the collection bottles to prevent evaporation and isotopic enrichment. The stream sampler was located 36 km downstream from Dinwoody Glacier and integrated a watershed area of 228 km$^2$ (USGS),

![Figure 1. Location of study area, Dinwoody Glacier, and the stream sampler in the Wind River Range, WY. The white stars in the right-hand panel are the sampling locations within the watershed.](image-url)
resulting in extensive spatial and temporal integration of watershed isotope and stream flow information. To determine the isotopic signatures of the source waters (rain, snow and glacier meltwater), we conducted summer field trips in both 2007 and 2008. In 2007 and 2008 we sampled in late summer (August) and in 2008 we sampled also in the early summer (early July). The early summer trip was the primary snowmelt period, and the late summer trip coincided with the period of maximum glacier melt. During each trip, we collected glacier meltwater from the tongue of Dinwoody glacier, the current year’s snowmelt (through direct sampling of melting snow), and precipitation (through opportunistic sampling). The contribution of glacier water to stream flow was assessed using Bayesian statistical modeling. This aided in hydrograph separation when integrated with data collected at the stream gauge. All samples were analyzed for δD and δ18O composition at the University of Wyoming Stable Isotope Facility.

Hierarchical Bayesian Analysis. A hierarchical Bayesian (HB) modeling approach (e.g., Berliner 1996; Clark 2005; Ogle and Barber 2008; Wikle 2003) was used to analyze the stable isotope data. The HB method provides a fully consistent statistical framework for analyzing the data within the context of a mixing model. The HB model has three components: (1) the data model that defines the likelihood of the observed data; (2) the mixing model and the models for the fractional contributions of different source waters; and (3) the parameter model that defines the prior distributions for the mixing model parameters and variance terms.

The first part of the data model combines the data likelihoods for observed δD and δ18O data from the source waters. We transformed the δ18O values by multiplying all the data by 2.5 to attain equal variation between the δD and δ18O data. We assume the isotope data (δD and δ18O) from the four water sources fit a multivariate normal distribution model with a mean and a precision covariance matrix. The multivariate normal distribution model accounts for correlation between the δD and δ18O data. The means for rain (r), glacier (g), and snow (s) source waters and the standard deviations for all four sources (including baseflow) are given by relatively diffuse, non-informative priors that come from a wishart distribution. Baseflow is a mixture of rain, snow, and glacier meltwater, so the mean for
baseflow (b) is given by the sum of means for these three sources, each with their own fractional contribution.

The second part of the data model is for the isotope data from Dinwoody Creek. We assume that Dinwoody Creek (stream) isotope data are given by a bivariate normal distribution with a mean and a covariance matrix. The data vary by time (T) and distance from Dinwoody Glacier (D). The mean stable isotope values for the stream are given by a mixing model, which is the sum of the fractional contribution ($p$) of each source multiplied by its isotope value, given by the source mean values. The $p$’s for rain, snow, and glacier were modeled as a function of time, and the $p$ for glacier was also modeled as a function of distance from glacier.

The fractional contribution of each source was multiplied by the streamflow ($\text{ft}^3\text{s}^{-1}$) data from the USGS stream gauge to determine the flow of water contributed by each source. We ran four chains for 5000 iterations, and we thinned every 100 while running the model and thinned every 5 after running the model. We discarded the first 400 samples, and this resulted in a total of 3680 samples for calculating the posterior statistics. The model fit the data well ($\delta^{18}$O: $R^2 = 0.77$, observed = 1.2*predicted + 3.2; $\delta$D: $R^2 = 0.95$, observed = 1.1*predicted + 13.1).

**Results**

Air temperatures and rainfall were similar between 2007 and 2008 (Figure 2a). Higher snowfall in 2008 resulted in a more persistent summer snowpack and higher streamflow in the summer of 2008 (Figure 2b). Abrupt increases in tritium values of stream water occurred with the onset of spring streamflow in 2008 (Figure 2b). The stable isotopes of stream water collected at the stream gauge showed distinct seasonal trends, with values becoming more depleted from the beginning to the middle of the summer, and then abruptly becoming more enriched from the middle of the summer into the fall (Figure 2c).

Results from the HB analysis show that glacier melt water dominated streamflow throughout the summer of 2007, followed by snow melt water, rain, and baseflow (Figure 3a). In the summer of 2008, glacier melt water dominated stream flow early (until ~ June 1st) and late in the summer (after August 1st), and snow melt water contributed to the highest stream flow in the mid-summer (Figure 3a-c). This is in accordance with field observations, where a large snowpack was observed in 2008 but not 2007. High stream flow is associated with a higher contribution of snow melt water (Figure 3a-c).
3). Baseflow consisted of 49% snow meltwater, 39.4% glacier meltwater, and 12% rain (Table 1).

Table 1. The mean and 95% credible interval for the percent contribution of snow meltwater, rain, and glacier meltwater to baseflow.

<table>
<thead>
<tr>
<th>Source water</th>
<th>Mean [2.5%, 97.5%]</th>
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<tr>
<td>Glacier</td>
<td>39.4 % [0.43 %, 36.8 %]</td>
</tr>
<tr>
<td>Rain</td>
<td>12.0 % [0.11 %, 11.5 %]</td>
</tr>
<tr>
<td>Snow</td>
<td>48.6 % [0.42 %, 51.2 %]</td>
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</table>

We show variation in estimates of the contribution of glacier melt and snowmelt to streamflow, which broadens the potential role of either source throughout the summers of 2007 and 2008 (Figure 3c). We note that although the stable isotope values for glacier and snowmelt water were very similar (Table 2), incorporating time and distance effects into the model constrained estimates of $p$ for all the sources. Further, our conclusions about the differences in the temporal contributions of snow and glacier melt water to streamflow are supported by the tritium data (Figure 2b). The tritium data show promise in distinguishing between snow and glacier meltwater.

Table 2. Predicted estimates of the mean and credible interval for the isotopic value of the water sources.

<table>
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<tr>
<th>Isotope</th>
<th>Water source</th>
<th>Mean [2.5%, 97.5%]</th>
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<td>$\delta^D$</td>
<td>Baseflow</td>
<td>-125.1‰ [-135.6‰, -112.2‰]</td>
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<tr>
<td></td>
<td>Glacier</td>
<td>-134.5‰ [-136.8‰, -132.0‰]</td>
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<tr>
<td></td>
<td>Rain</td>
<td>-39.57‰ [-54.68‰, -24.22‰]</td>
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<tr>
<td></td>
<td>Snow</td>
<td>-138.7‰ [-142.6‰, -135.0‰]</td>
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<tr>
<td>$\delta^{18}O$</td>
<td>Baseflow</td>
<td>-16.96‰ [-18.31‰, -15.22‰]</td>
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<tr>
<td></td>
<td>Glacier</td>
<td>-18.24‰ [-18.56‰, -17.92‰]</td>
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<tr>
<td></td>
<td>Rain</td>
<td>-5.89‰ [-7.46‰, -4.25‰]</td>
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<tr>
<td></td>
<td>Snow</td>
<td>-18.65‰ [-19.23‰, -18.04‰]</td>
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Conclusions

In this system, interannual variation in streamflow was largely due to differences in snowpack, where the reduced snowpack in 2007 was reflected in lower streamflow compared to 2008. Compared to baseflow and rain water, the large and fairly consistent interannual
contributions of glacier meltwater maintained streamflow in low flow years (contributing an average of 59% in 2007), and early and late in the summer (pre and post-snowmelt) in high flow years (contributing an average of 69% early summer and 53% late summer in 2008). ENSO may play a role in affecting the isotope values we observed. The transition between 2006 and 2007 was a warm or El Niño phase and the transition between 2007 and 2008 were a cold or La Niña phase (NOAA, 2009). Thus, the temperature of the sources of moisture for each year may have differed, and impacted the stable isotope composition of the snowpack. Continued reductions in glacial mass in the coming decades will reduce streamflow during critical times, such as dry years and dry parts of the year. Thayyen et al. (2006) also found glacier melt water to sustain streamflow in dry years in a small catchment in the Himalayas. While it is clear that variation in snowpack will increase variation in streamflow and water supply, glacier melt water is a somewhat constant “background” water supply that is declining. This consistency of water for streamflow might be important for water planning in the coming years in Wyoming.

Using a dual stable isotope approach in this study was useful when accounting for temporal and spatial autocorrelation in the isotope data in a hierarchical Bayesian framework. We found that when distance and time were not accounted for, the glaciemelt and snowmelt contributions were not discernable. The HB approach was powerful in this study because we could fully account for variation and estimate uncertainty in the contributions of glaciemelt and snowmelt water to streamflow.

Student support information

One postdoc, one graduate student, and one undergraduate student were supported in Year 1 and one postdoc and one part-time technician were supported in year 2 of this project. The postdoc, Dr. Jessica Cable, was supported at 0.25 time from June 2007 to March 2009. One graduate student, Mr. Peter Koenig, was supported on the project in Year 1 from March 2007 to June 2007. Mr. Koenig initiated the field and lab studies. One part-time undergraduate student, Mr. Patrick Juancorena, was supported on the project in Year 1. Mr. Juancorena assist with laboratory work associated with the project. Ms. Sarah Bachman was supported as a part time technician in Year 2 of the project. She assisted with field sampling and laboratory work in Year 2 of the project.

Awards and achievements

Dr. Jessica Cable, the postdoc working on this WWDC project, has successfully acquired $5000 funding from the National Park Service to conduct a parallel study on glaciated basins using isotopic tracers in Grand Teton National Park, WY. The title of her award is: Using stable isotopes of water to determine the contribution of glacial melt to streamflow and plant water use in Grand Teton National Park. Dr. Cable is the PI for this new project funded by the UW-NPS Research Center.

Literature Cited


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Publication


Year 2 Interim Progress Report

By:

Fred L. Ogden, Ph.D., P.E., P.H.
Mohamed Abdel-Hafez, M.S., Ph.D. student
Department of Civil & Architectural Engineering
University of Wyoming
Laramie, Wyoming

Melinda Harm-Benson, J.D., Asst. Professor
Department of Geography
University of New Mexico
Albuquerque, New Mexico

April 25, 2009
Statement of problem:

Both ground water and surface water are very important components of water resources in Wyoming. Since they are coupled in riparian areas, management strategies that neglect the interaction between them penalize senior surface water rights to the benefit of junior ground water rights holders within the prior appropriation water rights system. The Wyoming State Engineer faces a problem in deciding which wells need to be shut off first and on what basis to prevent impairment of senior surface water rights.

Methodology

A simulation model representing a combined hypothetical aquifer and stream has been developed using MODFLOW-2000 to capture parameter sensitivity, test management strategies and guide field data collection campaigns to support modeling. The Groundwater Modeling System (GMS version 6.5) was selected as the pre- and post-processor for MODFLOW-2000 input and output data.

Legal Analysis Results to date:

1) Detailed investigation of conjunctive groundwater/surface water management strategies employed in prior-appropriation jurisdictions; COMPLETE
2) Determination of the legality of the management strategies identified in Objective 1) within the context of Wyoming law. Management strategies that pass this test will be “candidate strategies”; COMPLETE
3) Translation of the candidate strategies into a set of quantitative operational rules that can be logically used to generate input to a numerical model of conjunctive management; COMPLETE

o Final report of the legal analysis will be complete in summer of 2009. This will include:
  $ a complete list of existing viable potential strategies for conjunctive management of surface and groundwater rights
  $ identification of candidate strategies
  $ implications for existing state law
  $ Once finalized, we will peer review of findings with water experts in the field.

• Once the report is finalized, we will stand ready to advise the SEO as needed.

Groundwater Modeling Results to date:

The model variables were divided into three groups. The first group represents the ground water parameters, while the second group represents the surface water parameters and the third group represents well system parameters.

Ground water parameters:

1. Aquifer geometry (length, width, and thickness)
2. Hydraulic conductivity
3. Saturated thickness
4. Water Table slope (monitoring well levels)
5. Recharge
Surface water parameters:
1. River stage
2. Conductance (river bed hydraulic conductivity)
3. Longitudinal slope
4. River bed thickness

Wells system parameters:
1. Pumping discharge
2. Distance from the river

A model with one layer was developed using dimensions of 2000 m width, 5000 m length, and 140 m depth. The model represents an unconfined aquifer, a river and a group of pumping wells. The aquifer boundary condition through the model width was defined as specified head while the aquifer boundary condition through the model length was defined as no-flow boundaries. The initial groundwater slope was selected to be 0.001 and is parallel to the stage of the river. The initial heads, simulation domain and model description are shown in Fig. 1.

Figure 1. Model description and simulation domain

The hydraulic conductivity, saturated thickness, and recharge were previously estimated during the Regional Aquifer System Analysis (RASA) project (Gutentag et al., 1984). So, the hydraulic conductivity chosen for study ranged from 3 to 15 m/d (9.84 to 49.2 ft/d), while the saturated thickness was chosen to range from 100 to 180 m (321 ft to 590 ft). Recharge values ranging from 0.03 mm/d to 3.0 mm/d were tested.

Steady-State Sensitivity Results
The conductance of the river is dependent on the river stage. Based on river width 9 m, bed conductivity of 0.53 m/d, and 0.02 m length of flow, the river conductance was
calculated (Glover, 1983). From the depth and wetted perimeter, river flow was calculated using Manning’s equation based on a river slope value of 0.001, Manning’s $n$ value of 0.025. The pumping system was represented with 9 wells, 3 wells in each row to represent a matrix 3x3. The reason for choosing this well arrangement was to identify the confounding influence of multiple pumping wells. The well pumping rates ranged from 3000 m$^3$/d to 6000 m$^3$/d (1.2 to 2.4 cfs or 538 to 1078 gpm). These rates were chosen to represent typical irrigation well capacity. The distance from the river to the well group was chosen to vary from 100 to 900 m (321 to 2952 ft). A summary of the range of model input values is shown in Table 1.

### Table 1. Model input parameters tested

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<tr>
<th>Hydraulic Conductivity (m/d)</th>
<th>Saturated Thickness (m)</th>
<th>Recharge (mm/d)</th>
<th>River Stage (m)</th>
<th>River bed Conductance (m$^3$/d)</th>
<th>River Flow m$^3$/d (cfs)</th>
<th>Pumping Discharge m$^3$/d (cfs)</th>
<th>Well Distance (m)</th>
</tr>
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<td>3</td>
<td>100</td>
<td>0.03</td>
<td>1</td>
<td>298</td>
<td>860,431 (351)</td>
<td>3000 (1.23)</td>
<td>100</td>
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<tr>
<td>6</td>
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<td>-</td>
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<tr>
<td>9</td>
<td>140</td>
<td>0.3</td>
<td>2</td>
<td>353</td>
<td>2,443,800 (1000)</td>
<td>4000 (1.64)</td>
<td>500</td>
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<tr>
<td>15</td>
<td>180</td>
<td>3.0</td>
<td>3</td>
<td>407</td>
<td>4,366,350 (1785)</td>
<td>6000 (2.45)</td>
<td>900</td>
</tr>
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The model grid resolution was refined near the wells to increase the precision of simulations near wells. This approach is commonly used to more accurately predict drawdown, the effects of well interference, and effects on surface waters. A sensitivity analysis involving 1620 MODFLOW simulations to steady-state using the model independent parameter estimation (PEST) scheme showed the average sensitivities of the different input parameters as shown in Figure 2.

![Parameter sensitivity](image)

**Figure 2.** Model parameters sensitivity weights under steady-state conditions. Note that the weight on the vertical axis of this chart is dimensionless.
There was no effect of changing the saturated thickness on the leakage from the river. However, the range of saturated thickness tested thus far is quite large. Smaller values will be used in the year 3 efforts, and they are likely to have a more significant effect in terms of model sensitivity. The effect of the pumping rate was most significant. Whenever the pumping rate increases, the river leakage increases. Also, the river leakage is strongly dependent on the aquifer hydraulic conductivity. The effect of the pumping discharge and the hydraulic conductivity is shown in Figure 3 for a recharge value of 0.03 mm/d, river stage of 1 m and distance of 100 m from the well group to the river.

![Figure 3](image-url)

**Figure 3.** Effect of the pumping discharge and hydraulic conductivity for wells pumping 3000, 4000, 5000, and 6000 m³/d.

The increase of recharge leads to a decrease of the leakage from the river. This can be demonstrated by comparing Fig. 3 with Fig. 4 which has the same input values except the value of recharge, which was increased to a value of 3.0 mm/d.

Increasing the river stage has an effect on the river leakage. When the river stage is increased, the total amount of the river flow increases greatly compared to the increase in the river leakage to the aquifer. So, the (river leakage/river flow) ratio decreases with increase of the river stage. This can be exhibited by comparing Fig. 3 with Fig. 5 which has the same input values except for the river stage value which was increased from 1 to 2 m.
Figure 4. Effect of increasing recharge

Figure 5. Effect of increasing river stage.
Unsteady Simulation Results

We found that in unsteady simulations, the distance from pumping well to river has a great effect. For instance, we consider the case where recharge is 0.03 mm/d, river stage is 1 m, aquifer hydraulic conductivity is 3 m/d, pumping discharge is 3000 m$^3$/d, and the specific yield is 0.15. The well group was pumped for 6 hours duration after 6 hours of model warm-up time. For these input values, it was found that the river leakage decreases with the increase of the distance of the well from the river until 400 m. Beyond 400 m distance from well to river, the river leakage is constant and does not change at all. This is of a great importance, as it helps deciding which wells are influencing streamflow. The effect of the well distance for the previous presented input data is shown in Fig. 6.

The previous simulations were repeated for pumping rates of 4000 m$^3$/d and 6000 m$^3$/d, respectively. With increasing the pumping rate, the distance after which there is no effect of the pumping on the river leakage increases. The distance increased to 500 m for a pumping rate of 4000 m$^3$/d and 600 m for pumping rate of 6000 m$^3$/d as shown in Fig. 7 and Fig. 8.

![Figure 6. Effect of pumping rate 3000 m$^3$/d on the river leakage.](image-url)
The investigation of the 3x3 well matrix was reduced to a simpler 1x3 well systems to simulate all the different possible combination of operating well at different distances.
from the river and in turn examine its response with the different model variables. The simulation duration was chosen to be 40 days. The effect of different recharge values (0.03 mm/d, 0.3 mm/d, 3.0 mm/d) is presented in Figs. 9, 10 and 11. As before, river leakage increases with decreasing recharge.

The effect of different river stage values (1, 2, and 3 m) was simulated and this effect is shown in Figures 12, 13 and 14. The river stages have almost no effect on the river leakage in the case of low flow stages for transient simulations.

The effect of various values of aquifer hydraulic conductivity (3, 6, 9, 12, and 15 m/d) was investigated and the results are presented in Figs. 15 through 19. The river leakage increases with the increase of the aquifer hydraulic conductivity.

The effect of pumping rate was examined using pumping rates of 3000, 4000, and 6000 m$^3$/d. Results of these simulations are presented in Figures 20 through 22. The river leakage increases with the increase of the pumping rate.

![Diagram](image_url)

Figure 9. Effect of recharge rate = 0.03 mm/d on the river leakage.
Figure 10. Effect of recharge rate = 0.3 mm/d on the river leakage.

Figure 11. Effect of recharge rate = 3.0 mm/d on the river leakage.
Figure 12. Effect of river stage 1 m on the river leakage.

Figure 13. Effect of river stage 2 m on the river leakage.
Figure 14. Effect of river stage 3 m on the river leakage.

Figure 15. Effect of aquifer hydraulic conductivity 3 m/d on the river leakage.
Figure 16. Effect of aquifer hydraulic conductivity 6 m/d on the river leakage.

Figure 17. Effect of aquifer hydraulic conductivity 9 m/d on the river leakage.
Figure 18. Effect of aquifer hydraulic conductivity 12 m/d on the river leakage.

Figure 19. Effect of aquifer hydraulic conductivity 15 m/d on the river leakage.
Figure 20. Effect of pumping rate 3000 m³/d on the river leakage.

Figure 21. Effect of pumping rate 4000 m³/d on the river leakage.
Figure 22. Effect of pumping rate 6000 m$^3$/d on the river leakage

**Preliminary Tests of Pump Modulation to Minimize Streamflow Impacts**

Figure 23 shows an initial attempt at using pump modulation to affect riverbed leakage. Figure 23 shows a trial and error solution where 10 days of recovery without pumping, followed by 17 days of pumping is a nearly-optimal cyclic pumping duration with a maximum of 1850 m$^3$/d (0.76 cfs) river leakage for the tested conditions. Such a scheme might be used to regulate well pumping without total shutoff.

Figure 23. Off pumping time = 10 days and on pumping time = 17 days
Work for Year 3

A simulation model representing a combined hypothetical aquifer and stream has been developed using MODFLOW-2000 to capture parameter sensitivity, test management strategies and guide field data collection campaigns to support modeling.

For an existing well or set of wells, shutoff at the appropriate time is the only certain way to curtail impacts on surface water. Cyclic pumping might be useful if there is sufficient knowledge about the hydrogeology. The only free variable is the pumping duration. A family of curves for different simulation scenarios could be developed to help operating the wells without affecting the river leakage beyond some threshold.

In the case of new or replacement wells to be permitted, an optimization approach is proposed to be applied to optimize both the well distance from the stream and the maximum pumping rate that does not affect the stream discharge downstream the pumping wells. Conjunctive management can be modeled by coupling the numerical simulation model (which has been developed) with an optimization technique using a response matrix. The response matrix can be obtained by calculating the response coefficient for each well and stream. The main assumption of the response matrix technique is that the flow of water from the stream to the aquifer is linearly proportional to the well pumping rate (Barlow et al., 2003). The results are presented in dimensionless form, which can be used by the water managers to solve conflicts between surface water and ground water holders by making the appropriate decision to choose which well need to be shut down first.

Groundwater Modeling Study Limitations

In our study, we are not considering the effects of return flows, because center-pivot irrigation is the water application technique being considered. Center pivot irrigation does not typically result in significant return flows.

In year 3, we are simulating an actual aquifer/river setting (Bates Creek), but we lack detailed hydrogeological data. The only data we have come from the written report by Glover (1984). According to the USGS, the data behind the Glover (1984) report are lost. Our sensitivity analysis results do indicate which aquifer/surface water properties and parameters are most needed if an actual setting is to be simulated in detail.

We are considering the alluvial aquifer to be homogeneous. It is possible that in an actual site, heterogeneity in aquifer properties will have a significant effect on the simulation outcomes in terms of which wells affect river flows the most.
Students Supported

Civil Engineering Ph.D. student Mohamed Abdel-Hafez
ENR M.S. Student Emiline Ostlind

Publications to date

Abdel-Hafez, M.H., and F.L. Ogden, 2008, Optimizing the well pumping rate and
distance from a stream, Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract
H21D-0865.

References

of high plains aquifer in parts of Colorado, Kansas, New Mexico, Oklahoma, South

Kent C. Glover, 1984. Digital model for the Bates Creek alluvial aquifer near Casper,

for Sustained Yield Of Stream- Aquifer Sstms, Water Resources Planning and
Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming Using the Wyoming Cloud Radar

Basic Information

| Title: Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming Using the Wyoming Cloud Radar |
| Project Number: 2007WY39B |
| Start Date: 3/1/2007 |
| End Date: 2/28/2010 |
| 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 |

Publication
Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming Using the Wyoming Cloud Radar

FY 2008 (Year 2) report for a three-year U. S. Geological Survey and the Wyoming Water Development Commission grant
Bart Geerts, PI

1. Abstract

This proposal called for 20 research flight hours of the University of Wyoming King Air (WKA) over the Snowy Range (Medicine Bow) mountains in Wyoming during the time of glaciogenic cloud seeding conducted as part of the five-year Wyoming Weather Modification Pilot Project. This pilot project, administered by WWDC and contracted to the National Center for Atmospheric research (NCAR) and Weather Modification Inc (WMI), involved seeding from a series of silver iodide (AgI) generators located in the Snowy Range. In Feb 2008 we conducted two WKA flights (8 flight hours), as discussed in the Year I report. The remaining three flights were conducted in early 2009 (18 and 20 February and 10 March). Thus we have flown all flight hours (20) supported by this award. All five flights were a success.

2. Progress

All five flights in this campaign (referred to as WWDC Cloud Seeding) followed the general flight pattern shown in Fig. 1. We targeted west- to northwesterly wind, because in such flow the Snowy Range forms the first obstacle following a long fetch over relatively flat terrain (the Red Desert), because three generators (Barret Ridge, Mullison Park, and Turpin Reservoir) are aligned with the cross-wind flight legs (Fig. 1), and because this flow pattern does not interfere with NCAR’s randomized experiment (because under such flow the seed generators are upwind of both the target and the control snow gauges). Aside from the along-wind leg (whose orientation depends on the prevailing wind, pivoting around GLEES), there are five fixed tracks roughly aligned across the wind. The NW-most of these five tracks is upwind of the three generators, and the 2nd, 3rd, 4th, and 5th tracks are about 2, 6, 9, and 13 km downwind of the generators. The first four legs are on the upwind side, while the 5th one (tracking over GLEES) is mostly on the downwind side.

The pattern shown in Fig. 1 was repeated 4 times on several flights: the first two patterns had the seed generators off, and the last two patterns were flown with the seed generators on. On other flights we concentrated on the three most-downwind legs, and the number of patterns with seeding was increased at the expense of flight time without seeding (Table 1).

On all flights the Wyoming Cloud Radar (WCR) operated flawlessly, with three antennas (up, down, and forward-of-nadir). We recently discovered a small (0.60 m s⁻¹) downward bias in the Doppler vertical velocity from the up-looking antenna, on all flights. This correction was found after extensive comparisons with the down-looking antenna and with flight-level vertical wind data. On all flights we also had the up-looking lidar (Wyoming Cloud Lidar, WCL). On the last two flights, we also collected data from the recently-purchased down-looking lidar.

No less than four graduate students participated in the field campaign (Table 1), although only one graduate student (Yang Yang) is focusing her MSc research on the data from these five flights.
Fig. 1. A schematic of the WKA flight legs in the Snowy Range, over the AgI plumes (shown schematically with a green outline) released from three generators on the ground. The color background field shows the terrain. On all flights the flight level was set at 4,276 m (14,000 ft) MSL, the minimum permissible flight level over the terrain. The prevailing wind was from the NW. One flight leg was across the terrain (along the wind), the other 5 flight legs were roughly across the winds at various distances downstream of the three active AgI sources.

Table 1: Summary of the five WKA flights

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<td></td>
<td>5</td>
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<td>280°</td>
<td>-23</td>
</tr>
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</table>
List of graduate students participating in the flight planning, the flight itself, the flight debriefing and the writing of the flight report:

- Qun Miao, PhD student, advisor: Dr. Geerts: field training opportunity (he is currently a post-doc in the group)
- Yonggang Wang, PhD student, advisor: Dr. Geerts: field training opportunity
- Yang Yang, MSc student, advisor: Dr. Geerts: both essential to her research, and a field training opportunity (Yang Yang is partly funded by this WWDC/USGS grant)
- Mahesh Kovilakam, PhD student, advisor: Dr. Deshler: field training opportunity

Preliminary results of the first two flights were presented at the joint 17th joint American Meteorological Society - Weather Modification Association Symposium on Planned & Inadvertent Weather Modification in Westminster CO (Geerts 2008). Here are the preliminary results from the five flights:

1. With so much natural variability it is very difficult to detect a seeding signature. Nearly 50% of the flights were in unseeded conditions (Table 1), and the 1st of 5 across-wind legs was upstream of the mountain (Fig. 1). These choices were made to detect a seeding signature by contrasting seeding to no-seeding patterns. Clearly the actual location of the plumes is uncertain. We do have excellent wind profile data from VAD analyses in the turns between across-wind legs. Still, the plumes may meander considerably in time. Visual inspection of WCR data along each leg indicates that there is no apparent change in radar reflectivity downwind of the AgI generators. Some boundary-layer eddies make it up to flight level, especially along the 4th leg going over the highest peaks. In these eddies, there appears to be no reduction in supercooled liquid water content nor a increase in number of ice crystals in areas downwind of the AgI plumes, compared to eddies in similar locations but clearly away from the AgI generators, or collected before the generators were turned on. This statement is preliminary, and will be investigated in more detail.

2. Deep planetary boundary layer (PBL) turbulence along the upslope section of the mountain was present on all days. The depth of PBL mixing was about 1 km, ranging from 600 to 1300 m. This turbulence effectively mixes the AgI aerosol released from ground generators into an orographic cloud where most of the supercooled water naturally resides, in other words, ground-based seeding of orographic clouds is more effective than airborne seeding. Note the PBL turbulence would also mix ice particles generated near the ground into cloud, thus making AgI seeding redundant. Such ice particles could result from blowing snow or from the splintering of supercooled water along rimed surfaces on the ground. The main evidence for this is the increase in reflectivity along the upwind slope, above cloud base, in the PBL, by local growth of ice crystals (Vali et al., 2008). This needs to be examined further. The methodology is discussed below.

3. We flew two additional flights in March, funded by a follow-up WWDC/USGS grant (referred to as Cloud Seeding II). On the last of these flights, on 3/25/09, there is a hint of a “seeding signature” downwind of mainly the middle generator (Mullison Park, see Fig. 1). This signature includes reduced flight-level liquid water and increased concentration of ice crystals (Fig. 2). It also includes increased radar reflectivity below flight level, and more rapid attenuation of the nadir lidar backscatter power. The high depolarization ratio indicates that this attenuation in the high-reflectivity plume is due to ice crystals. Three other passages along the same flight leg shows repetitibility, that is, the seeding signature is present in four successive legs during seeding, but absent on the first passage, before the AgI generators were turned on.
Fig. 2: Comparison of flight-level and remote-sensing data along flight leg #3, located 6 km downwind of the AgI generators (Fig. 1), on 3/25/2009. The AgI generators were off during WKA passage on the left, and on for the flight leg on the right. The top two panels show WCR reflectivity and vertical velocity, above and below the aircraft. The black stripe in the middle is the flight level, and the ground is evident as the sloping surface below flight level. The next two panels give nadir WCL backscatter power and depolarization ratio. The bottom three panels show flight-level data.

3. Objectives and methodology
1. Document the PBL turbulence and precipitation enhancement on the upslope side of the Med Bow mountains. This will be the main project for the incoming graduate student, Yang Yang. This research has these elements:
   a. Conduct a spectral analysis of WCR vertical velocity near the ground, to see whether the turbulence is consistent with theoretical expectations in the inertial subrange.
   b. Generate colored frequency-by-altitude diagrams (CFADs) showing vertical velocity variance over all depths including above flight level.
   c. Stratify these CFADs as a function of ambient wind speed, maybe stability, using aircraft profiles upwind of mountain in NASA06, and radiosonde data in WWDC Cloud Seeding.
d. In order to determine whether streamers rise from the ground, estimate snow crystal trajectories from vertical-plane dual-Doppler analysis and an assumed fall speed.

e. Isolate flight sections where WKA is in the PBL layer, and contrast these sections to upstream in-cloud sections (above the PBL), and
   i. in these sections, relate updrafts to LWC and ice crystal concentration;
   ii. also look at riming & aggregation using 2D-C, 2D-P data.

f. Develop a composite reflectivity (and vertical velocity) structure across the mountain (following the method in Kusunoki et al., 2005, in MWR). The following steps are needed:
   i. obtain a typical terrain profile;
   ii. assign coordinates to reflectivity (and vertical velocity) from each cross-section (x,z), with x=distance from crest, z=height above ground;
   iii. compute average reflectivity (Z, not dBZ) and vertical velocity for each (x,z) and plot this over typical terrain profile;

2. Examine the impact of cloud seeding on reflectivity
   a. develop a composite reflectivity (as in 1.f) as function of distance from the seeder (x,z) in each of the 4 downstream flight legs along the wind.

4. Principal findings

Preliminary findings are listed under Section 2 (Progress).

Geerts (2008) demonstrated, qualitatively, the importance of PBL turbulence on both seed dispersal, and on natural precipitation growth in cold clouds. Medina and Houze (2005, in Mon. Wea. Rev.) were the first to speculate that PBL turbulence is important to droplet growth in warm clouds by the collision/coalescence process.

Data collected in WWDC Cloud Seeding (2008) across the Snowy range in Wyoming consistently show a layer of substantial turbulence, about 1 km deep, on the upslope side of the terrain barrier. Cold-cloud processes operate in this environment. Since this turbulence occurs within cloud, precipitation growth though riming is likely in turbulent eddies whose updraft speed far exceeds the average ascent rate over the terrain. In fact this growth is suggested by the increase of the WCR reflectivity along the upwind slope of the Snowy Range, near the surface, in a layer that is sometimes disconnected from the snow layer aloft. The flight-level data were usually collected above the BL, but in some sections we were low enough to collect cloud microphysics data within the PBL, and they show large ice crystal concentrations and evidence of riming.

This natural growth process may be enhanced by ice crystal formation along rimed surfaces on the ground, such as trees, or by snow on the ground lofted by turbulent wind gusts, as suggested by Vali et al (2008).

5. Further plans

So far we conducted seven flights over the Snowy Range, five funded under the present project and two under Cloud Seeding II. Following the completion of a first peer-reviewed paper later this summer (Geerts and Miao 2009), we have several other orographic precipitation studies planned. First, Dr. Geerts is the PI of the SOLPIN component of the current University of Wyoming NSF EPSCoR proposal, called “Earth System Interactions in Complex Terrain”. The SOLPIN (Simulations and Observations of Land-Precipitation Interactions) component is worth
about $6 million, plus $2 million in UW matching. Both winter and summer orographic precipitation will be studied, using experimental data and numerical simulations. Second, Dr. Geerts is one of the P/Is in a large, collaborative proposal, known as SHARE (Sierra Hydrologic and Atmospheric River Experiment), to be funded by NSF and, if funded, to be conducted in the Sierra Nevada in the winter of 2010-11. The emphasis here is on natural orographic precipitation processes, in both warm and cold clouds.

The following new elements will be included in these proposal(s):

a. fly on a windy clear-sky day to look at the vertical distribution of blowing snow mixed into the PBL;
b. fly a mission downwind of seed generators under conditions unsuitable for ice particle generation near the ground, but suitable for seeding;
c. include crystal habit / riming measurements at the ground, preferably on the upwind side of the mountains
d. examine diurnal variation of PBL turbulence, and changes in stability & cloud depth in association with the passage of a frontal disturbance;
e. examine a broader parameter space (mainly in terms of temperature) by including spring snowstorms.

6. Significance

These findings may be very significant. The intense PBL turbulence yields effective dispersion of glaciogenic or hygroscopic seed material in orographic clouds. PBL turbulence tends to be more intense and deeper under stronger winds. We experienced winds between 20-45 kts at flight level. It is also more intense when the lapse rate is closer to moist adiabatic, which was the case on the two days in WWDC Cloud Seeding.

But at least at the temperature range observed (-5 to -12°C at the ground) ice particles appear to emerge naturally from near the ground, suggesting that AgI seeding would be redundant. At temperatures at or just above freezing this ice particle source should disappear, possible making ground-based seeding effective under strong wind conditions. Under low-wind and stable conditions between -2 and 8 °C, Hallet-Mossop ice multiplication along rimed surfaces is still possible, yet both these natural ice crystals and AgI seeds are unlikely to spread deep.

The key significance of this work then is to indicate additional conditions under which glaciogenic cloud seeding is not expected to be productive. Clearly future work need to be designed to expand the parameter space.

7. Publications


8. Presentations

(a) with abstracts:


(b) without abstracts
• Geerts, B.: Detecting glaciogenic cloud seeding in orographic clouds using an airborne cloud radar: a progress report and plans for the Feb-Mar 2008 field campaign. Presented at the Wyoming Cloud Seeding Pilot Project Advisory Team meetings in Cheyenne (Feb 08 and Dec 08).

9. Students supported
Several graduate students have been involved in Year 2 of this grant. We were fortunate to be able to attract Thomas Andretta, PhD student, to this project. He started in late August 2007, although coursework and PhD Qualifying Exam will be his main pre-occupations until May 2008. He did participate in the February 2008 cloud seeding validation field experiment. In June 2008 he decided to switch research topics and focus on natural snowfall processes in mountain lee convergence zones. His project is unfunded at this time, but he is making good progress. Starting in August 2009, he will have a UW NASA Space Grant Consortium fellowship.

A new MSc student, Yang Yang, joined us from China in August 2008, and is supported in part by this grant. Her father and grandfather have been involved in cloud seeding research in China, and she has strong credentials, so we are pretty excited to bring her on-board.

Finally, three other PhD students (Miao, Wang, and Kovilakam) participated in the field campaign in early 2009 (see Table 1). This participation has given them invaluable experience in airborne field research.
Weather Modification Impacts and Forecasting of Streamflow

Basic Information

| **Title**: Weather Modification Impacts and Forecasting of Streamflow |
| **Project Number**: 2007WY40B |
| **Start Date**: 3/1/2007 |
| **End Date**: 2/28/2010 |
| **Funding Source**: 104B |
| **Congressional District**: 1 |
| **Research Category**: Climate and Hydrologic Processes |
| **Focus Category**: Water Quantity, Climatological Processes, Hydrology |
| **Descriptors**: None |
| **Principal Investigators**: Glenn Tootle, Thomas C. Piechota |

Publication

Weather Modification Impacts and Forecasting of Streamflow
PIs: Glenn Tootle (UW and Univ. of Tennessee) and Tom Piechota (Univ. of Nevada)
Graduate Students (UW and Univ. of Tennessee): Cody Moser, Ty Soukup, and Oubeid Aziz
Post-Doctoral Research Assistant (Univ. of Nevada): Haroon Stephen
Year 2 Annual Report

Objectives:
The scientific objectives of the proposed three-year research project are to:
1. Identify and evaluate snowpack, unimpaired streamflow, soil moisture and air temperature datasets in weather modification target areas within the state of Wyoming.
2. Examine relationships between snowpack and streamflow, including the impacts from the previous Fall season soil moisture (antecedent moisture conditions) and following Spring-Summer season air temperature on resulting streamflow from snowpack. This includes determining the optimum (i.e., highest correlation) relationships (period and lag time) between snowpack and streamflow.
3. Utilizing the optimum relationships, develop statistically based models (regression) for snowpack and resulting streamflow and apply the models to quantify streamflow increase due to snowpack increase as a result of weather modification.
4. Utilizing relationships between snowpack and streamflow in Task 3, evaluate statistically based models, including regression and non-parametric approaches, and develop forecasts of streamflow including exceedance probability, forecast skill and uncertainties.

Current Progress:
Cody Moser and Ty Soukup (Master’s students in Civil and Arch. Eng.) completed their coursework and successfully defended their master’s thesis in April 2008. Cody’s thesis was entitled Incorporating Antecedent Soil Moisture Into Streamflow Forecasting Within the North Platte River Basin, Wyoming and Ty’s thesis was entitled Long Lead-time Streamflow Forecasting of the North Platte River Incorporating Oceanic-Atmospheric Climate Variability. Each thesis directly addresses the four scientific objectives of the proposal. Cody presented the results of his research at the American Society of Civil Engineers (ASCE) Environmental Water Resources Institute (EWRI) Conference in May 2008. Cody published the results of his research in the 2008 ASCE EWRI proceedings. Ty presented the results of his research at the American Geophysical Union (AGU) Fall Meeting in December 2008. Ty published the results of his research in the Journal of Hydrology. Both Cody and Ty have made local presentations at the WY State Engineer’s Water Forum and the University of Wyoming Graduate Seminars. Ty has accepted a position with Tri-Hydro in Laramie while Cody is pursuing a PhD at the University of Tennessee.

Preliminary Results:
Cody utilized existing Natural Resource Conservation Service (NRCS) methods (Principal Component Stepwise Linear Regression) in an attempt improve forecast skill. This was accomplished by including Antecedent Soil Moisture (ASM) as a streamflow predictor (in addition to snowpack, precipitation and streamflow persistence) and the development of an expert system based on ASM conditions (wet, normal, dry). During meetings with the NRCS (Tom Pagano, Portland, OR), they stressed the need to improve their “bad year” forecasts (i.e., years in which their forecast are significantly off). Cody determined the eight “bad years” of
NRCS forecasts for the two North Platte River basin streamflow stations of which he was developing forecasts. For the first station, Cody’s model “beat” the NRCS forecast six out of eight and for the second station, seven out of eight (Figure 1).

Ty was successful in generating a skillful long lead-time (3 to 6 months) forecast of North Platte River basin streamflow utilizing climate (Sea Surface Temperatures and 500mb Geopotentials). He utilized a non-parametric modeling approach (Kernel Density Estimator) and developed Exceedance Probability Forecasts (Figure 2) for four USGS streamflow stations in the North Platte River basin. He reported good to excellent skill for the forecasts.

USGS 06625000 (8 Worst NRCS Forecasts)

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**Figure 1:** Plot of NRCS % difference forecasted valued versus the % difference Expert System forecast for the 8 worst NRCS forecast years for USGS Station 06625000.

**Figure 2:** Example of Exceedance Probability Forecast.
Future Work:

Per meetings with Barry Lawrence (WWDO) and the Weather Modification Technical Advisory Group, it was concluded that the development of a physically based hydrologic model of the North Platte River basin would be of great benefit. Therefore, through cooperation with the University of Nevada, Las Vegas Department of Civil and Environmental Engineering and the University of Nevada, Las Vegas National Supercomputing Center for Energy and the Environment (NSCEE), we are developing a physical model (Variable Infiltration Capacity model) of the North Platte River basin. The lead investigators are Haroon Stephen, Cody Moser and Oubeid Aziz. We are evaluating various scenarios for the North Platte River basin. These scenarios include: What are the impacts of Weather Modification (cloud seeding) on streamflow? What are the environmental impacts (due to climate change) of massive high elevation deforestation due to the pine bark beetle? What does the incorporation of Global Circulation/Climate Models (GCMs) reveal for the future of North Platte River basin streamflow? Haroon plans to attend the American Water Resources Association (AWRA) spring meeting in May 2009 and present preliminary results of his research. He also plans to submit a paper (proceedings) for the AWRA meeting.

Cody is investigating differences in Snow Water Equivalent (SWE) measurements, comparing land-based (in-situ) SNOTEL data collections systems and satellite (NASA AMSR-E) collection systems. He is evaluating this data in western U.S. watersheds including the North Platte River Basin. Ty is continuing his research on using climate to develop a long lead-time streamflow forecast in the North Platte River Basin. He is currently improving upon his published work in the *Journal of Hydrology* by developing an operational streamflow forecast. Ultimately, he hopes to provide an experimental forecast website in which long lead-time forecasts (exceedance probabilities) are provided in advance of snowpack forecasts which begin on January 1st.

Invited presentations:


A New Method for Tracing Seepage from CBNG Water Holding Ponds in the Powder River Basin, Wyoming

Basic Information

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<td>Principal Investigators</td>
<td>Shikha Sharma, Carol Frost, Katta J Reddy</td>
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Publication

A New Method for Tracing Seepage from CBNG Water Holding Ponds in the Powder River Basin, Wyoming

PIs: Shikah Sharma, K.J. Reddy, and Carol Frost
Year 1 Progress Report

Abstract:

The proposed work will establish and verify the utility of a low-cost and innovative approach for understanding “Groundwater contamination caused by seepage out of CBM water holding ponds,” which has been identified as one of the critical areas of research under the CBNG Related Issues category in the Wyoming Water Research Program Request for Proposals (WRP RFP, 2008). Groundwater degradation caused by infiltration from CBNG water retention ponds is an issue of immense importance because groundwater is a major source for stock water, irrigation and drinking water for many small communities and ranchers in the Powder River Basin, Wyoming. It is necessary to develop a tracer that can fingerprint this water in order to trace seepage of water from these ponds into shallow aquifers. Strontium isotopes and other geochemical tracers have limited application in some instances because of significant contributions of these elements from local lithologies and high analysis costs. This study evaluates a low cost tracer that is less readily overwhelmed by near-surface sources.

Based upon preliminary analyses of CBNG co-produced water from the Powder River Basin, Wyoming, we suggest that the carbon concentrations and isotopic composition of Dissolved Inorganic Carbon (δ13C\text{DIC}) can be used as a natural tracer for fingerprinting CBNG co-produced water. Our results show that CBNG co-produced water has strongly positive δ13C\text{DIC} (+12 to +22‰) that is readily distinguished from the negative δ13C of most surface and groundwaters (-10 to -15‰). Furthermore, the DIC concentrations in co-produced water samples are also high (>100 mg C/l) compared to the 20-50 mg C/l in ambient surface and groundwaters of the region. The distinctively high δ13C and DIC concentrations allow us to identify surface and groundwaters that have incorporated CBNG co-produced water and can also be used to track the CBNG produced water infiltrating from the ponds. Accordingly, we suggest that the δ13C\text{DIC} and DIC concentrations of water can be used for long term monitoring of infiltration of CBNG co-produced water from the CBNG water holding ponds (Sharma and Frost, 2008).

Samples will be collected from the CBNG discharge wells, water holding ponds and monitoring wells in the Powder River Basin and analyzed for δ13C\text{DIC} and DIC concentrations, pH, dissolved oxygen (DO), electrical conductivity (EC), major cations (e.g., Ca, Mg, Na, and K), and major anions (e.g., alkalinity, sulfate, chloride, fluoride, nitrate, and phosphate) to assess changes in water quality as the CBNG water migrates along the recharge flow path.

The results from this study will demonstrate how we can trace the seepage out of CBNG water holding ponds using a low cost stable isotope approach. A graduate student will be an integral part of this project. The project results will be presented at state, regional, and national meetings and published in appropriate peer-reviewed journals.

Objectives

Potential groundwater degradation caused by infiltration from CBNG water holding ponds is an issue of immense importance in the state of Wyoming where infiltration ponds are a common method for disposal of CBNG co-produced water. The objective of this study is to establish the utility of a new method for tracing infiltration of CBNG water from these ponds to near surface
aquifers and shallow groundwaters. The method involves using stable isotope of carbon in dissolved inorganic carbon ($\delta^{13}$CDIC) and DIC concentrations for fingerprinting CBNG co-produced water. The specific tasks which will be undertaken to attain this broad objective include:

1) The CBNG co-produced water samples will be collected from discharge points, corresponding retention ponds and a series of monitoring groundwater wells at selected sites in Powder River Basin for a period of 2 years.

2) Samples will be analyzed for $\delta^{13}$C of DIC and DIC concentrations in water at the University of Wyoming Stable Isotope Facility.

3) Isotope mixing models will be used to calculate the fraction of CBNG co-produced water incorporated into the shallow groundwaters.

4) The geochemical parameters (pH, EC, major cations, major anions) will be used to assess the impact of infiltration of CBNG co-produced water on the ground water quality.

5) Convey research results to WY-DEQ, water users, landowners, and CBNG operators through project demonstrations, workshops, and local meetings.

**Methods**

Study sites have been chosen in Sheridan, Campbell and Johnson Counties (see Figure1). The sites were selected based on following criteria:

- All impoundment sites had upstream and downstream monitoring wells installed at similar depths (~40-140 feet) and in similar lithological horizons.
- All impoundments had received CBNG water for at least 1-2 years and had similar water holding capacity.
- Lithological logs were available for all monitoring wells.

The water sampling is done in accordance with the SAP (Sample Analysis Procedures) protocols of Wyoming DEQ-Water Quality Division. The monitoring wells are purged at rate of less than 1L /min with a submerged bladder pump until 3 casing volumes of water was removed. Water samples are collected when all field parameters (pH, EC, and Temperature) stabilized to within 10% for 3 consecutive readings. Three set of samples are collected at each sampling site 1) one sample for $\delta^{13}$CDIC and DIC concentration measurement 2) Duplicate samples for $\delta^{18}$O and $\delta^D$ measurement and 3) Duplicate samples for alkalinity, major anions (phosphate, nitrate, fluoride, chloride, sulfate), and major cations (aluminum, boron, barium, cadmium, chromium, copper, iron, manganese molybdenum, lead, zinc, sodium, magnesium).

The samples for dissolved inorganic carbon are taken into a 60mm syringe and passed through a 0.45 μm Whatman filter attached to the end of the syringe and filled into a 30mL Wheaton glass serum vial. Two drops of benzalkonium chloride are added to halt biologic activity. The vials are topped with a Teflon seal and capped with an aluminum top. The aluminum tops are crimped to close the vials. The $\delta^{13}$CDIC is measured on a Gas Bench-II device coupled to a Finnigan DELTA plus mass spectrometer in the central Stable Isotope Facility at the University of Wyoming. The reproducibility and accuracy was monitored by replicate analysis of internal lab standards and was better than ± 0.1 ‰. The $\delta^{13}$CDIC values are reported in per mil relative to V-PDB. The DIC concentrations in samples were also quantified from the mass spectrometry data. Three NaHCO$_3$ stock solutions of different DIC concentrations were prepared for this purpose. DIC concentrations were then quantified based on the peak areas of the mass 44-ion trace of these standards. Plotting peak area of CO$_2$ vs. concentration of DIC in these
standards gives an excellent correlation ($r^2=0.995$), indicating that DIC concentrations of the samples could be quantified using this method. The relative standard uncertainty of the DIC concentration measurement in this study was ± 3%. The samples for $\delta^{18}$O and $\delta$D are taken in 10 mL glass vials. The sample is filled up to the brim avoiding any headspace and then capped and sealed with layer of parafilm. The $\delta^{18}$O and $\delta$D measurement is done using the Los Gatos Liquid-water Isotope Analyzer housed in University of Wyoming Stable isotope Facility. Samples for alkalinity, major anions and major cations are taken in Fisher 1L plastic bottles which had been previously acid washed for three hours in a nitric acid bath at a pH below 2. Upon return to Laramie, these samples are filtered with 0.45 μm filters before testing for alkalinity, anions (aluminum, boron, barium, cadmium, chromium, copper, iron, manganese, molybdenum, lead, zinc, calcium, potassium, and arsenic), and cations (fluoride, chloride, nitrate, phosphate, and sulfate). Alkalinity is tested in the University of Wyoming Water Quality Lab using the 702 SM Titrino automatic titrator manufactured by Brinkmann. Anions and cations are measured using the ICP-MS and IC housed in UW Soil Testing Laboratory and Geochemistry Analytical Laboratory respectively.

**Principal Findings**

Three field trips have been taken so far for sampling. An initial trip was made into the field in July, 2008 to a CBM impoundment on the Daly Ranch, 16 miles northwest of Gillette, WY. This site is different from the others, because there are no operator installed upstream and downstream monitoring wells. Five shallow wells were dug upstream and two downstream of pond 166 on Daly’s ranch using a hand-auger with extensions. The target of these wells was the shallowest water table, about 12’ below the surface. As hypothesized the water sample from outfall had high $\delta^{13}$C$_{DIC}$ value of +23 ‰. The pond water had $\delta^{13}$C$_{DIC}$ signature of +9.8 ‰ indicating that it is receiving significant amount of fresh water having low carbon isotope values. Simple two end member mixing suggests that the pond receives up to 40% of water from fresh surface water discharge and 60% from the CBNG outfall. The water sampled from shallow wells dug up to 44 m upstream of the pond and 10 m downstream also show ambient carbon isotope signatures ranging from -11 to -13‰. Presence of ambient water at these shallow depths in vicinity of the pond indicates that there is no seepage of CBNG water from this pond into underlying shallow groundwater. This pond might be receiving a lot of snow melt recharge due to its hydrologically advantageous location in a natural playa. The contribution from isotopically lighter snow-melt recharge in turn dilutes the high carbon isotope signature from CBNG water. This pond has been receiving CBNG water since 1999. However, discharge in this pond was stopped for two years (2005 and 2006) when the SAR (Sodium Absorption Ratio) of water got very high and Arsenic went beyond the EPA limits. We hypothesize that during this 2 year time period precipitation of salts resulted in
formation of impervious salt plan at the bottom of pond causing it to self seal thus preventing any leakage of water out of the pond.

Second sampling trip was taken in September 2008. The scientists from Wyoming Department of Environmental Quality office in Sheridan helped us sample four study sites namely Termo, Gloden Eagle, Kline Draw located in northwest corner of Campbell county and Lori located in the north-central Sheridan county of Powder river basin (Figure 1). In November 2008, the third sampling trip was taken to sample four sites in Johnson County with the assistance of WWC Engineering, an environmental consulting firm based in Sheridan. All the samples have been analyzed for δ¹³CDIC and as hypothesized all water samples collected from the outfalls and ponds have very high δ¹³CDIC values in range of +12 to +20‰ (Figure 2). The ponds and outfalls at all the sites had very similar δ¹³CDIC signatures indicating that the pond water has not undergone any significant change in carbonate chemistry due to dissolution effects or due to CO₂ exchange with atmosphere. The monitoring wells had lower δ¹³CDIC values ranging from -10‰ (in wells not affected by seepage from ponds) to -6‰ (wells effected by seepage). Isotope mixing models will be used in the later part of this study to estimate the fraction of CBNG co-produced water incorporated into the groundwaters at the monitoring well sites.

Figure 3: Graph showing positive correlation of δ¹³CDIC with HCO₃ concentration (•) and negative correlation with SO₄ (△) concentrations
The major anion chemistry of the water samples indicates that the methanogenic waters with high $\delta^{13}$CDIC values have low concentrations of sulfate and high concentrations of bicarbonate (Figure 3). The low SO$_4^{2-}$ and high HCO$_3^-$ concentrations in CBNG co-produced waters are probably the result of bacterially-mediated oxidation–reduction reactions in the coal zones (Van Voast 2003; Rice et al., 2008; Brinck et al., 2008). We also noted that pH of the pond water is higher than the water from the outfall (Figure 4). This increase in pH of produced water discharged in the ponds is probably due to de-gassing of CO$_2$ from produced water (McBeth et al., 2003 and Patz. et al., 2004) or due to formation of NaOH by dissolution of NaHCO$_3$ in the co-produced water. The alkalinity was also higher in the ponds compared to outfalls. The increase in alkalinity in the ponds can be due to formation of OH$^-$ ions or interaction of the CBNG co-produced water with the soils of the pond. The major cation analysis of samples is in process and we anticipate that the geochemical indicators will provide us better understanding on the seepage related geochemical variations.

This project also partially supported another study entitled “Stable Isotope and Geochemical Analyses of Wyoming Coalbed Aquifers: A new tool to minimize water production and maximize gas production in a coalbed natural gas play”. This is a MS thesis project of Scott Quillinan graduate student in department of Geology and Geophysics, co-advised by Drs. Frost and Sharma. The primary funding sources of this project are Anadarko Petroleum and Wyoming Geological Survey. However, partial financial support in terms of stable isotope sample analysis and sampling supplies was provided by this WWDC-USGS funded project. The purpose of this study is to determine if stable isotopes are useful for CBNG reservoir characterization, coal zone distinction, and to test for fresh water intrusion. This study will investigate isotopic and water chemistry over a wide variety of attributes in the Atlantic Rim and Powder River Basin CBNG plays.

Preliminary samples have been collected and geospatial modeling of the data collected so far indicates strong correlations between enriched $\delta^{13}$C$_{\text{DIC}}$ and low water to gas ratios.

**Significance**

The initial results from this study demonstrate that the carbon isotope signatures of the waters can be used to fingerprint methanogenic waters and can potentially serve as low-cost method to trace seepage out of CBNG water holding ponds. Preliminary results from water samples collected from well-heads of producing wells in Atlantic Rim and Powder River Basin indicate strong correlations between enriched $\delta^{13}$C$_{\text{DIC}}$ and low water to gas ratios. The carbon isotope technique developed by these two projects can potentially help to solve regulatory issues related to discharge of CBNG co-produced water and also help CBM operators to maximize gas production while maintaining optimal drilling costs and protecting the valuable groundwater resources of the region.
Student Support Information

Graduate: Josh Baggett MS student in Renewable Resources advised by Dr. Sharma is working on this project for his Masters thesis in Rangeland Ecology and Watershed Management/Water resources. He received training in taking field water quality measurements, geochemical and isotope sampling protocols, geochemical analysis and stable isotope analysis. Scott A. Quillinan MS student in Department of Geology and Geophysics co-advised by Dr.’s Frost and Sharma received training in taking field water quality measurements, geochemical and isotope sampling protocols, geochemical analysis and stable isotope analysis.

Undergraduate: Paul Haselhorst, a Geology major and technician of Dr. Sharma, received training in preparing samples for geochemical and isotopic analysis and also in running samples on the stable isotope ratio mass spectrometer. Patrick Warden technician of Dr. Sharma and Biology major received training in preparing and running isotopic analysis on water samples.

Publications and Presentations


References Cited


Water Quality Criteria for Wyoming Livestock and Wildlife

Basic Information

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Publication
Abstract

Water is arguably the most essential nutrient for terrestrial animals. While most mammals can survive for a week or more without food, 2-3 days without water is invariably fatal. Livestock and wildlife in the arid West are often forced to subsist upon less-than-perfect drinking water such as that produced by oil and gas development ("produced water"). Water quality standards, as enumerated in Wyoming Department of Environmental Quality (WYDEQ) regulations governing surface discharges, are based upon science that is several decades old and have recently been challenged. The fact that the challenges were, themselves, based upon dubious information is in itself a reflection of the generally mediocre state of current water quality recommendations by various public institutions. It is not that the data don’t exist, but rather that they haven’t been compiled into any sort of useful, user-friendly summary or, in some cases, mineral production has itself created new questions (e.g. chronic toxicity of water-borne barium to ruminants) that never had to be answered before.

Our group recently completed a literature review of several water quality elements important to domestic livestock and large mammalian wildlife for the Wyoming Department of Environmental Quality (Raisbeck et al., 2007). We have received requests for hard copies of this document from as far away as Australia and South Africa. The current project is intended to expand upon the previous effort to include other elements, such as iron and uranium, which are potentially of future interest as they occur naturally in Western waters and are extremely toxic. Coincidentally, this project will provide a MS student and 2-3 undergraduates training in toxicology, risk assessment and water quality - skills which are currently needed in Wyoming.

Methodology

Our methodology is fairly simple, if laborious. Older (roughly pre-1990) reviews are obtained to validate the previous state of the art re: the toxicity of a given element in our species of interest (cattle, sheep, horses, antelope, deer and elk). After these documents are digested, a search is instituted for detailed, primary sources via biological literature databases such as Medline, Biosis and CAB. These papers are reviewed, rated for applicability and reliability and summarized in our database. The better papers are used as a basis for reverse-search strategies such as citation searches. If the amount of information available from conventional sources is inadequate, we contact regional animal health agencies for unpublished data such as diagnostic case reports and game and fish studies.

Each paper is rated for applicability (i.e. route of administration, class, age and species and chemical form of the toxicant typical of what is found in Wyoming) and reliability (adequate controls and sufficient numbers of animals to support conclusions, etc.). Case reports are evaluated upon the basis of similar criteria, as well as whether possible differentials have been ruled out and Koch’s postulates have been fulfilled. This process requires some judgment, which is where the expertise of our team comes into play. Controlled experimental studies are normally given more weight than case reports; however, an experiment which concludes there is no effect
in n=3 animals is less credible than a case report documenting a 5% mortality among 200 head exposed to the same substance and dose. In the absence of good quantitative data in each of the species of interest, we attempt to extrapolate from species for which there are data. Such extrapolations are based upon known comparative physiology of our various species and indicated as such in the final report.

**Progress to date**

During the first year of our project, we recruited a graduate student and compiled and prioritized a list of contaminants to review (B, Cd, Cr, Cu, Pb, Hg, Zn, U, Fe) in collaboration with the Wyoming DEQ. Our student has completed formal courses in toxicology, risk assessment and water chemistry and is coming up to speed on the project. We have compiled a database of several hundred documents, mostly peer-reviewed papers, and completed reviews of boron and cadmium. There is very little data on the toxicity of boron in large mammals; however, it appears that the safe upper limit of exposure is approximately 200 - 300 mg/L for short periods (less than a week). Chronic effects, due to decreased water consumption, should not occur at concentrations less than 50 mg/L.

There are three possible scenarios that must be considered when evaluating cadmium: acute toxicity, chronic toxicity and residues in edible tissues. Numerous field studies in wild ruminants suggest that they respond similarly to cadmium as domestic cattle, and thus don’t require special consideration. Extrapolation of dose-response data from laboratory animals and humans suggests that 25 mg/L is the upper safe limit of short term exposure in cattle. The chronic (> 180 days) LOAEL appears to be approximately 1.27 mg/kg BW/day in sheep and cattle. Thus, the upper “safe” limit in sustained, hot, weather is 5 mg/L. Assuming a year-round water consumption more typical of Wyoming weather, the limit is 10 mg/L. Violative cadmium residues in animal products destined for human consumption are a little trickier. Cadmium accumulates preferentially and to relatively high concentrations in kidney, and to a lesser extent, liver. We adapted a model developed in the Netherlands for cattle grazing contaminated pastures to our conditions, and, assuming 8 oz/day meat consumption and calculating back from the EPA reference dose of 0.001 mg/kg BW/day, lifetime exposure to 31 \( \Phi \) g Cd/L in drinking water would accumulate to regulatory action limits in kidney. A similar calculation indicates that 156 \( \Phi \) g/L in drinking water might produce illegal residues in liver. Although we cannot predict how various regulatory agencies will react to cadmium residues in foodstuffs, neither liver or kidney is consumed on any kind of regular basis in North America. Applying similar logic to skeletal muscle (red meat), which does not accumulate cadmium to any great extent, suggests that almost 4 mg Cd/L drinking water would be required to achieve violative concentrations.

We are currently compiling data for chromium and anticipate completing this chapter sometime after finals week in May. To date, we’ve accumulated approximately 80 references on the biological properties of chromium. Cr(III) is the predominant form of Cr found naturally in surface water, with Cr(VI) resulting mainly from human activity. Most sources indicate that relatively large doses of Cr(III) are required for toxicity, but that relatively small doses of Cr(VI) damage multiple organ systems.
Presentations

References
# Multi-Century Droughts in Wyoming's Past: Evidence of Prolonged Lake Drawdown

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## Publication

Multi-Century Droughts in Wyoming’s Past: Evidence of Prolonged Lake Drawdown

PIs: Bryan N. Shuman, Assistant Professor; Jacqueline J. Shinker, Assistant Professor; and Thomas A. Minckley, Assistant Professor, University of Wyoming
Final Project Report

Abstract
Wyoming has historically experienced prolonged periods of drought, which have had significant economic and social impacts. Yet, the severe droughts of the late 20th century are not unprecedented in the long-term context of climate variability, meaning droughts in the past may have exceeded recent dry periods in both magnitude and duration. Evidence from tree-ring and archeological records indicate that past centuries have contained multi-decadal “megadroughts” far more severe than any drought of the past 150 years. Using direct measurements of prehistoric shoreline elevations of lakes in Wyoming and Colorado, we show centennial-to-millennial scale drawdowns of lake levels that far surpass historic and dendrochronological records. Calculation of hydrologic budgets based on the inferred lake levels indicates that the drawdowns were produced by reductions in the balance of precipitation and evaporation of 0.3 to 0.7 mm/day. The spatial patterns and timing of past lake levels suggest episodes of widespread aridity, similar in magnitude and extent to droughts in AD 1954, 1960, 1988, and 2002, but which persisted from >8000 to <5000 years ago. Additional multi-century droughts were also documented, and resulted in changes in reduced tree cover in regional forests.

Statement of Problem
Understanding the full range of drought variability is important for informing long-term water resource planning in Wyoming in the future. By assessing prehistoric shoreline elevations of lakes in the North Platte watershed, we are able to extend knowledge of drought episodes beyond the range of historic and tree-ring records to provide a more complete assessment of the range of variability in water availability in the region. Based on evidence of past lake-level variations, these natural reservoirs experienced prolonged draw downs equal to a reduction in the regional hydrologic balance (precipitation minus evapotranspiration) of 0.3 to 0.7 mm/day for periods of centuries to millennia during the past 11,000 years. Such hydroclimatic changes were as severe as during years like AD 2002, and indicate the potential for shifts to severely dry hydrologic regimes that can persist well beyond societal planning horizons.

Objectives
In much the same way that data from local meteorological stations can be compared to assess weather patterns, arrays of lakes (via sediment deposits and proxy data such as pollen) can be studied to reconstruct past climate conditions. Submerged shorelines are indicative of periods of drier-than-present conditions (e.g. Dearing, 1996; Shuman and Finney, 2006). These paleoshorelines are buried under sediment deposited during subsequent wet periods providing a record of past hydrological conditions (i.e., water level). By identifying and dating past lake-shoreline features, we reconstructed the histories of lake water levels in Wyoming, particularly the North Platte River drainage. Through the mapping of the subsurface shorelines from numerous lakes, we were then able to determine regional patterns of water-level change. We compare these past hydrologic patterns with modern climatological data (e.g., Mock and Brunelle-Daines, 1999; Shinker et al., 2006) as a means to better understand the climate processes that are associated with reduction in lake levels. Our objectives are to assess the:
1. Potential that regional water supplies have undergone multi-century fluctuations; 
2. Spatial extent of ancient, long-term droughts in Wyoming; 
3. Potential climatic controls and land-surface feedbacks associated with droughts in the region; and 
4. Impacts of long-term drought on water resources and forest composition.

**Methodology**

Surveys of lakes throughout Wyoming (and the Colorado headwaters of the Platte River) were conducted with 1) ground-penetrating radar (GPR) to identify past shifts in shoreline position via sediment geometry; 2) sediment coring to date past shoreline deposits; and 3) pollen analysis of sediment cores taken from the basin centers to reconstruct past vegetation composition during long-term droughts. In addition, modern climate analogs of past drought conditions were analyzed to determine potential influences of climate on past low lake-level events.

**Ground-penetrating Radar**

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., Digerfeldt et al., 1992; Shuman et al., 2001; 2002). 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 (Almendinger, 1993). Therefore, stratigraphic analyses of such lakes can provide accurate records of paleoclimatic change. We collected and analyzed 137 shore-to-basin GPR profiles to detect changes in the geometry of the sediments that indicated past shoreline elevation, and thus, confirm the regional availability of moisture through time. When lake levels are low, sandy and macrophyte-rich substrates expand toward the center of the lake and sedimentation slows near shore. As a result, sandy layers and hiatuses (erosion surfaces) extend from shore, older sediment units become truncated at these hiatuses, and deepwater sediments “pinch out” towards shore.

**Sediment Cores**

In addition to GPR data, our results derive from sediment cores collected in ten lakes (Hidden Lake, Lily Lake, and Boettcher Lake in Jackson Co., Colorado; American and Creedmore Lakes in Larimer Co., Colorado; East Allen, Long and Little Windy Hill Lakes in Carbon Co., Wyoming; Little Brooklyn Lake in Albany Co., Wyoming; and Lake of the Woods in Fremont Co., Wyoming). Shuman (2003) showed that differences in sedimentary characteristics among sediment cores collected at different depths within a single lake can be used to determine lake-level changes. Cores were collected in multiple sections with a modified Livingstone piston corer with individual polycarbonate barrels for each drive, or section of core. Polycarbonate barrels were detached from the piston device, capped and returned to the University of Wyoming for description, subsampling and analysis. Core density and magnetic susceptibility were determined on whole core sections using a GeoTek Multi-Sensor Core Logger. Sections were then subsampled for loss-on-ignition (LOI), radiocarbon dating, pollen, and macrofossil analysis.

Detailed plots were created of sediment age and elevation that represent the water-level history. Loss on ignition, magnetic susceptibility, and grain-size analysis were assessed to indicate shifts in sediment composition and grain size indicating changes in shoreline positions. AMS radiocarbon dating of plant macrofossil and bulk sediment material was used to establish a
chronology of each sediment core analyzed. Pollen extraction from sediment cores followed
standard methodology (Faegri et al., 1989). Pollen samples were initially analyzed at 16 cm
intervals to determine when present-day forests established. Subsequent samples were examined
from “drought” and “non-drought” periods for determination of ecological responses to past
drought events.

Modern Climate Analogs
Comparison of the lake-level data with maps of climate anomalies allowed for the
examination of potential influences on spatial patterns of hydroclimatic change (e.g. Shinker et
al., 2006). The spatial and temporal variability of modern and past drought events can provide
information on conditions at the surface and in the atmosphere that lead to prolonged drought.
Analysis of modern climate processes provides an important framework for considering
mechanisms related to lake-level fluctuations and vegetation changes (Harrison et al., 2003;
Shinker et al., 2006). Data from the NCEP-NCAR Reanalysis Project (Kistler et al., 2001) were
used to link climatic controls on variations in lake levels and vegetation using a modern-analog
approach (Mock and Brunelle-Daines 1999; Shinker et al., 2006) that incorporates modern
climate data to represent surface and upper-level circulation conditions likely to support
prolonged droughts. Composite anomalies were calculated to compare recent extreme dry years
to long-term mean conditions within the climate system. Once calculated, composite-anomaly
maps were made to show the relationship between large-scale atmospheric circulation patterns
and surface climate responses (Yarnal 1993; Shinker et al., 2006; Shinker and Bartlein 2008).

Calculation of Impacts on Water Resources
We calculated the change in precipitation (P) minus evaporation (E), ΔP-E, at our two of our
primary study sites (Lake of the Woods, Wyoming; Hidden Lake, Colorado) to measure the
impact of past dry conditions on water resources. The two sites were chosen because their well-
defined watersheds enabled us to approximate the moisture budgets of the lakes. To use inferred
lake-level changes as a hydroclimatic indicator, we assume that changes in lake volume depend
on the annual balance of watershed inputs (precipitation) and outputs (evaporation and
groundwater leakage). We assume that groundwater leakage has remained constant through time
although reduced hydrostatic head during periods of low lake levels should reduce levels of
groundwater outflow, and thus make our ΔP-E estimates conservative. To calculate long-term
ΔP-E, we estimate elevational shifts in the wave base of each lake (based on the depths of sand
layers and erosion surfaces), and assume that changes in the elevation of the lake surface were
equal in magnitude. We then calculate the associated change in lake volume by accounting or
lake size and bathymetry. We assume the estimated change in lake volume represents a change in
the annual balance of inputs and outputs of the entire watershed and therefore divide by the
watershed area and 365 days to obtain a ΔP-E value in mm/day comparable to historic
observations.

Results
Lake-level Variations
At multiple lakes throughout the region, we have identified evidence that shorelines were
lower than today for prolonged periods in the past 11,000 years (Fig. 1, 2). GPR profiles show
dense paleoshoreline deposits and erosion/non-deposition surfaces; sediment cores contain sand
layers with very low accumulation rates as expected if near-shore wave-energy interacted with
these substrates. For example, at Creedmore Lake in Larimer Co., Colorado, near the headwaters
of the Laramie River, we found evidence that the lake was lower than its drought-induced low level in May 2008 from ca. 7900-3700 years before present (BP) (Fig. 1). Similar evidence was found at lakes from the southern reaches of the Platte River watershed in Jackson Co., Colorado, to the Wind River Range in Fremont and Sublette Counties, Wyoming (Fig. 2).

An important set of results show that Lake of the Woods, Fremont County, Wyoming, which is at the joint headwaters of the Snake-Columbia, Green-Colorado, and Wind-Bighorn-Missouri River systems, was substantially lower than today before 11,300 yrs BP, from 8900-2700 yrs BP, from 1900-1100 yrs BP. Sediment cores from the lake show three packets of dense sandy sediment, which interrupt intervals of deep-water sediments (olive silt), which date to these periods (Fig. 3). We infer that the packets represent paleoshorelines based on the geometry of the packets (i.e., their consistent appearance in GPR data from around the lake’s margins, and their development only near shore), the shift from silts to sand (i.e., from low to high energy environments) and the low net sedimentation rates of the sand layers (i.e., potentially associated with extensive near-shore sediment winnowing). From 8900 to 2700 yrs BP, the net sedimentation rate within core 2A (at 194-167 cm below the modern lake surface) averaged 4.3 cm/kyr, and was as low as 1.9 cm/kyr from 8900 to 6200 yrs BP. Such low sedimentation rates are inconsistent with high rates of deposition during floods, which is a primary alternative explanation for the sand deposits.

The most recent dense sediment layers also coincide in time with periods of frequent drought in local tree-ring data (Cook and Krusic 2004), and the combination of lake and tree-ring data indicate that recent centuries were probably some of the wettest in the past 8000 years (Fig. 4). Core 2A from Lake of the Woods contains a dense paleoshore deposit at ca. 1100 yrs BP when dendroclimatic evidence indicates >60 drought years in a century. Earlier dense layers indicate that conditions there were likely at least as dry from ca. 8900 to 2700 yrs BP, and before 11,300 yrs BP. Similarly, at the southern end of our study area, at Hidden Lake, Colorado, a core collected near shore contains high-density shoreline deposits with very low net sedimentation rates before 1200 years BP when tree-ring drought reconstructions reveal repeated periods with >50 drought years per century. The lake record indicates that earlier periods were even drier or had more frequent extreme droughts, particularly from 3700-2000 yrs BP and 8400-4400 yrs BP (when the water level was too low for sediment to accumulate at the core location). Notably both lakes were low from ca. 8400-4400 yrs BP, but the details of their histories may otherwise vary, which is also consistent with the spatial variability of most historic droughts and the tree-ring data.

Overall, we find that all of the lakes we studied were commonly low from >7900 to <5000 years ago when sedimentary isotopic data indicate high regional temperatures (Henderson et al., 2008; in prep.). To sustain these low levels, P-E must have dropped by 0.3 mm/day at Lake of the Woods and by 0.7 mm/day at Hidden Lake. These estimates are consistent with climate model simulations of the region for 6000 yrs BP (Diffenbaugh et al., 2006), and indicate regional aridity as intense as in AD 2002.

Modern Climate Analogs of Past Drought Conditions

Evidence of prolonged prehistoric periods of low lake levels across Wyoming indicate persistent dry conditions that were similar to dry conditions in recent years. Years from the modern record that exhibit similar (in magnitude but not in duration) dry conditions as seen in the lake-level record are 1954, 1960, 1988, and 2002. Figure 5 shows the composite-anomaly maps for late spring/early summer (May, June, and July) months of the selected modern analog
years. May, June, and July were selected to represent conditions during peak spring snowmelt and peak precipitation time (May) as well as summer months when evaporation is likely to be high. The modern analogs of ancient Wyoming aridity are characterized by lower-than-normal precipitation (Figure 5a), persistent reduced moisture availability through 850mb specific humidity (Figure 5b), enhanced sinking motions via 500mb vertical velocity (Figure 5c) leading to a mechanistic suppression of precipitation, and drier-than-normal soil moisture conditions (Figure 5d) in late spring and early summer months.

**Pollen Analysis**

A comparison of pollen percentages between drought and non-drought periods suggests millennial scale droughts had an impact on forest composition (FIG 6). Pine percentages decreased during drought period (median value 67%) when compared to non-drought periods (median value 69%). Median spruce percentages were 1% lower (3%) during drought period compared to non drought periods (4%). Fir percentages were indistinguishable between drought and non drought periods. Shrub and herbaceous taxa increase, illustrated by the change in sagebrush percentages, which had median values of 19% during drought periods and 17% during non drought periods. Further refinements of these results are needed to determine the statistical significance of these results. However, our results indicate the ecological significance of the ancient prolonged droughts inferred from the lake-level data.

**Significance**

The results of our study suggest that prolonged multicentennial to millennia scale drought, while not frequent, are common in the North Platte watershed indicating the region has not yet experienced the full range of possible drought conditions. Minimally, there were at least three major periods of drought centered on 3500, 1500 and 750 cal yr BP. GPR data from Lake of the Woods and Hidden lakes, suggest these drought periods could have been characterized by a series of shorter strong drought events with interspersed wet periods. Modulating drought periods might explain the high variance seen in the pollen percentage data during these times as forests responded to climate changes. The droughts in the past appear to have been widespread events most similar to conditions seen in during the AD 2002 anomaly. Conservatively, we calculate that if conditions like AD 2002 persisted over the timescales of drought in the past, perennial water supplies in the North Platte watershed, for example, could disappear. Platte River flows of ~25% of normal in AD 2002 were likely sustained by base groundwater flows that must have been significantly reduced during the past to produce the sustained low lake levels.

**Publications and Presentations**

Numerous presentations and related manuscripts have resulted from this project (detailed below). Current activity includes two manuscripts related to the funded project in preparation for submission to peer-reviewed journals. The first will be submitted to a short-format, high-impact journal (e.g., Geology) and includes initial findings of prolonged lake-level draw down related to long-term drought conditions that surpass historical and dendrochronological records. The second manuscript has been selected for a special volume of the Annals of the American Association of Geographers, and provides a long-term perspective on regional hydrology shifts in the headwaters of the North Platte River.
Related publications and presentations († high-school intern; *undergraduate; **graduate student author):


**Information Transfer**

Results from this research were presented through several scientific symposia and conference presentations including:

- EPCoR, Student Research Apprentice Program, University of Wyoming, July, 2008;
- American Geophysical Union, Fall Meeting, San Francisco, CA, December, 2008;

6
• Wyoming Undergraduate Research Day, University of Wyoming, May 2, 2009 (2 presentations);
• EPCoR, Student Research Apprentice Program, University of Wyoming, July, 2008; and

Student Support
The funded project supported training and mentorship of five students, one high school student, three undergraduate students, and one graduate student.

• Victoria Perez, a high school student from Denver, CO was supported through the EPSCoR Student Apprentice Research Program (SRAP) which supports the involvement of under-represented high school students in research project. Ms. Perez’s involvement in the project included training in field collection and lab analysis of sediment samples from Creedmore Lake, and a presentation of research results at a symposium (see Information Transfer above).

• Joshua Fredrickson, a Geography undergraduate student was funded through the project to be trained in summer field collection of lake sediment cores. As a result of his involvement with this project Mr. Fredrickson will be working on an independent study project in the summer of 2009 to analyze climate data associated with recent low stream flow events in the Platte and Colorado River drainages.

• Paul Pribyl, a Geology and Geophysics undergraduate student was funded through the project to be trained in lab analysis of grain-size analysis and loss on ignition in support of sedimentary analysis. Mr. Pribyl’s training resulted in an independent study project that received additional funding through the NSF EPSCoR and Wyoming NASA Space Grant Programs. Results from Mr. Pribyl’s research will be presented at the University of Wyoming Undergraduate Research Day (see Information Transfer above).

• Robert Shriver, a Botany undergraduate student, was funded through the project to be trained in lab analysis of sedimentary material. Mr. Shriver’s involvement in the project lead to an independent study project funded through NSF EPSCoR and an undergraduate research grant through the Ruckelshaus Institute of Environment and Natural Resources to analyze charcoal and macro-botanical fossils from sediment cores. Mr. Shriver’s research will be presented at the University of Wyoming Undergraduate Research Day (see Information Transfer above).

• Anna Henderson, a Ph.D. graduate student (mentored by Shuman) in Geology and Geophysics at the University of Minnesota (Shuman’s former institution) was responsible for analyses of cores at Hidden, American, Lily, and Boettcher Lakes. Henderson has used funding from this project to obtain radiocarbon dates for detailed lake-level analyses from Lily Lake (extending back ~14000 years) for comparison with results from Hidden Lake. She has also generated a detailed temperature reconstruction for northern Colorado over the past 8000 years based on sediment isotopes from American Lake.

References


Henderson, Anna K.; Grant Elliot; Vania Stefanova; Bryan N. Shuman; Yongsong Huang. 2008. Comparison Between Mid-Holocene and Twentieth Century Climatic Change and Alpine Treeline Fluctuations in the Western U.S. Based on Compound-Specific Hydrogen Isotopes, Tree Rings, Pollen, and Macrofossils. American Geophysical Union, Fall Meeting 2008, abstract #PP41B-1442.


Figure 1. Recent low water levels at Creedmore Lake in May 2008 (A) illustrate the hydrological impacts of the past decade of drought. Sub-surface geology (B), however, captured by ground-penetrating radar (GPR) and sediment core data reveal that the lake has been much lower in the past. In fact, despite water-levels as high as the lichen line on the rocks (A) as recently as AD 1999, no lake sediment has permanently accumulated in the current sandy beach zone since ca. 3750 years before present (BP) (BC 1800) – and then only briefly (see inset photo of a shovel pit from the beach). Paleoshorelines submerged within the lake date from ca. 7950-3750 yrs BP when sand was deposited nearly to the center of the lake (see lower paleoshorelines in B), and to before ca. 200 yrs BP. Bold numbers in B indicate ages and positions of radiocarbon ages on sedimentary features.
Figure 2. Lakes throughout the region contain submerged erosion surfaces at their margins that indicate prolonged periods of low water-levels. Representative ground-penetrating radar profiles from a geographically-diverse selection of lakes are shown. White indicates areas of high-density contrast within the vertical radar profiles. The middle column shows the interpretation of the profile with black lines denoting the submerged lake sediments, dashed lines marking erosion surfaces, and thin black lines showing truncated layers. At the right, the inferred position of the most prominent ancient shorelines (based on the erosion surfaces). Where dated at Lake of the Woods, Little Windy Hill, Creedmore, and Hidden Lakes, the inferred shoreline positions were occupied from >5000 to <3000 years ago (except during a few multi-century wet periods during this time).
Figure 3. Density profiles from cores collected near the margin of the Lake of the Woods show three packets of dense, sandy shoreline sediments (gray). Bold numbers indicate radiocarbon ages bracketing these paleoshorelines deposits in thousands of years before present.

Lake of the Woods (Fremont Co., WY) Core (Water Depth):
3A (105 cm) 2A (120 cm) 4A (120 cm) 1A (146 cm)

0 100 200 300
Depth (cm)

11.3 Radiocarbon Age (1000 Yrs B.P.)
Sandy silts

Gray clays

Gamma Ray Attenuation
Bulk Density (g/cm²)
Figure 4. Lake sediment cores track the low-frequency (long-term) trends in regional drought frequency, and show that the past few centuries have been the wettest period in >8000 years. During intervals when tree-ring evidence records frequent droughts (years with PDSI <-1) per century, cores collected near the margins of Hidden Lake and Lake of the Woods contain dense (sandy) shoreline deposits, which accumulate because the water level of each lake is lower than today during droughty periods. The results indicate periods of 2000-4000 years with >60 drought years per century. Gray box indicates the period when Hidden Lake was too low for sediments to accumulate at the core location (and thus more frequent drought years than during any period in the past 4400 years). Tree-ring data for the lake locations was obtained from Cook and Krusic (2004).
Figure 5. Composite-anomaly maps for summer (May, June, and July) of dry years (1954, 1960, 1988, and 2002, base period 1979-2000), illustrating modern analogs of climate conditions leading to basin-wide water deficits. Precipitation rate (a) showing lower-than-normal precipitation (orange); 850mb specific humidity (b) showing lower-than-normal moisture availability (brown); 500mb vertical velocity (c) showing greater-than-normal sinking conditions which suppress precipitation (orange); and soil moisture (d) showing lower-than-normal moisture at the surface (orange).
Figure 6. Box plots of Pine, Sagebrush, Fir and Spruce pollen percentages for millennial-scale drought periods centered on 3500, 1500 and 750 cal yr BP (left) compared to non-drought period (5000 cal yr BP to present) (right). Drought periods show greater variance in pollen percentages when compared to non-drought periods.
During FY08, 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 of 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's Advisory Committee on an annual basis. Presentations discussing final results are made by PIs of projects which were completed during the year at the Committee's July meeting. Presentations discussing interim results are made by PIs of continuing projects at the Committee's winter 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 information dissemination activities include the following:


Information dissemination activities reported by research project PIs include the following:


USGS Summer Intern Program

None.
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Notable Awards and Achievements

Project 2007WY40B: Weather Modification Impacts and Forecasting of Streamflow. Kyle Cheesbrough, University of Wyoming, Laramie, Outstanding Student Paper Award for paper presentation Glacial Change in the Wind River Range, Wyoming, USA at the 2007 Fall Meeting of the American Geophysical Union in San Francisco, California.

Project 2006WY33B: Precipitation Measurement and Growth Mechanisms in Orographic Wyoming Snowstorms. Grants from NASA and DEPSECoR, complimentary to the WWDC/USGS grant, were used to support two students (Wolfe and Pokharel) who conducted analyses of the WWDC/USGS data set as part of their MS thesis research.

Project 2007WY37B: Tracing Glacial Ice and Snow Meltwater with Isotopes. Dr. Jessica Cable, the postdoc working on this WWDC project, acquired funding from the National Park Service to conduct a parallel study on glaciated basins using isotopic tracers in Grand Teton National Park, WY. The title of her award was: Using stable isotopes of water to determine the contribution of glacial melt to streamflow and plant water use in Grand Teton National Park.
Publications from Prior Years