Wyoming Water Research Program
Annual Technical Report
FY 2007

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. 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 Office of Water Programs serves as the University of Wyoming advisor to the Wyoming Water Development Commission.

State support for the research program includes direct funding through the Wyoming Water Development Commission and active State participation in identifying research needs and project selection and oversight. Primary participants in the WRP are the USGS, the Wyoming Water Development Commission (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 progress. The Director of the Office of Water Programs 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 also provides direct funding (from the WWDC accounts) for the administration of the WRP through the Office of Water Programs, which was approved by the 2002 Wyoming Legislature.

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. Each project represents the education of one or more students.

Research Program

The primary purpose of the Wyoming Institute beginning with FY00 has been to identify and support water-related research and education under what has been entitled the Wyoming Water Research Program (WRP). 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 Legislative action beginning July 2002. The duties of the Office, which provides for the administration of the Wyoming Institute, 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's 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 Vice President of Research. 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 eight research projects are given herein. The reports consist of two 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 2008. The three new projects are listed below, but annual reports are not included herein. The three new projects were selected by the Institute's Advisory Committee based upon peer reviews and subsequent ranking by the Advisory Committee of proposals received in response to the Institute's FY08 RFP.

Reports (listed in order of presentation): (1) Final Report: Subsurface Drip Irrigation Systems: Assessment and Development of Best Management Practices. Drew Johnson, Civil Engineering; Renduo Zhang and George Vance, Renewable Resources, UW, Mar 03 Feb 06. (2) Progress Report: Real-Time Monitoring of E-Coli Contamination in Wyoming Surface Waters. Paul E. Johnson, Physics and Astronomy, UW, Mar 05 Feb 08. (This project has requested a no-cost extension to complete the work and submit a final report to be included in next year's report). (3) Final Report: Predicting drought in the Green River basin. Glenn Tootle and Stephen Gray, Civil and Architectural Engr., UW, Mar 06 Feb 08. (4) Annual Report: Precipitation Measurement and Growth Mechanisms in Orographic Wyoming snowstorms. J. Snider and B. Geerts, Dept. of Atmospheric Science, UW, Mar 06 Feb 09. (5) Annual Report: Tracing Glacial Ice and Snow Meltwater With Isotopes. Dave Williams, Dept. of Renewable Resources, UW, Mar 07 Feb 09. (6) Annual Report: Integrated Management of Groundwater and Surface Water Resources: Investigation of Different Management Strategies and Testing in a Modeling Framework. Fred Ogden, Civil and Architectural Engr., and Melinda H. Benson, Ruckleshaus Institute of Environment and Natural

Resources, UW, Mar 07 Feb 10. (7) Annual Report: Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstroms in Wyoming Using the Wyoming Cloud Radar. Bart Geerts, Dept. of Atmospheric Science, UW, Mar 07 Feb 10. (8) Annual Report: Weather Modification Impacts and Forecasting of Streamflow. Glenn Tootle, Civil and Architectural Engr., UW and Tom Piechota, Univ. of Nevada. Mar 07 Feb 10.

New Projects (as of March 2008): (1) A New Method for Tracing Seepage from CBNG Water Holding Ponds in the Powder River Basin, Wyoming. Shikha Sharma and K.J. Reddy, Dept. of Renewable Resources, UW, and Carol Frost, Dept. of Geology and Geophysics, UW, Mar 08 Feb 10. (2) Water Quality Criteria for Wyoming Livestock and Wildlife. Merl Raisbeck, Dept Veterinary Sciences; Cynthia Tate, Wyoming Game & Fish Dept; and Michael Smith, Dept of Renewable Resources, UW, Mar 08 Feb 11. .(3) Multi-Century Droughts in Wyoming's Past: Evidence of Prolonged Lake Drawdown. Bryan N. Shuman, Dept. Geology & Geophysics, UW; Jacqueline J. Shinker, Dept. of Geography, UW; and Thomas A. Minckley, Dept. of Botany, UW, Mar 08 Feb 09.

Subsurface Drip Irrigation Systems: Assessment and Development of Best Management Practices

Basic Information

Title:	Subsurface Drip Irrigation Systems: Assessment and Development of Best Management Practices
Project Number:	2003WY11B
Start Date:	3/1/2003
End Date:	2/29/2008
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Agriculture, Management and Planning, Non Point Pollution
Descriptors:	
Principal Investigators:	Drew W Johnson, George Floyd Vance, Renduo Zhang

Publication

1. Hao, X., R. Zhang, and A. Kravchencl, 2005. A Mass-conservation Switching Method for Simulating Saturated-unsaturated Flow. Journal of Hydrology 311:254-265.
2. Hao, X., R. Zhang, and A. Kravchenko, 2005. Effects of Root Density Distribution Models on Root Water Uptake and Water Flow under Irrigation. Soil Science 170:167-174.
3. Hao, X. and R. Zhang. 2004. A hybrid mass-conservative scheme for simulating variably saturated flow in soils with large outflow flux. Proceedings of Computational Methods in Water Resources 2004 Conference. UNC-Chapel Hill, North Carolina.

Subsurface Drip Irrigation Systems: Assessment and Development of Best Management Practices.
PIs: Drew W. Johnson and George F. Vance
Final Report

Abstract

Development of best management practices (BMP) for irrigated agriculture has become essential because efficient use of water is crucial with the ongoing drought in Wyoming and because irrigated agriculture contributes to nonpoint source pollution of our ground and surface waters. Proper management of water and the appropriate application of fertilizers can increase agricultural productivity while minimizing water quality degradation. Microirrigation, such as subsurface drip irrigation (SDI), offers the opportunity for precise application of water and fertilizers. Such irrigation methods are being developed as environmentally-friendly farming practices and systems. In this study, field experiments and computer modeling were conducted to quantify both water and fertilizer uptake by crops. Field data and numerical simulations help us to understand many theoretical and technical questions in the applications of SDI. The study provides information for developing and/or improving irrigation management to enhance crop (e.g. alfalfa) productivity.

Project Overview

Microirrigation such as subsurface drip irrigation (SDI) has many advantages for agriculture and the environment. However, many theoretical and design problems related to the application of SDI need further study. For example, how do we quantitatively describe the interrelationships among soil, water and plant? This research project addresses these concerns and provides answers to questions related to irrigation techniques and water-use efficiency.

Initial objectives of the research were to:

1: Compare traditional flood irrigation with an innovative SDI method.

2: Develop BMP for SDI to optimize crop productivity and profits, maximize water-use efficiency, and minimize groundwater contamination.

Project modifications were necessary during the study. The project field study was originally designed to take place at the Midvale irrigation district of Wyoming, however, because the original collaborator identified in the proposal was no longer willing to assist with the project as originally planned and other potential collaborators were only interested in performing the study on a large scale, the field study was changed and occurred at the University of Wyoming's Experimental farm in west Laramie. The Water Research Program (WRP) was notified that the field site had been moved in the 1st year project update.

The necessary relocation of SDI study site impacted activities related to project objective 1. The relocation site lacked access to flood irrigation water over the growing season. Lack of water is primarily because of drought and water allocation issues. Lack of available water due to drought was also a concern at the original field site. Also lacking at the field site are conveyance structures for flood irrigation water. Considering these constraints, sprinkler irrigation was substituted for flood irrigation for comparing the two systems. Sprinkler application does not generate sufficient runoff and leaching to make meaningful measurements and conclusions. This impacted research objective 2 and groundwater contamination aspects were not included in the research.

Experimental Setup and Methods

Details related to the field site measurements and modeling work are described in the following sections of this document.

Experimental Site

The field site was located on the University of Wyoming's Experimental farm in the Laramie Basin of southeastern Wyoming, which has an elevation of 2195 m above sea level. Average annual temperature of the study area is 5 °C with annual precipitation of 27 cm, and a frost-free period of 98 days (USDA, 2006). The Laramie Basin is a depositional remnant of a mid to late Wisconsin periglacial environment (Spackman and Munn, 1984). Soils in the Laramie Basin were formed by a sequence of alluvial deposition and carbonate accumulation. Soils are classified as Rock River sandy loam (fine-loamy, mixed, superactive, frigid Ustic Calciargids), which is approximately 0-8 cm of sandy loam, 8-43 cm of sandy clay loam, and 43-150 cm of fine sandy loam and sandy loam. Hydraulic conductivity of the Rock River soil is moderate, and water availability is high (USDA, 2006). The study site was originally a pasture that was used in a field study of pesticide transport in soil during 1993 – 1995 (Zhang et al., 2000). The field site had not been tilled until initiating the SDI study in 2004.

Site Preparation

The field site is approximately 90 × 30 m (Figure 1). The field was plowed to 20 cm depth, rototilled, and leveled in July 2003. A contour data analysis using theodolite and GPS at 60 locations evenly distributed across the field indicated the field had a 1 degree southeast slope. Average shallow (30 cm) saturated hydraulic conductivity for the field site was 2.3 m d^{-1} as determined using the infiltrometer test method (ASTM, 2002). Deeper soil (40 – 60 cm in depth) saturated hydraulic conductivity was on average 0.023 m d^{-1} as determined by auguring and collecting soil samples that were tested by both the constant head and falling head methods in the laboratory. The study site was divided into three zones, an SDI zone of 60 × 30 m, a sprinkler irrigation zone of 15 × 30 m and a non-irrigated 15 × 30 m control zone. The SDI zone was divided into 9 plots (Figure 1). Logistical constraints with regards to availability of land for the experimental area, as well as funds for the purchase of materials, limited the number of available plots for the experiment. We therefore partitioned each plot into three subplots. Preliminary analyses on soil characteristics indicated no differences among plots prior to alfalfa seeding and installation of irrigation tubing, so we used the subplots as replications in subsequent statistical analyses.

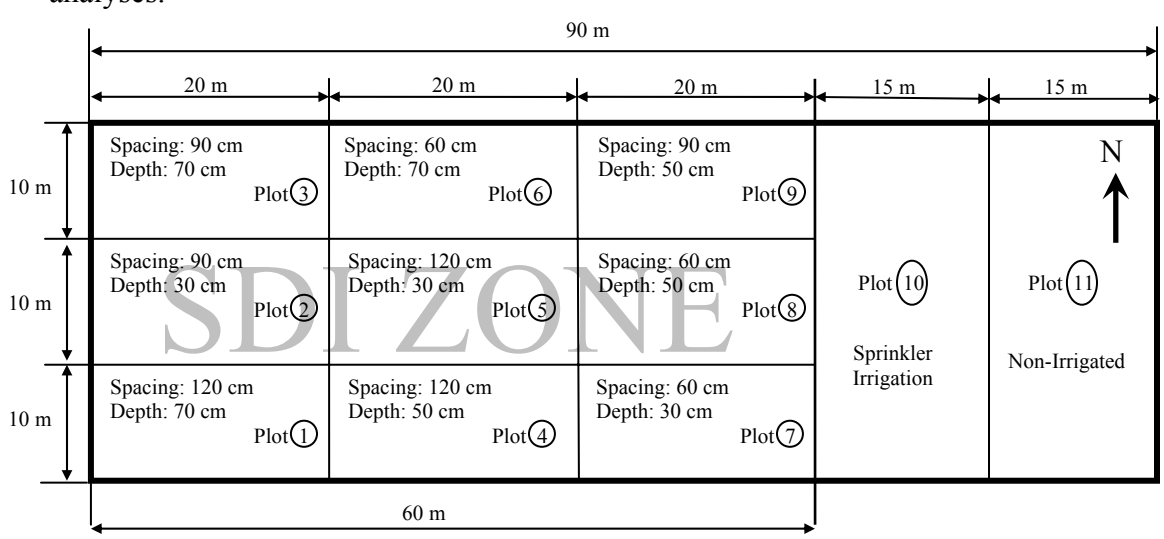

Figure 1 - Layout of the field site showing plot dimensions and the nine subsurface drip irrigation (SDI) zone emitter spacings and depths, sprinkler, and non-irrigated treatments.

In SDI plots, water was supplied by micro discharge from emitters on drip tubing. Drip tubing spacing was the same as emitter spacing on the drip lines. Parameters studied in our SDI system included two factors, depth and spacing of the buried emitters, with three treatment levels. Three depths of 30, 50 and 70 cm and three spacings of 60, 90 and 120 cm were studied. There were nine total treatments of the two factors studied, and thus nine different SDI plots randomly located in the SDI zone. Placement of the SDI lines occurred in 2004. The measured locations for drip lines and supply lines were marked before digging trenches. The size of the supply lines were 2.5 cm in inner diameter (ID) and the drip lines with emitters were 1.2 cm ID. Connecting drip lines to the supply lines was done by using connectors supplied by Netafim (Fresno, CA).

The emitters on drip lines (Netafim USA, Uniram 540 0.4GPH, Fresno, CA) were advanced pressure compensating to ensure uniform flow rate over a pressure range of 48 – 140 kPa.

City water, obtained from a spigot located near the field, was the irrigation water source. Individual supply lines were connected to a controlling/measuring system located inside a nearby pole barn. Water supplies to each plot were measured by flowmeters (Netafim, model M, Fresno, CA), and quantitatively controlled by a computer module (Eldar Shanny, model 0700371362, Yad-Mordechay, Israel). The amount of water supplied was based on published historical monthly evaportranspiration (ET) rates for alfalfa growth in Laramie, WY (Pochop et al., 1992).

Alfalfa Seeding and Irrigation Management

Alfalfa was seeded after plowing, rototilling and leveling of the study site in fall 2004. Fall planting is not common in the region but was tried in an attempt to avoid the need for surface irrigation to initiate seed germination. Winter kill occurred due to an early frost, which required us to replant the following spring. Alfalfa was seeded in mid May 2005 at a seeding density of 2.0 gram/m^2. After sprinkler irrigating to initiate seed germination, excellent germination and crop growth was established. In the 2005 seeding year, sprinkler irrigation was used for about one month. After the alfalfa germinated and resulted in a 15 cm height with sufficient coverage, water supply was managed using SDI for the SDI zones and sprinkler irrigation in the sprinkler zone. Water application was adjusted by the average monthly ET without considering the current monthly precipitation. The same amount of water per unit area was supplied to all plots by the end of July 2005. At the beginning of August 2005, water supply at the consumptive use rate (1.0 ET) was applied to the 9 SDI plots and the sprinkler zone until harvest on September 1, 2005.

In 2006, water was supplied at different fractions of consumptive use (ET) in an attempt to compare performance of different SDI parameters under alternative water supply scenarios. For 2006, all nine SDI plots and the sprinkler irrigated plot were supplied water at a level of 0.7 ET for the first harvest on June 14, 2006, 0.4 ET for the second harvest on July 30, 2006, and 0.4 ET for the third harvest on September 22, 2006. All SDI plots and the sprinkler irrigated plot were supplied water at a level of 0.5 ET for the two harvests in 2007. Precipitation varied throughout the growing seasons and total water application, the sum of irrigation supply and precipitation, as a ratio to historical ET is shown in Figure 2.

Weed Control

Common weeds in this field were Canada thistle (*Cirsium arvense* (L.) Scop.), common lambsquarters (*Chenopodium album* L.), and hoary cress (*Cardaria draba* (L.) Desv.). To reduce the impact of weeds on alfalfa growth, a herbicide treatment of glyphosate (Roundup UltraMax, Monsanto Co., 840 g acid equivalent per hectare) with non-ionic surfactant (Preference, Agriliance LLC, 0.25% volume/volume) and ammonium sulfate (5% weight/volume), was applied 20 days prior to alfalfa planting in April, 2005. Post emergence applications of

imazamox (Raptor, BASF Co., 36 g per hectare) plus the non-ionic surfactant and liquid nitrogen (2% volume/volume) were applied in June and July to selectively remove weeds from the alfalfa crop. No herbicide treatments were applied for the 2006 and 2007 growing seasons.

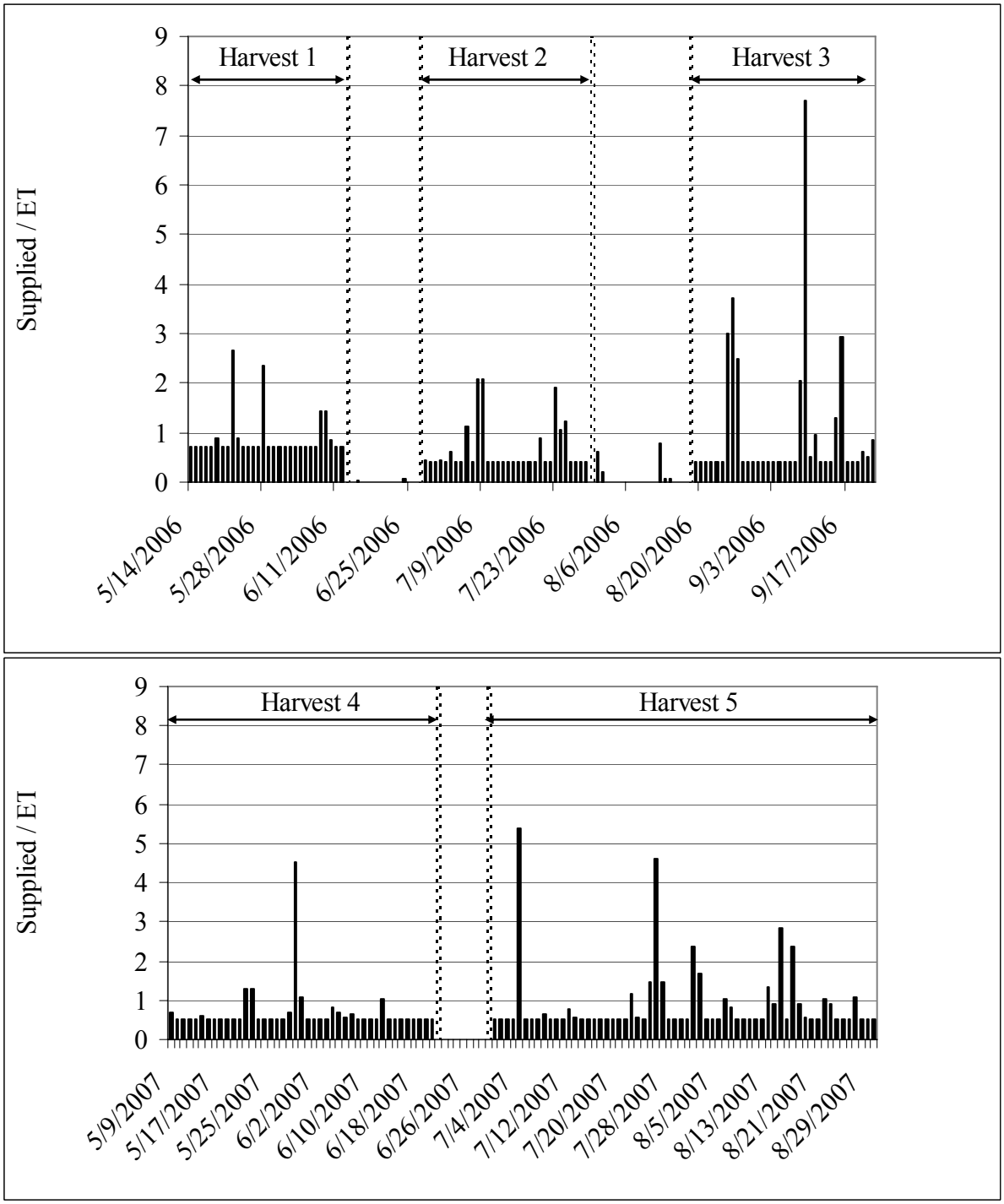

Figure 2 –Daily water supplied to experimental plots, adjusted for precipitation relative to ET for the 2006 and 2007 growing seasons.

Plant sampling, harvest and analysis

Biomass production of alfalfa is most rapid during the growth phase until early flowering, after which production decreases (Kilcher and Heinrichs, 1974; Koch, 1987). Plant sampling and harvests were conducted at the emergence of alfalfa flowering (approximately 10%). Sampling frames used in the plant collection processes were 50 × 50 cm (e.g., 0.25 m^2). Each plot was equally divided into three subplots, and five samples were randomly collected from each subplot by hand clipping. Alfalfa biomass was clipped and stored in paper bags that were marked by a unique sample location identifier.

In the seeding year (2005), a total of 165 samples were collected in SDI and sprinkler irrigated plots at the end of the growing season. In our first production year (2006), alfalfa was sampled and harvested three times with a total of 495 samples collected from eleven plots (SDI, sprinkler, and non-irrigated sites). In 2007, alfalfa was sampled and harvested two times with a total of 330 samples collected from the eleven plots. All samples were dried in an oven at 75°C for one week. A scale was used to weigh the dry alfalfa biomass weight.

Statistical Analyses

Two statistical analyses were conducted using data collected from the nine SDI, sprinkler, and non-irrigation plots during the 2006 and 2007 harvests. The first analysis tested the null hypothesis that spacing and depth do not interact ($\alpha = 0.1$). A two-factorial analysis of variance, set in a completely randomized design was used. If the interaction term was significant in this first analysis, then means were separated using the LSMEANS option of the Statistical Analysis System (SAS Institute, version 9.1). The second analysis considered all spacing × depth combinations as treatments along with the sprinkler and the non-irrigated applications for a total of 11 treatments. These treatments were analyzed in a one way analysis of variance set in a completely randomized design. If the *F* test indicated there were differences among treatments, mean separations were conducted using Fisher's protected LSD. Statistical calculations were facilitated by use of the GLM procedure of the Statistical Analysis System (SAS Institute, version 9.1).

Numerical Modeling

The numerical model HYDRUS-2D was used to investigate how emitter spacing and depth design parameters impact alfalfa root water uptake within the field plots. Simulated alfalfa yields were compared to measured alfalfa yields for each of the alternative spacing × depth scenarios. The HYDRUS-2D model solves the governing 2D Richard's equation using the van Genuchten-Mualem constitutive relationships. In the modeling analysis, the drip tubing was treated as a line source (Skaggs et al., 2004) and effects of individual emitters neglected. Natural precipitation and irrigation water supplied through the drip tubing for the second harvest of 2006 was input into HYDRUS-2D along with soil hydraulic properties of the field site (see site description). The following hydraulic HYDRUS 2-D parameters were used for the sandy loam soil layer: θ_s = 0.41, θ_r = 0.065, α= 0.075, n = 1.89, K_s = 106.1 cm d^{-1} and l =0.5. Parameters θ_s = 0.39, θ_r = 0.1, α= 0.059, ν = 1.48, K_s = 31.44 cm d^{-1} and l =0.5 were used for the sandy clay loam layer. These are the default values for sandy loam and sandy clay loam from the HYDRUS-2D soil catalog.

Uptake parameters for alfalfa, as described by Feddes et al. (1978), were also inputs to the model, where HYDRUS-2D allows the Feddes' parameters to be selected for alfalfa from a built-in database. Typical active rooting depths after 1-2 years of alfalfa growth in sub-humid environments are between 1-2 m (Auckly and Guitjens, 1995) and the root zone during simulations was assumed to be at a midpoint depth of 1.5 meters. Both uniform and linear root distributions were used in the simulations. Because no natural precipitation occurred and

irrigation water was not supplied for approximately two weeks prior to second harvest, the initial pressure head of the field site prior to irrigating was assumed to be equal to the value at which alfalfa can no longer uptake water at the maximum possible rate (-1500 cm) (Feddes et al., 1978). Alternatively, the wilting point of alfalfa (-8000 cm pressure head) (Feddes et al., 1978), could have been used, but visual observations at the time prior to irrigation of the second harvest did not support a wilting point assumption.

HYDRUS-2D uses the Galerkin finite-element method to solve Richard's equation. Symmetry at the midpoints between adjacent drip lines was assumed and the mesh was rectangular except for where the drip line was represented by a half circle of 0.6 cm radius with the center located at the depth of the drip lines. During irrigation, the drip tubing boundary had a constant water flux of 420 cm d^{-1} for all emitter spacing. This value was calculated based upon the daily amount of water supplied, area of drip tubing in each treatment, and required irrigation times. Irrigation times were 20, 30 and 40 minutes for the 60, 90 and 120 cm drip tubing spacing, respectively, and varied with length of drip tape used for each emitter spacing. The irrigation time used in the simulation for the narrow 60 cm spacing approximately matched required irrigation time necessary for the 60 cm spacing during the field trials to supply water at 0.4 ET. Significantly longer irrigation times were required for the wider drip line spacing in the field trials than those used in the simulations. This is because fewer emitters were present along the length of each drip tape at wider emitter spacing.

Effects of emitter spacing along the length of drip tape were neglected when treating the system as a line source. When irrigation ceased, the drip line boundary became a zero flux boundary. The remaining portion of the left boundary and the right boundary were zero flux boundary conditions due to symmetry. The upper boundary for the soil surface was an atmospheric boundary condition with an assumed zero evaporation loss (Skaggs et al., 2004). The computational domain was large and the bottom boundary did not affect the simulations.

Results and Discussion

Yields obtained for the five individual harvests are shown in Figure 3. Total average yield for all SDI treatments was 18.3 Mg ha^{-1} for 2006 and 15.2 Mg ha^{-1} for 2007, with 15.0 Mg ha^{-1} for 2006 and 13.8 Mg ha-1 for 2007 for the sprinkler treatment and 13.6 Mg ha^{-1} for 2006 and 13.4 Mg ha^{-1} for 2007 for the control treatment. The relatively high yield obtained for the control plot was higher than expected, and may have been influenced by the topography of the field. No separation was provided between plots, so runoff from the upslope surface irrigation plot likely influenced the non-irrigated plot's yields. Subsurface drip irrigation plots were upslope of the sprinkler plot and were therefore not influenced by runoff. Similarly, runoff from the SDI plots was presumably minimal, and therefore did not influence the sprinkler zone's yields.

Differences between treatments varied across the five harvests depending upon the amount of natural precipitation. Larger differences between the SDI plots and the sprinkler and non-irrigated plots were observed when irrigation represented a larger proportion of total water supplied (irrigation plus precipitation). The largest difference between treatments (standard deviation of 17%) occurred in the first harvest when water supplied via irrigation was 80% of total water supplied. The smallest difference between treatments occurred in the last harvest (standard deviation of 2%) when water supplied via irrigation was 60% of total water supplied.

Statistical analysis of the total alfalfa yields over two growing seasons for different treatments are shown in Table 1 where different letters for the *t*-grouping from the LSMEANS output indicate significant differences between treatments at the $P < 0.1$ .level.

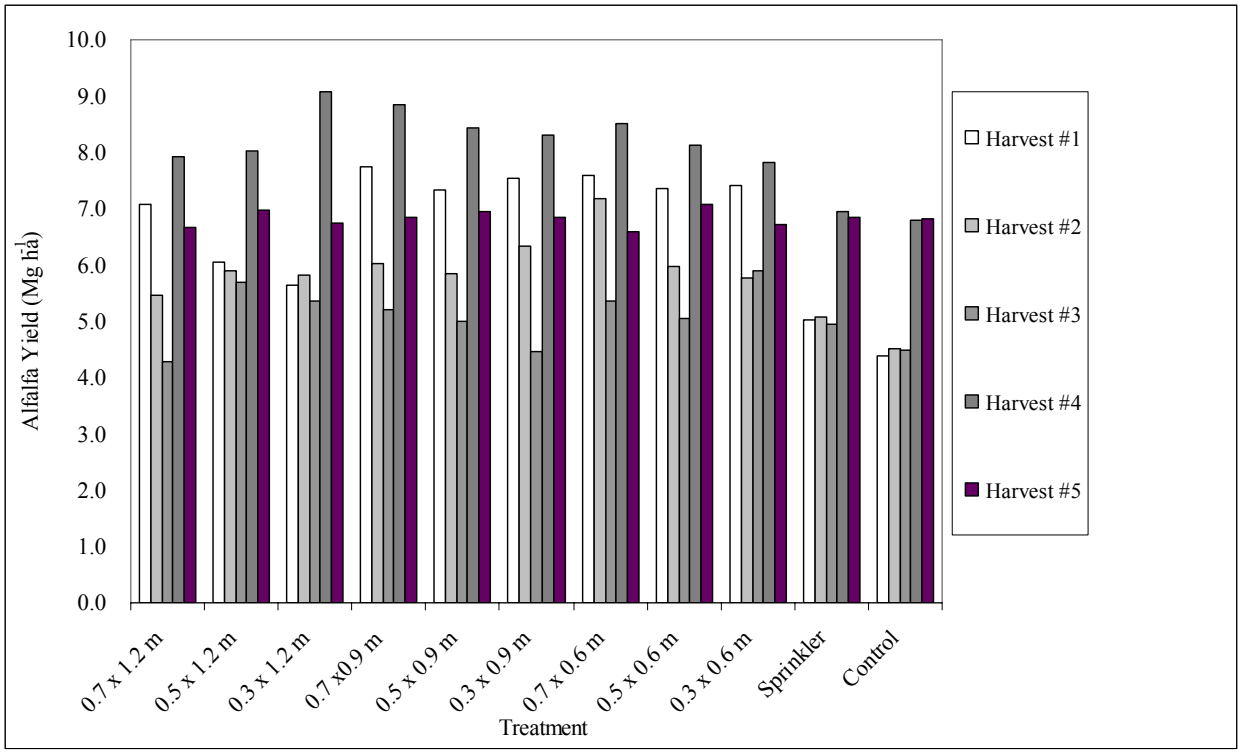

Figure 3 - Yields from each of five harvests for the nine subsurface drip irrigation (SDI), sprinkler and non-irrigated treatments. SDI treatments represent drip line depths and emitter spacings. Irrigation amounts and precipitation varied as indicated for the five harvests (see Figure 2).

Table 1 – Statistical analysis results comparing measured two-year total alfalfa yields of alternative subsurface drip irrigation (SDI), sprinkler and non-irrigated treatments*.

Irrigation Treatments	**Depth (cm)**	**Spacing (cm)**	**Two-year Total Alfalfa Yield (Mg/ha)**
SDI	70	60	35.2[a]
SDI	70	90	34.6[ab]
SDI	30	60	33.6[bc]
SDI	50	60	33.6[bc]
SDI	50	90	33.6[bc]
SDI	30	90	33.5[bc]
SDI	50	120	32.7[cd]
SDI	30	120	32.6[cd]
SDI	70	120	31.4[d]
Sprinkler			28.9[e]
Non-irrigated			27.0[f]

* Lower case letters following alfalfa yields indicate significance at the $P < 0.1$ level.

Treatments with two letters in the *t*-grouping are transition plots for neighbor groups where total alfalfa yields were not significantly different. Overall, the SDI treatments had significantly higher yields than the sprinkler and non-irrigated treatments. The highest two-year total yield, 35.2 Mg ha^{-1}, was obtained in the 70 cm depth × 60 cm spacing SDI treatment. This yield was significantly greater than in all other treatments except the 70 cm depth × 90 cm spacing SDI treatment. The lowest two-year total yield among the SDI treatments, 31.4 Mg ha^{-1}, was obtained in the 70 cm depth × 120 cm spacing SDI treatment. The sprinkler and non-irrigated treatments had significantly lower yields than the SDI treatments.

The relationships between yield and drip emitter spacing and depth are shown in Figure 4. The two-factorial analysis of variance found no depth effect ($F_{2, 18}$, P = 0.5275), a strong spacing effect ($F_{2, 18}$ = 8.96, P = 0.002), and no depth × spacing interaction ($F_{4, 18}$ = 2.08, P = 0.1264). Results indicate narrower spacing (90 cm or less), irrespective of depth, produce greater alfalfa yields. Note, however, that the highest two-year total yields were obtained from the 70 cm depth treatments.

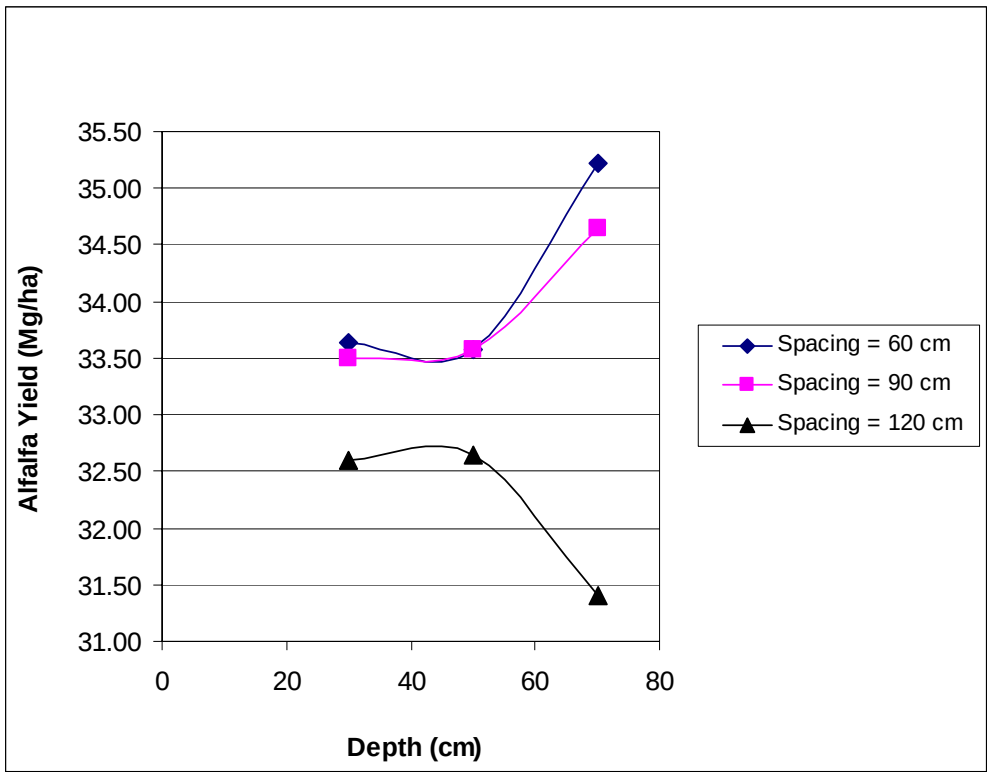

Figure 4 – Two-year total alfalfa yields for alternative subsurface drip irrigation (SDI) tubing depth and emitter spacing treatments.

Simulated water root uptake in undisturbed soil from the HYRDUS-2D model is shown in Figure 5. In general, root uptake and evapotranspiration rates correspond to yields (Auckly and Guitjens, 1995). The simulated values indicate greater yields for the narrow emitter placements. The simulated values also indicate better yields for deeper emitter placements; the depth effect is more apparent if a uniform root distribution model is assumed. The effect of emitter depth on soil water content at the end of the simulation time is shown in Figure 6 for the 60 cm spacing. More uniform water content is apparent with deeper emitter placements; that is, greater simulated root water uptake is primarily due to deeper and hence more uniform wetting zones.

The simulations show that both emitter spacing and depth influence simulated root water uptake and yield. This is in contrast to results from field measurements in this study and those of Alam et al., (2002a) which show that emitter spacing alone influences yield. Discrepancies between the measured and simulated results may be attributed to the assumed root distributions. Alfalfa rooting distributions are known to vary with water application scenarios (Abdul-Jabbar et al., 1982; Vaughan et al., 2002) and different rooting distributions among the SDI treatments may have existed within the field, compensating for different water distributions resulting from the various emitter depths used.

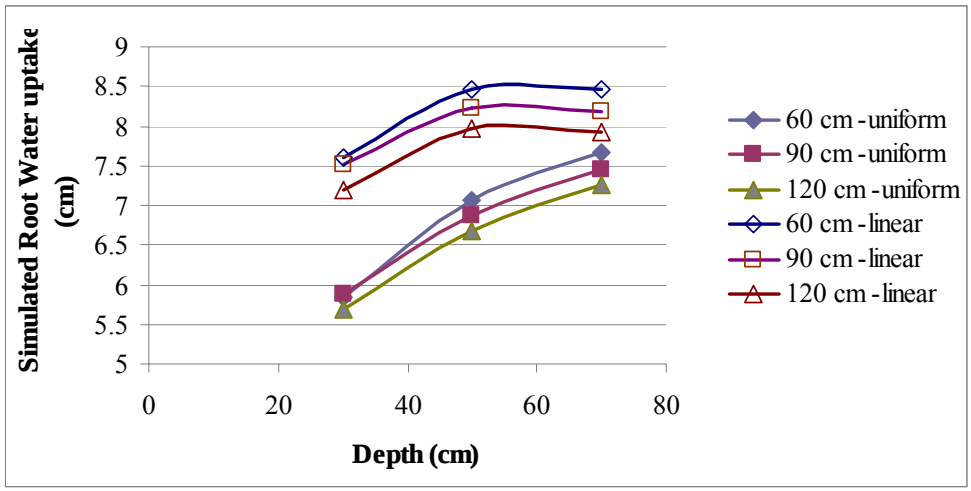

Figure 5 - HYDRUS-2D simulations of alfalfa water root uptake during the second 2006 harvest for two root distributions, subsurface drip irrigation (SDI) emitter depth, and spacing combinations.

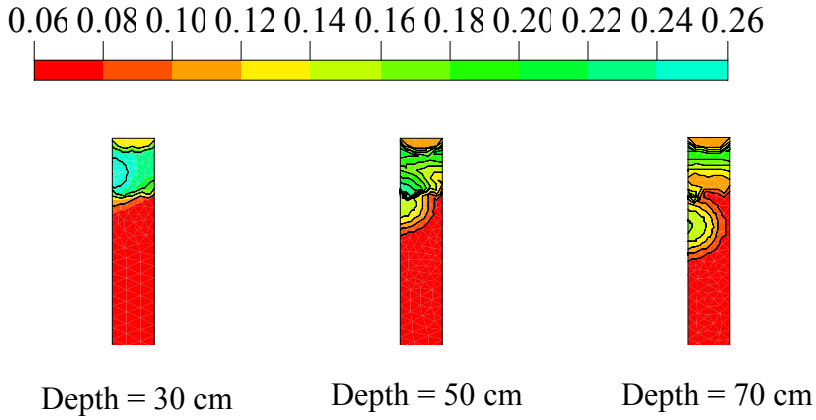

Figure 6 – Simulated soil water content for the 60 cm spacing emitters buried at three depths. More uniform water distribution within the root zone occurs with deeper depth.

Economic Analysis

Results of this study indicate that SDI can increase alfalfa biomass production as compared to sprinkler irrigation and natural precipitation, and that 70 x 60 cm and 70 x 90 cm depth by spacing SDI treatments resulted in the largest biomass production. All of the 60 and 90 cm spacing treatments were statistically the same, except for the 70 x 60 depth by spacing treatment. Therefore, we selected the 90 cm spacing treatment for the following economic analysis, which calculates the break-even alfalfa yield for SDI applications. The break-even yield is such that total revenue just covers total cost for a given output price.

Cost data from Breazeale et al. (2000) were used for this analysis. Breazeale et al. (2000) conducted a break-even analysis for a 65-ha field of alfalfa in Nevada with a 45 cm depth × 100 cm spacing SDI treatment. They reported an investment cost of \$2,980 ha^{-1} for an SDI system with 100 cm spacing, which was comparable to a \$2,562 ha^{-1} investment cost for SDI systems using this spacing (Alam et al., 2002b). The cost is also similar to the \$2,866 ha^{-1} investment cost that Klauzer (2005, personal communication) reported for an SDI system with 75 cm spacing. O'Brien et al. (1998), in contrast, suggested an investment cost of only \$1,331 ha^{-1} for an SDI system with 150 cm spacing. Adjusting this estimate for 100 cm spacing increases the required length of drip line by 3,333 m ha^{-1}. Assuming the cost of drip line is \$0.1473 m^{-1} (as extrapolated from Breazeale, and including the cost of fittings), investment cost increases by roughly \$491 ha^{-1}. The adjusted investment cost of \$1,822 ha^{-1} is still lower than other studies' estimates. The remaining cost discrepancies are attributable in part to different assumptions about the cost of drip line, filtration, and installation.

Investment cost data from Breazeale et al. (2000) were adopted in this study for the following reasons: (1) the focus of their study was alfalfa hay production, (2) their cost estimate was relatively consistent with other estimates found in the literature, and (3) their cost estimate was slightly higher than estimates in other studies, and thus generates conservative break-even yields. For this economic analysis, as in Breazeale et al. (2000), a theoretical 65-ha field was used; however, SDI spacing was assumed to be slightly narrower (90 cm rather than 100 cm) than used by Breazeale et al. (2000). Investment cost for the purchase and installation of the SDI system was therefore adjusted to account for more narrowly spaced drip lines. The narrower spacing required an additional 1,111 m ha^{-1} of drip line as well as additional fittings, which increased investment cost by approximately \$164 ha^{-1}, from \$2,980 to \$3,144 ha^{-1}.

The next step in the break-even analysis was to tabulate the annual total cost of producing alfalfa hay under SDI. Breazeale et al. (2000) cost data was again used with only slight modification. The investment cost of \$3,144 ha^{-1} was first depreciated over its 15 year useful life on a straight-line basis, such that the annualized investment cost (or depreciation cost) was \$210 ha^{-1}. The opportunity cost of invested funds, other fixed costs (e.g., land taxes and the annualized cost of establishing the alfalfa stand), and variable costs of alfalfa hay production summed to \$1,142 ha^{-1} (Breazeale et al., 2000). The total annual cost of SDI alfalfa hay production, assuming 90 cm SDI spacing, was therefore \$1,352 per hectare. Total cost does not include the cost of water, which varies widely throughout the western U.S. Additionally, it does not account for the investment and operating costs generated by the sprinkler irrigation system used in this study to germinate and establish the alfalfa stand. A fall-planted alfalfa stand would have to receive sufficient natural precipitation to germinate and become established. However, the cost estimates provided here offer a preliminary assessment of potential profitability, and can be adjusted to represent unique costs incurred or avoided by an individual producer.

The final step in the break-even analysis was to calculate the minimum yield required for total revenue to just equal total cost for a given output price. This was accomplished by dividing the total cost per hectare by the price received per Mg of alfalfa hay. Table 2 reports the break-even annual yields for various alfalfa hay prices.

Table 2 – Break-even yields (Mg ha^{-1}) for SDI alfalfa hay production, given alternative alfalfa hay prices.

		Price Received for Alfalfa Hay ($ Mg^{-1})				
Total Cost ($ ha^{-1})		$90	$100	$110	$120	$130
$1,352		15.0	13.5	12.3	11.3	10.4

The highest annual yield required to break even was 15.0 Mg ha^{-1} (or a total of 30 Mg ha^{-1} over two years), which occurs under a low output price of $90 Mg^{-1}. The average annual yield from the ×90 cm spacing SDI treatments for the two years of study was approximately 17.0 Mg ha^{-1}, which implies that the net return for SDI alfalfa production would be greater than zero at a low output price of $90 Mg^{-1}. Given a high output price of $130 Mg^{-1}, only 10.4 Mg ha^{-1} would be needed to break even. Net returns for SDI alfalfa hay assuming an output of 17.0 Mg ha^{-1} and an output price of $130 Mg^{-1} would equal about $900 ha^{-1}.

The above analysis indicates that alfalfa grown under a ×90 cm spacing SDI system would generate sufficient revenue to cover total cost. A producer could potentially enjoy large positive net returns if management and weather conditions similar to those in the experiment occurred. Management of a small plot differs, however, from that of an entire field, so yields at the field-level might be lower than those achieved in this study. Seed germination and the first month of alfalfa growth in the experimental plot, for example, was supported by sprinkler irrigation. The availability of a supplemental irrigation system for seed germination is unlikely in a commercial production setting, so yields might be lower. Field-level experiments and producer-led demonstrations are needed to determine, with more confidence, the profitability of SDI alfalfa at a commercial scale.

The break-even analysis indicates the potential for a producer to cover production costs of SDI alfalfa. However, it does not indicate whether net returns to SDI alfalfa exceed net returns to alfalfa grown under other irrigation systems, such as a center pivot. Cost data for center pivot-irrigated alfalfa were insufficient for a meaningful comparison to the cost data for SDI alfalfa provided in Breazeale et al. (2000). O'Brien et al. (1998) provided a detailed economic comparison of center pivot versus subsurface drip irrigation, but the analysis was for corn, rather than alfalfa. A more extensive meta-analysis of the existing literature, a companion study to Breazeale et al. (2000), or new enterprise budgets for southeast Wyoming would be necessary to address the relative profitability of alfalfa under alternative irrigation systems. Such efforts were beyond the scope of this project, and therefore remain an area for future research.

Summary and Conclusions

Results of this study were determined from alfalfa yields measured for three drip emitter depths (30, 50 and 70 cm) and three drip emitter spacings (60, 90 and 120 cm). Measured alfalfa yields were compared to HYDRUS-2D simulations of root water uptake for the different drip irrigation scenarios. The results of this study indicate that SDI can increase alfalfa biomass production as compared to sprinkler irrigation, and that the narrow spacing (60 and 90 cm) SDI

treatments resulted in greater yield increases in alfalfa biomass production than wider 120 cm spacing SDI treatments. An economic analysis indicated that alfalfa grown under a 90 cm spacing SDI system should be able to generate sufficient revenue to cover costs associated with using SDI technology.

Field tests showed that the highest two year yield, 35.2 Mg ha^{-1}, was obtained in the 70 cm depth × 60 cm spacing SDI treatment, which was significantly different than all other treatments except the 70 cm depth × 90 cm spacing. The sprinkler and non-irrigated treatments had significantly lower yields than all SDI treatments. While the two highest yields were generated by the 70 cm depth treatments, results indicate narrower spacing (90 cm or less), irrespective of depth, produce greater alfalfa yields. HYRDUS-2D simulations show that both emitter spacing and depth influence root water uptake. This is in contrast to results from field measurements, which show that emitter spacing alone influences yield. Differences may be due to assumed root distributions in the simulations. The economic analysis indicated that alfalfa grown under a ×90 cm spacing SDI system would generate sufficient revenue to cover total cost. A producer could potentially enjoy large positive net returns if management and weather conditions were similar to those in this SDI study.

Students Supported

Graduate Students:

Youquan Jiang, initially studied for a PhD Civil Engineering, and subsequently a MS, Renewable Resources, University of Wyoming. Degrees were not completed and the student has left the University of Wyoming.

Xinmei Hao, PhD, Renewable Resources, University of Wyoming, degree was completed in 2006, student was only partially supported with project funding.

Undergraduate students; these students assisted with experimental site installation, setup and harvest collection.

Christopher York, BS Civil Engineering, University of Wyoming

Diogo Lousa, BS Civil Engineering, University of Wyoming

Dan McGillvary, BS Civil Engineering, University of Wyoming

Presentations and Publication Information

George F. Vance. Subsurface Drip Irrigation of Alfalfa. W1128 Regional Research Committee on Reducing Barriers to Adoption of miccroirrigation, Honolulu, HI. October 2007.

Youquan Jiang, Drew W. Johnson, George F. Vance and David E. Legg. Subsurface Drip Irrigation for Alfalfa Production in Wyoming, University of Wyoming Graduate Research Symposium, April 2006.

Note: The last three publications listed under "Publications" at the front of this report are related to the research project with partial student support provided from the research project. Additional details may be obtained by contacting Dr. Renduo Zhang, at zhangrd@mail.sysu.edu.cn. Dr. Zhang was an original PI on the project before leaving the University of Wyoming

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Appendix A – Harvest Data

(See Figure 1 for Treatment Number Descriptions)

Treat	sub plot	repln.	2006_1	2006_2	2006_3	Total' 06 (Mg/ha)	2007_1	2007_2	Total'07 (Mg/ha)
1	1	1	7.77	4.73	4.50	17.00	8.39	6.11	14.49
1	1	2	6.56	5.80	3.43	15.78	6.86	5.76	12.62
1	1	3	6.65	5.28	4.41	16.34	6.45	6.29	12.74
1	1	4	5.90	5.27	2.89	14.06	7.21	6.52	13.74
1	1	5	5.53	5.07	5.01	15.61	8.50	7.28	15.78
1	2	1	7.86	6.56	4.24	18.66	9.11	5.63	14.74
1	2	2	6.54	4.83	3.95	15.32	8.79	6.54	15.33
1	2	3	7.44	4.72	4.36	16.52	7.80	6.65	14.45
1	2	4	7.52	6.13	3.86	17.50	6.39	5.23	11.62
1	2	5	8.06	5.83	3.60	17.49	7.79	8.20	15.99
1	3	1	9.17	4.99	4.82	18.98	6.93	7.08	14.01
1	3	2	7.21	5.76	4.76	17.74	9.90	7.41	17.32
1	3	3	7.72	6.59	4.40	18.71	7.66	8.53	16.19
1	3	4	5.66	5.20	5.42	16.27	8.90	7.02	15.93
1	3	5	6.50	4.98	4.76	16.24	8.09	5.68	13.77
2	1	1	6.65	6.84	4.00	17.49	7.47	6.31	13.79
2	1	2	6.88	6.68	4.49	18.06	7.58	8.25	15.83
2	1	3	6.04	5.74	3.98	15.75	8.69	5.06	13.75
2	1	4	6.23	5.60	4.39	16.22	8.63	7.14	15.77
2	1	5	9.68	6.22	4.75	20.65	8.10	6.81	14.91
2	2	1	7.99	6.28	5.22	19.49	7.52	6.57	14.09
2	2	2	9.53	6.70	3.92	20.15	6.63	8.34	14.97
2	2	3	7.64	7.29	4.72	19.64	7.88	6.63	14.51
2	2	4	5.44	6.23	4.32	16.00	6.78	6.10	12.89
2	2	5	7.33	6.62	4.52	18.48	9.26	6.03	15.29
2	3	1	6.52	4.83	4.35	15.70	10.26	6.50	16.76
2	3	2	7.28	6.41	4.55	18.24	9.19	8.60	17.79
2	3	3	9.88	5.54	4.80	20.22	8.37	6.39	14.76
2	3	4	7.04	7.98	4.38	19.39	9.93	6.57	16.50
2	3	5	9.08	6.19	4.39	19.66	8.35	7.44	15.79
3	1	1	6.85	6.30	5.82	18.97	7.71	7.95	15.66
3	1	2	8.88	6.20	4.87	19.94	7.97	6.41	14.37
3	1	3	7.65	5.66	5.29	18.60	6.26	6.94	13.20
3	1	4	7.30	5.71	5.94	18.94	7.88	8.33	16.21
3	1	5	8.44	5.94	4.83	19.22	8.76	6.78	15.54
3	2	1	8.19	7.32	5.49	21.00	8.86	5.74	14.60
3	2	2	6.81	6.64	4.95	18.40	10.25	6.44	16.69
3	2	3	7.85	5.16	5.24	18.26	9.93	7.75	17.67
3	2	4	5.21	5.98	5.02	16.22	8.13	6.63	14.76
3	2	5	8.84	6.28	5.24	20.36	9.29	9.12	18.41
3	3	1	6.87	5.15	5.44	17.46	10.30	5.30	15.61
3	3	2	6.70	6.41	4.66	17.76	9.20	6.17	15.37
3	3	3	8.88	6.21	5.44	20.54	9.70	5.95	15.64
3	3	4	8.64	5.58	4.58	18.80	10.15	5.94	16.09

3	3	5	9.01	5.85	5.24	20.11	8.17	7.09	15.25
4	1	1	5.57	5.86	5.17	16.60	8.79	6.77	15.56
4	1	2	6.49	5.24	6.58	18.32	8.26	7.14	15.40
4	1	3	6.41	5.73	4.80	16.94	8.52	7.00	15.52
4	1	4	5.19	5.54	5.71	16.44	8.68	7.63	16.31
4	1	5	5.67	6.77	4.88	17.32	7.11	5.29	12.40
4	2	1	7.84	7.04	7.47	22.36	8.68	7.72	16.40
4	2	2	6.16	6.28	6.32	18.76	7.11	8.12	15.24
4	2	3	4.83	5.71	4.94	15.49	7.90	7.27	15.18
4	2	4	5.74	5.29	6.03	17.06	9.09	7.09	16.18
4	2	5	6.64	5.83	5.05	17.52	8.25	8.15	16.40
4	3	1	7.37	6.45	6.87	20.69	7.87	5.64	13.52
4	3	2	4.88	4.53	4.92	14.33	7.05	7.70	14.75
4	3	3	6.56	5.60	6.08	18.24	7.39	6.07	13.46
4	3	4	5.62	6.19	4.54	16.35	8.95	6.33	15.28
4	3	5	5.98	6.41	6.09	18.48	6.66	6.62	13.28
5	1	1	6.42	4.79	5.70	16.91	8.73	5.61	14.34
5	1	2	4.96	6.58	4.94	16.48	10.08	5.95	16.03
5	1	3	4.79	5.07	6.14	16.00	10.11	4.84	14.95
5	1	4	5.76	5.24	4.73	15.73	7.96	6.34	14.30
5	1	5	6.45	5.42	6.45	18.32	10.12	7.92	18.04
5	2	1	6.09	5.24	5.75	17.08	7.13	7.46	14.59
5	2	2	6.16	5.55	5.44	17.16	8.14	6.50	14.63
5	2	3	5.33	5.46	5.37	16.16	9.63	5.91	15.53
5	2	4	5.18	6.07	6.10	17.35	9.17	8.04	17.21
5	2	5	5.74	5.58	6.86	18.18	9.09	5.91	15.00
5	3	1	5.16	6.15	4.50	15.81	9.27	8.04	17.31
5	3	2	4.86	6.25	4.92	16.04	9.71	8.90	18.61
5	3	3	5.98	7.00	3.98	16.96	9.54	6.11	15.65
5	3	4	4.81	6.27	5.48	16.56	9.08	8.69	17.77
5	3	5	6.84	6.44	3.95	17.24	8.34	4.77	13.11
6	1	1	9.07	7.80	4.52	21.40	9.96	7.14	17.10
6	1	2	9.29	6.46	5.86	21.61	6.43	4.23	10.66
6	1	3	6.62	6.71	4.73	18.06	8.17	6.79	14.96
6	1	4	6.82	8.02	5.08	19.92	8.79	4.28	13.07
6	1	5	7.01	7.25	5.19	19.45	8.82	6.39	15.20
6	2	1	7.01	7.37	6.50	20.88	9.04	7.82	16.86
6	2	2	8.62	7.86	5.25	21.73	8.83	6.77	15.60
6	2	3	6.48	6.80	4.60	17.88	9.87	6.69	16.55
6	2	4	8.16	6.72	5.72	20.59	7.71	7.49	15.19
6	2	5	8.98	7.18	6.59	22.75	8.89	5.92	14.81
6	3	1	8.25	7.46	5.68	21.39	8.14	7.46	15.60
6	3	2	7.05	6.31	5.04	18.40	7.32	6.36	13.68
6	3	3	6.68	7.74	5.88	20.29	8.79	7.61	16.40
6	3	4	7.60	6.80	4.74	19.14	8.40	6.74	15.14
6	3	5	6.32	7.06	4.98	18.36	8.63	7.02	15.64
7	1	1	8.01	6.29	5.92	20.22	6.27	5.21	11.48
7	1	2	7.53	5.26	5.74	18.53	7.28	7.37	14.65
7	1	3	6.27	7.20	5.73	19.20	7.70	6.76	14.46
7	1	4	6.89	5.28	5.74	17.92	9.28	5.83	15.12

7	1	5	6.15	5.98	5.84	17.96	9.78	6.40	16.18
7	2	1	8.15	4.98	5.42	18.56	7.50	7.72	15.22
7	2	2	7.04	5.92	6.83	19.79	5.81	8.20	14.00
7	2	3	6.88	5.30	6.47	18.64	9.45	7.61	17.06
7	2	4	8.63	5.91	6.02	20.56	8.22	8.39	16.62
7	2	5	7.10	5.53	5.99	18.62	6.64	7.42	14.06
7	3	1	6.87	5.49	5.53	17.90	7.89	6.20	14.08
7	3	2	6.38	5.88	5.75	18.01	8.11	6.84	14.94
7	3	3	7.83	5.42	6.02	19.27	7.92	5.31	13.23
7	3	4	9.26	6.26	5.08	20.60	7.94	7.06	15.01
7	3	5	8.24	5.81	6.41	20.46	7.69	4.59	12.27
8	1	1	7.86	5.11	4.15	17.13	8.17	8.00	16.17
8	1	2	6.70	5.69	4.02	16.40	8.09	8.30	16.39
8	1	3	8.80	5.17	3.36	17.32	8.34	7.07	15.41
8	1	4	8.38	6.51	4.91	19.79	8.25	7.11	15.36
8	1	5	7.53	5.64	4.35	17.53	7.45	7.50	14.94
8	2	1	7.82	6.74	5.80	20.36	7.80	5.65	13.44
8	2	2	7.11	6.20	4.41	17.72	6.98	6.24	13.22
8	2	3	8.23	6.10	5.14	19.47	6.94	8.99	15.94
8	2	4	6.08	5.98	4.90	16.97	6.89	7.65	14.54
8	2	5	9.04	6.27	5.74	21.05	8.33	5.85	14.18
8	3	1	7.40	6.01	7.38	20.79	8.47	6.38	14.85
8	3	2	6.85	5.59	6.56	19.00	7.88	7.05	14.93
8	3	3	5.48	6.01	5.08	16.57	9.34	7.04	16.38
8	3	4	6.50	6.68	5.88	19.05	9.08	5.79	14.87
8	3	5	6.43	6.06	3.90	16.38	9.88	7.61	17.49
9	1	1	7.65	7.66	5.41	20.72	8.28	6.59	14.87
9	1	2	8.05	5.61	4.22	17.88	8.45	7.84	16.29
9	1	3	7.60	5.78	4.54	17.92	9.51	5.62	15.13
9	1	4	7.16	6.77	4.27	18.20	9.08	7.54	16.62
9	1	5	7.09	6.50	4.34	17.92	8.77	8.12	16.89
9	2	1	7.63	5.86	4.46	17.95	8.92	5.83	14.75
9	2	2	6.72	5.43	4.40	16.55	7.53	4.86	12.39
9	2	3	7.98	5.98	5.22	19.18	7.58	6.48	14.06
9	2	4	7.27	5.41	5.17	17.85	9.04	6.79	15.83
9	2	5	7.30	5.70	4.99	17.99	6.82	9.70	16.52
9	3	1	6.98	5.33	6.36	18.68	9.42	5.24	14.66
9	3	2	8.26	5.81	5.24	19.31	8.44	6.52	14.97
9	3	3	7.46	5.51	4.29	17.26	7.80	8.13	15.93
9	3	4	6.48	4.99	5.52	16.99	8.56	8.55	17.11
9	3	5	6.51	5.41	6.76	18.68	8.16	6.36	14.52
10	1	1	4.90	6.63	5.21	16.73	7.65	6.11	13.75
10	1	2	6.50	5.59	4.76	16.86	6.87	6.31	13.18
10	1	3	4.11	4.65	5.23	13.99	7.32	7.08	14.40
10	1	4	5.01	5.36	4.69	15.06	6.10	5.77	11.87
10	1	5	4.68	5.74	4.80	15.21	6.95	5.87	12.82
10	2	1	4.82	4.45	4.76	14.03	6.99	6.19	13.19
10	2	2	4.94	4.30	4.14	13.38	7.18	7.89	15.07
10	2	3	4.68	4.37	4.83	13.88	6.52	5.81	12.33
10	2	4	4.79	5.31	5.62	15.72	6.10	8.03	14.12

10	2	5	4.86	4.55	4.13	13.54	6.13	6.52	12.65
10	3	1	4.74	6.20	4.84	15.78	6.10	6.74	12.85
10	3	2	5.50	4.10	4.90	14.51	8.22	9.19	17.41
10	3	3	4.37	4.66	5.77	14.80	6.55	7.40	13.96
10	3	4	5.96	5.53	5.28	16.77	7.77	7.01	14.78
10	3	5	5.68	4.60	5.14	15.42	7.84	6.81	14.65
11	1	1	4.19	3.80	5.57	13.56	7.99	6.16	14.15
11	1	2	4.33	6.10	5.15	15.58	5.46	5.70	11.16
11	1	3	3.28	4.46	4.74	12.48	6.95	6.64	13.59
11	1	4	4.16	3.84	4.38	12.39	5.00	5.66	10.67
11	1	5	4.55	4.54	4.74	13.83	5.48	8.13	13.62
11	2	1	4.18	4.72	3.91	12.80	6.29	6.17	12.47
11	2	2	4.83	5.03	3.81	13.67	6.26	7.44	13.70
11	2	3	4.42	3.91	4.78	13.11	7.69	7.08	14.77
11	2	4	4.66	4.47	4.63	13.76	6.65	6.38	13.03
11	2	5	4.72	4.19	3.42	12.34	7.22	4.62	11.84
11	3	1	4.66	4.58	4.77	14.01	8.54	7.57	16.11
11	3	2	4.50	4.32	4.52	13.34	7.75	7.49	15.24
11	3	3	5.07	3.99	4.72	13.78	6.19	9.04	15.23
11	3	4	4.32	5.48	3.83	13.63	7.80	6.63	14.42
11	3	5	4.07	4.47	4.28	12.81	6.62	7.51	14.12

Real-Time Monitoring of E. Coli Contamination in Wyoming

Basic Information

Title:	Real-Time Monitoring of E. Coli Contamination in Wyoming
Project Number:	2005WY24B
Start Date:	3/1/2005
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Water Quality, Methods, None
Descriptors:	
Principal Investigators:	Paul E. Johnson

Publication

1. Johnson, P.E., A.J. Deromedi, P. Lebaron, P. Catala, and J. Cash, 2006. Rapid detection and enumeration of Escherichia coli in aqueous samples using Fountain Flow Cytometry, Cytometry, 69A, 1212-1221.
2. Johnson, P.E., Deromedi, A.J., Lebaron, P., Catala, P., Havens, C., and Pougnard, C. 2007. High Throughput, Real-time Detection of Naegleria Lovaniensis in Natural River Water Using LED-Illuminated Fountain Flow Cytometry, J Appl Microbiol. 103 (3), 700710.

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, Chemchrome 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.

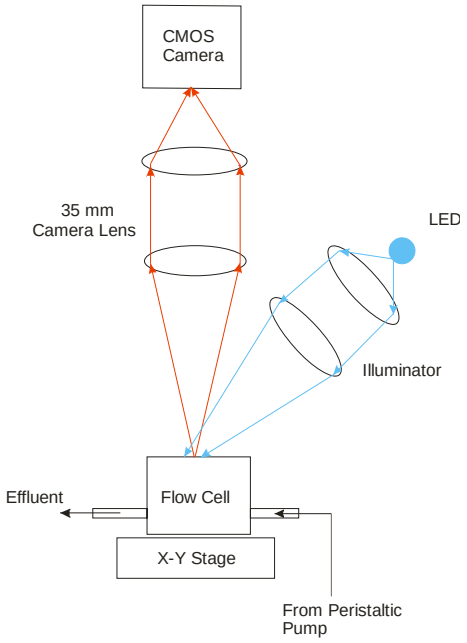

Figure 1. *Schematic diagram of an LED-illuminated epifluorescent Fountain Flow Cytometer. A sample of fluorescently tagged cells flows through the flow cell toward the CMOS camera and fore-optics. The cells are illuminated in the focal plane by an LED. When the cell(s) pass through the CMOS camera focal 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.*

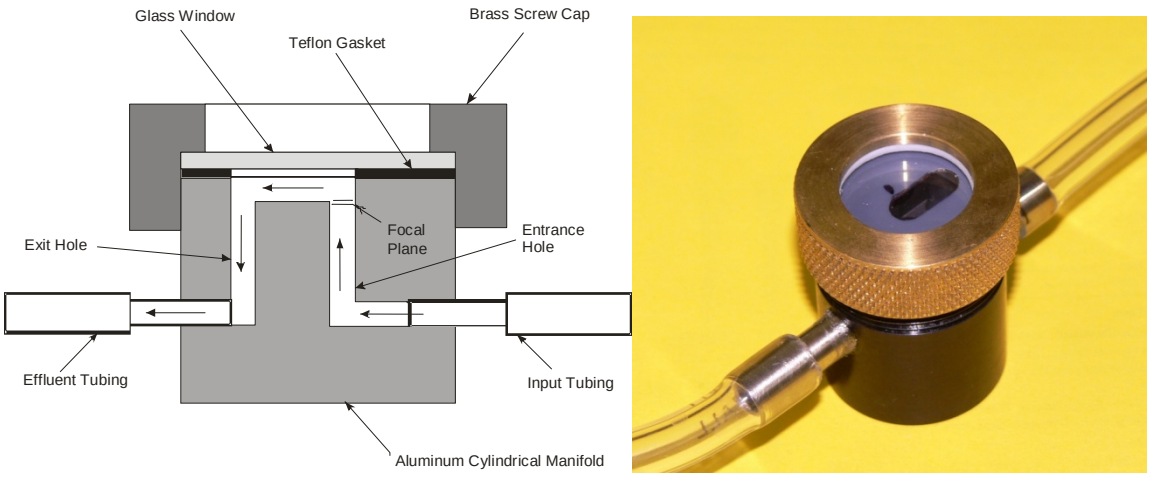

Figure 2. *The Fountain Flow™ Cytometer aluminum flow manifold as used in the device shown in Figure 1 (from Johnson et al., 2006).* ***Upper Panel:*** *The sample enters the flow block through a Tygon tube connected to a stainless steel tube and exits through a stainless steel tube. Two holes have been 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

1. Johnson, P.E., Havens, C., Lebaron, P., and Catala, P., *High Throughput, Real-Time Detection of Naegleria lovaniensis in Aqueous Samples using Two-Color Fountain Flow™ Cytometry,* Journal of Applied Microbiology.
2. Turque, Nathalie, et al., *Detection of Metal Contamination in River Water using Fountain Flow™ cytometry of Transgenic Xenopus Larvae*, Biotechnology.

Patents Pending

1. Apparatus and Method for Measuring the Fluorescence of Large Multi-Cellular Organisms, *patent pending*, P.E. Johnson.
2. Method and System for Counting Particles in a Laminar Flow with an Imaging Device, *patent pending*, P.E. Johnson.
3. Method for Pre-Sorting Microorganisms in Aqueous Solution prior to Selective Staining and Detection, *patent pending*, P.E. Johnson.
4. Copyrighted software, including XenopeImage, BioImage, and BioCount, P.E. Johnson.

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*

Predicting Drought in the Green River Basin

Basic Information

Title:	Predicting Drought in the Green River Basin
Project Number:	2006WY32B
Start Date:	3/1/2006
End Date:	2/28/2008
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Drought, Climatological Processes, Hydrology
Descriptors:	
Principal Investigators:	Glenn Tootle, Stephen Gray

Publication

1. Tootle, G.A., T. Hunter and T.C. Piechota, 2006. Pacific Oceanic / Atmospheric Variability and the Wind River Range. Proceedings of the ASCE World Water & Environmental Resources Congress 2006, May 21-25, 2006, Omaha, NE.
2. Hunter, T., Tootle, G.A., and T.C. Piechota, 2006. Oceanic-atmospheric variability and western U.S. snowfall. Geophysical Research Letters, 33, L13706.
3. Bellamy, J., G. Tootle, G. Kerr and L. Pochop, 2008. Frequency and Duration of Drought in the Green River Basin, WY, USA. Proceedings of the ASCE World Water & Environmental Resources Congress 2008, May 11-17, 2008, Honolulu, HI.
4. Hunter, Thaddeus, 2007. Oceanic-Atmospheric Variability and Western U.S. Snowfall. M.S. Thesis, Dept. of Civil and Architectural Engineering, Univ. of Wyoming, May.
5. Watson, Thomas, 2007. Wind River Basin (Wyoming) Streamflow Reconstructions. M.S. Thesis, Dept. of Civil and Architectural Engineering, Univ. of Wyoming, Aug.
6. Barnett, Faires Anthony, 2007. Upper Green River Basin Streamflow Reconstructions and Drought Variability. M.S. Thesis, Dept. of Civil and Architectural Engineering, Univ. of Wyoming, Dec.

Predicting Drought in the Green River Basin
PIs: Glenn Tootle and Steve Gray
Final Report

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Executive Summary and Research Results

Report Contents

This is the final report for the project *Predicting Drought in the Green River Basin*. The report is divided into this Executive Summary and 3 Chapters. Chapter 1 addresses Task 1 (Evaluation of Streamflow Reconstruction Methodologies) and Task 4 (Improvement of Streamflow Reconstructions for the Green River Basin with New Tree-ring Collections) of the proposal. Anthony Barnett and Tom Watson were the lead investigators and authors of this chapter. Chapter 2 addresses Task 3 (Probabilistic Forecasting of Droughts) of the proposal. John Bellamy was the lead investigator and author of this chapter. Chapter 3 addresses Task 2 (Linkages of Streamflow with Large-Scale Ocean / Atmosphere Phenomena) of the proposal. Thad Hunter was the lead investigator and author of this chapter.

Abstract

This two-year research project used proxy records derived from tree rings to examine climatic controls on the Wyoming Green River Basin (GRB) streamflow and assessed how natural interdecadal variability might impact delivery of water from the GRB. In the first year of the project we reviewed existing streamflow proxies for the GRB and laid the groundwork for an assessment of how reconstruction methodology might affect key elements (e.g. reconstructed drought magnitude) of these records. We also collected the necessary tree-ring chronologies to perform an investigation of long-term streamflow variability, focusing on extreme events such as mega-droughts. In year two this investigation included examinations of the influence of various atmospheric – oceanic influences [e.g., El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO)] on GRB streamflow. This analysis also addressed how large-scale climatic drivers affect the spatial distribution of droughts, and therefore the demand for Colorado River water, across the Compact states. Finally, in year two the results of the research were used to develop probabilistic drought forecasts for the GRB. These forecasts utilized both empirical probabilities for drought risk derived from the tree-ring record and links between streamflow and climatic drivers like ENSO and the PDO.

Statement of Critical Regional or State Water Problems

Seven years of nearly continuous drought, coupled with rapid population growth in the Lower Basin, has recently prompted a major re-evaluation of local, state and federal policies on the management of the Colorado River. In particular, as major reservoirs such as Lake Powell and Lake Mead dropped to approximately 50% of full reservoir capacity, many stakeholders began to consider the possibility of a "call" on the Upper Basin, while others formulated plans to "share the shortfall." During the September 2005 Water Forum meeting in Cheyenne, Pat Tyrrell, Wyoming State Engineer, announced the pending development of a program to evaluate and monitor water-related activities in the GRB. This program is in response to both the recent drought and increased interest in the state of Wyoming's apportionment of Colorado River water (approximately 1 million acre-feet per year or 14% of the Upper Colorado River state's allocation of 7.5 million acre-feet per year). The ability to provide information on the range of natural variability in the GRB, as well as improved operational forecasts (i.e., probability above

or below normal water year streamflow), is now of critical interest for both the state of Wyoming and Upper / Lower Colorado River states.

One proven approach to understanding both the range of natural variability and improving drought predictions in regions like the GRB is to examine oceanic / atmospheric drivers of streamflow. There is an increasing awareness that oceanic / atmospheric variability occurs on multiple timescales, and drives both interannual to decadal flow events. In particular, regional hydrologic extremes (e.g., floods and droughts) based on observed gage records have been linked to oceanic / atmospheric variability associated with ENSO, PDO, and AMO. However, instrumental records offer only a limited sample of extreme events, making statistically robust studies of ocean / atmosphere / hydroclimatic linkages difficult.

Interdecadal variability is especially important for understanding large river systems like the Colorado because changes in streamflow over 10-30 year timeframes can have a dramatic affect on policy and management. However, the investigation of interdecadal variability requires long records because phenomena such as the PDO and AMO, two likely drivers of interdecadal streamflow variability, occur at periodicities of 20-80 years. Historical (observed) records of streamflow are typically available for periods of 50-100 years. Unfortunately, this length of record generally covers only one to three phases of these interdecadal phenomena.

Streamflow reconstructions using tree rings offer a means to address these limitations of the instrumental record. Two reconstructed streamflow datasets are now available for the Green River near Green River, UT (Stockton and Jacoby, 1976; Woodhouse et al. 2005), and a new, preliminary reconstruction has been developed for the Green River near Green River, Wyoming (Woodhouse et al. 2005). Our current research centers on using these and other tree-ring reconstructions to assess patterns (temporal and spatial) and sources of streamflow variability in the GRB. This work is also aimed at evaluating reconstruction methods and incorporating newly acquired tree-ring chronologies to further extend the proxy record for the Upper GRB.

Objectives

The scientific objectives of the proposed two-year research project were to:

1. Evaluate methodologies used to reconstruct GRB streamflow.
2. Examine linkages between GRB reconstructed streamflow and large scale oceanic / atmospheric phenomena that act at interannual and interdecadal time scales.
3. Develop probabilistic forecasts of droughts, and frequency / duration analysis of droughts.
4. Supplement existing tree-ring chronologies for the Upper GRB with new collections. .

Statement of Results or Benefits

From 2001 to 2003, Professor Stephen T. Jackson, Ph.D. and Stephen T. Gray, Ph.D. of the University of Wyoming's Department of Botany were funded by the Water Resources Program (WRP) on a study entitled "Combining Modern and Paleo-Climate Data to Enhance Drought Prediction and Response." Key findings of the Jackson – Gray study included: (1) Strong evidence that droughts of a greater magnitude and duration than any 20th century events have regularly occurred in western Wyoming over the past 800 year; (2) Droughts in western Wyoming show strong links to circulation patterns in the northern and tropical Pacific Ocean; (3) However, connections between western Wyoming drought and the Pacific Ocean may also be modulated by variations in other ocean basins (e.g. the North Atlantic).

Our current research is extending this previous work and addressing additional research needs identified in the Jackson – Gray study. In particular, the current project is further examining linkages between interannual and interdecadal ocean / atmosphere phenomena and GRB streamflow. Ultimately, this work will focus on developing a lead-time approach where ocean / atmosphere conditions, and the resulting potential for drought, are evaluated prior to the beginning of each water year. An additional goal of the research was to develop probabilistic forecasts of drought and to perform a frequency – duration analysis of drought.

The results of the research made several contributions including:

- The development of six new tree-ring chronologies for the Upper Green River Basin.
- The first successful streamflow reconstructions in the Upper Green River Basin. This includes streamflow reconstructions at major nodes used by the Bureau of Reclamation (BOR). BOR uses both instrumental and reconstructed streamflow in their Colorado River System Simulation System (CRSS) model. Also, headwaters gages were reconstructed which allowed for observing spatial variation in drought.
- The streamflow reconstructions revealed that significant "mega-droughts" have occurred. These mega-droughts far exceeded (in both length and magnitude) those droughts observed in the instrumental record. These results provide important information for water managers and planners.
- The magnitude, severity and risk of drought in the Upper Green River Basin were quantified and the recent (2000 to 2004) five year drought was examined. This resulted in the 2000 to 2004 drought having a frequency (probability of recurrence) of approximately 130 years.
- A distinct El Niño-Southern Oscillation (ENSO) was observed in streamflow and snowpack in the Wind River Range, including the Upper Green River Basin. A previous year summer La Niña (El Niño) results in increased (decreased) streamflow (or snowfall).

Student Support

The research provided outstanding training and support for four MS level graduate students in Civil Engineering. Three of the four graduate students have completed their master's degree and are currently employed at engineering firms in the State of Wyoming. The fourth student will defend in Fall 2008.

Publications and Presentations

The results of the research have been submitted to various peer-reviewed journals and as conference proceedings. The published publications and proceedings are listed at the beginning of this report while presentations given and publications submitted are summarized below.

Watson, T., F.A. Barnett, S. Gray and G. Tootle, 2008. Reconstructed Streamflow for the Headwaters of the Wind River, Wyoming USA. Submitted to *Journal of American Water Resources Association* (under 2nd review).

Barnett, F.A., T. Watson, S. Gray and G. Tootle, 2008. Upper Green River Basin Streamflow Reconstructions and Drought Analysis. Submittal pending to *Water Resources Research*.

Bellamy, J., G. Tootle, G. Kerr and L. Pochop, 2008. Frequency and Duration of Drought in the Green River Basin, WY, USA. Presentation at ASCE World Water & Environmental Resources Congress 2008, May 11-17, 2008, Honolulu, HI.

Bellamy, J. and G. Tootle, 2008. Frequency, Duration and Risk Assessment of Drought in the Upper Green River Basin, Wyoming. Presentation at American Geophysical Union (AGU) Hydrology Days, March 26-28, 2008, Fort Collins, Colorado.

Barnett, F.A., T. Watson, S. Gray and G. Tootle, 2007. Streamflow Reconstructions and Periods of Drought in the Upper Green River Basin, Wyoming, USA. American Geophysical Union (AGU) Fall Meeting, December 10-14, 2007, San Francisco, California.

Tootle, G.A., T. Hunter and T.C. Piechota, 2006. Pacific Oceanic / Atmospheric Variability and the Wind River Range. Presentation at ASCE World Water & Environmental Resources Congress 2006, May 21-25, 2006, Omaha, NE.

Hunter, T. and G.A. Tootle, 2006. Oceanic-Atmospheric Variability and Western Snowfall. Presentation at American Geophysical Union (AGU) Hydrology Days, March 20-22, 2006, Fort Collins, Colorado.

In addition, numerous local presentations were made including the WY State Engineer's Water Forum and the University of Wyoming Graduate Seminars.

Chapter 1 – Development of Upper Green River Basin Tree-Ring Chronologies and Streamflow Reconstructions

Abstract—Chapter 1

The upper Green River represents a vital water supply for southwestern Wyoming and Upper / Lower Colorado River Compact states. Rapid development in the southwestern U.S. combined with the recent drought has greatly stressed the water supply of the Colorado River system and has increased interest in historic streamflows. The current research developed proxy records (streamflow) derived from tree ring chronologies in the Upper Green River Basin (UGRB). These streamflow reconstructions provide an effective way to analyze patterns of drought over a period of time extending beyond any instrumental record.

Nine streamflow reconstructions were developed for both headwaters stations (utilizing unimpaired streamflow records) and stations lower in the basin (utilizing naturalized streamflow records). Traditionally, streamflow reconstructions have mostly been limited to large rivers, but reconstructing headwaters records provides information to water users in the upper basin as well as providing spatial variability in streamflow throughout the river basin. In this study, all upper basin reconstructions extended back to the year 1615. The most downstream station in the UGRB (Green River near Greendale, UT) was extended to 1439 A.D. The coefficient of variance explained (R^2) for this reconstruction is 0.65.

Different modes of drought were identified within this reconstruction. Annual extremes (wet and dry) and persistent wet and dry (drought) periods were identified compared with long term trends in the reconstructed streamflow record.

Introduction—Chapter 1

The Upper Green River Basin (UGRB, Figure 1) is a vital contributor to the Colorado River system, and the severity of the current multi-year drought has raised concerns about the ability of the upper basin states to meet obligations set fourth in the Colorado River Compact. Approximately thirteen percent of the available surface water in the Upper Colorado River Basin (UCRB) originates in the headwaters of the UGRB. The UGRB headwaters were one area of focus of the Lake Powell Research Project Bulletin, the first streamflow reconstruction effort based on information derived from tree rings (Stockton and Jacoby, 1976) and remain an area of interest for water planners within the Colorado River System (Brandon, 2005). In the three decades following the Stockton and Jacoby report, tree ring based research has been greatly improved by the addition of computer aided techniques and an increase in the number of available tree ring chronologies located within and adjacent to the Upper Colorado River Basin. The resulting improvement in streamflow proxy records has provided greater insight into the effects of severe sustained drought and the resulting economic impacts on water users within the Colorado River System (Lord et al., 1995; Young, 1995).

Recent reconstruction efforts have typically focused on streamflow gages at main nodes of the larger rivers (Woodhouse et al., 2006a; Meko et al., 2001; Cook and Jacoby, 1983) due to the larger area and population affected by potential streamflow deficits during periods of severe drought. Headwater stream reconstructions, in contrast, may not be representative of an entire basin but do provide information pertaining to inter-basin variability, and to water supplies in the upper reaches of the given watershed (Woodhouse et al., 2006b; Woodhouse 2001). Ultimately,

climate driven variations in streamflow affect all users from irrigators to individual domestic users. By examining long-term streamflow variations through dendrohydrological studies, a relative understanding of past, present, and future drought severity and duration can be obtained.

In order to create a network of streamflow proxies within the UGRB, two obstacles had to be overcome. First, there are many stream gaging stations in the UGRB but few have the required length and continuity in the instrumental record required to calibrate a streamflow reconstruction model. Second, few current tree ring chronologies are available in or adjacent to the UGRB.

Initially, the identification of serviceable stream gaging stations was performed, which resulted in nine spatially varied stations being selected. Next, six sites were selected for tree core collection in the foothills of the Wind River Mountain Range (on the eastern boundary of the UGRB, in Wyoming) that were used in the creation of six new tree ring chronologies (current to 2006). Two of the new chronologies were developed for sites sampled in the development of chronologies used for streamflow reconstructions in the UGRB (Stockton and Jacoby, 1976) and the original chronologies have since been employed in drought analysis in the UCRB (Meko et al., 1995). The addition of these six new chronologies to be used in conjunction with existing current chronologies (located in Wyoming, Colorado, and Utah) enables some tributary stream gages to be reconstructed for the first time in the UGRB. Also, the addition of these new chronologies provides information leading to more robust reconstructions of gages that have been reconstructed in the past (i.e. Green River at Warren Bridge and Green River at Green River, Wyoming).

Finally, the nine selected instrumental stream gages were reconstructed using the available tree ring chronologies in the region. Different modes of streamflow were examined in the streamflow proxy record developed for USGS gage #09234500 (Green River near Greendale, UT) which is located near the lower extent of the UGRB. Examination of these records shows extreme differences between flows in the instrumental and pre-instrumental periods, particularly in the duration and magnitude of droughts. These differences raise questions about how current management plans would address a severe sustained drought or wet period, as seen in reconstructed streamflow proxy records.

Study Area and Background—Chapter 1

The UGRB has a watershed area of approximately 22,600 square miles and is located between the Wind River Mountain Range and the Wyoming Mountain Range in southwestern Wyoming. Winter snowpack is responsible for the majority of water year streamflow, which peaks during the spring-summer season (Mock, 1996). Due to the limited spring-summer season for peak streamflow, reservoir storage within the UGRB is designed to capture peak runoff allowing year-round distribution to the Colorado River System. The UGRB reservoir storage capacity is 4.36 million acre-feet in the ten largest reservoirs (Wyoming State Water Plan, 2007). This storage volume is over twice the average water year instrumental streamflow for the Green River near Greendale, Utah, near the lower extent of the UGRB. The storage capacity in the basin has allowed water managers and planners to mitigate the effects of drought events in the decades since the construction of the various dams.

Long-term hydroclimatic variability within individual river basins contributing to the Colorado River System has recently become an issue of greater interest given the current (1999 to present) drought. The UGRB headwaters were first studied as part of the Lake Powell Research Project Bulletin (Stockton and Jacoby, 1976), where headwater gage records as well as main stem river gage records were reconstructed (using tree ring data) to examine long-term

variability in streamflow. In this 1976 report, three headwater gage reconstructions were successfully completed in the UGRB for the Green River, New Fork River, and North Piney Creek.

Although limited in scope, recent research has attempted to update and improve the Stockton and Jacoby (1976) UGRB results. The Palmer Drought Severity Index (PDSI) was reconstructed for the continental United States on a gridded network (Cook et al., 1999; Cook et al., 2004). However, the PDSI research did not provide information specific to inter-basin variability in the UGRB or provide any information directly pertaining to surface runoff.

Two projects directed at new and/or improved streamflow reconstructions include Woodhouse et al. (2006a) and Timilsena (2007). Woodhouse et al. (2006a) developed a reconstruction for the Green River near Green River, WY streamflow station and coefficient of variance of 0.48 was obtained for the reconstruction. This study relied heavily on tree ring chronologies from northern Colorado and Utah due to few updated chronologies being available in southwest Wyoming.

Timilsena (2007) attempted reconstructions at three gage locations in the UGRB including; Green River at Green River, WY, Green River at Warren Bridge, and East Fork River near Big Sandy, WY. This research demonstrated the need for an increased number of moisture sensitive tree ring chronologies in the region. For the Green River at Warren Bridge and East Fork River near Big Sandy, WY, Timilsena (2007) determined an insufficient number of predictors (i.e. tree ring chronologies) were available for the reconstruction regression model. Additionally, the Green River near Green River, WY reconstruction was unable to achieve a coefficient of variance of 0.40 (considered a minimum value for useful reconstructions) when utilizing tree ring chronologies available in the region.

Data and Methods—Chapter 1

Streamflow Data

To create statistically robust streamflow reconstructions, it is necessary to use the most accurate streamflow information available for a given gage station. Therefore, unimpaired or naturalized streamflow data must be utilized to obtain true hydroclimatic variability (Slack et al., 1993). An unimpaired stream gage station is defined as a station with minimal effects of anthropogenic uses including storage, diversion, and consumptive use. The difference between unimpaired and naturalized streamflow is that naturalized flow is back calculated from an impaired gage record to represent a prehistoric flow at that station using information from unimpaired instrumental records higher in the watershed.

United States Geological Survey (USGS) stream gage information was obtained for all stream gages in the UGRB from the National Water Information System (NWIS) (http://waterdata.usgs.gov/nwis/sw). Although there are many gages in the UGRB, few have the continuous 40-50 year instrumental record necessary to calibrate a regression model while remaining unimpaired. Unimpaired stations were identified using the Hydro-Climatic Data Network (HCDN)(Slack et al., 1993; Wallis et al., 1991). Of the gages meeting these criterion, six gages were selected for their spatial distribution within the UGRB and an additional three naturalized gages were added at three locations on the Green River. The naturalized data were provided by the United States Bureau of Reclamation (USBR) (Prairie, 2004) at river nodes used in the Colorado River Simulation System (CRSS). A total of nine gages were selected for reconstruction (Figure 1, Table 1).

Monthly streamflow data were converted to water year streamflow for all gage stations except Big Sandy River near Big Sandy, Wyoming (Q9). In the case of the Big Sandy River, March through September instrumental flow records were the only available data in the recent record. Cleaveland (2000), summer streamflow was reconstructed successfully using tree ring records, and in Watson et al. (2008) spring-summer streamflow was reconstructed for the Little Popo Agie River (a tributary to the Wind River). Results in Watson et al. (2008) showed that information vital to the local system could be obtained from reconstructed streamflow records at gage sites limited to spring-summer record.

Tree-Ring Chronologies

Tree ring data were obtained from multiple sources including the International Tree Ring Data Bank (ITRDB, 20 chronologies) (http://hurricane.ncdc.noaa.gov/pls/paleo/fm_createpages.treering), recent paleo-hydrological studies in regions surrounding the UGRB (9 chronologies) (Gray et al., 2004a; Gray et al., 2004b; Gray et al., 2007), and new tree ring collections (6 chronologies). The new tree ring chronologies were necessary to fill a spatial gap in existing chronology coverage within the headwater areas of the UGRB, along the Wind River Mountain Range. A total of 35 regional tree ring chronologies were considered in the UGRB streamflow reconstructions (Figure 1). Tree species used in these chronologies are considered moisture sensitive and include Douglas-fir (*Pseudotsuga menziesii*, PSME), piñon pine (*Pinus edulis*, PIED), limber pine (*Pinus flexilis*), and ponderosa pine (*Pinus ponderosa*, PIPO) (Fritts, 1976).

New Tree Ring Chronologies

Six new tree ring chronologies were developed from samples taken in the foothills of the Wind River Mountain Range. Three sampling sites were located within the UGRB, and an additional three sites were located (east across the continental divide) in adjacent river basins (Figure 1). Open stands of the available moisture sensitive species, Douglas-fir and limber pine, were sampled at elevations ranging from 6505 feet to 8610 feet. Sites were selected in areas having poorly developed and shallow soil, typically on rocky slopes, to minimize effects of persistent soil moisture (Fritts, 1976).

In an attempt to capture a broad spectrum of climatic variability, three Douglas-fir sites and three limber pine sites were sampled. Douglas-fir were sampled at one site near the southern terminus of the Wind River Mountain Range on Anderson Ridge (ARR), and at two sites on the southwest face of the Wind River Mountain Range near Boulder Lake (BLE) and near Fremont Lake (FMT). Limber pine were sampled at one site on the southwest face of the Wind River Mountain Range southeast of Fremont Lake (FSE) and two sites near the southern terminus of the Wind River Range, on the eastern end of Anderson Ridge (ARE) and near Red Canyon (RCU).

Trees were sampled using increment borers and a minimum of two cores were taken from each tree. After drying, the cores were glued to mounting blocks to preserve the samples. Cores were then progressively sanded and individual ring widths were measured with an accuracy of 0.001 mm. The resulting series were cross-dated using standard methods (Stokes and Smiley, 1968; Swetnam et al., 1985; Cook and Kairiukstis, 1990). The number of trees used in the new chronologies ranged from 20-35 trees and the number of core samples used in the new chronologies ranged from 28-70 samples (Table 2). Accuracy of the cross-dating procedure was verified using the COFECHA program (Holmes, 1983). COFECHA compares ring width measurements of a given series to measurements for the same year within the site, and provides statistics such as the overall inter-series correlation for a given site (Table 2).

Chronologies were created using the Auto-Regressive Standardization program (ARSTAN) (Cook, 1985; Cook and Kairiukstis, 1990). As employed here ARSTAN removes growth trends in individual tree ring series using a negative exponential or linear spline. The program then creates a chronology using a bi-weight robust mean approach, and outputs different chronology types; a chronology without detrended series (raw), a detrended chronology that is standardized to a value of one (standard), and a detrended residual chronology (residual). The residual chronology has low order autocorrelation that may be attributed to biological tree-growth factors removed (Fritts, 1976).

Since chronologies consist of two or more samples from 20-35 trees of differing ages, the number of samples typically decreases as the chronology extends back in time. The loss of sample depth can lead to shifts in variance (signal strength) in the early portions of the chronology. The subsample signal strength (SSS) statistic was assessed for each chronology throughout time (Wigley et al., 1984). A chronology cutoff point was established whereas the SSS statistic dropped below 0.85 (85% of the common variance is retained in the chronology of reduced sample depth when compared to the complete chronology), a threshold recommended in Wigley et al. (1984). Chronologies were abbreviated at the given cutoff before being used in streamflow reconstructions.

Pearson correlation values between the newly developed chronologies were significant at a 99% level ($r = 0.32$ to 0.80) and considered strong with the exception of RCU (Table 3). The new chronologies were also compared to others within the immediate region ($r = 0.14$ to 0.53) to determine if regional growth relationships exhibit continuity between individual tree ring-width indices. Evaluation of these inter-site relationships also provides an additional check of the cross-dating procedure performed in the creation of the new chronologies.

New Chronology Precipitation and Temperature Growth Linkages

Climate-growth relationships between the six new chronologies and different combinations of precipitation and temperature were evaluated by correlating instrumental climate records against both standard and residual chronologies. This procedure verifies the moisture sensitivity within each chronology (Fritts, 1976), and water-year precipitation emphasized, due to the goal of reconstructing water-year streamflow. Precipitation and temperature data were obtained for the surrounding climate divisions from the Western Regional Climate Center (http://www.wrcc.dri.edu). Climate-growth relationships were evaluated against individual climate stations in the region as well, but these stations were limited in length and continuity of record. Tree growth at five of the six new sites proved to be significantly correlated (95% level) to water-year precipitation. Ring-width growth was negatively correlated with climate division temperature records in all chronologies. Growth at RCU showed sensitivity to both precipitation and temperature but was not significantly correlated to either at a 95% level.

Reconstruction Procedure

Utilizing twenty nine existing tree ring chronologies and the six newly developed chronologies (35 total), regression models were calibrated to create reconstructions for the nine selected stream gage stations. Three standard regression techniques were assessed for the creation of these new reconstructions. Techniques included stepwise multiple linear regression (Woodhouse et al., 2006a), principal component regression (PCR, Hidalgo et al., 2000), and partial least squares regression (PLSR, Tootle et al., 2007). All tree ring predictors were subjected to a rigorous prescreening process (as described in 3.3.1) for use with specific instrumental stream gage records before being considered in the regression model for that

station. Stepwise multiple linear regression was selected based on its wide acceptance in water resources and the similar skill obtained when compared to the other methods.

Preliminary reconstructions showed that the inclusion of chronologies from the region surrounding the UGRB improved the statistical strength of the streamflow reconstructions. This was most likely due to the lack of usable inter-basin chronologies. The addition of regional chronologies can provide more complete information pertaining to climatic variability observed in the tributary drainage basin (Gedalof et al., 2004; Cook et al., 1999, 2004; Watson et al., 2008). Reconstruction models using out of basin chronologies were statistically evaluated against a model calibrated with only inter-basin chronologies to verify statistical improvement, and this was attributed to the general lack of inter-basin chronologies.

Prescreening of Predictors

When comparing low order autocorrelation displayed in the nine instrumental stream gage records ($r = -0.06$-0.23, Table 1) to autocorrelation in both the standard chronologies ($r = 0.46$-0.55) and the residual chronologies ($r = 0.00$-0.01) it is evident that streamflow will be more accurately represented by the residual chronologies. Therefore, residual chronologies were considered in the regression model for each of the nine gage stations and were selected from the original pool of thirty five tree ring chronologies (predictors) using two methods in succession. First, only chronologies exhibiting 30% of the variability observed in the instrumental streamflow record ($R \geq 0.30$) that were 99% significantly correlated ($p < 0.01$) were considered. The retained chronologies were then subjected to bootstrapped correlation using evolutionary and moving intervals applying DENDROCLIM2002 (Biondi et al., 2004), a program designed to test stability in the relationship between the predictor and the hydroclimatic variable. Forward and backward evolutionary windows were evaluated for various base lengths and predictors that maintained stable correlations over time were retained in the pool of predictors for each stream gage reconstruction model.

Stepwise Multiple Linear Regression and Validation Statistics

Stepwise multiple linear regression was utilized to create reconstructed streamflow proxy records for the nine instrumental gage stations selected. A forward and backward stepwise reconstruction process entered and removed predictors with a threshold F value of 4 (Draper and Smith, 1998). The F value is a measurement of the difference between individual distributions and the confidence of the difference (i.e. as F values increase, p values decrease). The predictor with the highest partial F value is entered into the model first with additional predictors being individually entered if the addition is significant (F greater than 4) in the regression equation. Likewise, if retaining a predictor is not significant (F less than 4) in the regression equation it will be removed. The statistical strength and fit of the resulting regression models are summarized by the following statistics: R^2, R^2(adjusted), R^2(predicted), F statistic, root mean square error (RMSE; Weisberg, 1980), cross validation standard error (CVSE, Garen, 1992), variance inflation factor (VIF; Haan, 2002), Mallows' C-p (Weisberg, 1980), the predicted error sum of squares (PRESS; Maidment, 1993), and the Durbin-Watson statistic (Draper and Smith, 1998).

The regression models were evaluated using two validation techniques. A regression model was first calibrated on the first half of the data and validated on the second half of the data. This procedure is then reversed by calibrating on the second half of the data and validated on the first half. A second more robust approach, leave-one-out cross validation, was also applied (Michaelsen, 1987). Leave-one-out cross validation creates a validation series by dropping each

year, creating a regression equation, and then predicting a value for the dropped year. The original regression model is then validated against the leave-one-out validation series.

Integrating Gage and Reconstructed Records

Ideally, the variance observed in historic stream gage record will be equal to the variance observed in the reconstruction calibration period. Depending on the observed variance explained in the reconstructed time series, this may not be the case. To remedy this discrepancy in standard deviation, a conservative approach described in Timilsena et al. (2007) was employed. This method rescales reconstructed streamflow values to force the standard deviation in the reconstructed record to be equal to the standard deviation observed in stream gage record using:

$$\hat{x}_a = \left(\frac{\hat{x}_i - \hat{\bar{x}}}{\hat{\sigma}} \right) \sigma + \hat{\bar{x}}$$

where, $\hat{x}_i$ is the initial reconstructed variable, $\hat{\bar{x}}$ is the mean of the entire reconstructed time series, $\hat{\sigma}$ is the standard deviation of the entire reconstructed time series, σ is the standard deviation observed in the gage record used in model calibration, and $\hat{x}_a$ is the adjusted reconstructed variable.

Performing this adjustment allows the stream gage record to be joined with the reconstructed time series. This integration is necessary when using chronologies in the regression model that are not as current as available stream gage record and to retain as much current information as possible for analysis. All reconstructions were adjusted using this procedure to integrate available gage record.

Analysis of Reconstructed Wet and Dry Periods

A comprehensive analysis of wet and dry periods was completed for the Green River near Greendale, UT reconstruction. The first analysis compares these streamflow reconstructions to a precipitation reconstruction from northeastern Utah (Gray et al., 2004b). This comparison focused on extreme (above the ninety fifth quantile and below the fifth quantile) wet and dry years in the reconstruction. Next, five year periods of persistent severe wet and dry conditions were examined by setting a threshold for wet water year values as the third quartile and the threshold for dry water year values as the first quartile.

Significant wet and dry periods were identified by applying confidence bands to reconstructed values at a 95% significance level. The confidence bands are based on the RMSE estimate from the calibration period of the reconstruction (Jain et al., 2002). If the mean streamflow for the reconstruction falls within the confidence band of plus or minus two times the RMSE for any reconstructed value, the reconstructed value is assumed not to be a significant event and the mean value of for the reconstruction is inserted in place of the reconstructed value. To examine long term variability in streamflow, a twenty five year filter (centered) was applied to an extended version (1439 to 2004) of the Greendale, UT reconstruction.

Streamflow Reconstruction Analysis (Results and Discussion)—Chapter 1

Streamflow reconstructions were completed for the nine gages identified as having adequate continuous instrumental gage record for calibration. The Green River near Greendale, UT (Q1) gage station, the most downstream station in the UGRB, was a focal point of the analysis since it encompasses streamflow contributions for the entire UGRB (Figure 2). Correlations between the Green River near Greendale, UT reconstruction and other reconstructed gage records in the UGRB were relatively high (R = 0.73–0.96). Statistical evaluation of all reconstructed

streamflow records shows a general trend of increasing explained variance from the upper reaches of the basin to the basin outlet (Table 4).

Streamflow Reconstructions

The regression model for Green River near Greendale, UT incorporated six tree ring chronologies extending back to 1615 A.D. (or earlier). The model was calibrated from 82 years of naturalized gage record (1914-1995). The full naturalized gage record (1905-2004) was not used due to few operational gage stations being available in the UGRB during the early years of the naturalized record and not all of the chronologies selected for the regression analysis were current (to 2006). A set of descriptive statistics were developed to describe and validate the final reconstruction model (Table 4), which captured sixty five percent of the observed variance in the gage record (Figure 3).

Collectively, statistics testing the strength and fit of the Green River near Greendale, UT reconstructions were strong. Analysis showed little variance inflation added by any predictors within the model (i.e., VIF not significantly greater than 1), and the Durbin-Watson statistic revealed little autocorrelation within predictors included in the model. Cross validation of the regression model verifies that total variance explained (R^2) is not exaggerated by the regression model since the R^2 (predicted) from the leave-one-out cross validation technique is not significantly less than the overall R^2. The RMSE and CVSE calculated for the calibration period were smaller than one standard deviation. The Green River Greendale, UT reconstruction (Figure 4) displays well-known droughts in 1930's and 1950's as well as wet periods in the 1920's and 1980's.

Headwater Reconstructions

Six streamflow reconstructions were completed for headwater gage stations. The total variance explained in the headwaters gage reconstructions ranged from 0.44-0.58 (Table 4). The regional (spatial) variation in reconstructed UGRB headwater gages can be identified by correlating the reconstructed records or by visual inspection (Figure 5). Correlation values range from 0.67-0.98 for the reconstructed headwater gages (Table 5). Similarities in the reconstructed headwater records may in part be attributed to the use of many of the same tree ring chronologies in the individual regression models.

When rescaling the reconstructed record to incorporate the instrumental gage record at three headwater gages, negative values for water year streamflow were observed. The stations where negative values were observed had relatively short calibration periods that did not include the severe drought of the 1930's. Integrating the gage record into the reconstructed record provides a comparison for water managers and planners between current drought events and events observed in the reconstructed historic record, but values can only be evaluated on a relative scale.

CRSS Node Reconstructions

Three statistically robust reconstructions of CRSS node gage stations were completed. Similar to the reconstructed headwater gages, the reconstructed records for the three nodes on the main stem of the Green River are highly correlated. In both naturalized records and reconstructed records, correlation of the Green River near Green River, WY (Q2) and the Green River below Fontenelle Reservoir (Q3) show the two gage stations behave the same throughout time. The addition of tributary streamflow lower in the UGRB results in variation in the streamflow for the Green River near Greendale, UT (Q1). This variation is evident by visual inspection (Figure 6), when compared to the other two CRSS nodes, but correlation values remain high ($R > 0.95$).

Extended Greendale Reconstruction

A second, extended, reconstruction was completed for the Green River near Greendale, UT (Q1) gage station to examine long term changes in streamflow. Only one tree ring chronology from within the UGRB was utilized since no other chronologies passing the prescreening requirements extended back before 1603 A.D. (Table 2), the year in which a cutoff point was established for the new chronology at Fremont Lake (FMT). Using extended chronologies in the region, a reconstruction achieving fifty percent of the variance observed in the instrumental record was completed. When applying the paired t-test the extended reconstruction (1439-1999) was not statistically similar ($p<0.05$) to the original reconstruction (1615-1999) of water year streamflow for the overlapping period of record. However, when a ten year filter was applied to both reconstructions, a visual analysis reveals possible usefulness of the extended reconstruction in an evaluation of long term changes in reconstructed streamflow (Figure 7).

Summary of Reconstructed Streamflow Characteristics

Comparing the newly developed UGRB streamflow reconstructions with other reconstructions in the region shows relative similarity in values of explained variance (i.e., Front Range and Upper Colorado River Basin reconstructions (R^2=0.63-0.76) per Woodhouse et al., 2006b and Yellowstone River (R^2=0.52) per Graumlich et al., 2003). Previously reconstructed stations and first time reconstructions have been improved or enabled by the addition of new tree ring chronologies and longer calibration periods. The Green River at Warren Bridge, near Daniel, WY was previously reconstructed by Stockton and Jacoby (1976), and the variance explained was improved from 0.41 to 0.44. The Green River near Green River, WY was reconstructed by Woodhouse et al. (2006a) and the variance explained was improved from 0.48 to 0.60.

A comparison of instrumental and reconstructed gage records for the nine selected gages in the UGRB show increased variability (between minimum and maximum flows) in water year streamflow in the reconstructed records when compared to the instrumental records (Table 6). This comparison shows that the 20th century instrumental streamflow records alone do not provide a sufficient base of information for water managers and planners to fully understand historic streamflow regimes. Combining instrumental gage records with reconstructed records can provide greater insight into possible periods of future drought and above average streamflow. It should be noted that the standard deviation of the instrumental gage record is greater than the standard deviation of the reconstructed record without applying the rescaling method (described in section 3.4). By rescaling the reconstructed records, standard deviations are forced to be equal.

Drought and Wet Periods Observed in Greendale, UT Reconstruction

Reconstructed flows within the streamflow proxy for the Green River at Greendale, UT capture wet years (i.e. 1917, 1983, and 1986) and dry years (i.e. 1934 and 1977) observed in the instrumental gage record. Comparisons with the Gray et al. (2004b) precipitation study show that pre-instrumental wet years (e.g. 1680 and 1701) and dry years (e.g. 1685, 1735, 1756, 1773, and 1871) in the reconstructions are similar. The analysis of consecutive wet and dry years revealed only one five-year run of deficit streamflow. This period is notable since it occurred during the current drought (i.e. 2000-2004).

Significant Water Year Events

An examination of streamflow events either exceeding the 95th quantile or failing to exceed the fifth quantile reveals the relative wetness of the 20th Century. Seven of the twenty two

individual water-year streamflow values exceeding the ninety-fifth quantile are within the 20th Century and only two of the twenty one individual water year streamflow values failing to exceed the fifth quantile occur within the same period of time (Figure 8). The two water-year values failing to exceed the fifth quantile (i.e. 1934 and 1977) were within the instrumental gage record.

Long Term Streamflow Variability

Evaluation of wet and dry periods throughout the extended streamflow reconstruction again reveals the 20th Century as being wetter than average. The twenty five year cubic spline used to analyze the wet to dry phase changes was validated by plotting it with all water year values considered to be significantly wet or dry (Figure 9). The trend of the spline followed patterns seen in the significantly wet or dry values with greater magnitudes in areas of dense clusters of values significantly deviating from average.

The analysis of the twenty five year moving average reveals another unique scenario pertaining to water management and planning. Within any given 25- year period varies above and below the mean value of streamflow, but the period as a whole is typically skewed towards wet or dry (Figure 10). One evident period of severe sustained drought is the 16th Century "Mega Drought" (Stahle et al., 2000), and is displayed in nearly all tree ring based reconstructions in the western United States (e.g., Stockton and Jacoby, 1976 and Woodhouse et al., 2006a). The instrumental gage record alone does not display any of these extended shifts toward either the wet or dry side of average, but does display one of the wettest periods in the entire record. Comparing the instrumental mean to the mean of the entire reconstructed record shows how wet the 20th Century has been (Figure 10, Figure 11). If a threshold for surplus / deficit streamflow is set at the instrumental mean, it would appear that periods of drought have been the dominate trend in historic streamflow. Setting the threshold at the mean of the entire reconstructed record shows that duration and magnitude vary in both wet and dry periods, but distribution of these events are relatively even.

Summary and Conclusions—Chapter 1

The addition of six new tree ring chronologies enabled the creation of nine new or updated streamflow proxy records in the UGRB. Three of the gages for which reconstructions were completed are important forecasting points in the Upper Colorado River Basin (CRSS nodes). The addition of the CRSS node proxies are important in understanding the contribution to the Colorado River System provided by the UGRB. The UGRB has been shown to be one of the controlling subbasins (e.g. severe droughts in the UGRB such as the 1930's outweighed the effects of higher flows from the San Juan River Basin in historic records for Lees Ferry, AZ) in the Upper Colorado River Basin (Woodhouse et al., 2006a). Streamflow proxy records developed for headwater stream gages were similar to the proxies developed for the CRSS nodes and identified periods of extreme drought apparent in all reconstructed proxy records.

All streamflow proxies developed in the research show the 20th Century to be noticeably wetter than previous centuries. While periods of drought observed in the 1930's and 1950's severely impacted water users in the UGRB, it is likely these droughts have been exceeded by events occurring prior to instrumental stream gage records. The historic approximation of streamflow derived from tree ring records provides pertinent information to water managers when planning for future events by examining historic variations in streamflow. Using these pre-instrumental records, climatic teleconnections may be identified and drought frequency /

duration analysis may provide water planners and managers with appropriate tools to better plan for future availability.

References—Chapter 1

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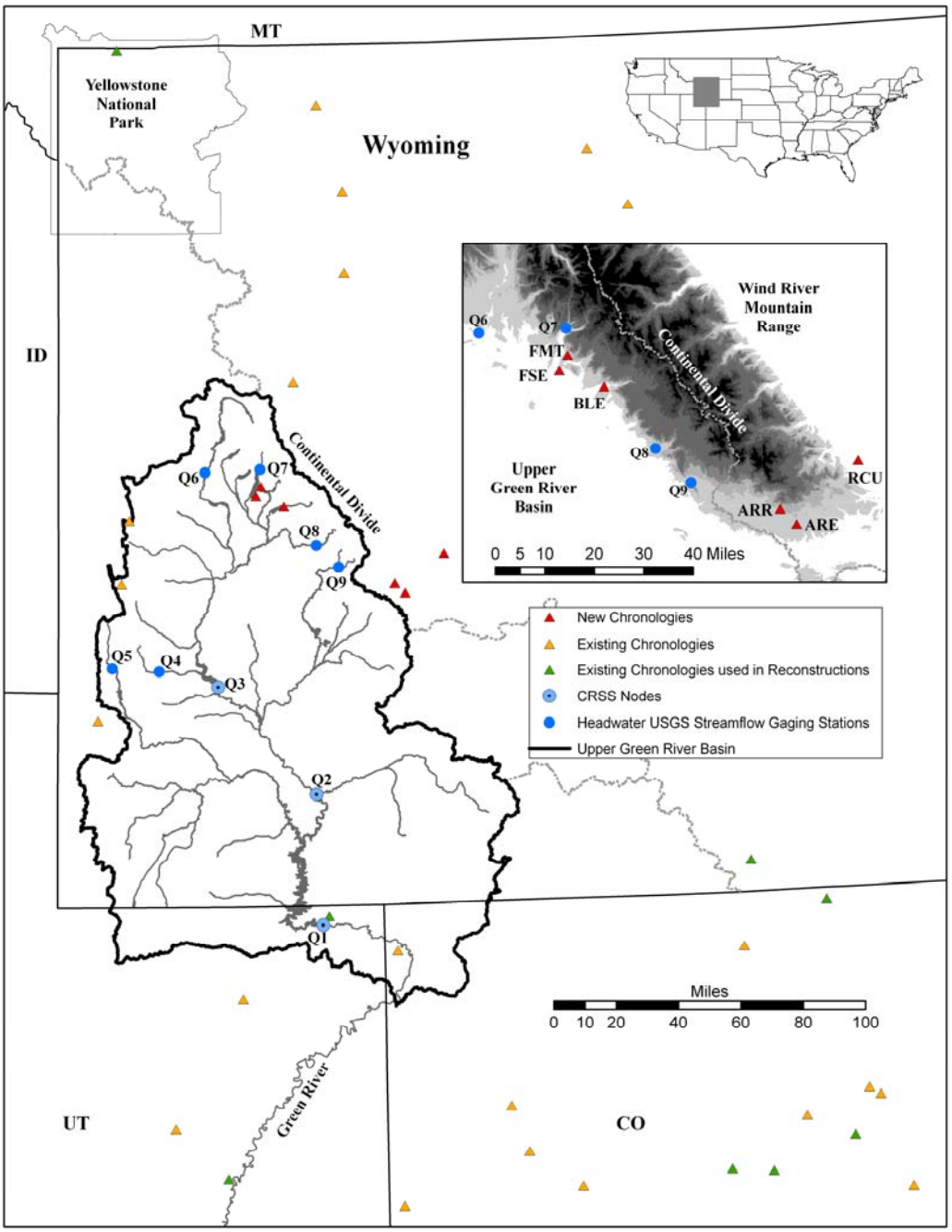

Figure 1: Map of Study area

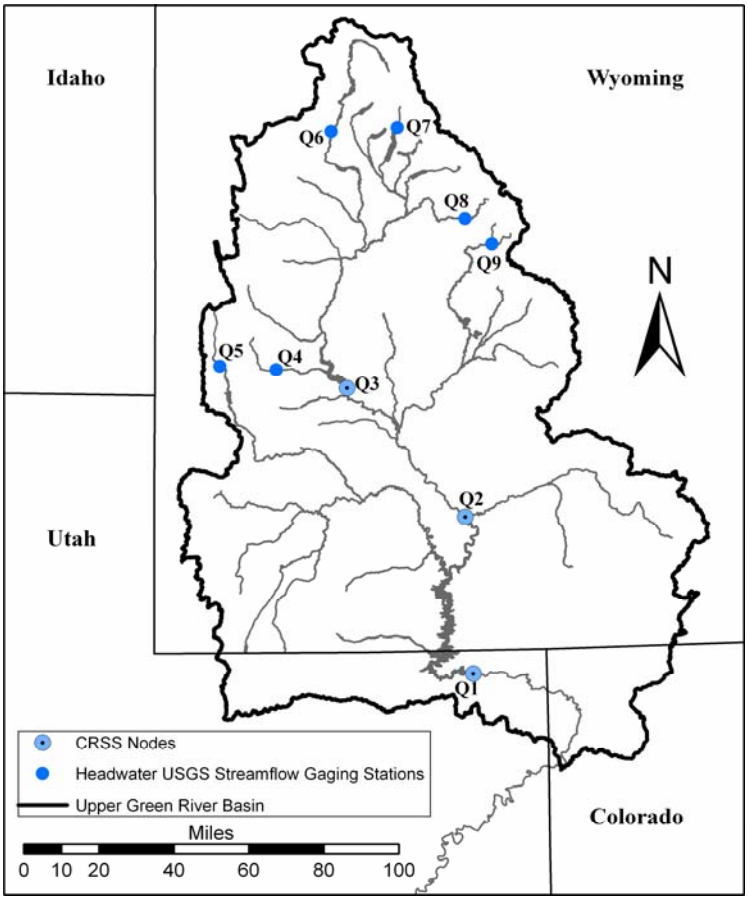

Figure 2: Location of reconstructed UGRB stream gage stations.

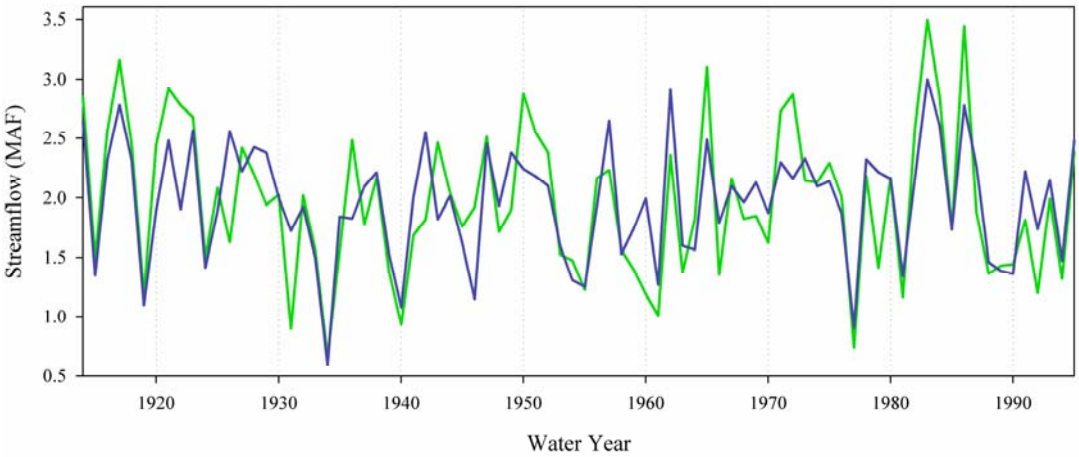

Figure 3: Comparison of observed (blue line) and reconstructed (green line) streamflow for the Green River near Greendale, UT for the calibration period.

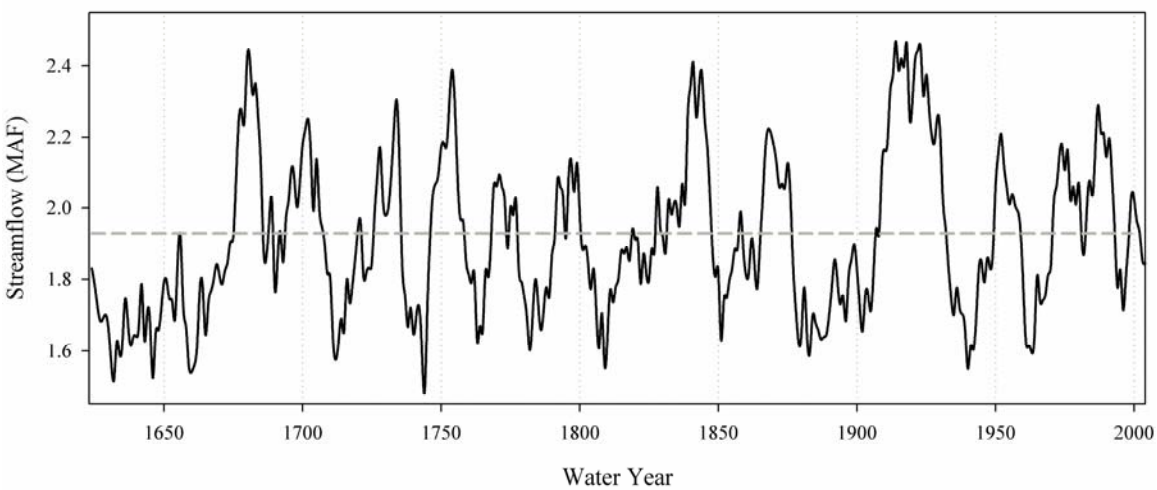

Figure 4: Reconstructed streamflow (black line) with ten year filter (end year displayed) and mean reconstructed flow (grey line) for the Green River near Greendale, UT.

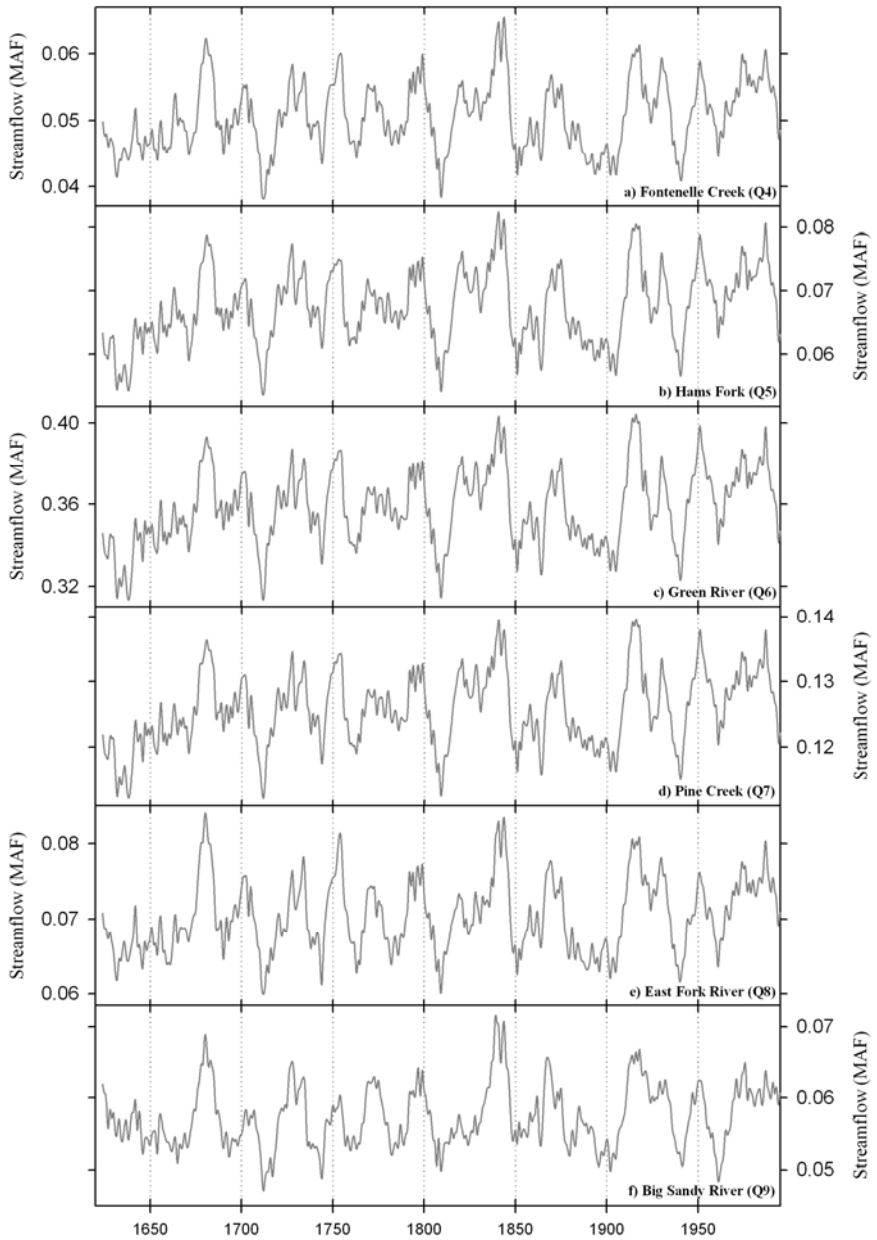

Figure 5: Comparison of reconstructed streamflow for headwater stream gage stations with ten year filter (end year displayed) of water year discharge (excluding the Big Sandy River (Q9) where spring-summer discharge was reconstructed).

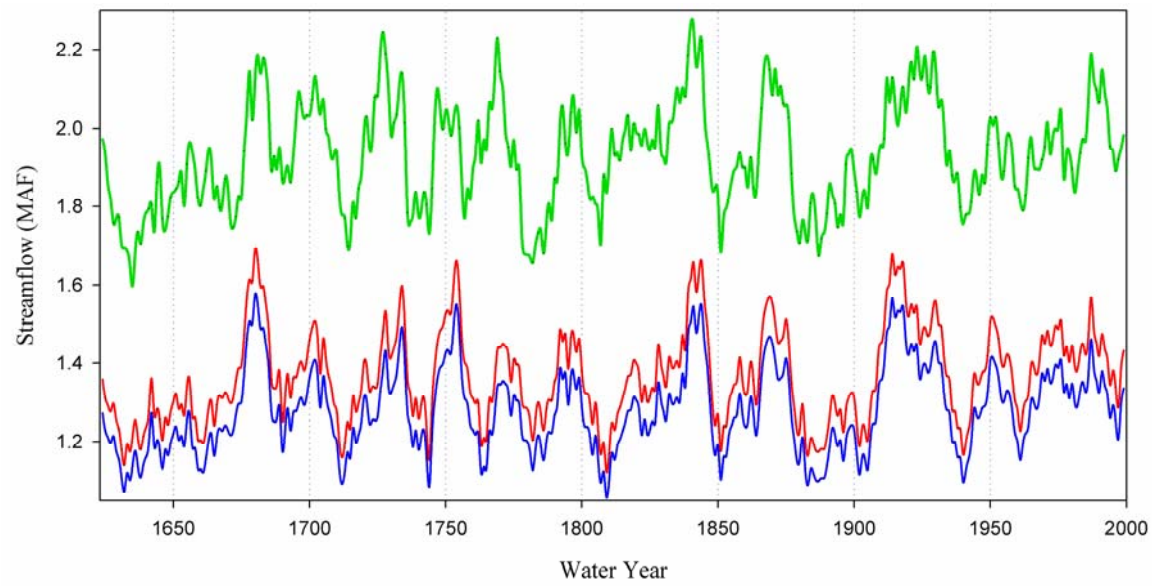

Figure 6: Comparison of reconstructed streamflow for CRSS nodes with a ten year filter (end year displayed); Green River near Greendale, UT (green line), Green River near Green River, WY (red line), and Green River below Fontenelle Reservoir, WY (blue line).

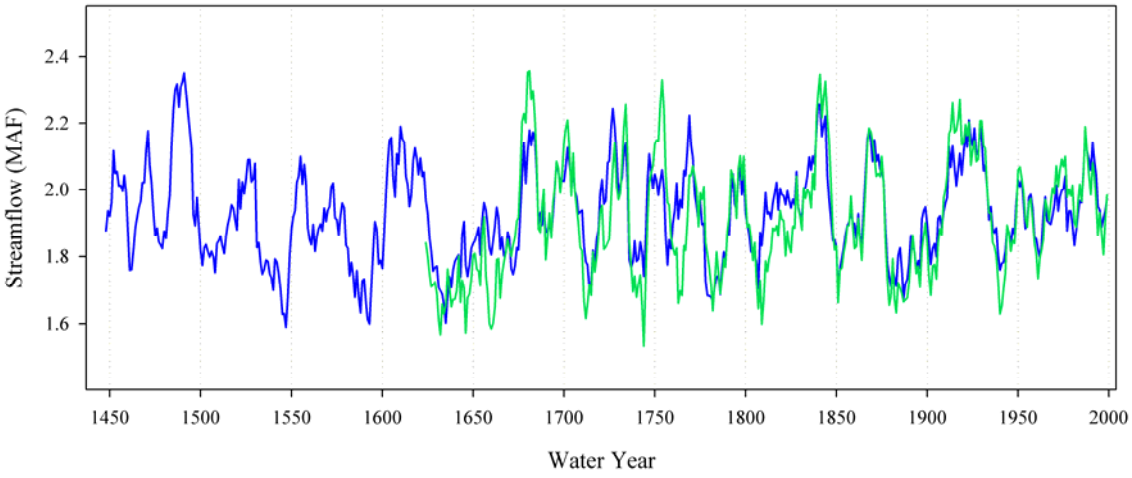

Figure 7: Comparison of the extended reconstruction (blue line) and the 1615-1999 reconstruction (green line), from 1615, the Green River near Greendale, UT. Data are plotted with a 10-year filter (end year displayed).

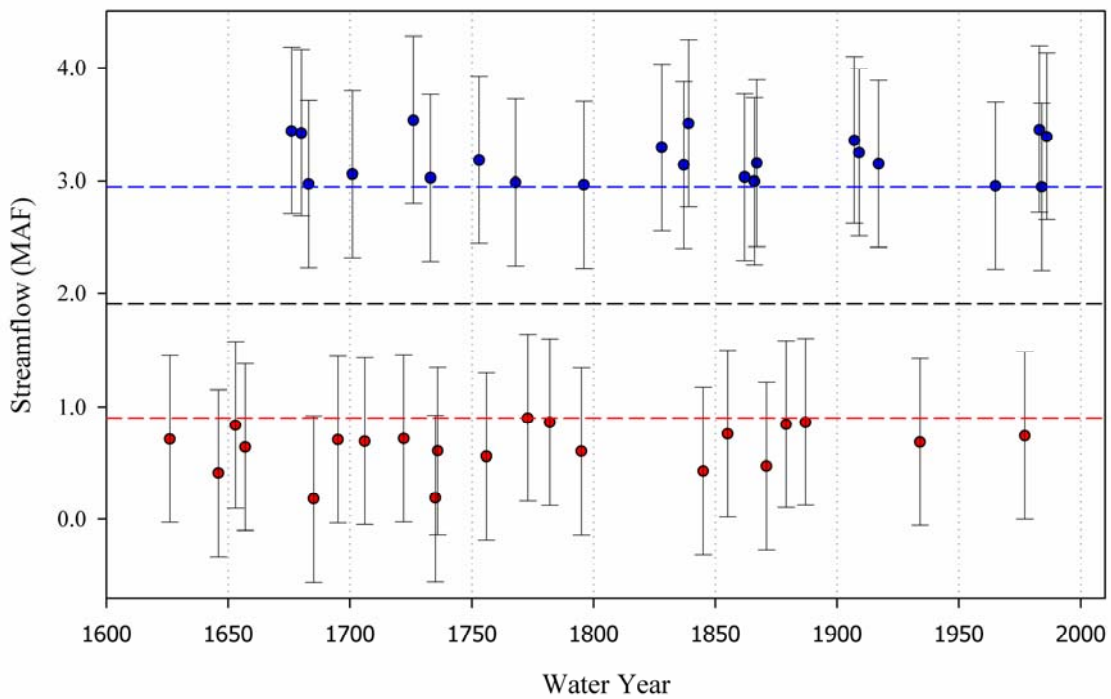

Figure 8: Significant wet years (blue dots) exceeding the 95th quantile (dashed blue line) and significant dry years (red dots) not exceeding the 5th quantile (dashed red line) for reconstructed Green River near Greendale, UT streamflow (1615-2004) plotted with the average flow of the reconstruction (dashed black line).

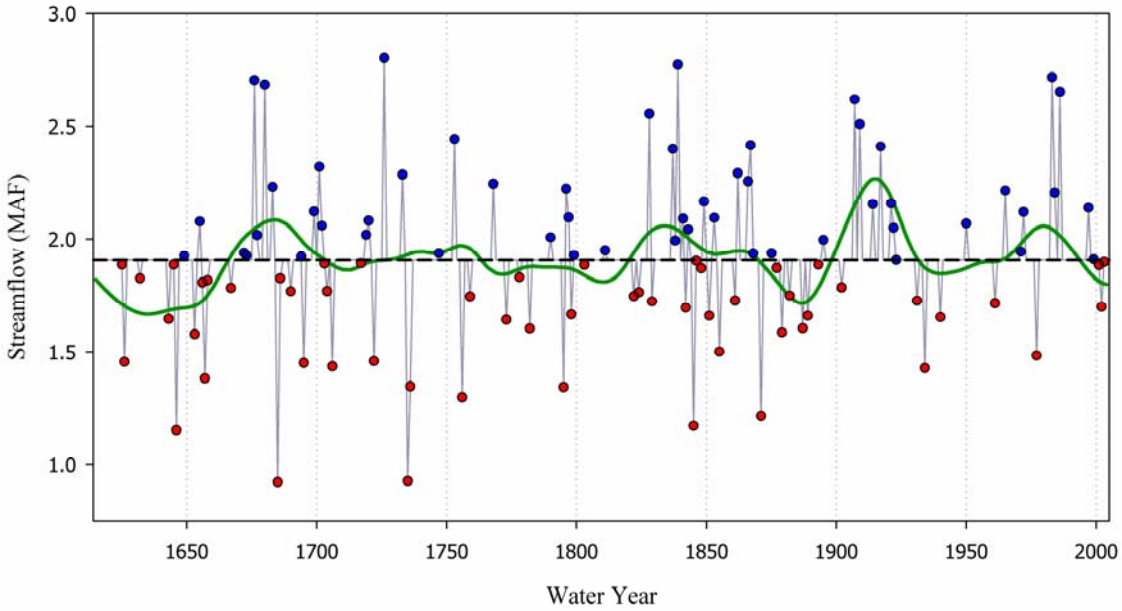

Figure 9: Significant wet years (blue dots) and significant dry years (red dots) for reconstructed Green River near Greendale, UT streamflow (1615-2004) plotted with the average flow of the reconstruction (dashed black line) and a 25 year cubic spline (green spline).

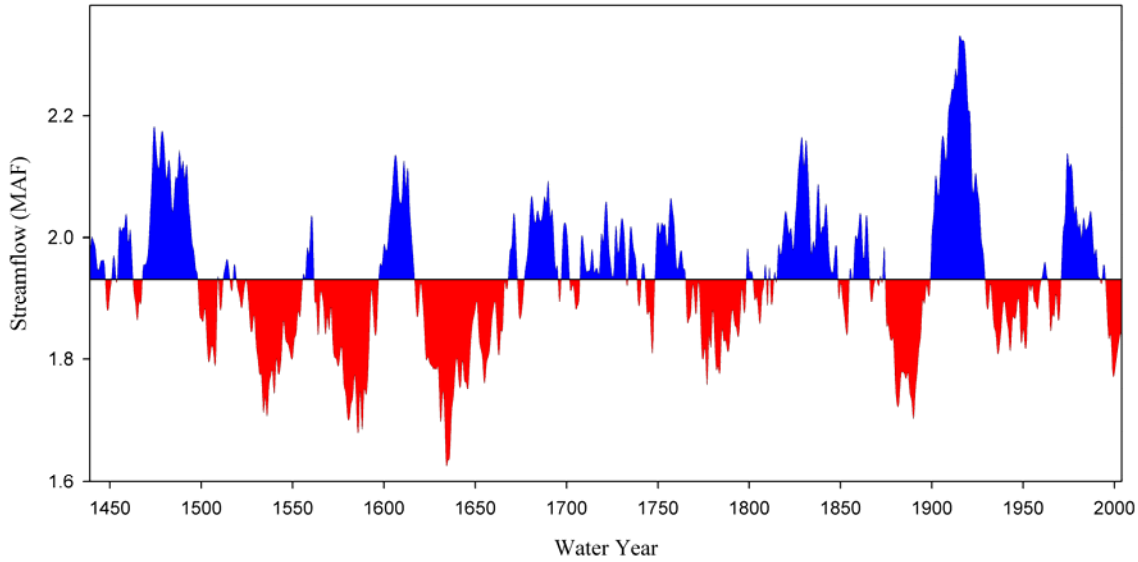

Figure 10: A 25-year moving average with deficit streamflow, based on the mean of the entire reconstructed record, (filled in red) and surplus streamflow (filled in blue), using an extended reconstruction (1439-2004) for the Green River near Greendale, UT.

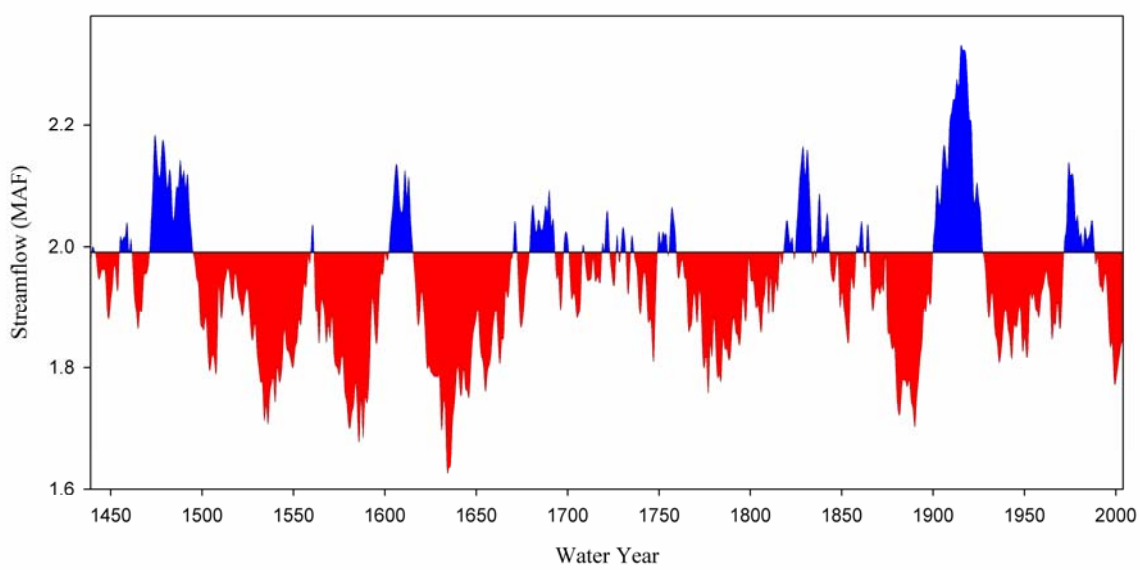

Figure 11: A 25-year moving average with deficit streamflow, based on the mean of the entire reconstructed record, (filled in red) and surplus streamflow (filled in blue), using an extended reconstruction (1439-2004) for the Green River near Greendale, UT.

Table 1: USGS stream gages selected for reconstruction.

	USGS Stream Gage Information		**Gage**	**Basin Area**	
ID[a]	**Name**	**ID #**	**Record**	(sq. miles)	**r** [e]
Q1	Green R. nr. Greendale, UT	09234500	1906-1995[c]	19350	0.23
Q2	Green R. nr. Green River, WY	09217000	1906-1995[c]	14000	0.19
Q3	Green R. bel. Fontenelle Res., WY	09211200	1906-1995[c]	4280	0.15
Q4	Fontenelle C. nr. Fontenelle, Wy[b]	09210500	1952-2006	152	0.07
Q5	Hams Fork nr. Frontier, Wy[b]	09223000	1953-2006	128	0.14
Q6	Green R. nr. Daniel, Wy[b]	09188500	1932-1992	468	0.04
Q7	Pine C. ab. Freemont Lake, WY	09196500	1955-1997	76	-0.06
Q8	East Fork R. nr. Big Sandy, WY	09203000	1939-1992	79	0.09
Q9	Big Sandy R. nr. Big Sandy, Wy[b]	09212500	1940-1987[d]	94	-0.06

[a]Gage identification shown on map in Figure 1.
[b]Full gage names – Fontenelle C. nr. Herschler Ranch, nr. Fontenelle, WY; Hams Fork below Pole Creek, nr. Frontier, WY; Green River at Warren Bridge, nr. Daniel, WY; Big Sandy R. at Leckie Ranch, nr. Big Sandy, WY.
[c]Record is naturalized flow (U.S.B.R.).
[d]Spring-summer instrumental record only.
[e]Significant autocorrelation (95% level).

Table 2: Descriptive statistics for new tree ring chronologies.

Site Name	Species	Elevation (feet)	Time Span (yr A.D.)	Year SSS > 0.85	Number of Trees	Number of Series	Inter-series Correlation
ARE	PIFL	8040-8440	1200-2006	1203	20	28	0.71
ARR	PSME	8530-8610	1519-2006	1615	25	53	0.77
BLE	PSME	7320-7500	1576-2006	1672	21	41	0.79
FMT	PSME	7500-8400	1507-2006	1603	35	70	0.77
FSE	PIFL	7650-8000	1654-2006	1692	23	35	0.80
RCU	PIFL	6500-6610	1600-2006	1613	24	41	0.69

Table 3: Correlation matrix of newly developed tree ring chronologies.

	ARE	ARR	BLE	FMT	FSE
ARR	0.74				
BLE	0.47	0.60			
FMT	0.54	0.63	0.80		
FSE	0.53	0.52	0.66	0.75	
RCU	0.45	0.45	0.32	0.32	0.32

Table 4: Reconstruction model calibration and verification statistics.

Gauge Name	Calibration Period	R^2	F	Mean[c]	RMSE[c]	CVSE[c]
Green River (Q1)	1914-1995	0.65	23.27[b]	1.909	0.370	0.403
Green River (Q1)[a]		0.50	19.21[b]	1.930	0.437	0.462
Green River (Q2)	1914-1995	0.60	28.43[b]	1.370	0.279	0.297
Green River (Q3)	1914-1995	0.59	27.29[b]	1.282	0.260	0.277
Fontentelle Creek (Q4)	1952-1999	0.48	14.09[b]	0.051	0.016	0.016
Hams Fork (Q5)	1953-1999	0.48	20.48[b]	0.069	0.022	0.022
Green River (Q6)	1932-1992	0.44	22.46[b]	0.358	0.062	0.064
Pine Creek (Q7)	1955-1997	0.53	22.73[b]	0.124	0.020	0.021
East Fork River (Q8)	1939-1987	0.58	22.81[b]	0.072	0.014	0.015
Big Sandy River (Q9)	1940-1987	0.54	12.52[b]	0.058	0.013	0.014

[a]Green River nr. Greendale, UT extended reconstruction.
[b]$p < 0.001$
[c]Mean, Root Mean Square Error (RMSE), and Cross Validated Standard Error (CVSE) are expressed in million acre-ft.

Table 5: Correlation matrix of reconstructed UGRB headwater stream gage stations.

	Q4	Q5	Q6	Q7	Q8
Q5	0.94				
Q6	0.90	0.96			
Q7	0.91	0.97	0.98		
Q8	0.93	0.85	0.87	0.87	
Q9	0.76	0.69	0.68	0.67	0.80

Table 6: Flow characteristic comparisons (in acre-ft) between instrumental and reconstructed water year records (not combined with instrumental gage record).

	Instrumental Record				Reconstructed Record			
Variable	Mean	StDev	Min	Max	Mean	StDev	Min	Max
Q1	1.992	0.642	0.659	3.495	1.909	0.552	0.392	3.343
Q2	1.421	0.455	0.440	2.569	1.370	0.360	0.401	2.345
Q3	1.329	0.418	0.454	2.453	1.282	0.329	0.397	2.173
Q4	0.051	0.021	0.018	0.112	0.051	0.016	0.009	0.104
Q5	0.069	0.031	0.013	0.155	0.069	0.022	0.008	0.127
Q6	0.364	0.081	0.203	0.556	0.358	0.058	0.184	0.500
Q7	0.128	0.029	0.070	0.183	0.124	0.023	0.056	0.180
Q8	0.074	0.022	0.031	0.129	0.072	0.018	0.025	0.121
Q9	0.059	0.018	0.025	0.105	0.058	0.014	0.009	0.105

Chapter 2 – Drought Frequency-Duration-Deficit Analysis

Abstract—Chapter 2

The limited length of instrumental streamflow data impacts the true magnitude of natural interdecadal variability of water delivered from the UGRB. This limited period of instrumental record can be expanded by utilizing proxy records (reconstructed streamflow) derived from tree rings. Two reconstructed streamflow datasets are now available for the Green River near Green River, UT (Stockton and Jacoby, 1976; Woodhouse et al., 2006), and a new preliminary reconstruction has been developed for the Green River near Green River, Wyoming (Woodhouse et al., 2006). Also, recent research has resulted in the development of nine streamflow reconstructions spatially located throughout the UGRB (Barnett et al., 2008). The proposed research would use these streamflow reconstructions to assess patterns (temporal and spatial) and sources of streamflow variability in the UGRB. An investigation of long-term streamflow variability, focusing on extreme events such as mega-droughts, will be performed. The research will result in the development of probabilistic drought forecasts. Salas et al. (2005) provides drought definitions and equations that can be utilized by water planners in storage dependent systems. Loaiciga (2005) utilized the compound renewal process, which generalizes the Poisson process, to calculate return periods for drought events. This may result in frequency – duration curves for UGRB drought. Such probability curves can then be analyzed in light of Compact agreements to answer questions such as, "How often might the outflow from the UGRB fail to meet 10-year delivery obligations?"

Introduction—Chapter 2

The Upper Green River Basin (UGRB, Figure 1) represents a vital water supply region for southwestern Wyoming and Upper / Lower Colorado River Compact states. Rapid development in the southwestern U.S. (e.g., Las Vegas, Phoenix) combined with the recent drought has greatly stressed the water supply system of the Colorado River. This has resulted in increased interest in the Colorado River Compact and related "Law of the River." The limited length of instrumental streamflow data impacts the true magnitude of natural interdecadal variability of water delivered from the UGRB. This limited period of instrumental record can be expanded by utilizing proxy records (reconstructed streamflow) derived from tree rings. Two reconstructed streamflow datasets are now available for the Green River near Green River, UT (Stockton and Jacoby, 1976; Woodhouse et al., 2006), and a new preliminary reconstruction has been developed for the Green River near Green River, Wyoming (Woodhouse et al., 2006). Also, recent research has resulted in the development of nine streamflow reconstructions spatially located throughout the UGRB (Barnett et al., 2008). Increasing the length of streamflow records will provide more accurate frequency and risk assessment of drought events. Water managers will be better able to plan for drought events and will have a better understanding of the true nature and variability in their river systems. Biondi et al., (2005) developed a stochastic model based on the theory of random sums to quantify droughts. Information provided from this model would include: (1) given a drought event (i.e., the recent 2000 to 2004 drought), there is an (X)% chance of a drought occurring of longer duration or magnitude; (2) a drought of such magnitude has a (Y)% chance of lasting for (Z) years or longer. This type of question can also be answered by the drought definitions and analysis presented by Salas et al. (2005). The inherent scarcity of water in the semiarid to arid regions of the southwestern United States is exacerbated by the occurrence

of frequent and persistent droughts (Stockton et al., 1991; Tarboton, 1994). Drought events can be defined in many ways and each definition will change as analysis needs change. Meko et al. (1995) cites Sastri et al. (1982) as reporting that there were more than 60 definitions of drought found in literature. Young (1995) provides two possible definitions of drought based in meteorological terms, limited or no rainfall, or agricultural terms, available soil moisture for evapotranspiration. Young (1995) selected a hydrologic measure as a drought indicator that follows the same parameters as Tarboton (1994). This research utilizes the drought definition presented by Tarboton (1994) and his referenced authors: A drought is defined as a consecutive series of years during which the average annual streamflow is continuously below some specified threshold level, which is typically taken to be the long-term mean (Tarboton, 1994). The most recent identified drought generally lasted from 2000 to 2004, although differing analysis methods may reduce this window or have no drought identified. This drought is used as a defining or threshold event.

Data—Chapter 2

Four streamflow reconstructions from Barnett et al. (2008) were used for drought analysis in the UGRB. The four stream flow gages are denoted as Q1, Q3, Q5, and Q7 (Table 1, Figure 1). United States Geological Survey (USGS) stream gage information was obtained for all stream gages in the UGRB from the National Water Information System (NWIS) (http://waterdata.usgs.gov/nwis/sw). Few gages in the UGRB have a continuous 40-50 year instrumental record necessary to calibrate a regression model while remaining unimpaired. Unimpaired stations were identified using the Hydro-Climatic Data Network (HCDN) (Barnett et al., 2008; Slack et al., 1993; Wallis et al., 1991). Stream gages with naturalized data were provided by the United States Bureau of Reclamation (USBR) (Barnett et al., 2008; Prairie, 2004) at river nodes used in the Colorado River Simulation System (CRSS) (Barnett et al., 2008). Gage records for Q1 and Q3 are naturalized records while records for Q5 and Q7 are unimpaired. Naturalized or unimpaired records provide streamflow data that would occur absent anthropogenic interference. Barnett et al. (2008) utilized tree ring chronologies to create reconstructed records that were integrated with gage records to produce the final water year records used in this paper (Figure 2). The final reconstructed records were rescaled to force the standard deviation in the reconstruction to be equal to that of the stream gage record (Barnett et al., 2008; Timilsena et al., 2007).

Methodology—Chapter 2

A drought occurs when an individual reconstructed water year's value (x_t) is below a defined threshold creating a deficit (d_i). The threshold used in this part of the study is the mean (μ) of the entire reconstructed record (1615-2004). The duration (L_i) of a drought event is the sum of consecutive years with values, or running averages, below the mean ($x_t < \mu$). The beginning year of a drought is the year when $x_t < \mu$ and the end year is the last consecutive year below the threshold. The magnitude (M_i) of a drought is the sum of all deficits included in the duration. The severity (S_i) of a drought is obtained by dividing magnitude by duration (M_i / L_i).

Drought Magnitude (Method 1)

The first analysis technique (Method 1) used to identify and compare drought events follows those used by Timilsena et al. (2007). Method 1 consists of 5 parts denoted Method 1a through

Method 1e. Method 1a only considers droughts with duration of 2 years or more. As stated by Timilsena et al. (2007), this method does not take long periods of drought into account because a single x_t value equal to or above the threshold (creating a surplus) causes the duration to end. Longer dry periods with multi-year averages below the threshold are analyzed by taking moving averages of the entire record. Moving averages of 3, 5, 7, and 10 years (Figure 3) are offset at the beginning of the reconstructed record to include the end year of 2004. These methods are denoted 1b, 1c, 1d, and 1e respectively. When drought events are sorted according to magnitude (deficit: absolute value of magnitude), the probability (ρ) and return period (R) can be determined by a Weibull distribution (Equation 1, Equation 2).

$$\rho = \frac{m}{(N+1)} \tag{1}$$

$$R = \frac{1}{\rho} \tag{2}$$

$$N = \Sigma\ (\text{all recorded events}) = 390 \tag{3}$$

Where: m is the rank of an event, the largest drought in deficit or intensity is ranked 1, and R is in years.

Drought Severity (Method 2)

The second analysis technique (Method 2) uses a compound renewal approach (Timilsena et al., 2007; Loaiciga, 2005). Method 2 considers an event's magnitude as well as its duration. This is accomplished by only considering drought events that are equal to or greater than a defined event or threshold (θ). The defining event for this research is the most recent drought (~2000-2004). The only events considered are equal to or greater than $L_{current}$ ($\theta = 5$; i.e., length of recent drought) and $M_{current}$ simultaneously. The renewal time ($\bar{R}$) is equal to the sum of the expected values duration (L) and interval time (T) or:

$$\bar{R} = \theta + \frac{1}{a_1} + \frac{1}{a_2} \tag{4}$$

$$a_1 = \frac{1}{(\bar{L} - \theta)} \tag{5}$$

$$a_2 = \frac{1}{\bar{T}} \tag{6}$$

The parameters a_1 and a_2 are representative of the average duration ($\bar{L}$) and average interval time ($\bar{T}$) between selected events. Equation 4 assumes that $a_1 \neq a_2$. The time before the first selected event and the time after the last selected event are not considered in the average interval time.

Drought Risk (Method 3)

The third analysis technique (Method 3) characterizes droughts by defining four drought events, $P(E)$, to analyze severity and risk (Salas et al., 2005). Case 1 events (Equation 7) are characterized by droughts with accumulated deficit (D) greater than a specified deficit (D_0) and duration (L) equal to an analyzed event's duration or threshold duration (l_0). Case 1 droughts can be analyzed for duration only, by setting the specified deficit to zero ($D_0 = 0$). Case 2 events (Equation 8) are similar to Case 1, however the duration is greater than or equal to the threshold duration ($L \geq l_0$). Events can be analyzed without regard for duration by setting $L \geq 1$ and regardless of deficit by setting $D > 0$. Cases 3 and 4 (Equations 9 and 10 respectively) utilize the same analytical procedures as Cases 1 and 2 by replacing deficit with intensity

($I = L/D$). The occurrence probability of each case is described by the bivariate probability distribution functions (pdfs) shown in equations 7 through 10. Each expression follows a gamma distribution characterized by their individual shape (r) and scale (β) factors. The shape and scale factors used in the equations were obtained by plotting all identified droughts, for each Method 1 scenario, with a gamma distribution. Each expression is also defined by a prescribed length (l_0) and deficit (D_0) or intensity (I_0), where intensity is the same as severity as defined above. Transition probabilities (p_{xx}) can be calculated for each water year record with equations 11 and 12 (Jackson, 1975 and Fernández et al., 1999). It is assumed that the sequence of surpluses (denoted by 1) and deficits (denoted by 0) follow a Markov chain. The number of transitions (N) from fail (f) to safe (s) or 0 to 1 is the number of times that the water year record transitions from a drought event to a surplus event. This process is also used for transitions from safe to fail, fail to fail, and safe to safe. The return period (T) of any event described by Salas et al. (2005) can be evaluated with Equation 13.

$$P[D > D_0, L = l_0] = \int_{D_0}^{\infty} \frac{1}{\beta\Gamma(l_0 r)} \left(\frac{z}{\beta}\right)^{l_0 r - 1} e^{-z/\beta} p_{01}(1 - p_{01})^{l_0 - 1} dz \tag{7}$$

$$P[D > D_0, L \geq l_0] = \int_{D_0}^{\infty} \sum_{l=l_0}^{\infty} \frac{1}{\beta\Gamma(lr)} \left(\frac{z}{\beta}\right)^{lr-1} e^{-z/\beta} p_{01}(1 - p_{01})^{l-1} dz \tag{8}$$

$$P[I > I_0, L = l_0] = \int_{I_0}^{\infty} \frac{l}{\beta\Gamma(l_0 r)} \left(\frac{l_0 z}{\beta}\right)^{l_0 r - 1} e^{-l_0 z/\beta} p_{01}(1 - p_{01})^{l_0 - 1} dz \tag{9}$$

$$P[I > I_0, L \geq l_0] = \int_{I_0}^{\infty} \sum_{l=l_0}^{\infty} \frac{l}{\beta\Gamma(lr)} \left(\frac{lz}{\beta}\right)^{lr-1} e^{-lz/\beta} p_{01}(1 - p_{01})^{l-1} dz \tag{10}$$

$$p_{fs} = p_{01} = \frac{N_{fs}}{N_{ff} + N_{fs}} \tag{11}$$

$$p_{sf} = p_{10} = \frac{N_{sf}}{N_{ss} + N_{sf}} \tag{12}$$

$$T = \frac{p_{01} + p_{10}}{p_{01} p_{10}} \frac{1}{P(E)} \tag{13}$$

Results—Chapter 2

Rankings for Method 1a through 1e are summarized in Tables 2 and 3. Table 2 shows identified drought ranks when sorted for magnitude. Table 3 shows identified drought ranks when sorted for severity. The recent drought rank is reported for each ranking method along with the top five drought events. Return periods for Method 1 and 2 are reported on the left hand side of Table 2. As seen in Figure 2 and Table 2, the deficit created by the most recent drought (~2000-2004) is a notable event but it is not the greatest event of record. If gage station Q1 is considered, the ranking and return times for Methods 1 and 2 diminishes as longer moving averages are considered. This shows that the years leading up to that event were, on average, in surplus. This trend is not the same when gage station Q1 is considered for severity, Table 3. The recent drought event is ranked 2nd and 1st for the 3 and 5 year moving averages (Method 1b and 1c respectively), while ranked 5th for when droughts of a minimum 2 year duration are considered (Method 1a). This shows that the recent event does not exhibit the greatest deficit for drought events, however its severity is the greatest when examining a 3 to 5 end-year average. Figure 4 illustrates the solutions for Method 3 Case 1 (Equation 7) when only duration is considered ($D_0 = 0$). The solutions for each gage station are plotted together with Q5 and Q7 overlapping one another. As seen in Figure 4, the return period for a 5 year duration drought is

roughly 100 years. This method also allows the estimation of greater return periods as compared to Method 1 & 2. When Equation 7 is used to evaluate the recent drought, Method 1a ($D > 3653818, L = 5$), the return period is 133 years. Graphical solutions for Equation 7 are shown in Figure 5.

Conclusions—Chapter 2

The use of dendrochronology to create reconstructed streamflow records can improve stochastic estimates of streamflow variations by extending the available period of record. The reconstructed period of record contains drought events that well surpass any events that would be part of the instrumental record, in terms of magnitude and duration. The mean for instrumental and reconstructed records are of notable difference (Table 1). This is caused by the wet period in the early 20th century exemplified in the instrumental record and the long dry period exemplified in the early 17th century (Figure 3). Methods 1 and 2 are directly dependent on the reconstructed record for the calculation of return periods. This dependence creates scaling errors in return period. Method 1 return periods are limited to bin sizes that are dependent on the record length. The difference between return periods becomes more pronounced at the less probable values. As in this paper, the largest possible return period for Method 1 is 391 years. Method 2 is similarly limited to return periods based on the number of observed events and the time between. Method 3 is based on the same record, however it allows for the interpolation of greater return periods than Methods 1 and 2. Future research may focus on identifying climate drivers (e.g., ENSO) of UGRB drought events.

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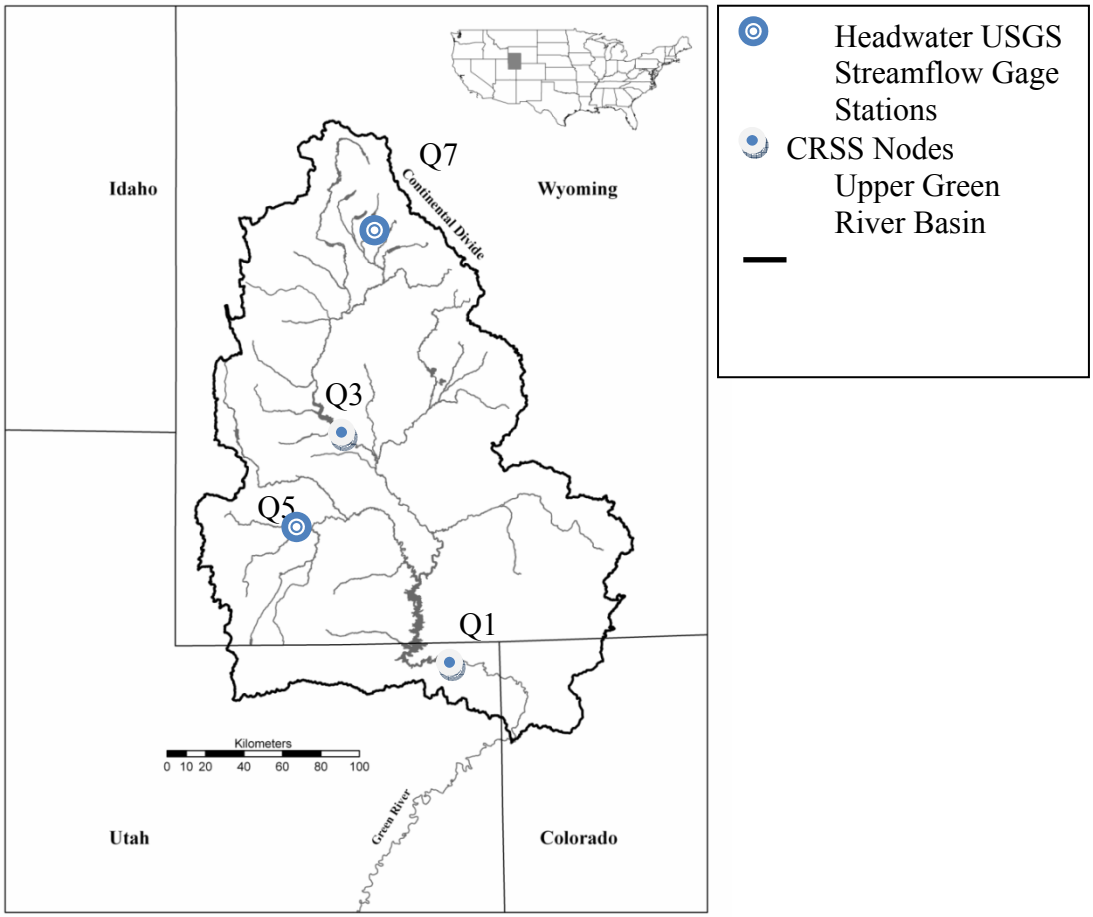

Figure 1: Upper Green River Basin

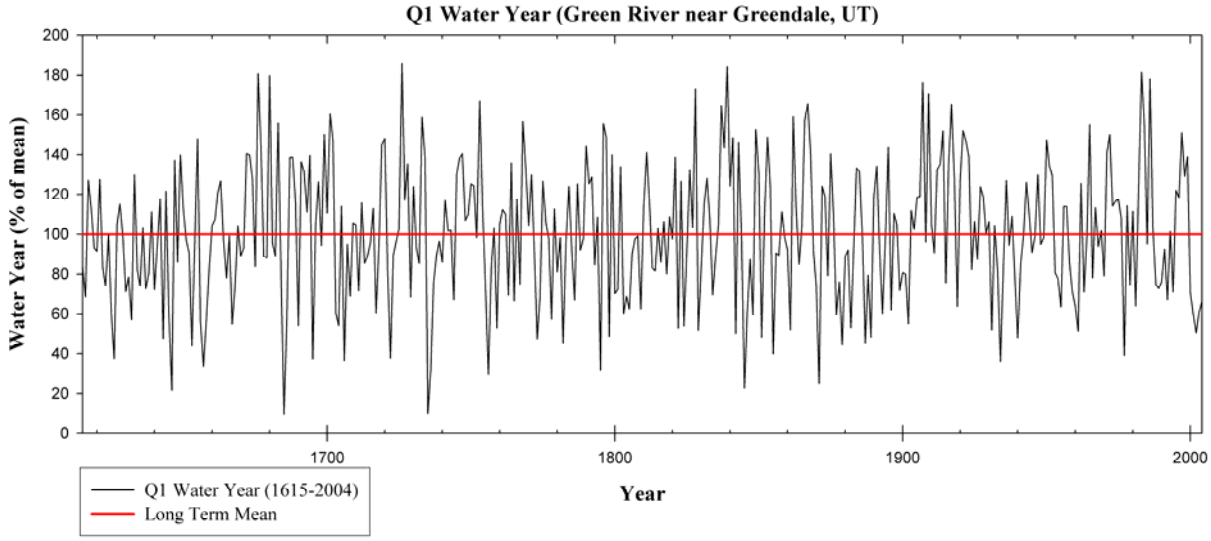

Figure 2: Q1, Reconstructed Water Year (1615-2004)

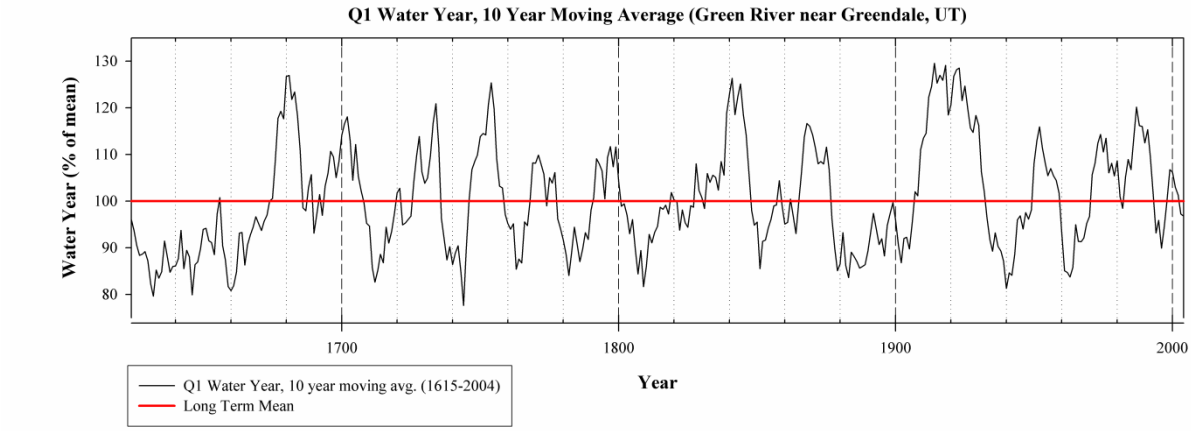

Figure 3: Q1, 10 Year Moving Average (1624-2004)

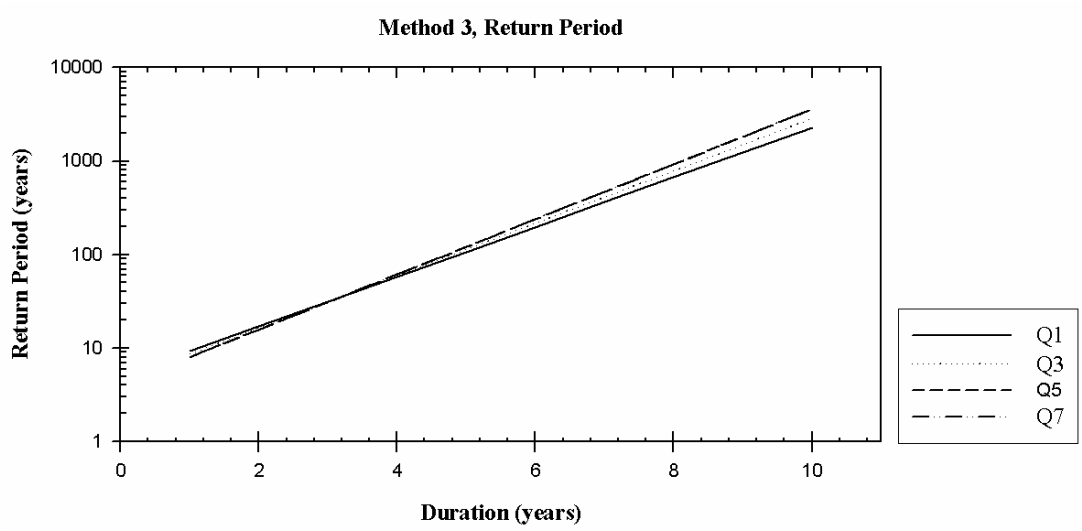

Figure 4: Method 3, Return Periods for Duration Only

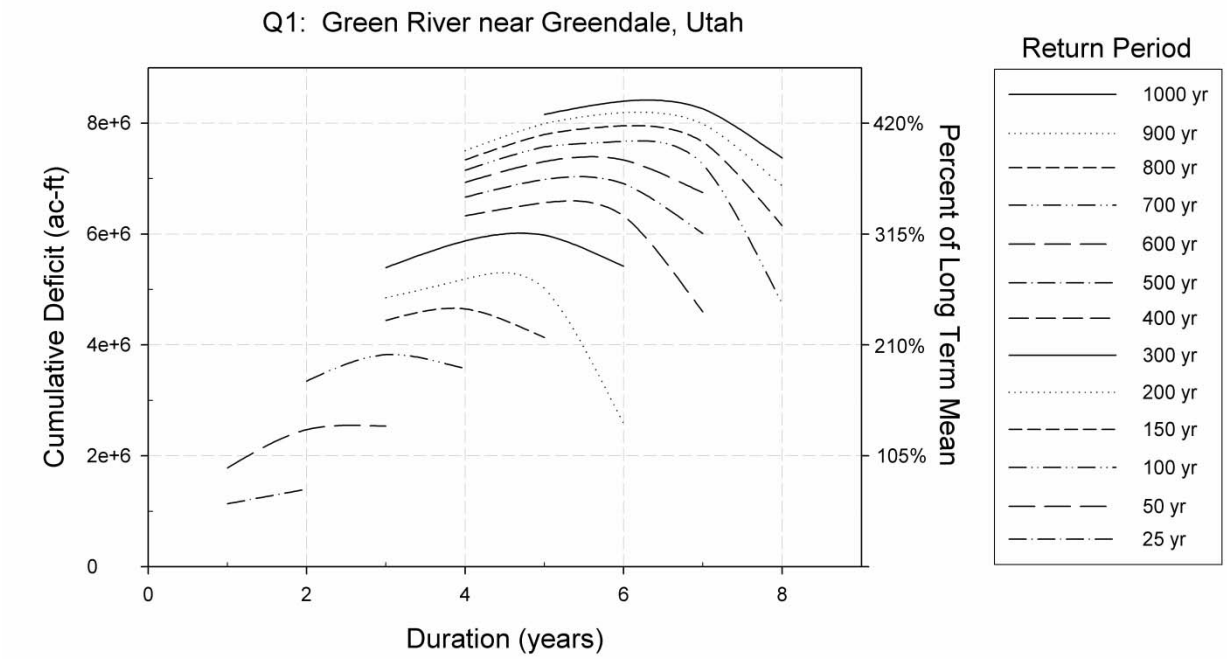

Figure 5: Frequency, Duration and Deficit Curves

Table 1: USGS Stream Gage Information and Reconstructed Mean

	USGS Stream Gage Information						
ID[a]	**Name**	**ID #**	**Gage**	**Record**	**Basin Area** (sq. kilometers)	**Reconstructed Mean** (m^3)	**Instrumental Mean** (m^3)
Q1	Green R. nr. Greendale, UT	9234500	1906-1995[c]		50116	2.35E+09	2.46E+09
Q3	Green R. bel. Fontenelle Res., WY	9211200	1906-1995[c]		11085	1.57E+09	1.64E+09
Q5	Hams Fork nr. Frontier, Wy[b]	9223000	1953-2006		332	8.44E+07	8.49E+07
Q7	Pine C. ab. Freemont Lake, WY	9196500	1955-1997		197	1.53E+08	1.58E+08

[a]Gage identification shown on map in Figure 1.

[b]Full gage name: Hams Fork below Pole Creek, nr. Frontier, WY

[c]Record is naturalized flow (U.S.B.R.)

Table 2: Ranking Sorted for Magnitude

Gage Station	Drought Identificaiton Method 1	Ranked 1st	Ranked 2nd	Ranked 3rd	Ranked 4th	Ranked 5th	Rank of Recent Drought	Average Duration (years)
Q1	a	1735-1740	1877-1883	2000-2004	1844-1848	1656-1659	# 3 (2000-2004)	3
	b	1630-1648	1704-1719	1653-1661	1878-1884	1736-1742	# 8 (2001-2004)	4
	c	1623-1650	1932-1944	1653-1662	1706-1718	1735-1742	# 17 (2002-2004)	6
	d	1624-1652	1879-1895	1931-1946	1656-1664	1706-1719	# 19 (2003-2004)	7
	e	1624-1655	1877-1906	1657-1673	1933-1949	1801-1818	# 18 (2003-2004)	9
Q3	a	1877-1883	1844-1848	1803-1809	2000-2004	1735-1740	# 4 (2000-2004)	3
	b	1800-1810	1878-1884	1704-1715	1844-1849	1653-1660	# 8 (2001-2004)	4
	c	1878-1894	1622-1641	1931-1944	1801-1811	1845-1852	# 16 (2002-2004)	6
	d	1879-1906	1624-1651	1931-1946	1803-1813	1706-1719	# 16 (2003-2004)	7
	e	1624-1673	1877-1908	1933-1949	1801-1816	1708-1719	# 15 (2003-2004)	10
Q5	a	1703-1711	1803-1809	2000-2004	1844-1848	1931-1936	# 3 (2000-2004)	3
	b	1704-1713	1630-1639	1802-1810	1989-1996	1896-1906	# 8 (2001-2004)	4
	c	1619-1640	1704-1715	1804-1811	1896-1906	1933-1941	# 12 (2001-2004)	5
	d	1879-1907	1621-1641	1704-1718	1803-1813	1934-1942	# 14 (2002-2004)	6
	e	1624-1655	1878-1908	1706-1718	1804-1815	1993-2004	# 5 (1993-2004)	8
Q7	a	1703-1711	1803-1809	1629-1632	1931-1936	1844-1848	# 20 (2000-2004)	3
	b	1630-1639	1704-1713	1802-1810	1932-1938	1897-1904	# 19 (2001-2004)	4
	c	1619-1641	1887-1906	1704-1713	1804-1811	1933-1941	# 19 (2002-2004)	6
	d	1621-1643	1880-1907	1803-1813	1706-1715	1934-1941	# 20 (2004)	6
	e	1624-1655	1878-1908	1802-1815	1706-1718	1935-1943	No Drought	7

Table 3: Ranking Sorted for Severity

Gage Station	Drought Identification Method 1	Ranked 1st	Ranked 2nd	Ranked 3rd	Ranked 4th	Ranked 5th	Rank of Recent Drought	Number of Identified Droughts
Q1	a	1645-1646	1684-1686	1656-1659	1703-1704	2000-2004	# 5 (2000-2004)	51
	b	1685-1687	2001-2004	1736-1741	1871-1873	1887-1890	# 2 (2001-2004)	47
	c	2002-2004	1878-1884	1735-1742	1653-1662	1667-1671	# 1 (2002-2004)	35
	d	1656-1664	1803-1811	1846-1852	1624-1652	1735-1745	# 7 (2003-2004)	29
	e	1736-1745	1624-1655	1657-1673	1960-1970	1877-1906	# 19 (2003-2004)	23
Q3	a	1703-1704	1625-1626	1645-1646	1684-1686	1844-1848	# 7 (2000-2004)	50
	b	2001-2001	1878-1884	1685-1687	1844-1849	1736-1740	# 1 (2001-2004)	52
	c	2002-2004	1845-1852	1645-1661	1801-1811	1991-1996	# 1 (2002-2004)	37
	d	1846-1852	1656-1663	1803-1813	1992-1996	1879-1906	# 6 (2003-2004)	31
	e	1877-1908	1801-1816	1933-1949	1708-1719	1624-1673	# 15 (2003-2004)	21
Q5	a	1919-1920	1684-1686	1901-1902	1625-1626	1886-1887	# 8 (2000-2004)	42
	b	2001-2004	1846-1849	1685-1687	1704-1713	1802-1810	# 1 (2001-2004)	53
	c	1804-1811	2001-2004	1845-1852	1989-1996	1756-1761	# 2 (2001-2004)	40
	d	1846-1853	1803-1813	1621-1641	2002-2004	1934-1942	# 4 (2002-2004)	32
	e	1804-1815	1706-1718	1624-1655	1936-1943	1878-1908	# 6 (1993-2004)	26
Q7	a	1919-1920	1625-1626	1684-1686	1629-1632	1721-1722	# 37 (2000-2004)	45
	b	1846-1849	1685-1687	1630-1639	1704-1713	1802-1810	# 17 (2001-2004)	48
	c	1804-1811	1704-1713	1933-1941	1845-1852	1619-1641	# 12 (2002-2004)	36
	d	1706-1715	1934-1941	1803-1813	1846-1853	1621-1643	# 16 (2004)	35
	e	1624-1655	1706-1718	1802-1815	1935-1943	1878-1908	No Drought	29

Chapter 3 – Oceanic Atmospheric Variability and Drought

Abstract—Chapter 3

A study of the influence of interdecadal and interannual Pacific oceanic / atmospheric variability on the Wind River Range (WRR), Wyoming is presented. The WRR is an unbroken 160-kilometer barrier that is host to 63 glaciers, the largest concentration of glaciers in the American Rocky Mountains. Glacial recession over the past half century has resulted in an increased interest in the region. Instrumental datasets were obtained for unimpaired streamflow and snow water equivalent for stations in the Green River Basin (GRB – west slope of WRR) and the Wind-Bighorn River Basin (WBRB – east slope of WRR). The phases (cold or warm) of Pacific [El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO)] oceanic / atmospheric phenomena were identified. Statistical significance testing of the datasets, based on the interdecadal and interannual oceanic / atmospheric phase (warm or cold), was performed applying the parametric t-test test. The results show that the interannual ENSO phase influences streamflow and snow variability in the WRR and the interdecadal PDO phase influences snow variability during La Niña events.

Introduction—Chapter 3

The Wind River Range (WRR) is located in western-central Wyoming and is the headwaters of the Green River (tributary to the Colorado River) and the Wind River (tributary of the Missouri and Mississippi Rivers). The WRR is an unbroken 160-kilometer barrier that is host to 63 glaciers, the largest concentration of glaciers in the American Rocky Mountains (Figure 1).

As with many mountain glaciers in the Northern Hemisphere, the recession of Dinwoody Glacier (Figure 1) has been documented on a number of occasions since the mid-1800's (Wolken, 2000). The prominent recession of Dinwoody Glacier was noted in the 1930's. The 1940's and 1950's were a period of a slower rate of recession, with the estimated surface area of Dinwoody Glacier at 3.47 km^2 (Meier and Post 1962). A period of accelerated rate of recession followed, with the next quantitative evaluation estimating Dinwoody Glacier's surface area at 2.90 km^2 in the late 1980's (Pochop, et al. 1989). The most recent mapping of the surface area and elevation of Dinwoody Glacier was in 1999, where the surface area was estimated as only 2.33 km^2 (Wolken, 2000).

There is an increasing awareness that the oceanic / atmospheric variability occurs on interannual and interdecadal time scales. Furthermore, recent studies have shown the influence of coupled oceanic / atmospheric variability on climate of regions around the world. The study presented here investigates WRR hydrologic response to the influences of the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

ENSO refers to the interaction of the periodic large-scale warming or cooling of the central-eastern equatorial Pacific Ocean with the Southern Oscillation, a large-scale atmospheric pressure pattern across the tropical Pacific. The warm phase of ENSO is referred to as El Niño and the cool phase is referred to as La Niña. ENSO displays a periodicity of two (2) to seven (7) years (Philander, 1990). The PDO is a oceanic / atmospheric phenomena associated with persistent, bimodal climate patterns in the northern Pacific Ocean (poleward of 20° north) that oscillate with a characteristic period on the order of 50 years (a particular phase of the PDO will typically persist for about 25 years) (Mantua, et al., 1997).

Recent research has focused on the coupling of the interannual ENSO phenomenon with the PDO. Gershunov and Barnett (1998) evaluated the PDO's influence on ENSO for sea level

pressures and heavy daily precipitation in the Atlantic / Pacific Oceans and continental United States. El Niño (La Niña) signals were found to be strong and stable during the warm (cold) PDO phase. Harshburger et al. (2002) determined that the largest departures for Idaho spring streamflow occurred during the La Niña / PDO cold phase. This is consistent with the findings of Gershunov and Barnett (1998) that ENSO (El Niño or La Niña) is strongest during the similar PDO (warm or cold) phase. In forecasting Columbia River streamflow, Hamlet and Lettenmaier (1999) defined six climate categories for ENSO (warm, cold or neutral) and PDO (warm or cold). The utilization of the climate categories significantly improved long lead-time forecasts. Also in the Pacific Northwest, Beebee and Manga (2004) found significant relationships between seasonal streamflow and, both ENSO and PDO. Hidalgo and Dracup (2001 and 2003) evaluated spring-summer streamflow and rainfall in the Upper Colorado River basin, considering the influence of ENSO and PDO and acknowledged a possible ENSO – PDO modulation of cold season precipitation.

The goal of the research presented here is to evaluate GRB / WBRB hydrology as influenced by interdecadal and interannual Pacific oceanic / atmospheric variability. In determining areas influenced by atmospheric / oceanic variability, verification was accomplished by parametric statistical testing.

Data—Chapter 3

The major datasets used to develop the relationships between Pacific oceanic / atmospheric variability and hydrologic variability are instrumental unimpaired streamflow and snowfall data for the GRB and WBRB, and, oceanic / atmospheric data for the Pacific Ocean.

Unimpaired streamflow stations in the GRB and WBRB were identified from Wallis et al. (1991) (Figure 2 and Table 1). Monthly streamflow data was obtained from the U.S. Geological Survey (USGS) NWISWeb Data retrieval (http://waterdata.usgs.gov /nwis/). The average monthly streamflow rates (in cubic feet per second – cfs) were averaged for the water-year (October of the previous year to September of the current year) and converted into streamflow volumes (km^3) with proper conversions. The period of record for the streamflow data varied from station to station. The Natural Resources Conservation Service (NRCS) maintains a remote-sensing system (*http://www.wcc.nrcs.usda.gov/snotel/Wyoming/wyoming.html*) to collect snowpack and related climatic data in the Western United States (Wyoming) referred to as SNOTEL (i.e., SNOwpack TELemetry) (Figure 2 and Table 1). Monthly Snow Water Equivalent (SWE) values (inches) were obtained for the months of March, April, May and June. The monthly values were then summed to determine the total seasonal SWE and converted to centimeters. Unlike the streamflow data, a 40 year common period of record (1961 – 2000) was identified for all the SNOTEL stations. For each station, yearly water-year streamflow volumes (km^3) [or yearly total seasonal (March, April, May and June) SWE (cm)] were standardized (i.e., mean of zero and standard deviation of one).

PDO Index values are available from the Joint Institute for the Study of the Atmosphere and Ocean, University of Washington (*http://tao.atmos.washington.edu/pdo/*). For the period 1900 to present, the warm phase (1925 to 1945 and from 1977 to present) of the PDO Index was a positive numerical index value while the cold phase (1900 to 1925 and 1945 to 1977) was a negative numerical value (Mantua et al., 1997). A review of the PDO Index indicates a shift to the cold phase around 2000. McCabe et al. (2004) evaluated coupled effects of the PDO and the Atlantic Multidecadal Oscillation. McCabe et al. (2004) assumed the PDO was in a warm phase from 1926 to 1943 and from1977 to 1994, and the PDO was in a cold phase from 1944 to 1976.

The PDO phase periods used in the McCabe et al. (2004) study were adopted for this study with the assumption that the PDO shifts to the cold phase in 2000.

The NOAA-CDC (*http://www.cdc.noaa.gov/ENSO/Compare/*) defined the ENSO summer season as May to September and identified core El Niño and La Niña years for the summer season. The summer season was selected for ENSO since it was better represented by a season (e.g., an interannual oceanic / atmospheric phenomena). Various techniques were available to define the occurrence of a seasonal ENSO event (e.g., Gershunov, 1998; Hamlet and Lettenmaier, 1999; Harshburger et al., 2002; Rogers and Coleman, 2003]. When evaluating ENSO and PDO, Gershunov and Barnett (1998) defined a seasonal El Niño (La Niña) as when the anomaly in the Niño 3.4 sea surface temperature region (Trenberth, 1997) is greater (lesser) than 0.8 standard deviations of the long-term mean. They concluded that this value was high enough to exclude questionable ENSO events and would allow for an adequate number of ENSO events when combining the PDO (Gershunov and Barnett, 1998). For this study, the approach of Gershunov and Barnett (1998) was applied to the Niño 3.4 index and the Troup Southern Oscillation Index (*www.bom.gov.au*) for the summer (May to September) season and the results (summer season ENSO years identified) were used to compliment the NOAA-CDC core summer season ENSO year data set (i.e., recognize and incorporate additional ENSO years). This provides an adequate number of ENSO events to evaluate the impacts of the PDO while excluding questionable ENSO events (Gershunov and Barnett, 1998). Interdecadal and interannual climatic indices were evaluated one-year prior to streamflow and snowfall.

Methodology—Chapter 3

First, spatial and temporal streamflow variability for the GRB and WBRB was evaluated by applying a 5-year filter to standardized water-year streamflow volumes for the two GRB stations and the three WBRB stations. Next, spatial and temporal snowfall (SWE) variability for the GRB and WBRB was evaluated by applying a 5-year filter to standardized seasonal SWE values for the four GRB stations and the three WBRB stations.

Finally, the impacts of the interdecadal (PDO) and interannual (ENSO) oceanic / atmospheric influences on WRR streamflow and snowfall were evaluated by testing of water-year (or seasonal) means for the individual and coupled oceanic / atmospheric influences.

The current water-year (October through September) was the period selected for streamflow and the spring season (March, April, May and June) was selected for SWE. The previous year (or season) was selected to define the phase (e.g., warm or cold) of the PDO and ENSO. This analysis evaluated the current water-year streamflow (or seasonal SWE) response (e.g., positive or negative shifts in means) to the previous year (or season) of the oceanic / atmospheric (PDO, ENSO) phase (cold or warm). The testing performed here was for both the individual and coupled oceanic / atmospheric indices with streamflow (or SWE).

The parametric two-sample t-test (Maidment, 1993) was performed on the response of streamflow means to changes in oceanic / atmospheric phase, including coupling. The t-test compares two independent data sets and determines if one data set has significantly larger values than the other data set (Maidment, 1993). The t-test assumes that the two data sets are normal with equal variances (Maidment, 1993). A detailed discussion of this method is provided in Maidment (1993) and is also provided in most statistical textbooks.

Results—Chapter 3

Spatial and Temporal Variability of Streamflow and SWE

The 5-year filter analysis resulted in stations (both GRB and WBRB) having similar spatial and temporal relationships (Figure 3a and 3b).

The period of record varied for the streamflow stations while a common period of record (1961 – 2000) was identified for the SNOTEL stations. While the late 1980's recession of Dinwoody Glacier (Pochop, et al. 1989) may be associated with deficit snowfall (Figure 3b), the continued recession, as identified in 1999 (Wolken, 2000) appears to coincide with normal, long-term (40 year period of record) snowfall (Figure 3b). The glacial recession may be a result of increased summer temperatures (ablation) in the region (Naftz et al., 2002).

Interestingly, for the 40 year period of record (1961-2000), the average seasonal SWE for the four GRB SNOTEL stations was 48.3 inches with a standard deviation of 17.8 inches. The average seasonal SWE for the three WBRB SNOTEL stations was 51.9 inches with a standard deviation of 15.2 inches. Therefore, snowfall amounts were virtually identical on each side of the continental divide.

Atmospheric-Oceanic Influences on Streamflow and SWE

Initially, the phases (cold and warm) were evaluated for the PDO and ENSO (individually) such that significant (greater than 90%) differences in streamflow (and SWE) means were reported. Next, the coupled impacts of the interdecadal PDO phases on La Niña (and El Niño) on streamflow (and SWE) means were evaluated.

The PDO signal (at 90% significance) was not detected in either streamflow or SWE. However, a significant ENSO signal was detected in three of five streamflow stations and all seven SWE stations. Figure 4 presents standardized seasonal SWE for La Niña and El Niño years. For all the SWE stations, the average standardized seasonal SWE after a previous summer season La Niña (El Niño) was +0.67 (-0.41). Neutral previous year summers resulted in average standardized seasonal SWE of -0.12. Therefore, a previous year summer La Niña (El Niño) results in increased (decreased) snowfall. Interestingly, the two streamflow stations (Dinwoody Creek – 06221400 and Bull Lake Crrek – 06224000) that failed to show an ENSO signal appear to have high contributions of glacial meltwater. This may explain why the ENSO signal was not identified in these streams.

Finally, an evaluation of the PDO's influence on ENSO was performed. For example, given the occurrence of a La Niña (or El Niño), how does the phase (cold or warm) of the PDO enhance (or dampen) the influence of La Niña (or El Niño) on streamflow (or SWE). The testing of PDO Cold – El Niño and PDO Warm – El Niño and, the testing of PDO Cold – La Niña and PDO Warm – La Niña for the streamflow stations resulted in no stations having a statistically significant difference in water-year streamflow.

The testing of PDO Cold – El Niño and PDO Warm – El Niño for the SWE stations resulted in no stations having a statistically significant difference in seasonal SWE. However, when testing PDO Cold – La Niña and PDO Warm – La Niña, three of the seven SWE stations were identified as having statistically significant differences in means (Figure 5). For all seven stations, the average standardized seasonal SWE, given a previous summer season La Niña during a PDO Cold phase, was +1.09 while the average standardized seasonal SWE, given a previous summer season La Niña during a PDO Warm phase, was +0.04. Given that La Niña (i.e., ENSO cold phase) results in increased SWE, the PDO Cold phase enhances La Niña in this region. This is consistent with the findings of Gershunov and Barnett (1998) and Harshburger et

al. (2002) that ENSO (El Niño or La Niña) is strongest during the similar PDO (warm or cold) phase.

Conclusions and Future Work—Chapter 3

- Snowfall spatial and temporal variability (and average snowfall – SWE) were similar on each side (Green River Basin and Wind-Bighorn River Basin) of the continental divide.
- The PDO signal was not detected but a significant ENSO signal was detected in streamflow and SWE. A previous year summer La Niña (El Niño) results in increased (decreased) streamflow (or snowfall).
- The PDO Cold phase enhances La Niña in this region resulting in increased snowfall (SWE). Given a PDO Cold phase began on or about 2000, the development of a La Niña could result in above average snowfall.
- Future research will focus on extending the instrumental records (tree-ring reconstructions) of streamflow, SWE and temperature; evaluating Atlantic Ocean influences such as the Atlantic Multidecadal Oscillation and the North Atlantic Oscillation; and evaluating Pacific and Atlantic Ocean sea surface temperatures.

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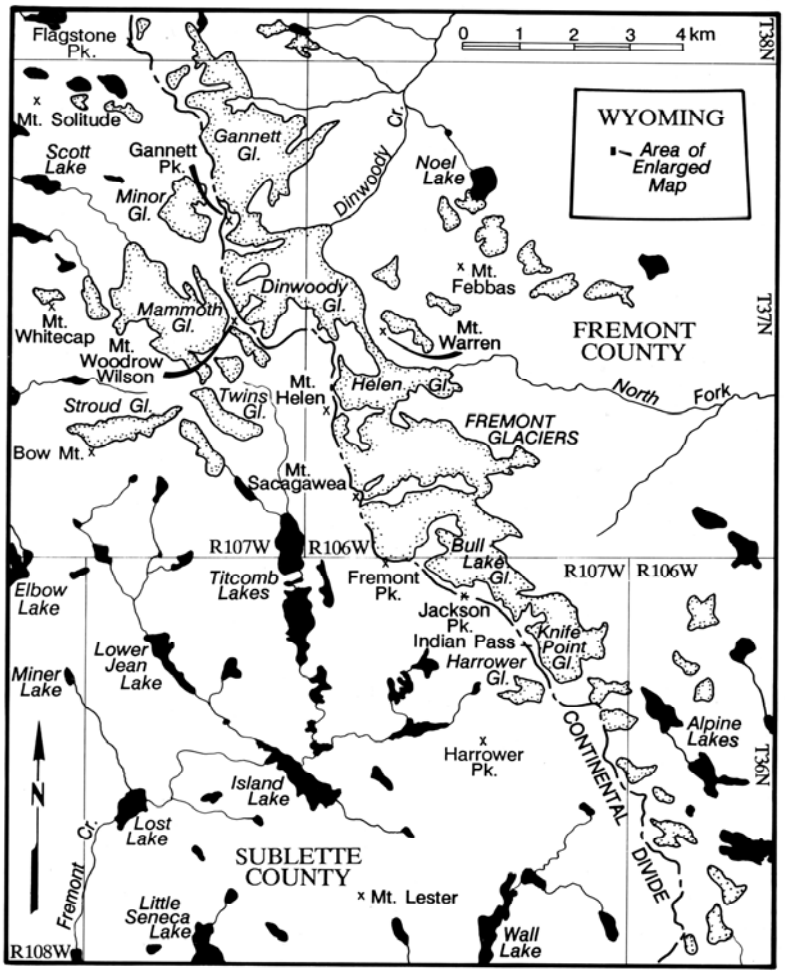

Figure 1: Area Map of Wind River Range Glaciers (Wolken, 2000).

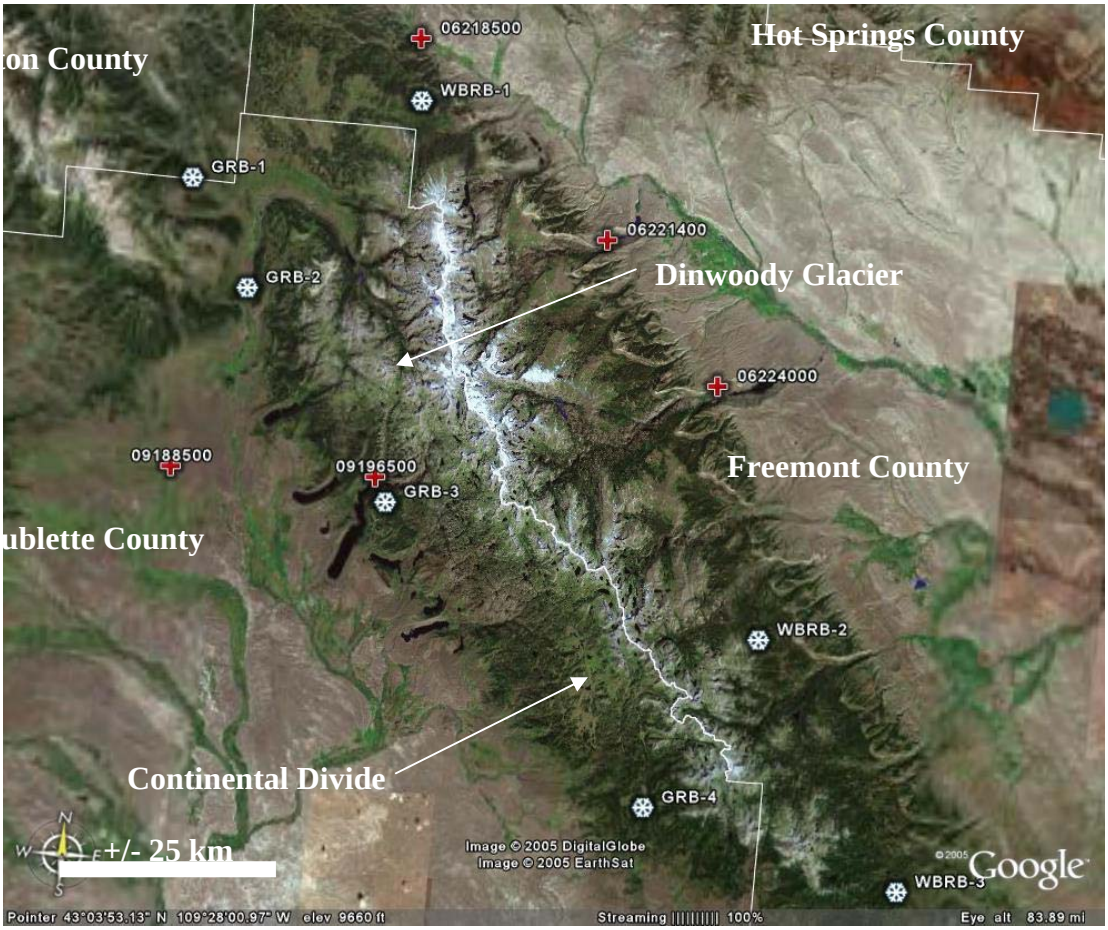

Figure 2: **Locations of unimpaired USGS streamflow stations and NRCS SNOTEL stations in the Wind River Range.**

(a)

(b)

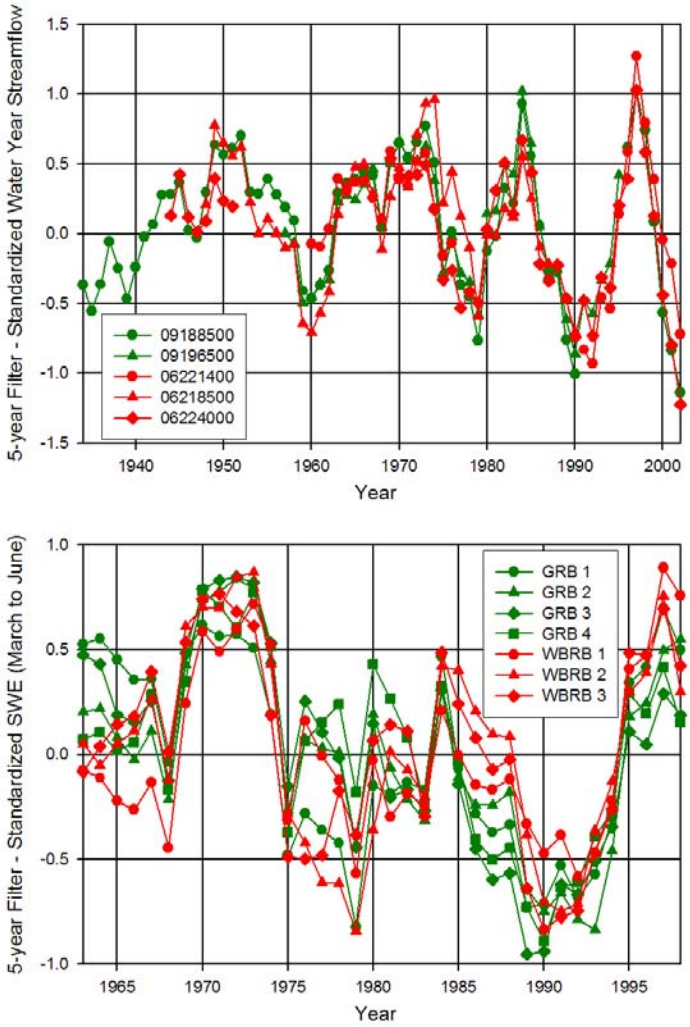

Figure 3: **5-year filter applied to Standardized (a) Water-year Streamflow (b) Seasonal SWE.**

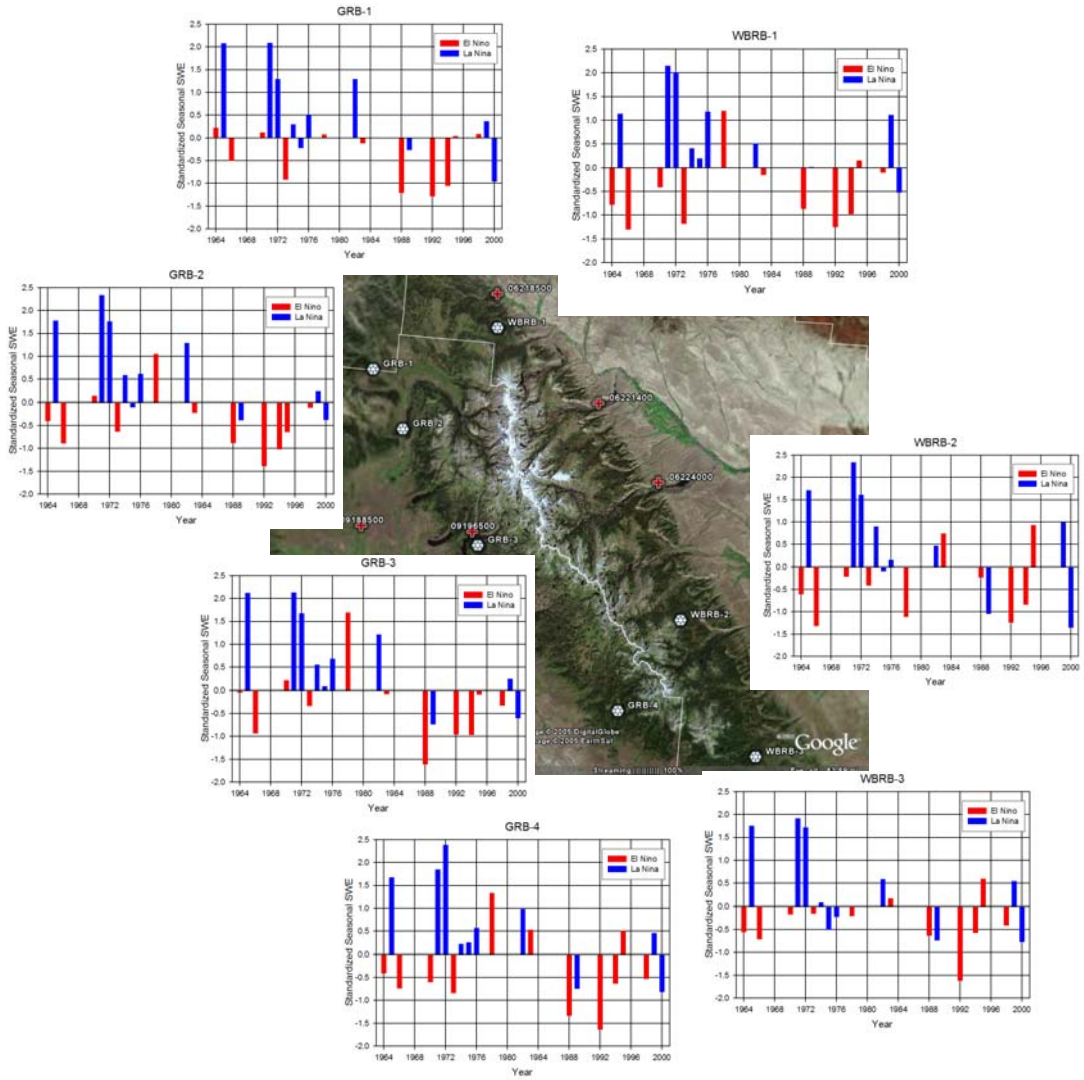

Figure 4: Standardized seasonal SWE for La Niña (blue) and El Niño (red) years.

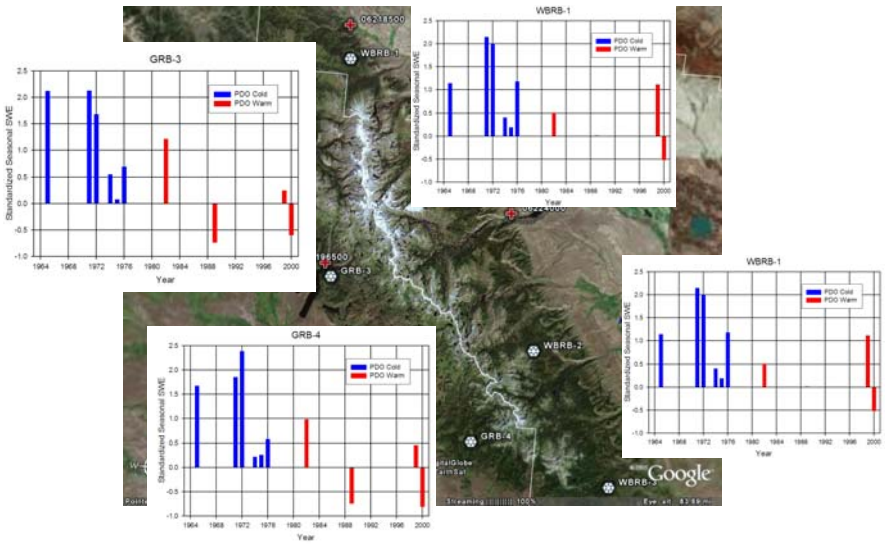

Figure 5: **Standardized seasonal SWE for PDO Cold (blue) and PDO Warm (red) for La Niña years.**

Table 1: **List of unimpaired USGS streamflow stations and NRCS SNOTEL stations in the Wind River Range.**

River Basin	Site Name	USGS or NRCS Site #	Latitude / Longitude
Green	Green River, Near Daniel, WY	09188500	43.02/-110.12
Green	Pine Creek Above Fremont Lake, WY	09196500	43.03/-109.77
Wind-Bighorn	Wind River Near Dubois, WY	06218500	43.58/-109.76
Wind-Bighorn	Dinwoody Creek, Near Burris, WY	06221400	43.35/-109.41
Wind-Bighorn	Bull Lake Creek Above Bull Lake, WY	06224000	43.18/-109.20
Green	Gros Ventre Summit, WY	506 (GRB-1)	43.39/-110.13
Green	Kendall R.S., WY	555 (GRB-2)	43.25/-110.02
Green	Elkhart Park G.S., WY	468 (GRB-3)	43.01/-109.76
Green	Big Sandy Opening, WY	342 (GRB-4)	42.65/-109.26
Wind-Bighorn	Little Warm, WY	585 (WBRB-1)	43.50/-109.75
Wind-Bighorn	Hobbs Park, WY	525 (WBRB-2)	42.87/-109.09
Wind-Bighorn	South Pass, WY	775 (WBRB-3)	42.57/-108.84

Precipitation Measurement and Growth Mechanisms in Orographic Wyoming Snowstorms

Basic Information

Title:	Precipitation Measurement and Growth Mechanisms in Orographic Wyoming Snowstorms
Project Number:	2006WY33B
Start Date:	3/1/2006
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Water Quantity, Climatological Processes, Hydrology
Descriptors:	None
Principal Investigators:	Jefferson Snider, Bart Geerts

Publication

1. B.Pokharel, J.R.Snider and D.Leon, 2007. Freshly-Formed Aerosol Particles: Connections to Precipitation, In Nucleation and Atmospheric Aerosols, 17th International Conference, Galway, Ireland, Edited by C.D.Odowd and P.E.Wagner, pp.484-488, Springer.

Precipitation Measurement and Growth Mechanisms in Orographic Wyoming Snowstorms
PIs: Jefferson Snider and Bart Geerts
Year 2 Progress Report

Abstract

We review the three 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. Jonathan's thesis is completed and submitted to an international conference; he anticipates submitting his work for peer review in 2008. The second is Binod Pokharel's study of airflow and cloud processes inferred using Wyoming King Air and Wyoming Cloud Radar measurements made in mountain wave clouds formed over the Medicine Bow Mountain Range. This work is also submitted to an international conference and Binod anticipates defending his Masters Thesis during summer 2008. The third is Bujidmaa Borkhuu study of snowfall rates and accumulations made 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.

Our progress is detailed below under the names of the graduate students working in collaboration with professors Jefferson Snider and Bart Geerts. Acronyms are defined in an appendix.

1. Jonathan Wolfe

Jonathan Wolfe conducted an investigation of the relationship between radar reflectivity (Ze) water equivalent snowrate (S). He hypothesized that the fit coefficient (α), in the parameterization $Ze=\alpha S^2$, should vary inversely with temperature. Field measurements of snowrate were made using the Yankee Environmental Systems hotplate snowrate sensor. Snowrate was correlated with values of radar reflectivity acquired by Cheyenne, Wyoming National Weather Service Radar. Wolfe's analysis has advanced since his MS thesis defense and is now available as an extended abstract submitted to the 15th International Cloud Physics Conference. The extended abstract can be accessed online at the following link: http://www-das.uwyo.edu/~jsnider/snow/preliminary/wolfe_ICCP_extended_abstract.doc

2. Binod Pokharel

Binod Pokharel is finishing his Masters thesis in the summer of 2008. His submission to the 15th International Cloud Physics Conference can be viewed online at the following link: http://www-das.uwyo.edu/~jsnider/snow/preliminary/pokharel_ICCP_extended_abstract.doc

The emphasis of Binod's work is the development of a computer model, initialized with measurements, which air parcel trajectories that pass through mountain wave clouds. Motivation for the model comes from limitations imposed on airborne observations in cloudy environments by FAA regulation of minimum flight altitude, by advances in the use of airborne Doppler radar for quantifying wind velocities and by the need to better understand the genesis of ice particles in winter mountain wave clouds. Model development is summarized here starting with the measurement of Doppler velocities, and their assimilation into the model, and ending with a prediction of aerosol removal and its comparison to observations.

The three panels of Figure 1 show cloud radar measurements made on 18 January 2006, including the radar reflectivity (top panel), the vertical component of Doppler velocity (middle panel) and the horizontal velocity derived via the technique described in Leon et al. (2006)

(bottom panel). The figure highlights the fact that radar velocity data is only available when scatterers (i.e., snowflakes) are present within the viewing volume of the radar.

Since the Doppler velocity is the vector sum of vertical air velocity and the particle fall speed, a retrieval of the former requires an estimate of the latter. For the estimate we use vertical Doppler velocity measurements acquired at the first range gates above and below the altitude of the aircraft; these two values were averaged and then correlated with measurements of vertical velocity acquired from the King Air gust probe. The particle fall speed inferred from the correlation range between 1.4 and 0.8 m/s for the four case studies examined by Pokharel (January 18, January 26, January 31 and February 2).

The horizontal velocity field (bottom panel, Figure 1) was derived from an analysis of data from the two downward pointing beams of the Wyoming Cloud Radar (Leon et al., 2006). The corrected vertical Doppler velocity field and the horizontal velocity field provide an unprecedented view of wind velocities in these mountain wave cloud systems. Two assumptions are needed to go from the velocity field to air parcel trajectories: 1) The actual velocity vector field does not have a component normal to the vertical plane defined by the track of the aircraft and the downward-pointing radar beam, and 2) the vector velocity field is steady state. If these assumptions are valid we can start with an air parcel at an upwind location, for example at 3000 m altitude in Figure 1, integrate the x-z dependent velocities, and produce an air parcel trajectory. An example of this is shown in all three panels of Figure 1.

Figure 2 shows two air parcel trajectories that originate from the same upwind point. One of the trajectories is the same as shown in Figure 1, here referred to as the "Radar Trajectory", and the other is derived using gust probe horizontal and vertical velocities with the assumption that velocities below the flight track are the same as that measured along the track ("Gust Probe Trajectory"). Differences between the trajectories are substantial and point to a possible bias in trajectories that are contingent on the vertical uniformity assumption. For example, the condensate mixing ratios differ by 0.2 g/kg, at the highest points on the trajectories, and this difference is a significant fraction of trajectory-maximum condensate mixing ratios (0.4 and 0.6 g/kg). The condensate mixing ratio difference results because the trajectory ascends higher when computed using the radar-derived velocities. Higher ascent is a consequence of the larger vertical velocities, seen upwind of the barrier and below the aircraft track, compared to upwind of the barrier and along the track. This is evident at the along-track distances -16 and -11 km in the middle panel of Figure 1.

Figure 3 shows cloud properties predicted by a parcel model, including supersaturations with respect to water (S_w) and ice (S_i), condensate mixing ratios and particle radii. One outcome is that the predicted ice-to-water ratio is significantly smaller than that observed. This discrepancy indicates that the parcel assumption may not be adequate in situations where ice particles, originating from aloft, fall across trajectories originating from lower altitudes.

We are also using the model to predict the loss of ultrafine aerosol particles occurring via Brownian attachment to ice and water particles. The difference between ultrafine particle concentration measurements made upwind and downwind of the cloud provides a direct measure of the attachment. The observed and modeled ultrafine aerosol losses are in reasonable agreement as is shown in Figure 4. This suggests that the model is making a realistic estimate of the cloud condensate mixing ratio and the water particle size along the trajectory.

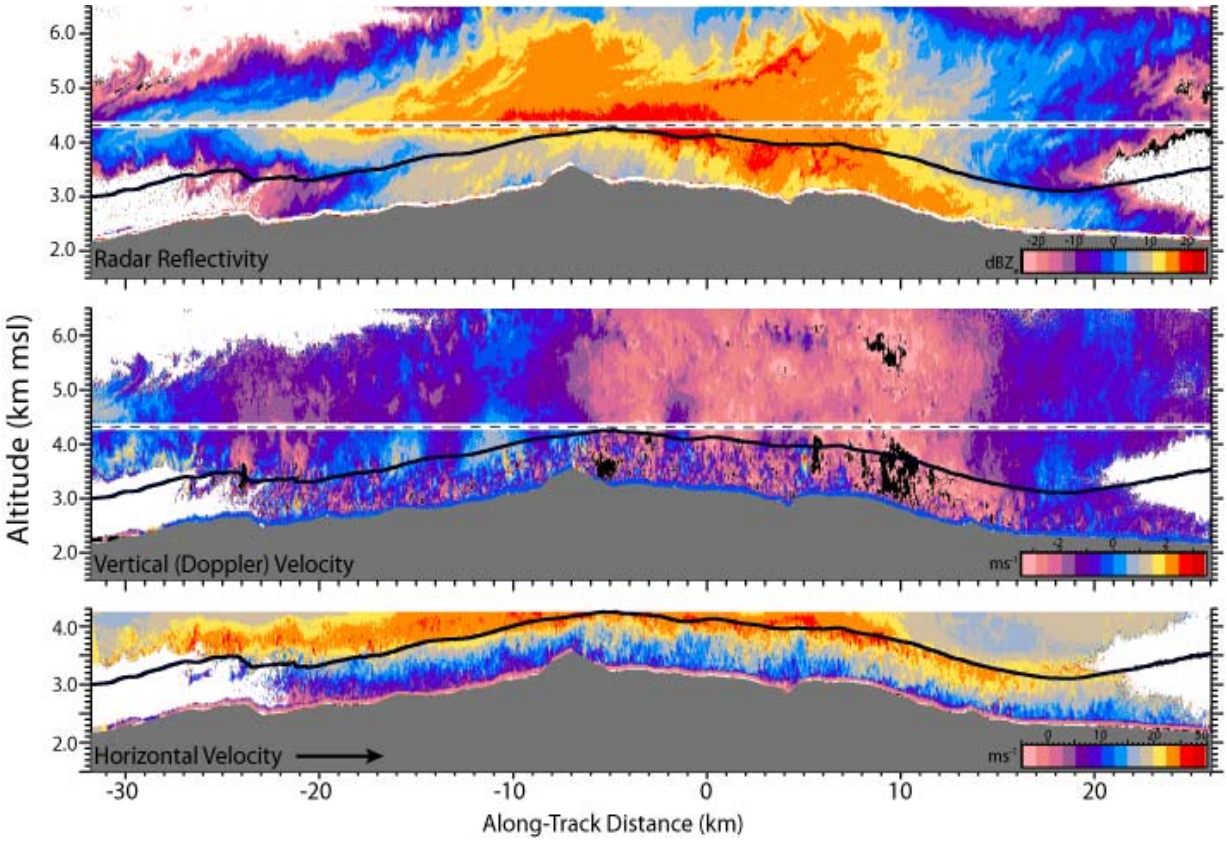

Figure 1 – Radar reflectivity (top panel) and radar vertical Doppler velocity (middle panel), plus the flight track (dashed horizontal line). The bottom panel shows the horizontal wind velocity field below the aircraft track. Superimposed is the air parcel trajectory. Particle fall speed is estimated at 1.4 m/s and the vector sum of the fall speed and the vertical Doppler velocity is the vertical air velocity. The largest vertical velocity is 4 m/s (at along-track distance = -10 km). Results are from 18 January 2006.

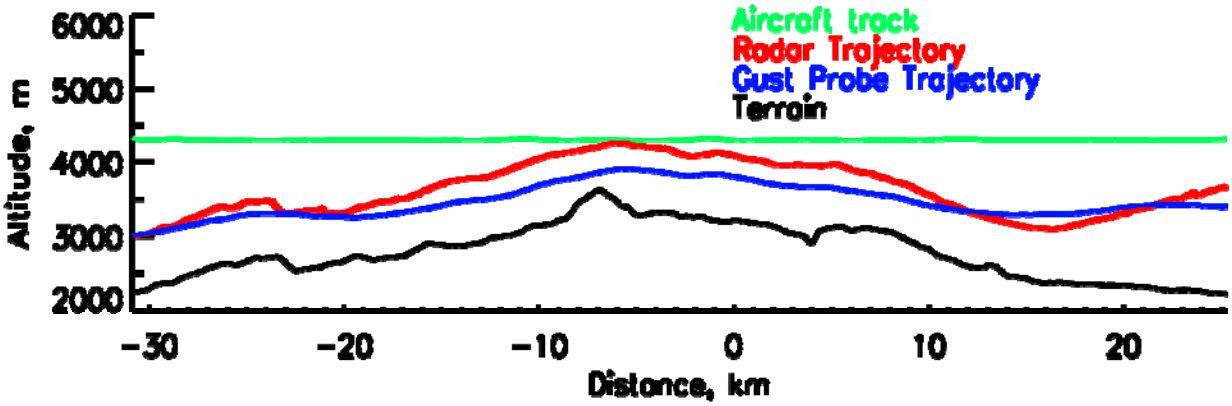

Figure 2 – Air parcel trajectories derived from radar-derived air velocities and from gust probe-measured velocities. Results are from 18 January 2006.

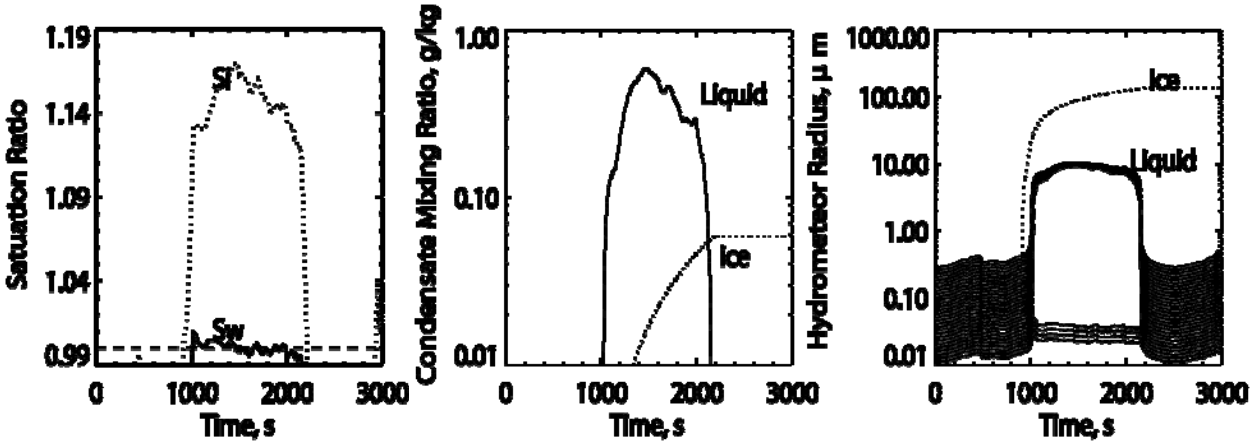

Figure 3 – Model predictions of cloud properties within an air parcel following the "Radar Trajectory" shown in Figure 2.

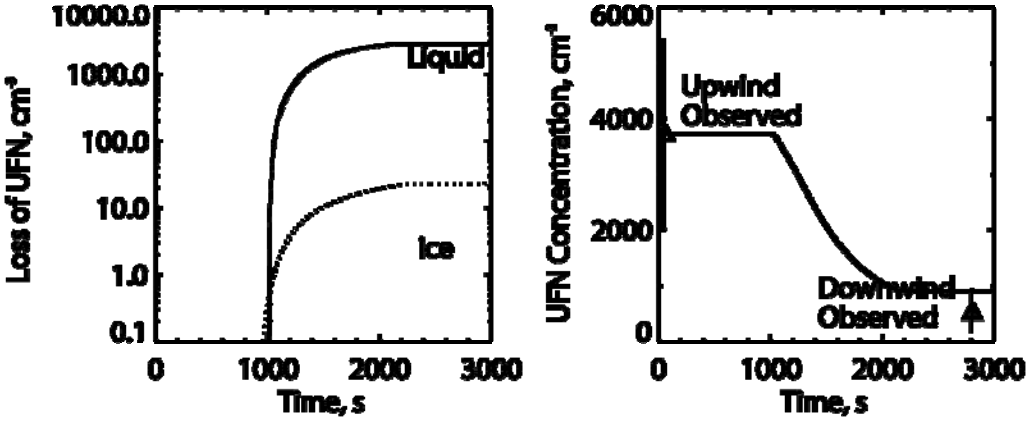

Figure 4 – Model prediction of the time-history of ultrafine aerosol particle concentration along the trajectory and comparison to airborne measurements of the ultrafine concentration made upwind and downwind of the cloud.

3. Bujidmaa Borkhuu

The measurement of snowfall is complicated by many factors. In windy areas of the Rocky Mountains, for example in Wyoming's Medicine Bow Mountains which are currently the focus of attempts to increase snowfall by cloud seeding, complications arise because gauge catch efficiency varies inversely with horizontal wind speed, because snowfall can be intercepted by trees before reaching gauges operated below a forest canopy, and because of the inadvertent measurement of snow that is resuspended. The first two of these result in the underestimation of snowfall and the third results in snowfall overestimation. We refer to these three phenomena as undercatch, shadowing and resuspension.

Bujidmaa Borkhuu research has two foci: 1) to compare snow accumulations derived from gauge measurements made at the Glacier Lakes Ecosystem Experiment Sites (GLEES), and 2) to delineate which of the phenomenon, discussed above, is a significant source precipitation measurement bias at the GLEES. In 2007 this work was compromised by inaccuracy in the hotplate snowrate data set. Bujidmaa has developed a protocol which

recalibrates the hotplate sensor and she redeployed the hotplate at GLEES in March 2008. Measurements made in March and April 2008 are too preliminary to show in this report, but they appear to be sufficient for addressing the two objectives Bujidmaa has set out for her Masters thesis. Below we provide a comparison of the 2007 snow accumulation data obtained from the Brooklyn Lake SNOTEL, and from the Vaisala Rain Gauge (VRG) and National Atmospheric Deposition Program (NADP) gauges operated at the GLEES. The SNOTEL site located is 1 km southeast of GLEES.

Figure 5 shows the comparison of the SNOTEL, VRG and NADP accumulations. In the top panel it is evident that that the NADP accumulation is larger than both the SNOTEL and the VRG values. Although we are uncertain of the reason for this bias, our surveys of the measurement sites suggest that the NADP site is more prone to positive bias due to snow resuspension. On the other hand, our site surveys also reveal that the SNOTEL and the VRG locations are more shadowed by the tree canopy, possibly making measurements from SNOTEL and VRG smaller than those from the NADP. The snow accumulation data we are acquiring during 2008 should help to resolve these questions, in particular if the measurements are analyzed with windspeed as is shown in the bottom panel of Figure 5. During our analysis of the 2008 data we will also be using the hotplate measurements made on the 30 m AMERIFLUX tower, which should be less prone to either resuspension or shadowing effects. That aspect of the hotplate snowrate measurements should help us distinguish among the bias scenarios evoked by Figure 5.

Outlook for Year-3

During year-3 we aim to complete two MS theses (Pokharel and Borkhuu) and to submit two manuscripts for peer review (one each for Wolfe and Pokharel).

Student Involvement Supported by the Grant

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

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

Presentations with Abstracts Supported by the Grant

Geerts, B., J.R.Snider, G.Vali, and D.Leon, Orographic precipitation enhancement by boundary-layer turbulence: a vertically pointing airborne cloud radar view, 13th Conference on Mountain Meteorology, Whistler, British Columbia, 2008

Wolfe, J.P., J.R.Snider and B.Geerts, Development of a temperature-dependent radar reflectivity to snowrate relationship for the S-band, 15th International Conference on Clouds and Precipitation, Cancun, Mexico, 2008

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. and G. Vali, Impact of surface interaction and cloud seeding on orographic snowfall: A downlooking airborne cloud radar view. Oral presentation at the 17th AMS/WMA Symposium on Planned & Inadvertent Weather Modification, Westminster, CO, 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

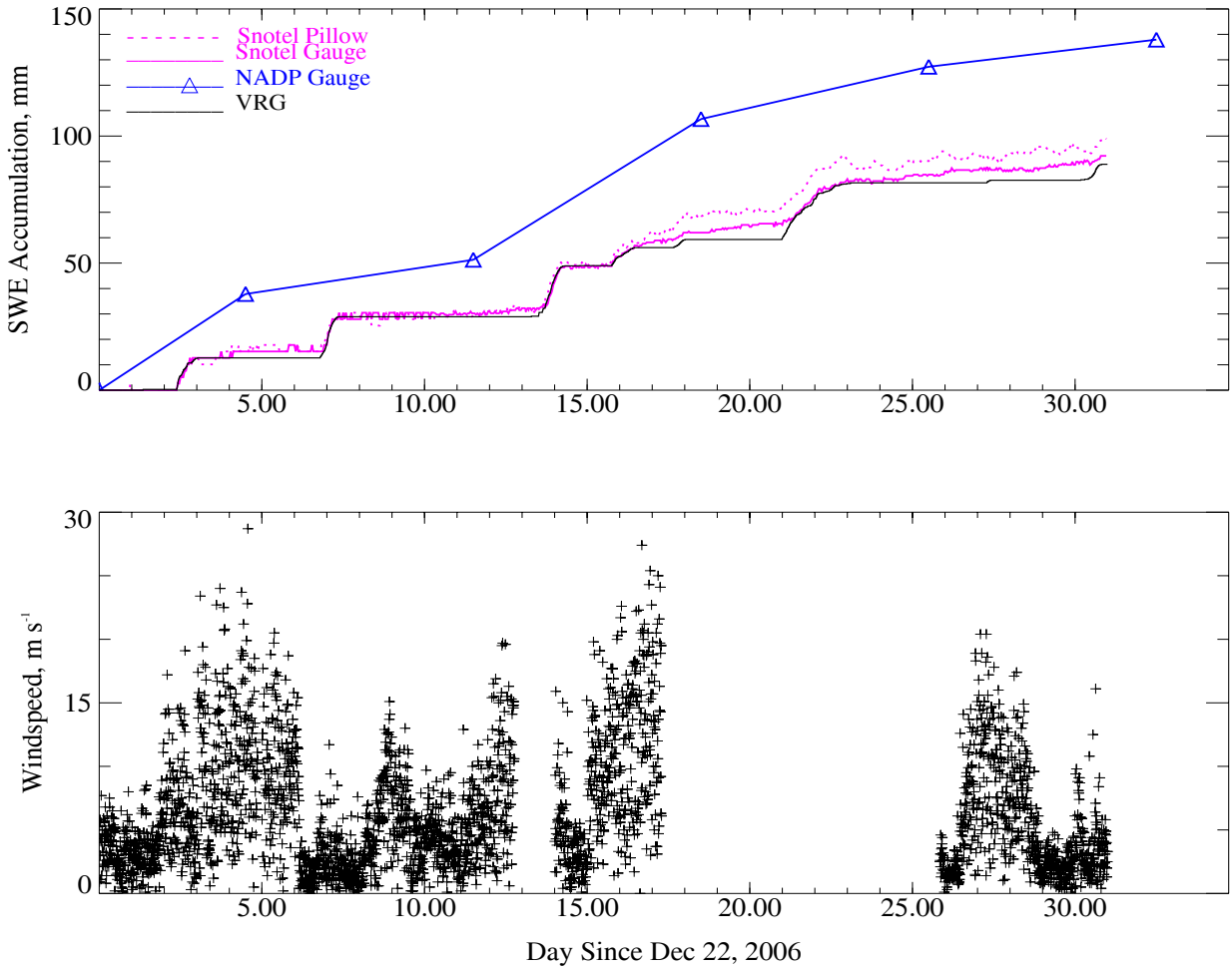

Figure 5 – Snow accumulations derived from the Brooklyn Lake SNOTEL sensors (gauge and snow pillow systems), from the Vaisala Rain Gauge (VRG) and National Atmospheric Deposition Program (NADP) gauges operated at GLEES. The time series start at December 22, 2006 and end on January 22, 2007. The windspeed data is from the Vaisala WXT510 weather station we deployed on the top of the AMERIFLUX tower at GLEES. The windspeed time series is incomplete because of power outages occurring on day 13 and on day 17.

Presentations without Abstracts Supported by the Grant

Wolfe, J., Radar-estimated Upslope Snowfall Rates in Southeastern Wyoming, MS Thesis defense, 15 February 2007

Snider, J.R., Precipitation Measurement and Growth Mechanisms in Orographic Wyoming Snowstorms, Wyoming Weather Modification Technical Advisory Board, January 18, 2007

Snider, J.R. (for B.Geerts), Detecting the Signature of Cloud Seeding with the Wyoming Cloud Radar, Wyoming Weather Modification Technical Advisory Board, January 18, 2007

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

Wolfe, J., Temperature dependence of the Z-S relationship for upslope snowfall, presented at the Wyoming-NCAR RAL workshop in Boulder, CO, September 6, 2006

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Leon, D., G. Vali, and M. Lothon, 2006: Dual-Doppler analysis in a single plane from an airborne platform. *J. Atmos. Oceanic Technol.*, **23,** 3-22.

Appendix

DEPSCoR – Defense Experimental Program to Stimulate Competitive Research
FAA – Federal Aviation Administration, (http://www.faa.gov)
NADP – National Atmospheric Deposition Program (http://nadp.sws.uiuc.edu/)
NASA – National Aeronautic and Space Administration
NCAR – National Center for Atmospheric Research (http://www.ncar.ucar.edu/)
NSF – National Science Foundation
SNOTEL – SNOpack TELemetry (http://www.wcc.nrcs.usda.gov/snotel/)
NRCS – National Resource Conservation Service (http://www.wcc.nrcs.usda.gov/)
NWS – National Weather Service (http://www.crh.noaa.gov/cys/)
WCR – Wyoming Cloud Radar (http://www-das.uwyo.edu/wcr/)
WMI – Weather Modification, Inc. (http://www.weathermod.com/index.php)
WSR – Weather Surveillance Radar (http://weather.noaa.gov/radar/radinfo/radinfo.html)
YES – Yankee Environmental Systems Inc. (www.yesinc.com)

Tracing Glacial Ice and Snow Meltwater with Isotopes

Basic Information

Title:	Tracing Glacial Ice and Snow Meltwater with Isotopes
Project Number:	2007WY37B
Start Date:	3/1/2007
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Climatological Processes, Radioactive Substances
Descriptors:	None
Principal Investigators:	David Williams

Publication

Tracing glacial ice and snow meltwater with isotopes
PI: David G. Williams
Year 1 Progress Report

Abstract

This report describes progress for the first year of a two-year project investigating isotopic signatures of glacial meltwater in the Dinwoody Creek drainage of the Wind River Range in western Wyoming. The primary objectives of the project are to 1) characterize diurnal, seasonal and interannual variation in the isotopic composition of 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. We are obtaining monthly integrated precipitation samples from two high elevation sites in the Wind River Range close to Dinwoody Glacier. These samples are being used to develop a local meteoric water line to assist in the interpretation of isotope ratio values of surface waters collected in the Dinwoody Creek drainage basin. Stream and glacier samples collected in August 2007 revealed substantial variation for oxygen-18 and deuterium isotope ratios. Glacial ice, firn and meltwater had isotope ratio values that were distinguishable from those of August precipitation and streamwater. Oxygen-18 isotope values in Dinwoody Creek varied systematically over a diurnal cycle reflecting the enhanced contribution of Dinwoody Glacier and other glaciers during the daytime periods. Variation in the deuterium isotope ratio values mirrored that of the oxygen-18 values with fairly constant deuterium excess (d-excess) values of between 5 and 9. However, d-excess of the outflow from several high elevation lakes revealed substantial evaporation enrichment. Automated sampling of stream discharge from the USGS gauging station on Dinwoody Creek began in June 2007 and continued through October 2007. Over this period, the oxygen-18 and deuterium isotope ratio values became progressively more positive as stream discharge declined. Taken together, findings from the first year of this study have shown marked differences in the isotope ratio of sources of stream flow in Dinwoody Creek, which will establish the basis for isotopic partitioning of surface runoff contributions into rainfall, snowmelt and glacial melt components.

Objectives

The principal scientific objective of this proposed work is to evaluate several isotopic tracers for their ability to distinguish sources of flow in a glacier-fed stream. Specific objectives are 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
3. Partition the surface runoff component of stream discharge into that derived from glacial melt, snowmelt, and summer precipitation

Methodology

Field sampling: We sampled streamflow of Dinwoody Creek continuously at 3-day intervals from June 2007 to October 2007 to characterize the isotopic composition of baseflow and total flow during melt periods. Sampling was automated with an ISCO Inc portable streamflow sampler placed at the USGS gauging station on Dinwoody Creek. Pure white mineral oil was added to sample containers to prevent evaporation and isotopic fractionation between visits to

collect the samples from the automated sampler. We evaluated diurnal changes in the isotopic composition streamwater at two locations on Dinwoody Creek between August 14 and 18, 2007. During this visit to the drainage basin we also sampled all the main tributaries for Dinwoody Creek as well as Dinwoody Glacier itself. Glacial ice, firn and glacial meltwater from the tongue of Dinwoody Glacier were be collected on a single visit to the glacier on August 17, 2007. We obtained monthly integrated precipitation samples from two high-elevation USFS meterological stations and NADP collection sites in the northern and southern Wind River Range. Rainfall samples were also collected opportunistically during the August field collection trip.

Isotopic analysis: Samples were analyzed for oxygen-18 and deuterium content at the University of Wyoming Stable Isotope Facility (UWSIF; http://uwacadweb.uwyo.edu/sif/), which is directed by Williams. Analysis of oxygen-18 was carried out by an automated CO_2 equilibration technique. The analytical precision for this technique in the UWSIF based on repeated analysis of internal working standards was 0.05 per mil. Analysis of deuterium content was carried out using an off-line zinc reduction method. Analytical precision for this technique in the UWSIF was 1.0 per mil.

Principal Findings

We successfully completed a major field campaign in August 2007 to obtain surface water samples and glacial ice and meltwater samples with high spatial and temporal resolution within the Dinwoody Creek drainage basin. Several hundred water samples were collected from multiple points in the drainage system, including samples from the major tributaries of Dinwoody Creek and associated integration points along the main stem of the creek. We sampled extensively from Dinwoody Glacier to obtain glacial meltwater, glacial ice and firn. We also obtained samples of precipitation falling during the field campaign. More than 40 samples were collected for tritium analysis, although because of budget constraints we may only analyze a subsample of these for tritium concentration. Stream and glacier samples collected in August 2007 revealed substantial variation for oxygen-18 and deuterium isotope ratios. Glacial ice, firn and meltwater had isotope ratio values that were distinguishable from those of August precipitation and streamwater (Table 1).

Table 1. Mean values for oxygen-18 and deuterium isotope composition from samples collected during August 14-19, 2007 in the Dinwoody Creek drainage basin.

Water Source	$\delta^{18}O$	$\delta^{2}H$	d-excess
Glacier			
Firn	-18.2	-142	5
Meltwater	-18.6	-142	8
Ice	-18.7	-144	7
Surface Water			
Clear side streams	-16.8	-130	6
Dinwoody Creek	-17.2	-131	8
Gannett Creek	-17.2	-130	9
Lake outflow	-16.7	-136	-1
Precipitation (rain)	-8.7	-61	9

Precipitation samples collected during August near the base of Dinwoody Glacier had an average oxygen-18 value of -8.7 per mil, while firn, surface ice, and meltwater from Dinwoody Glacier had values of -18.2, -18.6 and -18.7 per mil. It is very evident that the meltwater and surface ice and firn from Dinwoody Glacier is isotopically distinct from summer rainfall and from water further down Dinwoody Creek which represents a mixture of glacial meltwater, runoff from summer rainfall and discharge from high elevation lakes and non-glacially fed streams. We conclude from this initial inspection of our 2007 data that the partitioning of stream flow into baseflow, glacial melt and rainfall runoff is very feasible. We will expand our sampling in summer 2008 to capture variation associated with snowmelt runoff in July, as well as to intensify sampling of the diurnal variation in glacial meltwater inputs.

Diurnal variation in the contribution of glacial meltwater in Dinwoody Creek is reflected in the diurnal variation in isotopic values of stream water. We obtained samples from Dinwoody Creek every three hours for a 24-h period at the base camp at Wilson Meadows approximately three miles from Dinwoody Glacier. Oxygen-18 isotope values in Dinwoody Creek varied systematically over a diurnal cycle reflecting the enhanced contribution of Dinwoody Glacier and other glaciers during the daytime periods (Figure 1). At its lowest flow at 4am Dinwoody Creek at Wilson Meadows about 5 km from the base of Dinwoody Glacier had an oxygen-18 value of -16.1 per mil. At peak flow between 4 and 7pm, the value had declined to -16.8 to -17.2 per mil. Variation in the deuterium isotope ratio values mirrored that of the oxygen-18 values with fairly constant deuterium excess (d-excess) values of between 5 and 9 (data not shown). However, d-excess of the outflow from several high elevation lakes revealed substantial evaporation enrichment; d-excess values from these sources had an average value of -1 reflecting the preferential loss of deuterium relative to oxygen-18 during evaporation (Table 1).

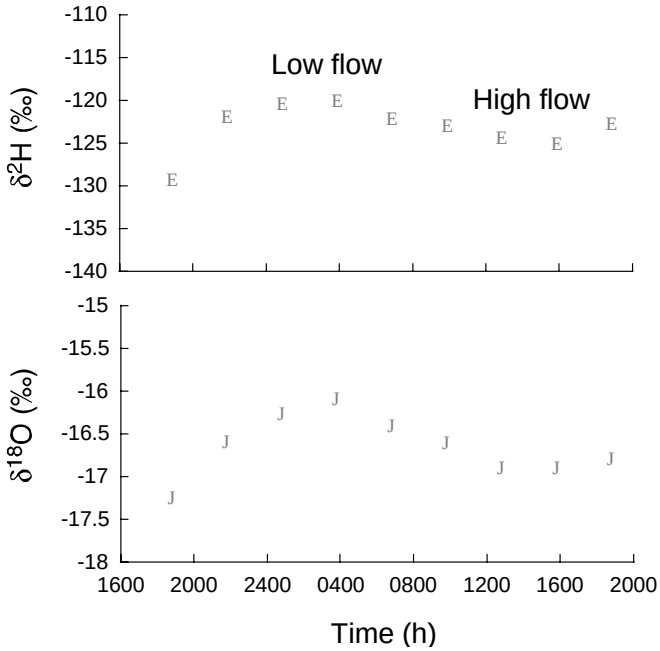

Figure 1. Diurnal variation in water isotopic composition on August 17-18, 2007 at Wilson Meadows on Dinwoody Creek.

We obtained authorization from the Tribal Water Engineer Mr. Bill Russell to establish an automated stream sampler on Dinwoody Creek at the USGS gauging station below Mud Lake on tribal lands. The sampler was installed in mid June 2007 and samples for isotopic analysis were being collected every 3 days until late October 2007. Automated sampling of stream discharge from the USGS gauging station on Dinwoody Creek began in June 2007 and continued through October 2007. Over this period, the oxygen-18 and deuterium isotope ratio values became progressively more positive as stream discharge declined (Figure 2). At peak discharge in June,

the oxygen-18 value was approximately -18.7 per mil, likely reflecting substantial snowmelt runoff. Values increased to as high as –16.6 per mil by mid October.

Terry Svalberg of the USDA Forest Service Pinedale Ranger District is assisting this project by collecting precipitation at two high elevation sites in the Wind River Range close to the Dinwoody drainage basin. These samples are being analyzed for isotopic ratios (Figure 3) to establish a local meteoric water line (LMWL) for the Wind River Range. A LMWL for the Wind River Range will be of high value to water managers and hydrologists of the region as the Wind River Range is the source of two major river systems in the west. A LMWL is required to understand patterns of isotopic mixing and discharge sources within the Dinwoody Creek drainage basin.

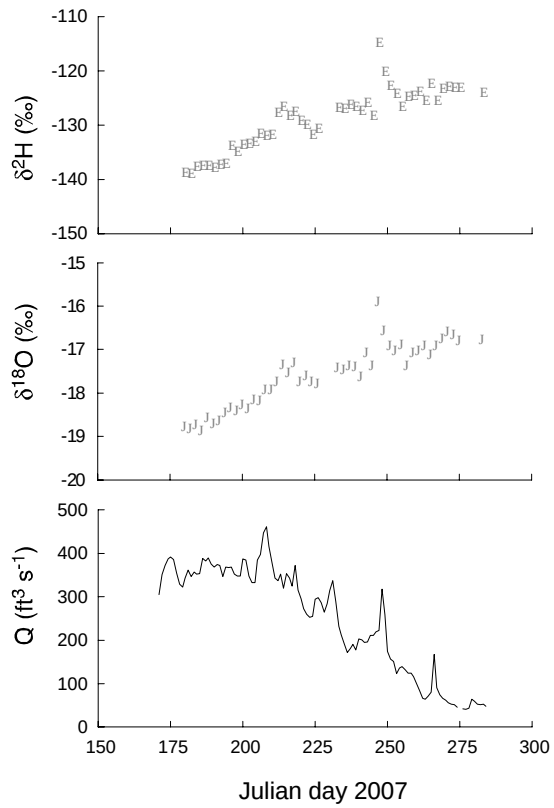

Figure 2. Isotopic composition (δ^2H and δ^{18}O) and discharge rate (Q) of Dinwoody Creek at the USGS gauging station (USGS 06221400).

Significance

Glacially fed streams in the Rocky Mountains support wildlife and agriculture during the late part of the growing season after most snowpack has disappeared. There is considerable uncertainty about how changes in snowpack and loss of alpine glaciers due to climate warming are likely to translate into changes in stream and river discharge. Efforts to predict how streamflow will be affected by climate change hinges on our ability to reduce the level of uncertainty in hydrologic models in snowmelt-dominated catchments. This work

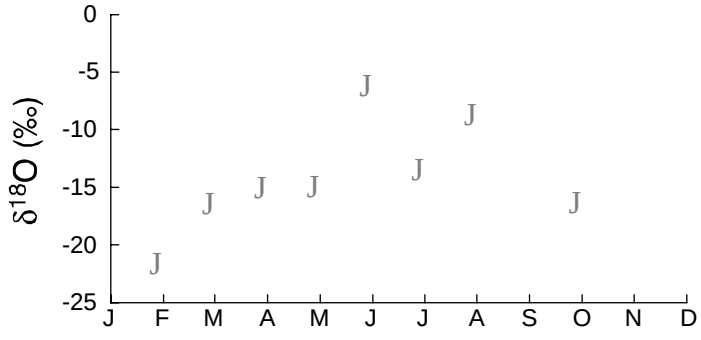

Figure 3. Oxygen-18 composition of precipitation collected from high-elevation NADP collection sites in the Wind River Range, WY in 2007.

explores the use of isotopic tracers as a means to identify the contribution of glacial meltwater, snowmelt, summer precipitation and baseflow to stream discharge in the Wind River Range in the glacially fed Dinwoody Creek catchment.

Student Support Information

One postdoc, one graduate student, and one undergraduate student were supported in Year 1 of this work. The postdoc, Dr. Jessica Cable, was supported at 0.25 time from June 2007 to February 2008. She will continue to lead the field and lab work on the project in year two. One graduate student, Mr. Peter Koenig, was supported on the project 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 one. He will remain on the project as a laboratory technician in year two.

Publication and presentation citations

None to report.

Awards and achievements

Dr. Jessica Cable, the postdoc working on this 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.

Integrated Management of Groundwater and Surface Water Resources: Investigation of Different Management Strategies and Testing in a Modeling Framework

Basic Information

Title:	Integrated Management of Groundwater and Surface Water Resources: Investigation of Different Management Strategies and Testing in a Modeling Framework
Project Number:	2007WY38B
Start Date:	3/1/2007
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	1
Research Category:	Social Sciences
Focus Category:	Law, Institutions, and Policy, Groundwater, Surface Water
Descriptors:	None
Principal Investigators:	Fred Ogden, Melinda H. Benson

Publication

Integrated Management of Groundwater and Surface Water Resources
PIs: Fred L. Ogden and Melinda H. Benson
Year 1 Progress Report

This annual project report is split into two distinct sections. The first covers progress to-date on the surface water ground water interaction modeling study. The second reports progress on the study of the legality and potential applicability in Wyoming of different conjunctive management strategies.

Section 1—Progress on ground water/surface water modeling

Objectives—Section 1

1) Identify relevant aquifer and forcing parameters for implementation of a MODFLOW model to assess impact of pumping from alluvium on surface water flows.
2) Test legally- viable management strategies within the MODFLOW to ascertain their potential effectiveness.
3) Communicate results to State of Wyoming, State Engineer's Office.

Methodology—Section 1

MODFLOW-2000 was selected as the ground water flow modeling code for this study. The Groundwater Modeling System (GMS version 6.5) was selected as the pre- and post-processor for MODFLOW-2000 input and output data.

Progress—Section 1

The model variables have been 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 the link between the previous earlier two groups which is the wells system parameters.

Ground water parameters:

1. Aquifer geometry (length, width, and thickness)
2. Hydraulic conductivity
3. Saturated thickness
4. Regional water table slope
5. Recharge

Surface water parameters:

1. River stage
2. Conductance
3. Longitudinal slope

Wells system parameters:

1. Pumping discharge
2. Distance from the river

A one layer model has been developed with 2 km width, 5 km length, and 140 m to represent an area such as that in Goshen County as shown in Figure 1.

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 to range from 3 m/d to 15 m/d, while the saturated thickness was chosen to range from 100 m to 180 m. The recharge value was found significant at the range

from 0.00003 m/d to 0.004 m/d. The regional water table slope was selected to be 0.001 as parallel to the stage of the North Platte River in Goshen County.

Figure 1. North Platte River in Goshen County

The conductance of the river is dependent on the river stage. Based on river width 27 m, bed conductivity of 0.53 m/d, and 0.3048 m length of flow (Glover, 1983). A range of river stages and river conductances were used to demonstrate model sensitivity.

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 test the center well pumping which will be affected by the surrounding wells. It is very clear from Figure 1 that the irrigation wells are located in a reasonably grid-oriented pattern. The well system was placed adjacent to the river so that the distance from the nearest well to the river was set equal to the presumed radius of influence. According to this configuration, the center well in the 3x3 array is at a distance from the river of 1.5 times the well radius of influence.

A pumping range from 2500 m^3/d to 6000 m^3/d was selected to represent different irrigation well capacity. Well radii of influence ranging from 200 m to 600 m was chosen. To increase the ability of the model to accurately predict drawdown at the well center, a refine module was applied at the well points.

In an effort to reduce the effect of units on the results, dimensionless parameters were developed to report the results such as:

- A = [River conductance (m^2/d)] **/** [River stage (m)/ Aquifer Hydraulic conductivity (m/d)]
- B = [Center well distance from the river (m)]/[Draw down (m)]

The sensitivity analysis resulted in a family of curves which can very helpful for making decisions on the distance of the well from the river that would not affect the river stage or flow.

Family Curves Samples—Section 1

Using the (A) dimensionless parameter on the horizontal axis and the (B) dimensionless parameter on the vertical axis, based on recharge rate of 0.00003 m/d:

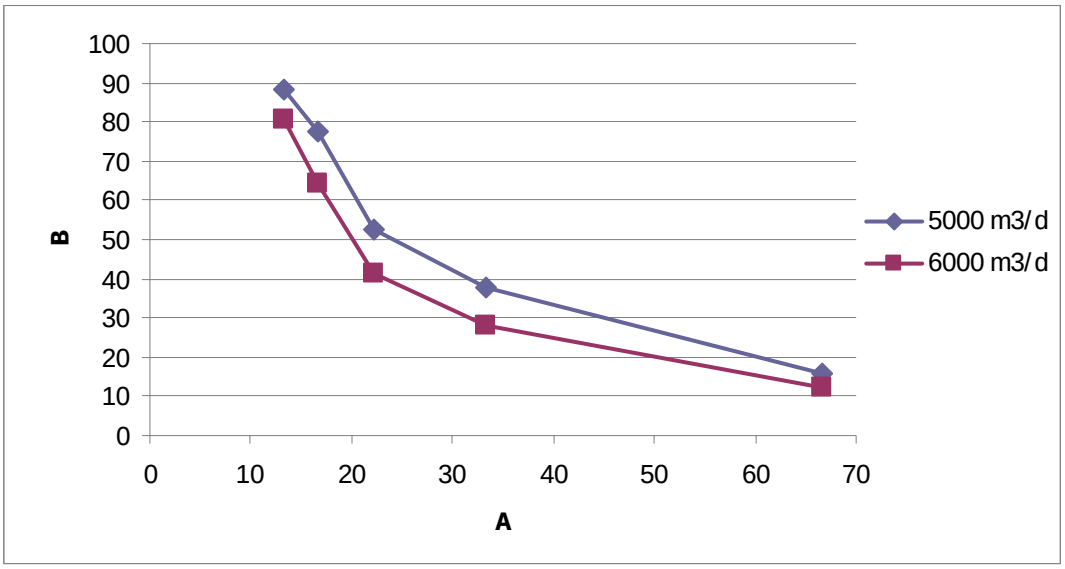

Figure 2. Based on 200 m influence radius of the well.

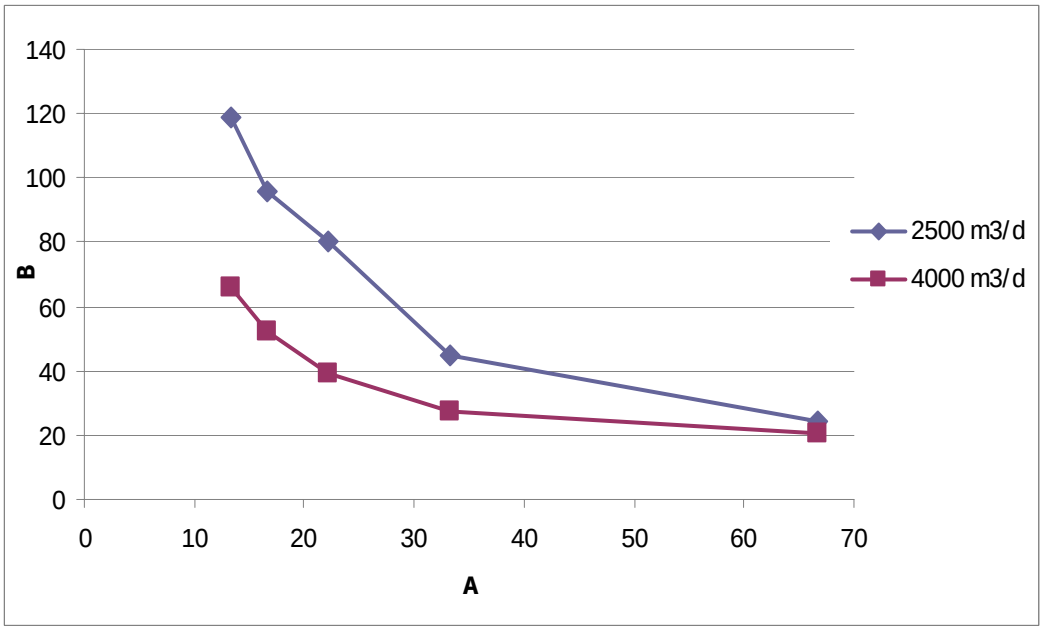

Figure 3. Based on 100 m influence radius of the well.

Preliminary Conclusions—Section 1

Based on the resulting curves shown in Figs 2 and 3, the recharge rate can be used to choose the correct graph then calculate the (A) dimensionless parameter and head vertically to hit the curve of the well under consideration. A value of (distance/ draw down) can be obtained from which the well location can be determined when the permitted draw down is known. We are continuing to refine our sensitivity analysis and are exploring the utility of different

dimensionless variables. In the next reporting period we expect to have completed this analysis and prepared a publication for submission to a peer-reviewed journal.

Student Support Information—Section 1

Funds from this project have partially support Mr. Mohamed Abdel-Hafez, Civil Engineering Ph.D. Student.

Section 2—Progress on Legal Analysis

Objectives—Section 2

The legal portion of the project consists of evaluating strategies for conjunctive management of surface and groundwater rights in alluvial aquifers in Wyoming. Year one of the project had the following objectives:

1) Conducting a detailed investigation of conjunctive groundwater/surface water management strategies employed in prior-appropriation jurisdictions;
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";
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; and
4) Testing of the effectiveness of the candidate strategies in a variety of hypothetical hydrogeological settings. This testing will be performed using the MODFLOW-2000 6 groundwater model. All relevant geophysical parameters, pumping rates, the number and spatial distribution of wells will be varied in a sensitivity analysis.

Methodology—Section 2

The methodology for conducing this research consist of traditional legal research tools, primarily consisting of the utilization of the legal research database Westlaw to conduct comprehensive searches of both primary and secondary materials. For searches involving information not available on Westlaw (e.g. state district court cases that are not formally published), information is obtained by contacting courts directly.

Principal Findings and Significance—Section 2

Objective one is now eighty percent (90%) complete, with an analysis of the conjunctive management strategies in the following states: Idaho, Arizona, Colorado, Kansas, California, Washington and New Mexico. Research is estimated for completion by June 1, 2008. Once Objective One is complete, it will by synthesized in a separate report for utilization by the research team and the candidate strategies will be chosen. The analysis of Wyoming law outlined in Objective Two is also complete and is now ready for comparison with the candidate strategies. The translation of those strategies into operational rules will be conducted this summer and fall, along with the testing of effectiveness using the MODFLOW-2000 6 groundwater model outlined in Objective 4.

Student Support Information—Section 2

This project has provided support for two law students at the University of Wyoming College of Law. Kris Koski and Tenille Castle are both third year law students who will be graduating this spring. Both will be continuing work over the summer.

Preliminary Results

This is an annual project report for a project that is in progress. The results contained within this report are preliminary and should not be cited or disseminated to third parties.

References

Gutentag, E.D, F.J. Heimes, N.C. Krothe, R.R. Luckey, J.B. Weeks. 1984. Geohydrology of high plains aquifer in parts of Colorado, Kansas, New Mexico, Oklahoma, South Dakota, Texas, and Wwoming. U.S.G.S. Professional Paper 1400-B, U.S. Government Printing Office, Washington D.C.

Kent C. Glover, 1984. Digital model for the Bates Creek alluvial aquifer near Casper, Wyoming: Wyoming water planning report, Wyoming State Engineer's office, 43 p.

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

Basic Information

Title:	Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstroms 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
PI: Bart Geerts
Year 1 Progress Report

Abstract

This proposal called for a series of research flights 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 generators located in the Snowy Range. We conducted the allotted two WKA flights in Year 1 of this project, one on 11 Feb and one on 25 Feb 2008. Both flights were successful. In this report we discuss some preliminary results.

Progress

The two flights in this campaign (referred to as WWDC Cloud Seeding) followed the general flight pattern shown in Fig. 1.

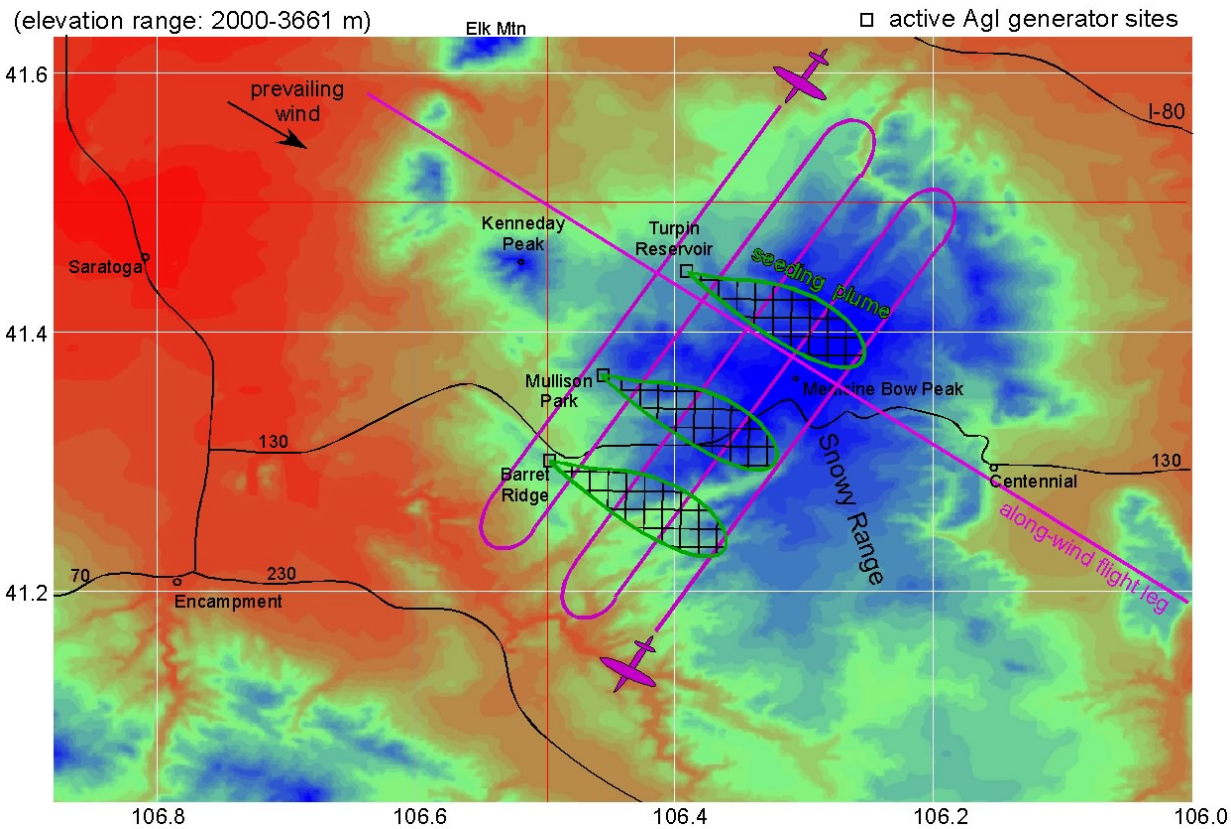

Fig. 1. A schematic of the WKA flight legs in the Snowy Range, over the AgI plumes (shown schematically with a green outline) released from three generators on the ground. The color background field shows the terrain. The flight level was 4,276 m (14,000 ft) MSL, the minimum permissible flight level 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 across the winds at various distances downstream of the seed sources.

The first flight was reported on at the Feb 2008 Wyoming Cloud Seeding Pilot Project Advisory Team meeting in Cheyenne. Similar conclusions can be drawn from the 2nd flight (Geerts 2008, AMS/WMA meeting in Westminster CO). With so much natural variability it is

very difficult to detect a seeding signature. About 50% of the flights were in unseeded conditions, and the 1st of 5 across-wind legs was upstream of the mountain (Fig. 1). These choices were made to detect a seeding signature, but the results were not conclusive. The most remarkable result was that deep planetary boundary layer (PBL) turbulence along the upslope section of the mountain was present on both days. While this turbulence would effectively mix the AgI into cloud, it may have also mixed sufficient ice particles from near the ground into cloud, thus making AgI seeding redundant. These 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.

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 <u>in</u> 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.

Principal Findings

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).

Further Plans

So far we conducted two flights over the Snowy Range. In early 2009, we hope to conduct flights over AgI generators in the Sierra Madre. Clearly the 20 WKA flight hours to be funded under the present grant are not sufficient to establish the significance of PBL turbulence under the broad range of orographic snowfall conditions. The PI hopes to continue both natural and seeded orographic precipitation research in his group for several years. Following the completion of a first peer-reviewed paper later this summer (Geerts et al. 2008), we plan to submit a proposal for additional flight hours to the Colorado River Lower Basin states water consortium by late summer. The choice of the Sierra Madre Mountains is motivated by the interest of this consortium in water draining into the Colorado River. We may also submit another WWDC/USGS proposal in the Fall. Bart 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.

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.

Students Supported

Two graduate students have been involved in Year 1 of this grant. The first is Heather McIntyre. Unfortunately she performed sub-standard in her MSc coursework in her first semester (December 2006), and she did not manage to bring her GPA up to the Graduate School's mandatory minimum of 3.0 in the spring semester (May 2007), so she left the group in May.

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.

A new MSc student, Yang Yang, will be joining us from China in August 2008, and will be 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.

Publications

- Geerts, B., Q. Miao, and G. Vali, 2008: Boundary-layer turbulence and orographic precipitation growth in cold clouds: evidence from vertical-plane airborne radar transects. Mon. Wea. Rev., in preparation.

Presentations

(a) with abstracts:

- Andretta, T., and B. Geerts, 2008: Snowfall in mountain lee convergence zones: a case study. 13th Conference on Mountain Meteorology, Whistler, BC, 11–15 August 2008.
- Geerts, B., 2008: Impact of surface interaction and cloud seeding on orographic snowfall: A downlooking airborne cloud radar view. Oral presentation at the 17th joint American Meteorological Society - Weather Modification Association Symposium on Planned & Inadvertent Weather Modification, Westminster, CO, April 21-25, 2008.
- Geerts, B., J. Snider, G. Vali, and D. Leon, 2008: Orographic precipitation enhancement by boundary-layer turbulence: a vertically pointing airborne cloud radar view. 13th Conference on Mountain Meteorology, Whistler, BC, 11–15 August 2008.
- Vali, G., B. Geerts, J. Snider, and D. Leon, 2008: Surface source of ice particles in mountain clouds. 15th International Conference on Clouds and Precipitation (ICCP), 7-11 July, Cancun, Mexico.

(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 Lander (May 07), in Cheyenne (October 07), and in Cheyenne (Feb 08).

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 and Tom Piechota
First Year Progress Report

Overview

This is a summary of the progress from the first year of a proposed three-year research project. Two M.S. graduate students, Cody Moser and Ty Soukup, received training in Civil Engineering by working on this project during the first year. This report summarizes their efforts.

Scientific Objectives

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.

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.

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

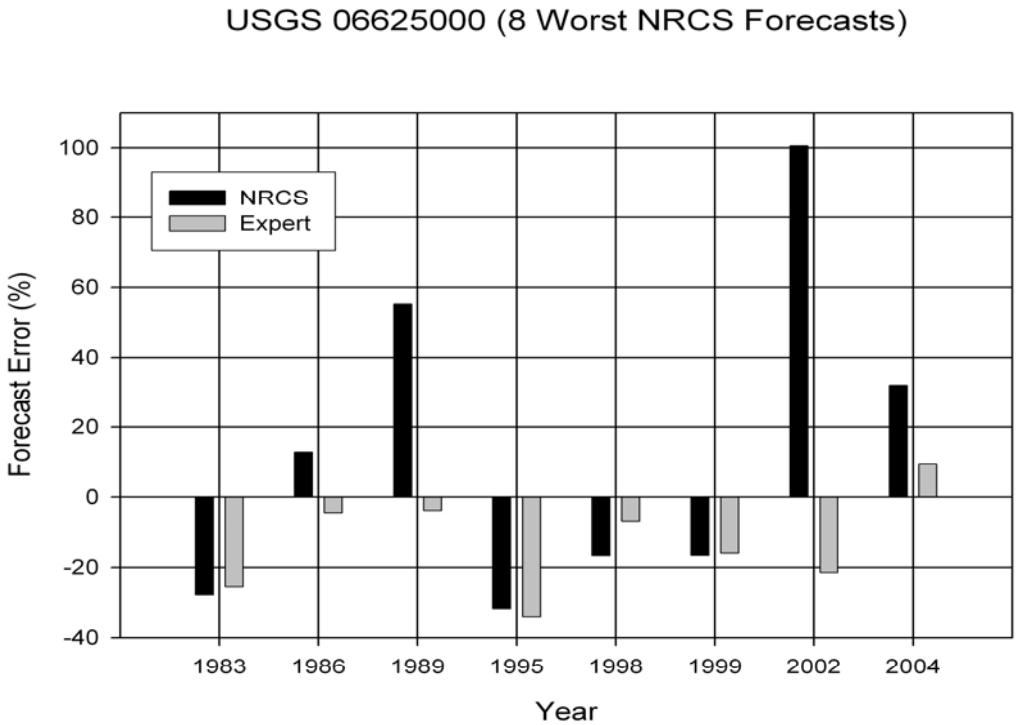

Figure 1: Plot of NRCS % difference forecasted valued versus the % difference Expert System forecast for the 8 worst NRCS forecast years for USGS Station 06625000.

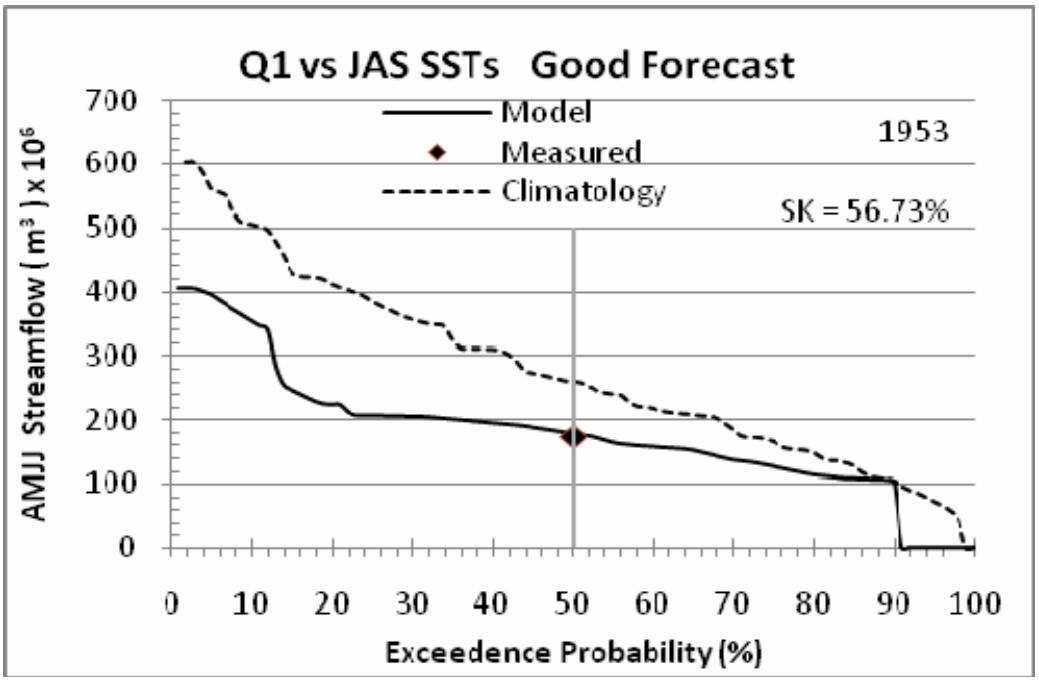

Figure 2: Example of Exceedance Probability Forecast.

model) of the North Platte River basin. The lead investigators are Haroon Stephen 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?

Student Support

Cody Moser and Ty Soukup (Master's students in Civil Engineering.) 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. Ty has accepted a position with an engineering firm in Laramie while Cody is in the process of interviewing.

Publications and Presentations

Cody and Ty have been invited to present the results of their research at the American Society of Civil Engineers (ASCE) Environmental Water Resources Institute (EWRI) Conference in May 2008. Additionally, they have made local presentations at the WY State Engineer's Water Forum and the University of Wyoming Graduate Seminars. Their work has been accepted for publication in the ASCE EWRI proceedings:

Moser, C., T. Soukup, G. Tootle and T. Piechota, 2008. An Expert System Approach to Improve Streamflow Forecasting in the North Platte River Basin, Wyoming, USA. Proceedings of the *ASCE World Water & Environmental Resources Congress 2008*, May 11-17, 2008, Honolulu, HI (In press).

Additionally, each of them has submitted their work to peer-reviewed journals:

Moser, C., T. Soukup, G. Tootle , T. Piechota and S. Wulff, 2008. Incorporating Antecedent Soil Moisture into Streamflow Forecasting. Submitted to *ASCE Journal of Hydrologic Engineering*.

Soukup, T., O. Aziz, G. Tootle, T. Piechota and S. Wulff, 2008. Long Lead-time Streamflow Forecasting of the North Platte River Incorporating Oceanic-Atmospheric Climate Variability. Submitted to *Journal of Hydrology*.

Information Transfer Program

During FY07, 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:

Director Service: (1) State of Wyoming, Residential Issues and Raw Water Supply Opportunities for Irrigation Districts in Wyoming. Powell, WY., January 31, 2007. (2) National Institute's for Water Resources Annual Meetings. Washington, DC., February 11 - March 14, 2007. (3) Wyoming Water Development Commission Workshop/Meeting. Cheyenne, WY., March 8-9, 2007. (4) Serve as a member of the Ruckelshaus Institute of Environment & Natural Resources, Water Working Group for the State of Wyoming. (5) Governor's Drought Task Force. Cheyenne, WY., April 13, 2007. (6) Wyoming Water Development Commission Meeting. Cheyenne, WY., May 11, 2007. (7) Wyoming Water Development Commission /Select Water Committee Workshop. Cheyenne, WY., June 6, 2007. (8) Wyoming Water Development Commission/Select Water Committee Meetings. Cheyenne, WY., June 7, 2007. (9) Wyoming Water Association, Summer Meeting and Tour (High Savery Dam, CBM). Carbon County, WY., July 12-13, 2007. (10) UW Water Research Program Meeting. WRP Priority and Selection Committee to select research priorities. Cheyenne, WY., July 24, 2007. (11) Four States Irrigation Council summer tour. North Platte River System (Wyoming to Nebraska), July 30 August 1, 2007. (12) Wyoming Weather Modification Technical Advisory Team Meeting, Cheyenne, WY., October 16, 2007. (13) Wyoming Water Association Board Meeting (Advisor), Cheyenne, WY., October 30, 2007. (14) Wyoming Water Association, Education Seminar and Annual Meeting. Cheyenne, WY., October 31 - November 2, 2007. (15) Wyoming Water Association Board Meeting (Advisor), Cheyenne, WY., November 26-27, 2007. (16) UW Water Research Program Meeting. WRP Priority and Selection Committee to select research projects. Cheyenne, WY., November 29, 2007. (17) Wyoming Water Development Commission Workshop. Cheyenne, WY., December 5, 2007.

Director Presentations: (1) Office of Water Programs and Wyoming Water Research Program, present annual report. Wyoming Water Development Commission. Cheyenne, WY., January 12, 2007. (2) Office of Water Programs and Wyoming Water Research Program, present annual report. Legislative-Select Water Committee. Cheyenne, WY., January 13, 2007. (3) Wyoming Legislative Water Law Workshop, Present UW Water Research, Cheyenne, WY, Jan 8, 2007. (4) Legislative Meeting-Advisor to the

Wyoming Water Association, UW Office of Water Programs Report. Cheyenne, WY., January 10, 2007. (5) Wyoming Weather Modification Technical Advisory Team Meeting, Presentation on the Water Research Program and Wind River Glaciers. Cheyenne, WY., January 18, 2007. (6) Legislative Reception and Presentation on Wyoming Water. Cheyenne, WY., February 7, 2007. (7) Wyoming Water Forum, Report on the Water Research Program. Cheyenne, WY., March 6, 2007. (8) Wyoming Joint Ag Committee. Presentation on research for the Wind River Glaciers. Laramie, WY., April 23, 2007. (9) Snake River User's Group, Presentation on research for the Wind River Glaciers. Jackson Hole, WY., May 16, 2007. (10) Wyoming Weather Modification Technical Advisory Team Meeting, Presentation on research for the Wind River Glaciers. Lander, WY., May 23-24, 2007. (11)Tootle, G., G. Kerr, K. Cheesbrough, J. Edmunds and L. Pochop, 2007. Glacial Change in the Wind River Range. Presentation at International Commission on Snow and Ice Hydrology (ICSIH) Glaciers in Watershed and Global Hydrology Workshop, August 27-31, 2007, Obergurgl, Austria., Presented by Kerr. (12) Wyoming Water Development Commission/Select Water Committee Meetings. Presentation on Office of Water Programs, Wyoming Water Research Program. Casper, WY., November 7 - 9, 2007. (13) Wyoming Water Development Commission/Select Water Committee Meetings. Presentation on Office of Water Programs, Wyoming Water Research Program. Cheyenne, WY., December 6 - 7, 2007.

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

Project: Predicting Drought in the Green River Basin. In addition to the national presentations listed below, local presentations were made to the Wyoming State Engineer's Water Forum and the University of Wyoming Graduate Seminars. (1) Bellamy, J., G. Tootle, G. Kerr and L. Pochop, 2008. Frequency and Duration of Drought in the Green River Basin, WY, USA. Presentation at ASCE World Water & Environmental Resources Congress 2008, May 11-17, 2008, Honolulu, HI. (2) Bellamy, J. and G. Tootle, 2008. Frequency, Duration and Risk Assessment of Drought in the Upper Green River Basin, Wyoming. Presentation at American Geophysical Union (AGU) Hydrology Days, March 26-28, 2008, Fort Collins, Colorado. (3) Barnett, F.A., T. Watson, S. Gray and G. Tootle, 2007. Streamflow Reconstructions and Periods of Drought in the Upper Green River Basin, Wyoming, USA. American Geophysical Union (AGU) Fall Meeting, December 10-14, 2007, San Francisco, California. (4) Tootle, G.A., T. Hunter and T.C. Piechota, 2006. Pacific Oceanic / Atmospheric Variability and the Wind River Range. Presentation at ASCE World Water & Environmental Resources Congress 2006, May 21-25, 2006, Omaha, NE. (5) Hunter, T. and G.A. Tootle, 2006. Oceanic-Atmospheric Variability and Western Snowfall. Presentation at American Geophysical Union (AGU) Hydrology Days, March 20-22, 2006, Fort Collins, Colorado.

Project: Precipitation Measurement and Growth Mechanisms in Orographic Wyoming Snowstorms. Presentations with Abstracts: Geerts, B., J.R.Snider, G.Vali, and D.Leon, Orographic precipitation enhancement by boundary-layer turbulence: a vertically pointing airborne cloud radar view, 13th Conference on Mountain Meteorology, Whistler, British Columbia, 2008. Wolfe, J.P., J.R.Snider and B.Geerts, Development of a temperature-dependent radar reflectivity to snowrate relationship for the S-band, 15th International Conference on Clouds and Precipitation, Cancun, Mexico, 2008. 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. and G. Vali, Impact of surface interaction and cloud seeding on orographic snowfall: A downlooking airborne cloud radar view, Oral presentation at the 17th AMS/WMA Symposium on Planned & Inadvertent Weather Modification, Westminster, CO, 2008.

Project: Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming Using the Wyoming Cloud Radar. Presentations with abstracts: Andretta, T., and B. Geerts, Snowfall in mountain lee convergence zones: a case study. 13th Conference on Mountain Meteorology, Whistler, BC, 1115 August 2008. Geerts, B., Impact of surface interaction and cloud seeding on orographic snowfall: A downlooking airborne cloud radar view, Oral presentation at the 17th joint American Meteorological Society - Weather Modification Association Symposium on Planned & Inadvertent Weather Modification, Westminster, CO, April 21-25, 2008. Geerts, B., J. Snider, G. Vali, and D. Leon, Orographic precipitation enhancement by boundary-layer turbulence: a vertically pointing airborne cloud radar view, 13th Conference on Mountain Meteorology, Whistler, BC, 1115 August 2008. Vali, G., B. Geerts, J. Snider, and D. Leon, Surface source of ice particles in mountain clouds, 15th International Conference on Clouds and Precipitation (ICCP), Cancun, Mexico, 7-11 July, 2008. Presentations 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 Lander (May 07), in Cheyenne (October 07), and in Cheyenne (Feb 08).

Project: Weather Modification Impacts and Forecasting of Streamflow. Two of the graduate students working on the project have been invited to present the results of their research at the American Society of Civil Engineers (ASCE) Environmental Water Resources Institute (EWRI) Conference in May 2008. Additionally, they have made local presentations at the WY State Engineer's Water Forum and the University of Wyoming Graduate Seminars.

Previous Projects: Project: Subsurface Drip Irrigation Systems: Assessment and Development of Best Management Practices. George F. Vance, Subsurface Drip Irrigation of Alfalfa, W1128 Regional Research Committee on Reducing Barriers to Adoption of miccroirrigation, Honolulu, HI. October 2007. Project: Land Use Impacts on Nitrogen Fixation in Jackson Hole Streams. Lisa Kunza (Neerhof), a Ph.D. student, presented a talk entitled The Contribution of Nitrogen Fixation to Nitrogen Cycling in Ditch Creek, WY throughout the Summer Season at the national meeting of the North American Benthological Society in June 2007. Project: Geochemistry of CBM Retention Ponds Across the Powder River Basin, Wyoming. Vance, G.F., H.T. Zhao, M.A. Urynowicz, G.K. Ganjegunte and R.W. Gregory, Potential utilization of natural zeolites for treating coalbed natural gas (CBNG) produced waters: Batch and column studies, Presented at the 2007 National Meeting of the American Society of Mining and Reclamation, Gillette, WY, June 2-7, 2007. R.I. Barnhisel (Ed.) Published by ASMR, 2134 Montavesta Rd., Lexington, KY 40502. 8 pp.

Student Support

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	2	0	0	0	2
Masters	13	0	0	0	13
Ph.D.	3	0	0	0	3
Post-Doc.	2	0	0	0	2
Total	20	0	0	0	20

Notable Awards and Achievements

Publications from Prior Projects