Wyoming Water Research Program
Annual Technical Report
FY 2010

Introduction

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

State support for the WRP includes direct funding through the WWDC and active State participation in identifying research needs and project selection and oversight. Primary participants in the WRP are the USGS, the WWDC, and the University of Wyoming. A Priority and Selection Committee (P&S Committee), consisting of representatives from agencies involved in water related activities in the State, solicits and identifies research needs, selects projects, and reviews and monitors project progress. The Director of the OWP serves as a point of coordination for all activities and serves to encourage research by the University of Wyoming addressing the needs identified by the P&S Committee. The State provides direct WWDC funding for the OWP, which was approved by the 2002 Wyoming Legislature, to identify water related research needs, coordinate research activities, coordinate the Wyoming WRP, and serve as the University advisor to the WWDC.

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

Research Program Introduction

Since inception of the NIWR program in 1965, the Wyoming designated program participant has been the University of Wyoming. Until 1998, the Wyoming NIWR program was housed in the Wyoming Water Resources Center (WWRC). However, in 1998 the WWRC was closed. In late 1999, the Wyoming Water Research Program (WRP) was initiated to oversee the coordination of the Wyoming participation in the NIWR program. The primary purpose of the Wyoming Institute beginning with FY00 has been to identify and support water-related research and education. The WRP supports research and education by existing academic departments rather than performing research in-house. Faculty acquire funding through competitive, peer reviewed proposals. A goal of the WRP is to minimize administrative overhead while maximizing the funding allocated toward water-related research and training. Another goal of the program is to promote coordination between the University, State, and Federal agency personnel. The WRP provides interaction from all the groups involved rather than being solely a University of Wyoming research program.

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

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

Reports for the following eleven FY10 WRP projects are given herein in the order listed below:

Project 2008WY44B, Final Report: 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 2008 thru Feb 2011.

Project 2009WY46B, Annual Report: Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming II: Further Airborne Cloud Radar and Lidar Measurements, Bart Geerts, Dept of Atmospheric Science, UW, Mar 2009 thru Feb 2012.

Project 2009WY47B, Final Report: Effects of Warm CBM Product Water Discharge on Winter Fluvial and Ice Processes in the Powder River Basin, Robert Ettema, Engineering and Applied Science, and Edward Kempema, Dept of Geology and Geophysics, UW, Mar 2009 thru Feb 2011.

Project 2009WY48B, Final Report: Characterization of Algal Blooms Affecting Wyoming Irrigation Infrastructure: Microbiological Groundwork for Effective Management, Naomi Ward, and Blaire Steven, Dept of Molecular Biology, UW, Mar 2009 thru Feb 2011.

Project 2010WY54B, Final Report: Is the Muddy Creek Food Web Affected by Coalbed Natural Gas Inputs?, Lusha Tronstad, Research Scientist, and Wendy Estes-Zumpf, Research Scientist Wyoming Natural Diversity

Database, UW, Mar 2010 thru Feb 2011.

Project 2010WY56B, Final Report: Using Voluntary Arrangements to Reduce Diversions and Improve Stream Flows for In-channel Benefits in Wyoming, Lawrence J. MacDonnell, Professor of Law, University of Wyoming College of Law, Mar 2010 thru Feb 2011.

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

Project 2010WY58B, Annual Report: Development of GIS-based Tools and High-Resolution Mapping for Consumptive Water Use for the State of Wyoming, Gi-Hyeon Park, Assistant Prof. and Mohan Reddy Junna, Prof., Dept. of Civil and Architectural Engineering, UW, Mar 2010 thru Feb 2012.

Project 2010WY59B, Annual Report: Treatment of High-Sulfate Water used for Livestock Production Systems, Kristi M. Cammack, Ph.D., Assistant Professor, and Kathy J. Austin, M.S., Senior Research Scientist, Dept. of Animal Science, UW, and Ken C. Olson, Associate Professor, West River Ag Center, South Dakota State University, Rapid City, SD, and Cody L. Wright, Associate Prof., Dept. of Animal and Range Sciences, South Dakota State University, Brookings, SD, Mar 2010 thru Feb 2012.

Project 2010Wy60B, Annual Report: Multi-Century Droughts in Wyomings Headwaters: Evidence from Lake Sediments, Bryan N. Shuman, Associate Prof., Dept. of Geology & Geophysics, Jacqueline J. Shinker, Assistant Prof., Dept. of Geography, Thomas A. Minckley, Assistant Prof., Dept. of Botany, UW, Mar 2010 thru Feb 2013.

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

Water Quality Criteria for Wyoming Livestock and Wildlife

Basic Information

Title:	Water Quality Criteria for Wyoming Livestock and Wildlife
Project Number:	2008WY44B
Start Date:	3/1/2008
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Water Quality, Water Supply, Agriculture
Descriptors:	Water Quality, Animal Health, Livestock, Wildlife
Principal Investigators:	Merl Raisbeck, Michael A. Smith, Cynthia Tate

Publications

1. Raisbeck, M. F., S. Riker, B. Wise, R. Jackson, 2010. Safety of produced water for livestock and wildlife, In Coalbed Natural Gas: Energy and Environment (ed. Reddy, KJ), Nova Science Publishers, Haupage, NY, pp 81-120.
2. Wise, B., 2011. Water Quality for Wyoming Livestock and Wildlife. MS thesis in ANVS and ENR, University of Wyoming.

Water Quality Criteria for Wyoming Livestock and Wildlife
Final Report

M. F. Raisbeck[1], B. Wise[1], J. Zygmunt[2], M. Smith[3] and C. Tate[4]
[1]Dept Veterinary Sciences, University of Wyoming
[2]Wyoming Dept Environmental Quality
[3]Dept Renewable Resources, University of Wyoming
[4]Wyoming Dept Game and Fish
Duration: 3/1/2009 - 2/28/2011

Abstract

Water is arguably *the* most essential nutrient for terrestrial animals. Thus, it isn't surprising that water quality plays a significant role in animal health and productivity. Never in great supply, high quality water for livestock and wildlife is becoming scarcer as the result of competition by mineral development and urbanization. While animals can, and often do, subsist upon less-than-perfect drinking water such as that produced by oil and gas development ("produced water"), there are tradeoffs with health and productivity. Water quality standards, as promulgated by various educational and regulatory agencies, are often based upon science that is several decades old. It is not that the data don't exist, but rather that they haven't been compiled into any sort of useful, user-friendly summary or, in some cases, mineral production has itself created new questions (e.g. chronic toxicity of water-borne barium to ruminants) that never had to be answered before.

Our group recently completed a literature review of several water quality elements important to domestic livestock and large mammalian wildlife for the Wyoming Department of Environmental Quality (Raisbeck *et al.*, 2007), which has since been released as UW Agricultural Experiment Station Bulletin #1183. The present project expands the previous effort to include other elements, such as iron and uranium, which are of future potential interest as they occur naturally in Western waters and are extremely toxic. Our objective to provide a summary of the current knowledge base that is both simple enough for laymen to use, and comprehensive enough to permit sound decision making by experts.

Methodology

Our methodology was fairly simple, if laborious. Older (roughly pre-1990) scientific literature reviews were obtained to validate the previous state of the art re: the toxicity of a given element in our species of interest (cattle, sheep, horses, antelope, deer and elk). After these documents were digested, a search was conducted for detailed, primary sources via biological literature databases such as Medline, Biosis and CAB. These papers were reviewed, evaluated for applicability and reliability, and summarized in our database. Then, the better papers were used as a basis for reversed (e.g. citation) searches and the process repeated. As the amount of information available from conventional sources was frequently inadequate, we also contacted regional animal health agencies for unpublished data such as diagnostic case reports or game and fish studies.

As noted previously, each report was rated for applicability (i.e. route of administration, class of animal, and chemical form of the toxicant) to what is found in Wyoming and reliability (adequate controls and sufficient numbers of animals to support conclusions, etc.). Controlled experimental studies were normally given more weight than case reports; however, this rule was tempered by common sense and the professional expertise of our team. For example, an experiment concluding "no effects" based upon n=3 animals exposed is obviously less credible than a case report documenting a 5% mortality among 200 head exposed to the same substance and dose. If there was *no* quantitative data in our species of interest, we extrapolated from species for which there are data. Such extrapolations were based upon the known comparative physiology of the various species and are detailed in the final report.

Principle Findings and Significance

Boron - There is almost no experimental, and very little clinical, data regarding poisoning by water-borne boron (B) in ungulates. In areas where better quality (low B) water is available, most species will avoid water containing potentially toxic concentrations of B. There is insufficient data to name a safe upper limit for acute, non-toxic, exposure (an acute NOAEL), but it is probably in excess of 200 mg/L. Chronic effects, mainly decreased productivity, should not occur below 50 mg/L.

Cadmium – The biggest economic risk associated with cadmium (Cd) contamination of livestock water is illegal Cd residues in edible livestock products (e.g. meat). This is because Cd has a very long biological half-life and tends to accumulate indefinitely in edible tissues, especially kidney of exposed animals. We calculate (see full text for assumptions) that lifetime exposure to 0.03 mg Cd/L drinking water would result in violative residues and condemnation of the carcass. By contrast, the literature indicates that concentrations greater than 10 mg/L would be required to produce toxic effects in livestock species.

Chromium – The toxicity of chromium (Cr) depends upon its valence, with hexavalent Cr being much more toxic than trivalent Cr; however, hexavalent Cr is relatively rare in natural surface waters. Hexavalent Cr is also reduced to trivalent Cr by the ruminant GI tract, unless the dose is large enough to overwhelm this capacity. That said, hexavalent Cr *does* occasionally occur in natural waters, and, in the absence of any convenient way of predicting which is going to occur in a particular pond or stream, we opted to base recommendations upon the more toxic hexavalent form. Chronic health effects should not occur in our species of interest at concentrations less than 5 mg Cd/L.

Copper – Sheep are the domestic species most sensitive to copper (Cu). Cattle are less sensitive, but consume more water per unit of body weight, thus the calculated hazardous drinking water Cu concentrations are similar for these species. Dietary (feedstuffs) Cu also contributes to the total dose received by any animal, and must be factored into any estimation of potential hazard. The NOAEL calculated for sheep and cattle, assuming typical Wyoming forage concentrations of 7 ppm, were 4.5 and 4.125 mg Cu/L, respectively. The lack of reported Cu intoxication in large mammalian wildlife or horses suggests that such is relatively rare. Extrapolation from the comparative physiology between these species supports the notion that recommendations based upon cattle and sheep will provide adequate protection for elk, pronghorn, etc. and horses. Thus, we recommend a maximum concentration of no more than 4 mg Cu/L.

Lead – Lead (Pb) is also a residue concern. At present there are no *fixed* tolerance limits for Pb in human foodstuffs, such as meat, in the US, thus we used the WHO reference dose of 25 μg Pb/kg BW/week and a BTF for kidney to calculate residue-driven limits for various tissues. While it is possible that exposure to 20 mg/L would produce violative residues in kidney, the accumulation in red meat is sufficiently low that overt toxicity would likely occur in the animal before residue limits were exceeded. Calculations based upon nervous damage in the most sensitive receptor, lambs, suggest that Pb concentrations should be kept less than 3 mg/L.

Mercury – Like Cd, the biggest risk from mercury (Hg) exposure is condemnation as a result of Hg accumulation in edible tissues with potential human exposure. Unlike Cd, the chemical form of Hg determines both its short term toxicity and its accumulation in animal tissues. Ideally, we would have preferred to establish limits for each of the three major forms of Hg; however these forms are somewhat interchangeable in the aquatic environment, thus we opted to base recommendations upon the most toxic form, methyl Hg. Based upon residue considerations outlined in the thesis, concentrations greater than 0.24 mg/L are economically hazardous. Critical readers will note that this recommendation is noticeably higher than the 1972 NAS recommendation. The difference is that the latter were based upon the amounts found in useable waters at the time of the report, and not upon animal data. Given the emphasis of various regulatory agencies on Hg in the food chain, it may well be that our upper tolerance limit will need to be re-evaluated in the future.

Uranium – There is a serious paucity of data on uranium (U) in large animals of any sort. Extrapolating from rodent and human data suggests an temporary upper limit of exposure of 0.065 mg/L/day for our species of interest until better data becomes available. Given the resurgence of nuclear power, and the importance of Wyoming as a source of U, this is an area that urgently needs further study.

Zinc - Zinc (Zn) intoxication from drinking water appears to be unlikely as the concentrations required to produce poisoning are substantially higher than those which induce refusal under experimental conditions. Pregnant sheep seem to be the most sensitive receptor to Zn, and we calculated a maximum tolerance concentration of 70 mg/L for them. Non-pregnant sheep and other species should be protected by 100 mg/L.

Publications & Presentations

M. F. Raisbeck: Water quality for animals. Some theoretical considerations. Wyoming VMA meeting, Laramie, WY, 6/14/08.

M. F. Raisbeck: Water quality for animals. Wyoming Environmental Quality Council, Laramie, WY, 11/23/08.

M. F. Raisbeck: Water quality for Wyoming Livestock and Wildlife. CLE, Int’l, Wyoming Water Law, Cheyenne, WY 4/17/09.

B. Wise and M. F. Raisbeck: Water quality for livestock and wildlife. RMSETAC Denver, CO, 4/24/2009.

B. Wise and M. F. Raisbeck: Water quality for Wyoming Livestock and Wildlife. Soc Toxicol annual meeting, Salt Lake City, 3/9/10.

B. Wise and M. F. Raisbeck: Water quality for Wyoming Livestock and Wildlife. RMSETAC, Denver, CO, 4/15/10.

B. Wise: Water Quality for Wyoming Livestock and Wildlife. MS thesis, UW (attached).

M. F. Raisbeck, B. Wise, J. Zygmunt, M. Smith and C. Tate (in peer review April, 2011): Water Quality for Wyoming Livestock and Wildlife, vol II. UW AES Bulletin.

Student support & training

Undergraduate

Kaitlin McDaniel, currently a graduate student in molecular toxicology at Pennsylvania State University.

Graduate

Ben Wise, MS in ANVS and ENR, currently seeking employment in the water quality with various state and federal agencies.

Rebecca Morris, PhD (partial support), currently employed by CBM Associates.

Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming II: Further Airborne Cloud Radar and Lidar Measurements

Basic Information

Title:	Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming II: Further Airborne Cloud Radar and Lidar Measurements
Project Number:	2009WY46B
Start Date:	3/1/2009
End Date:	2/29/2012
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Water Quantity, Climatological Processes, Hydrology
Descriptors:	Weather modification, Cloud radar, Aircraft measurements
Principal Investigators:	Bart Geerts

Publications

1. Geerts, B. and Q. Miao, 2010. Vertically-pointing airborne Doppler radar observations of Kelvin-Helmholtz billows, Monthly Weather Review, 138, 982-986.
2. Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010. An airborne profiling radar study of the impact of glaciogenic cloud seeding on snowfall from winter orographic clouds. J. Atmos. Sci., 67, 3286 3302.
3. Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010. The impact of glaciogenic seeding on orographic cloud processes: preliminary results from the Wyoming Weather Modification Pilot Project. J. Weather Mod., 42, 105-107.

Detecting the signature of glaciogenic cloud seeding in orographic snowstorms in Wyoming II: Further airborne cloud radar and lidar measurements

Year 2 report

(for a three-year project: Mar 2009 – Feb 2012)

U. S. Geological Survey and the Wyoming Water Development Commission grant

Dr. Bart Geerts, PI

4/25/2011

1. Abstract

This proposal (referred to as Cloud Seeding II) called for two 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 (WWMPP). This pilot project, administered by WWDC and contracted to the National Center for Atmospheric research (NCAR) and Weather Modification Inc (WMI), involved seeding from a series of silver iodide (AgI) generators located in the Snowy Range. The flights were conducted on 3/25 and 3/30 2009. A previous grant from the UW Office of Water programs, referred to as Cloud Seeding I, supported five WKA flights, flown in Feb 2008 and in Feb-Mar 2009. All seven flights were a success in terms of both the target weather conditions and instrument performance.

2. Summary of the field work

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

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

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

No less than 4 graduate students participated in the field campaign, although only one graduate student (Yang Yang) is focusing her MSc research on the data from these five flights.

The seven cases have been used to construct composites of radar data and flight-level data, in order to tease out the effect of AgI seeding on cloud processes and snowfall. In all cases the static stability was rather low, and the wind speed strong, such that (a) boundary-layer turbulence effectively mixed tracers over a depth of at least 1 km, and sometimes above flight level (2,000 ft above the Med Bow Peak) up to cloud top, and (b) the Froude number exceeded one and thus the flow went over (rather than around) the mountain range.

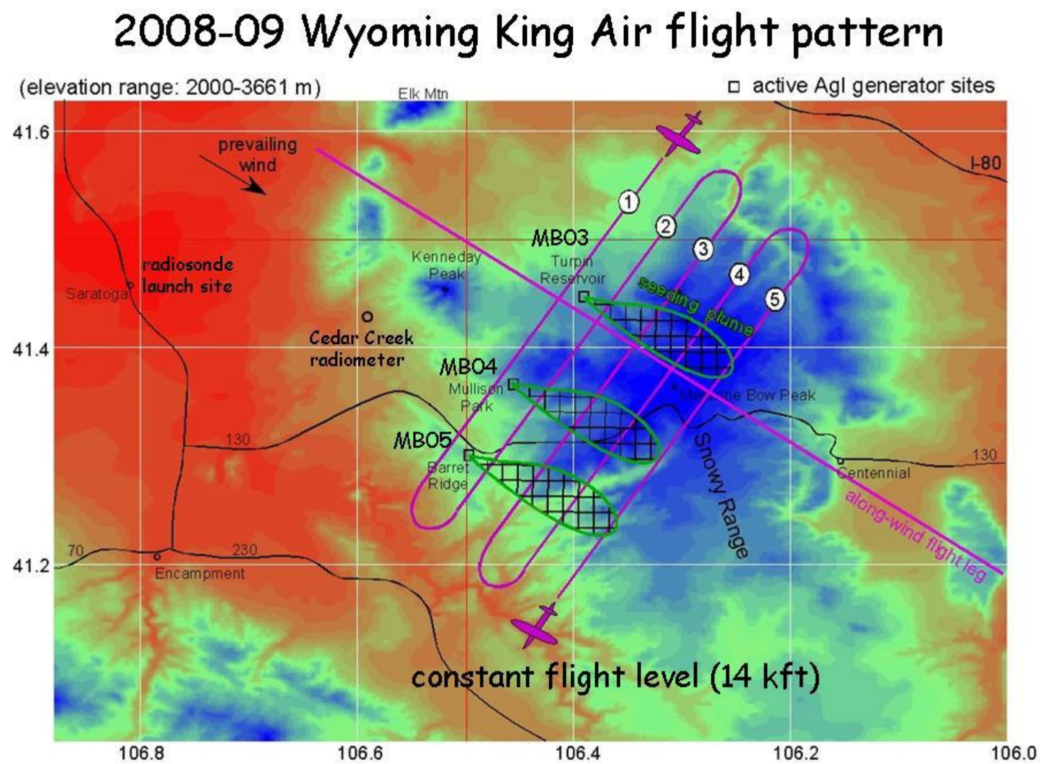

Fig. 1. A schematic of the WKA flight legs in the Snowy Range, over the AgI plumes (shown schematically with a green outline) released from three generators on the ground. The color background field shows the terrain. On all flights the flight level was set at 4,276 m (14,000 ft) MSL. The prevailing wind was from the NW. One flight leg was across the terrain (along the wind), the other 5 flight legs were roughly across the winds at various distances downstream of the three active AgI sources.

3. Objectives and methodology

The key objective is to examine the impact of cloud seeding on radar reflectivity between the AgI generators and the slopes of the target mountain. To do this, a composite of reflectivity for seed and no-seed conditions for all downstream flight legs along the wind needs to be built. And it needs to be ascertained that the observed differences in composites is both statistically significant and not attributable to differences in vertical air velocity.

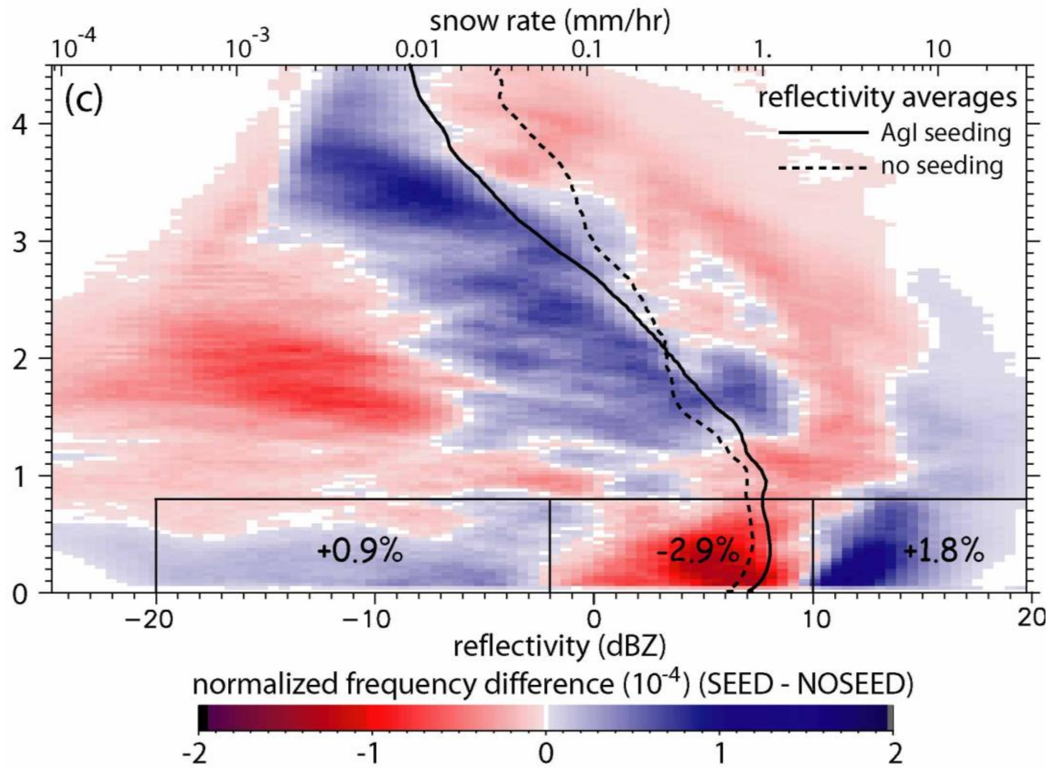

Fig. 2: Normalized frequency by altitude (FAD) of the difference in WCR reflectivity during seed and no-seed conditions. Also shown are cumulative normalized frequency differences (seed minus no-seed) in three boxes near the ground, expressed as a percentage, and the mean reflectivity profile during seed and no-seed conditions. The snow rate (S) shown in the upper abscissa is inferred from S=0.11 $Z^{1.25}$ (Matrosov 2007).

4. Principal findings

In Feb 2010 a paper was submitted to *J. Atmos. Sci.* (Geerts et al. 2010), the most prestigious journal in its field. This paper is still in review, but the reviewers' comments are relatively minor, so we are confident that it will be accepted. In April 2010, Geerts was an invited keynote speaker at the Annual Weather Modification Association meeting in Santa Fe NM. In that talk, he presented the main findings of the *J. Atmos. Sci.* paper.

Our ongoing study provides experimental evidence from vertically-pointing airborne radar data, collected on seven flights (Table 1), that ground-based AgI seeding can significantly increase radar reflectivity within the PBL in shallow orographic snow storms. Theory and a comparison between flight-level snow rate and near-flight-level radar reflectivity indicate a ~25% increase in surface snow rate during seeding (**Fig. 2**), notwithstanding slightly stronger updrafts found on average during no-seeding periods. The partitioning of the dataset based on atmospheric stability and proximity to the generators yields physically meaningful patterns and strengthens the evidence.

Firstly, the AgI seeding signature is stronger and occurs over a greater depth on the less stable days than on the three more stable days. Secondly, it is stronger for the two legs close to the generators than for the two distant legs. A random resampling of all flight passes irrespective of seeding action indicates that the observed enhancement of high reflectivity values (>10 dBZ) in the PBL during AgI seeding has a mere 2.2% probability of being entirely by chance (**Fig. 3**).

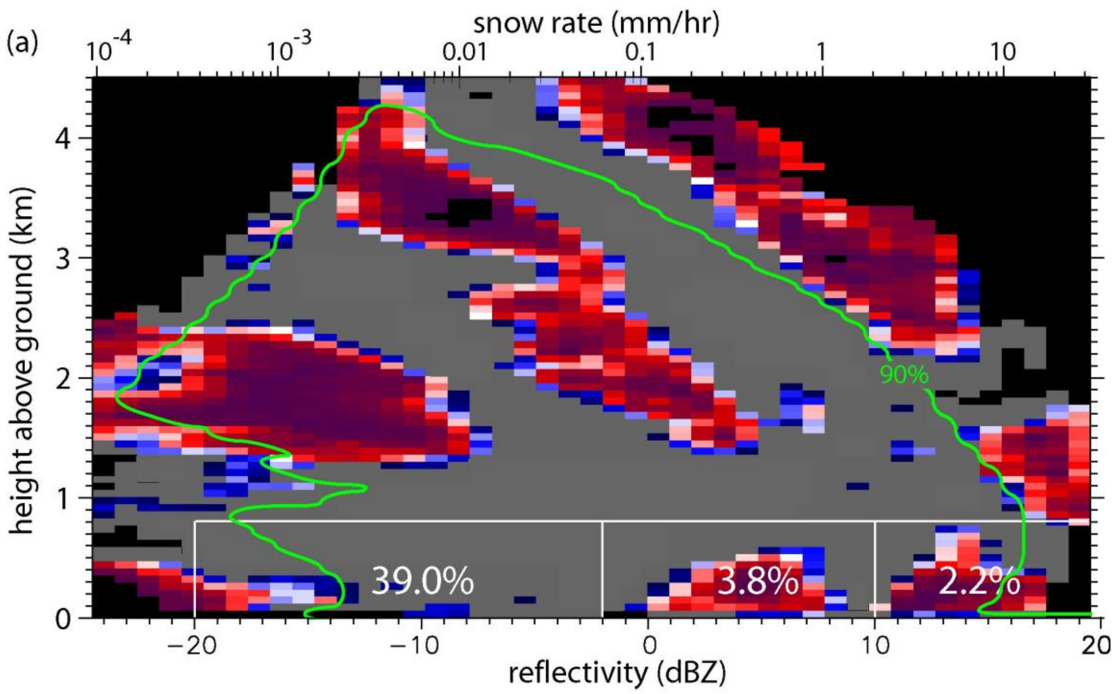

Fig. 3: Percentage of differences between randomly selected subgroups that exceeds the observed seed minus no-seed difference in WCR reflectivity (shown in Fig. 2). The white numbers show the same, not at the bin level but within the same boxes as in Fig. 2. In the grey areas there is a more than 10% probability that the seed minus no-seed difference is by chance. The green contour comprises 90% of the cumulative data frequency.

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

5. Further plans

So far we conducted seven flights over the Snowy Range, five funded under Cloud Seeding I and two under this grant (Cloud Seeding II). Following the review of the *J. Atmos Sci.* paper (Geerts et al. 2010), we are preparing a paper dealing with the importance of PBL turbulence on orographic precipitation (Geerts et al. 2011), and another paper further exploring seeded cloud properties with flight-level data (Yang et al. 2011).

We also have two other orographic precipitation studies planned. First, Dr. Geerts is the PI of the SOLPIN component of the current University of Wyoming NSF EPSCoR proposal, called "Earth System Interactions in Complex Terrain". The SOLPIN (Simulations and Observations of Land-Precipitation Interactions) component is worth about $6 million, plus $2 million in UW matching. If funded, then both winter and summer orographic precipitation will be studied, using experimental data and numerical simulations.

Second, Dr. Geerts is the PI in a proposal, known as ASCII (AgI Seeding of Cloud Impact Investigation), funded by the National Science Foundation. This grant is a collaboration with NCAR (Rasmussen, Breed, Xue). The USGS/WWDC-funded field work and data analysis (esp. Geerts et al. 2010, in *J. Atmos. Sci.*) were instrumental in the success of this grant of $493,320 entitled "The cloud microphysical effects of ground-based glaciogenic seeding of orographic clouds: new observational and modeling tools to study an old problem" (Aug 2011 – Jul 2014; reference: AGS-1058426). ACII will be conducted in the Sierra Madre (**Fig. 4**) between 4 Jan and 4 March 2012, in the context of the WWMPP, which will be in its last year. The emphasis here is on the cloud microphysical effects of glaciogenic seeding in cold orographic clouds.

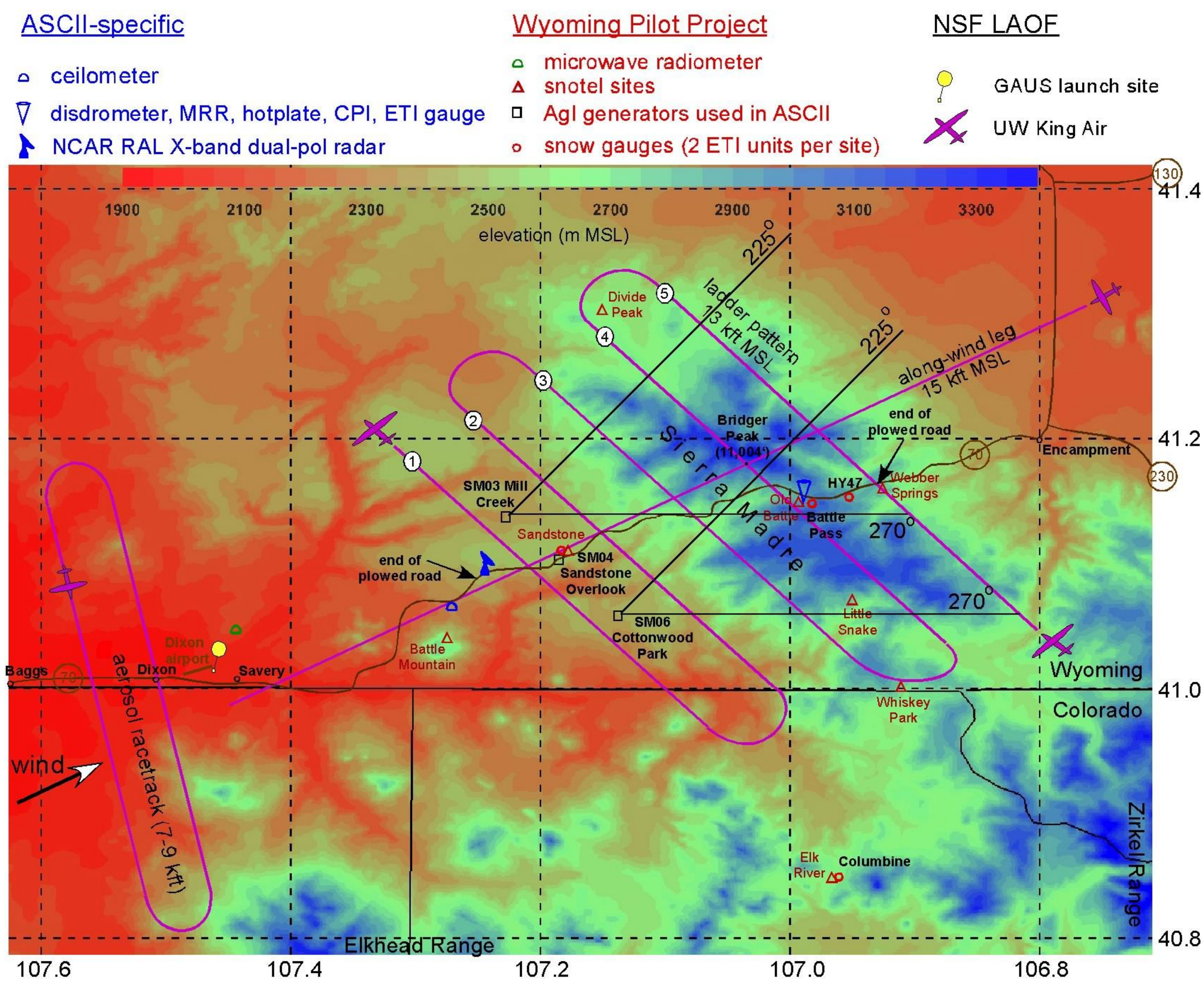

Fig. 4: *A schematic of the experimental design of the ASCII campaign in early 2012 over the Sierra Madre in southern Wyoming. WKA flight legs are shown as in Fig. 1.*

6. Significance

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

7. Peer-reviewed publications

Geerts, B. and Q. Miao, 2010: Vertically-pointing airborne Doppler radar observations of Kelvin–Helmholtz billows. *Mon. Wea. Rev.*, **138**, 982–986.

Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010: An airborne profiling radar study of the impact of glaciogenic cloud seeding on snowfall from winter orographic clouds. *J. Atmos. Sci.*, **67**, 3286–3302.

Geerts, B., Q. Miao, Y. Yang, R. Rasmussen, and D. Breed, 2010: The impact of glaciogenic seeding on orographic cloud processes: preliminary results from the Wyoming Weather Modification Pilot Project. *J. Weather Mod.*, **42**, 105-107.

Geerts, B., Q. Miao, and Y. Yang, 2011: Boundary-layer turbulence and orographic precipitation growth in cold clouds: evidence from profiling airborne radar data. J. Atmos. Sci., accepted.

Yang, Y., B. Geerts and Q. Miao, 2011: The impact of glaciogenic cloud seeding on winter orographic clouds, based on vertically-pointing airborne Doppler radar data and flight-level data. *J. Appl. Meteor. Climat.*, in preparation.

8. Presentations supported by the Grant

Cloud seeding: Dr. Geerts gave an oral presentation at the 2010 Annual Meeting of the Weather Modification Association and the North American Interstate Weather Modification Council (Santa Fe, NM, April 2010). We also continue to give regular research updates at the WWMPP Technical Advisory Team (TAT) meetings, in Lander (typically in July) and in Cheyenne (typically in January), at the WWMPP Ground School (typically in November), and in 2011 also at the WWMPP seasonal debriefing meeting in mid-April. And we have provided the WWMPP team with material for use in their presentations at meetings of the Select Water Committee, a group of Wyoming state senators and representatives, in the context of updates and further funding requests.

PBL turbulence and orographic precipitation: Dr. Geerts gave talks on the importance of PBL turbulence on the growth of snow particles over mountains at the 19th AMS Conf. on Boundary Layer Processes and Turbulence, Keystone CO (2-6 August 2010), the 10th Annual Meeting of the European Meteorological Society, Zurich, Switzerland (13-17 Sept), and the UW Department of Atmospheric Science seminar on 11/23/2010.

9. Dissertations/theses

No USGS/WWDC graduate students have graduated yet. Ms. Yang Yang (MSc) will defend her thesis later this year. I have 3 new graduate students coming in this summer, to work on the topics of glaciogenic cloud seeding and wintertime orographic precipitation. They are to be funded by the present grant, the NSF grant mentioned above, and the 2-year grant from the WWDC to the Department of Atmospheric Science. They are: Binod Pokharel (PhD), Liran Peng (PhD), Xia Chu (MSc). So while we have been slow graduating graduate students working on this grant, the prospect for graduate student participation and graduation is good.

One post-doctoral scientist, Dr. Qun Miao, has also been partly supported by this grant. He was essential in the data analysis leading to the *J. Atmos. Sci.* paper (Geerts et al. 2010). He left the group in Jan 2010 to assume a faculty position in Ningbo University. He will be back in summer 2011 and during the NSF-supported field campaign as a visiting research scientist

Effects of Warm CBM Product Water Discharge on Winter Fluvial and Ice Processes in the Powder River Basin

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EFFECTS OF CBM WATER DISCHARGE ON WINTER FLUVIAL AND ICE PROCESSES IN THE POWDER RIVER BASIN

Final Report

(For a two-year project: Mar 09 – Feb 11)

Submitted to
The Wyoming Water Research Program,
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and
The United States Geological Survey

by

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Contents

ABSTRACT 4
ACKNOWLEDGMENTS 4
1. INTRODUCTION 6
1.1 Objectives 6
1.2 Ice Formation in Rivers 7
1.3 Powder River Basin Coalbed Methane Production and CBM Product Water 9
1.4 The Powder River 10
2. METHODS 13
3. RESULTS 22
3.1 Winter Water Temperatures and Ice Processes in Tributary Streams 22
3.1.1 Prairie Dog Creek (No CBM Water Flow) 22
3.1.2 Burger Draw (Small Discharge of CBM Water) 24
3.1.3 Beaver Creek (Substantial Flow of CBM Water) 25
3.1.4 Powder River (Recipent of CBM Inflow) 26
4. DISCUSSION 54
4.1 River Ice Effects on Channel Morphology 54
4.2 River Ice and Thermal Effects on Channel Banks 57
4.3 Approaches to Management of CBM Water Discharge 58
4.4 Impact of Open Water on Winter Fluvial and Ice Processes 61
5. CONCLUSIONS AND RECOMMENDATIONS 62
5.1 Conclusions 63
5.2 Recommendations for Further Research 65
6. PUBLICATIONS 66
7. PRESENTATIONS 66
8. STUDENT SUPPORT 66
9. REFERENCES 67
10. APPENDICES 71
10.1 Appendix 1: Powder River Cross Sections, 2010-2011 72
10.2 Appendix 2. Powder River Ice Thickness Profiles 81

ABSTRACT

The potential adverse geochemical impacts of discharging coalbed methane (CBM) product water into stream drainages are well recognized and reasonably well studied. However, not well recognized or understood are the impacts of heat commonly conveyed with CBM product water (pumped from underground coal beds) entering the Powder River and its tributary streams. The present study shows that heat transported with CBM product water has an annual visible impact on the thermal balance of the Powder River during winter. However, the long-term effects on the river and its ecology are unclear. The study, conducted over two winters (2009-2010 and 2010-2011), entailed detailed surveys at two representative sites where CBM water was discharged into the river. Besides adding to river's flow, the most visible influence of CBM water discharged was the frequent formation of lengthy open-water leads extending along a channel bank typically for several kilometers along the river. The observed leads, which persisted throughout the two winters, were three to seven meters in width. An analysis shows that, for constant values of air temperature and CBM water temperature discharged, the surface area of the open-water leads scales with the discharge rate of CBM water. The leads comprised a form of density or buoyancy current flowing in the river, cooling and eventually dissipating when exposed to frigid air. Lead presence altered flow distribution, concentrating flow along the lead, causing modest scour of the bed and, at some locations, accelerating bank erosion. Because the bed at one site scoured down to expose rock, it presently is unclear whether deeper bed scour would have occurred there. The magnitudes of the measured channel changes were determined to be less than those typically caused by spring ice cover breakup and the larger spring flows conveyed by the river. Possible ecological aspects of lead formation are recommended as a topic of further research. The report additionally provides suggestions on how to manage lead formation, should further research on ecological influences indicate that lead extent should be minimized. Lead size can be reduced by several actions that decrease inflow water temperature and promoting greater transverse mixing across the river. In addition, the study provides insights into winter fluvial processes in Wyoming streams.

WRP Focus Category:	Hydrology, geomorphological processes
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1. INTRODUCTION

The recovery of coalbed methane (CBM) requires the removal of groundwater to depressurize the coalbed aquifers. In the Powder River Basin (PRB) large amounts of groundwater are removed from coalbed aquifers during CBM production. These CBM-produced waters, which can be saline and sodic, are discharged into surface impoundments, used for irrigation (if salinity isn't too high), and discharged into perennial and ephemeral streams. Depending on its geochemistry, discharged CBM product water can increase salt content of soils, decrease soil porosity, harm riparian plants and crops, and change the chemistry of surface water features. Because of these potential problems, and the volume of water produced, Powder River CBM product water has been the subject of numerous geochemical studies (e.g., Frost and Brinck, 2005; Frost et al., 2002; Jackson and Reddy, 2007a; Jackson and Reddy, 2007b; Johnson, 2007; Mcbeth et al., 2003; Rice et al., 2002).

In addition to its geochemical load CBM product water carries one further quantity **–** *heat*. Evidently, no prior published work addresses how CBM heat affects fluvial processes in the PRB or similar rivers and streams.

Introducing heat into a stream may disrupt ice formation processes and potentially affect channel stability. This study shows that the continuous heat flux associated with CBM product water discharged into water ways impedes formation of a surface ice cover and changes the winter ice dynamics of the Powder River and its tributary streams. Instead of a more-or-less continuous ice cover, accumulations of frazil and anchor ice may form, causing rapid local changes in flow conditions resulting in flooding, increased bed and bank scour, and possibly adversly affecting winter stream habitat. Frazil ice comprises millimeter-sized discs of ice that form in supercooled, turbulent water. Anchor ice is ice that is attached to, and grows on, the river bottom.

1.1 Objectives

This project's principal objective was to determine if and how heat from CBM product water discharged into PRB streams impacts the winter flow and ice regime in the Powder River and PRB streams. Of practical interest is whether altered ice regimes affect channel stability and winter habitat. The study's results include:

- An overall evaluation of winter flow and ice processes in streams and the Powder River receiving CBM product water;
- Quantitative information including measurements of winter water temperatures along stream reaches with CBM product water discharge;
- Knowledge about frazil and anchor ice formation in the Powder River and similar Wyoming streams.

The project does not provide in-depth documentation of specific biologic impacts of CMB heat discharged into winter streams. Instead it focused on physical processes associated with CBM heat discharge and preliminarily delineated areas where this discharge has potential biological impacts. Such impacts associated with altered ice regimes should be the focus of future studies. The immediate direct need is better understanding of the effects CMB product water discharge exerts on winter flow processes and ice formation.

1.2 Ice Formation in Rivers

For rivers like the Powder River conveying turbulent flows, three different types of ice form as the water column losses heat to the atmosphere and starts freezing (Figure 1.1). The most visible ice type is border ice that grows at the water surface. The second ice type, frazil ice (usually termed frazil), consists of millimeter-sized ice disks that grow while suspended in turbulent, supercooled water (water cooled to below the freezing point). The third ice type, anchor ice, is ice that is attached to river bed. All of these ice types can form simultaneously in a given river reach. The relative abundance of each ice type depends on complex interactions between flow characteristics, heat loss to the atmosphere, number of seed-ice crystals, and bed materials (e.g., Tsang 1982, Ashton 1986).

Anchor ice formation is always associated with frazil formation. Frazil is a prevalent fluvial ice type, readily visible, when large areas of the river are open to the atmosphere (Daly, 1994). Frazil in supercooled water is ”sticky,” and exhibits strong cohesive tendencies between individual ice crystals and between ice crystals and bottom materials (Carstens, 1966). When frazil crystals stick to the bottom, they form initial anchor ice.

Environmental conditions leading to frazil and anchor ice formation have been studied in some detail, with the goal of minimizing the adverse effects of ice on engineering structures (Altberg, 1936; Arden and Wigle, 1972; Barnes, 1928; Daly, 1991; Daly, 1994; Daly and Ettema, 2006; Michel, 1971; Richard and Morse, 2008; Tsang, 1982). Tsang (1982, p.25) succinctly summarizes the conditions leading to frazil and anchor ice formation as: “. . .*requires zero solar radiation heat input, and large heat losses by long wave radiation, evaporation, and convection from a small water body. In common language, one says frazil and anchor ice are likely to form at night when the wind is strong, the humidity of the air is low and the river is at minimum flow, especially if such a night follows a cold, windy and cloudy day.*” Daly (1991) is more quantitative, reporting that frazil formation is associated with air temperatures less than about 6^{o}C, open water, and clear nights. Open water (lack of a surface ice cover) is critical for frazil and anchor ice formation. Daly (1991) states emphatically that frazil cannot form and, by extension, anchor ice will not form, where a continuous, stable ice cover is present. Water supercools at the surface; this supercooled water is mixed downward into the river by turbulence. Frazil crystals are mixed into the water column along with the supercooled water (Hammar and Shen, 1995). Supercooled water cools the riverbed and anything in the water column to below the freezing point. Once the bottom or an object in the flow is colder than the freezing point, frazil will adhere to it (Arden and Wigle, 1972; Daly and Ettema, 2006). This condition is often described as the frazil being "sticky" or "active" (Carstens, 1966; Michel, 1971; Tsang, 1982).

Anchor ice masses can grow to be quite large, covering hundreds of square meter of the riverbed, and stick tenaciously to the bottom for as long as the water remains supercooled. These large anchor-ice accumulations raise stage locally. In extreme cases, anchor-ice masses build up to the river surface, creating anchor-ice dams (Kempema and Konrad, 2004) that can create significant backwaters. Usually, incoming solar radiation during daylight hours warms the river water to the freezing point in the morning. When this occurs, anchor ice releases from the bottom and floats to the surface (Arden, 1970; Arden and Wigle, 1972; Wigle, 1970) carrying entrained sediment that can potentially be ice rafted long distances downstream (Kempema and Ettema, 2010). Although frazil ice usually forms at night, when weather conditions are particularly severe frazil can form in the water column at any time of the day, and anchor ice accumulations can stick to the bottom for several days (Daly and Ettema, 2006; Stickler and Alfredsen, 2009).

Fluvial anchor-ice formation depends on a number of factors working in combination (Kempema et al., 2008; Stickler and Alfredsen, 2009). The factors determine when and where anchor ice will form along a river reach, and can be grouped into three broad categories: heat flux from the water to the atmosphere; characteristics influencing flow mixing: channel morphology, gradient, bed material, water depth, and current velocity; and the availability of seed ice particles.

There is a consensus in the literature, extending back to Barnes (1906), that supercooling of the water column is necessary for the formation of "sticky" frazil ice and subsequent anchor ice formation. There is also a broad, though vague, consensus on the stream characteristics where anchor ice forms. Anchor ice forms in highly turbulent riffles (Tsang, 1982) on gravel or coarser beds (Arden and Wigle, 1972; Gilfilian et al., 1972; Tsang, 1982; Wigle, 1970). This consensus does not adequately delineate the details of flow associated with observed anchor ice. For example, Terada et al. (1999) studied anchor ice formation in a Hokkaido stream with water depths varying from 30 to 60cm. Anchor ice was hardly observed in the deeper portions of the stream, leading Terada et al. to conclude that flow depth was one of the controlling parameters for anchor ice formation. In contrast, Altberg (1936) reported a 1m-thick anchor ice accumulation at 20m depth in the Neva River. Similarly, reported limiting minimum water velocities for anchor ice formation range from $0.1 ms^{-1}$ (Stickler and Alfredsen, 2009) to $0.7 ms^{-1}$ (Hirayama et al., 2002). Stickler and Alfredsen (2009) discuss the range of values of stream characteristics associated with anchor ice formation. They conclude that anchor ice has a wider spatial distribution (in terms of stream characteristics) than previously recognized. Bisaillon and Bergeron (2009) modeled the presence/absence of anchor ice on three gravel-bed rivers in

Quebec. They found that water had to be supercooled for anchor ice production, and that fast and shallow conditions (as expressed by a Froude number[1]) favor anchor ice formation. In summary, the various observations about flow velocity and depth, and bed conditions, actually express information about mixing within the flow. Accordingly, conditions leading to anchor ice formation are best expressed in terms of parameters characterizing flow mixing (Kempema and Ettema, 2010.

Eventually, released anchor ice and frazil agglomerate and rise through the water column, forming drifting slush whose surface freezes over when exposed to the frigid air (Figure 1.1); a phenomenon frequently observed in the Powder River. As the consolidating slush drifts it accumulates as ice masses covering the channel which gradually freezes over. In sufficiently low velocity flows, drifting ice masses accumulate, along with border ice, to form a more-or-less uniform cover that thickens by thermal ice growth. In swifter flows, ice accumulates as non-uniform formations termed freeze-up jams and hanging dams, which develop under ice covers (Beltaos, 1995).

Stream flows shallower than the potential thickness of a thermally grown ice cover, and of low unit discharge (flow rate per unit width of channel), may become largely blocked by ice that extends down to the channel bed. The blocked flow then seeps over and freezes as laminations of ice (aufeis) on the ice cover. The resulting spreading and thickening ice growths are called aufeis formations. Aufeis formations commonly grow in areas of relatively steep topography (Carey, 1973; Harden et al., 1977; Kane, 1981), including steep streams feeding into the Powder River. Once formed, aufeis formations are notably resistant to decay and break-up, because they rest on the channel bottom, and usually are thick and strong. Spring and summer flows passing over aufeis formations erode down through them, exposing the channel bed, fragmenting the formations, and eventually washing them from the channel. During cooler and drier summers at some locations, aufeis formations may persist for more than a year. Aufeis presence retards flow, usually dispersing it laterally.

1.3 Powder River Basin Coalbed Methane Production and CBM Product Water

The Powder River Basin is known for its coal deposits, and indeed the basin is the largest coal mining region in the United States, though most of the coal is buried too deeply to be economically accessible. The region produces forty percent of the United States coal production. In 2007, Powder River Basin coal production was 436 million tons of coal, more than twice as much as the next largest coal region (Reddy, 2005). Coal production is an important commercial activity in the region. Because large extents of Powder River Basin coal beds are located at great depths challenging to physical excavation of the coal considerable attention is given to utilizing the coal by means of extracting its methane as CBM.

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[1] The Froude number is a dimensionless number relating a body's inertia to gravitational forces. It is defined as $Fr=U/(gY)^{-1/2}$, Fr: Froude number, U: velocity, g: gravitational acceleration, Y: water depth.

PRB coal seams contain an abundance of coal bed natural gas, predominantly coalbed methane (CBM), a substantial source of hydrocarbon energy that can be recovered by means of well systems constructed at numerous locations over PRB coal seams. These wells pump water from coal-bearing aquifers. Pumping from the aquifer allows CBM to desorb from the coal and be recovered at the well head. However, water pumped from the coal seam must also be disposed of. Options for disposal of CBM product water include storage in lined or unlined impoundments, water treatment with subsequent use of the treated water, managed surface irrigation, underground injection control (UIC) facilities, and direct or indirect discharge into surface streams. Disposal options depend on the quality of the recovered CBM product water.

In a 2009 report, the Wyoming Department of Environmental Quality (2009) estimated that 916 million barrels of CBM product water were extracted from Powder River Basin CBM wells during 2008. Of this volume, 20% (183 million barrels, consisting of a mix of treated and untreated water) was directly discharged into surface drainages. Most of this water was discharged into ephemeral tributaries of the Powder River (here termed “perennialized streams”) some distance upstream of respective Powder River/tributary confluences. This volume of CBM product water translates into an average annual discharge of 33cfs ($0.9m^3s^{-1}$). Based on available data, the average temperature of this product water at the wellhead is about 20^oC (Rice et al. 2002). This volume of water, at this temperature, adds a very large amount of heat to Powder River Basin drainages during the winter month. It is this water, and its entrained heat, that are the subject of this investigation.

1.4 The Powder River

The majority of the research effort for this study took place at and around two tributaries of the Powder River that discharge CBM product water into the River. This section contains a short description of the Powder River in this area.

The Powder River is a northward-flowing river with headwaters in the Bighorn Mountains of Wyoming. It flows northward out of Wyoming, eventually discharging into the Yellowstone River in Montana. CBM product water entering the River directly affects the water quality. At the gaging station nearest the study sites (Powder River upstream of Burger Draw, USGS station #06313590) for the water years 2003 to 2010, the average discharge for the winter season (defined here as November 1 through March 15) is about 100cfs ($2.8m^3s^{-1}$).

Hembree et al. (1952) characterize the Powder River at the study area as a “wide, flat, meandering stream that flows over a sand-covered stream bed between predominantly low stream banks. The lowlands in close proximity to the Powder River consists of a flood plain and a series of alluvial terraces that grade into alluvial fans (Moody et al., 1999). These unconsolidated sediments are underlain by Tertiary sandstones, siltstones, and shales of the

Fort Union and Wasatch Formations. Away from the river, badlands topography rises to a high plain. These badlands are dissected by ephemeral tributary streams.

The annual hydrograph for the Powder River is twin-peaked, with a first peak that occurs between late February and mid-April when lowland snows in the southern part of the basin melt (Moody et al., 1999). A second, larger-peaked flow occurs in mid-May to late June driven by snowmelt from elevations above 3000m. After this peak, discharge can be very low to non-existent in the middle Powder River (as defined by Hembree et al., 1952). The middle Powder River has a slope of ~0.001 and has an estimated average bedload discharge of 160,000 tons per year. All of the bedload sediment is sand-sized, with a median grain size of about 0.250mm (Hembree et al. 1952). Moody et al. studied river cross sections on the Powder River in Montana over a 17 year period after a large flood in 1978 (peak discharge of $930m^3s^{-1}$) severely eroded the river channel and floodplain. They report that the floodplain redeveloped by vertical accretion at an average annual rate of 2 to 8cm per year over the length of their study. Moody et al. also report that spring discharge peaks often cause ice jams to form, leading to local flooding.

Senecal (2009) studied the possible effects of energy development on fish assemblages in the Powder River. She notes (as do Moody et al., 1999) that the Powder River in Wyoming is one of the last relatively intact, unregulated prairie stream ecosystems in the United States. Senecal cites Hubert (1993) as characterizing the river as having highly variable intermittent flow regimes that have unique prairie-river flow regimes and ecosystems. As such, the Powder River is an example of “a highly-evolved and increasingly-rare native fish assemblage.” Senecal restricted her study to summer observations, and mostly considered the effects of increases in discharge caused by CBM product water flow into the Powder River. She concluded that alteration of summer flows caused CBM discharge affect both habitat and fish assemblages in the Powder River.

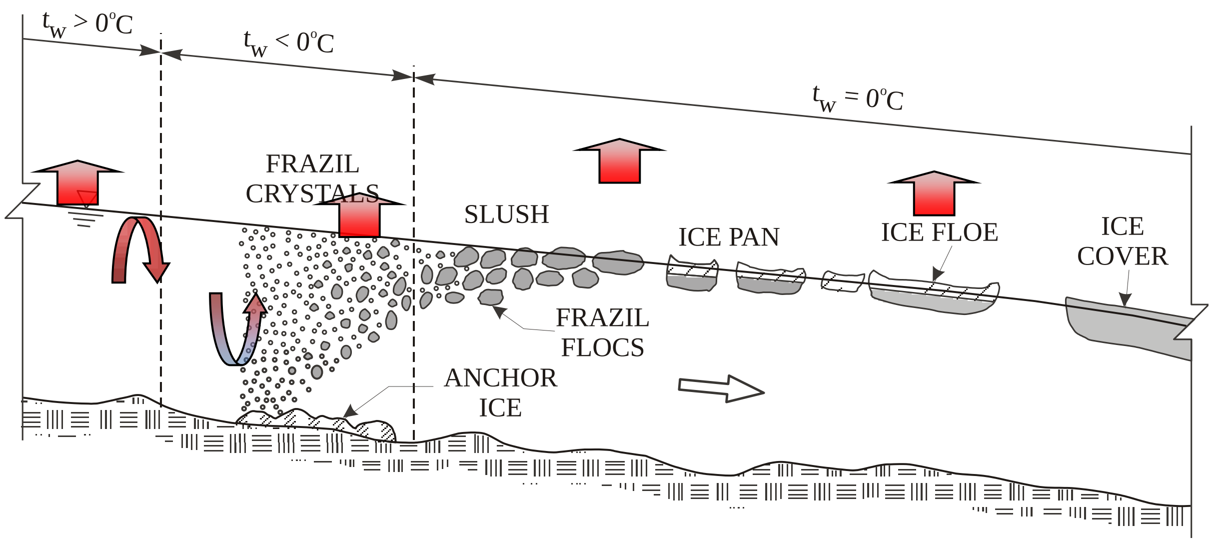

Figure 1.1 Sketch showing longitudinal river profile during ice formation. In turbulent river flow, the water becomes supercooled through heat loss to the atmosphere (red arrows); as a result the first ice to form is frazil and anchor ice. This frazil and anchor ice eventually rises to the surface and is incorporated into the growing thermal ice cover (right side of figure).

2. METHODS

The research for this project was carried out over two field seasons, the winters of 2009-2010 and 2010-2011. Winter is defined here as the period between November 1, when ice may begin forming on Powder River Basin streams, and March 15, when the ice cover has usually melted.[2]

Winter 2009-2010 studies entailed an initial reconnaissance of the Powder River Basin to identify suitable sites for more detailed survey. The investigators worked closely with hydrologists from the USGS office in Casper who regularly make water quality measurements in the PRB. In November 2009, they visited a number of sites along the Powder River (and minor tributaries): Crazy Woman Creek, Clear Creek, Prairie Dog Creek, and the Tongue River. Based on these visits, two sites were chosen for detailed study: *Prairie Dog Creek at Acme* (USGS Station 06306250; there was no CBM discharge at this site; note that logger sites are in italics through the rest of the report) and *Powder River below Burger Draw* (USGS Station 06313590). The locations of these study sites are shown on Figure 2.1. The *Powder River below Burger Draw* site included observations of the small creek that drains Burger Draw (referred to as "Burger Draw" through the rest of this report, USGS Station 06313604). Burger Draw's winter discharge consists entirely of CBM product water. Studies during the first year of the project consisted of instrumenting the study sites, and visiting the sites at three- to four-week intervals during the winter season. During visits, the investigators walked the study reaches, observed ice conditions, collected ice samples using methods outlined in Kempema and Ettema (2010), and serviced instruments. Since the USGS station Prairie Dog Creek at Wakeley (USGS Station 06306200) was on the road between the Prairie Dog Creek Acme and Burger Draw study reaches, the investigators often stopped at Wakeley to observe ice conditions and compare these conditions to the Acme site.

The instruments placed at *Prairie Dog Creek at Acme* consisted of two Onset Hobo U20 water level data loggers and one hobo TidbiT water temperature data logger. One water level logger and the TidbiT were mounted via stainless steel cable to a T-stake that was driven into the bed of Prairie Dog Creek 3m downstream of USGS gaging station. The second water level logger was placed under the USGS equipment shed, about 15m from the T-stake. The water level loggers were set to record temperature and pressure at 10-minute intervals. Placing a water level logger in air allowed the researchers to use Onset's Hoboware Pro software to compensate the stream data logger for atmospheric pressure variations, resulting in true water level measurements with a manufacturer-reported accuracy of 0.5cm and resolution of 0.2cm. The water level recorders also recorded temperature with an accuracy of 0.37^{O}C and a

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[2] An ice season is a period that has a slightly different meaning than winter, in that it implies that ice, of some form, is present on the study reach. A winter season denotes the potential for ice formation, whereas ice season implies that potential is fulfilled. The two years of the research project nicely define the two phases of the project.

resolution of 0.1°C. The Tidbit, which also recorded every 10 minutes, had a reported accuracy of ±0.2°C and resolution of 0.02°C. In practice, the investigators found that the working accuracy is much better than the Onset reported accuracy. However, a zero-point calibration in an ice/water bath was performed on the loggers at the end of the field season to check how close recorded freezing points were to the actual freezing point. Temperature offsets observed in the zero-point calibration were removed from the data logger records during processing. There was no easy way to check the absolute calibration of the pressure sensors on the water level recorders. However, at the end of the field season all water level records were placed in the same location, in air, and allowed to record data for several days. The pressure logs were inter-compared, and no significant difference was found between recorders, so the pressure data was deemed acceptable.

The instrumentation at Burger Draw was similar to those at the Prairie Dog Creek reach: Hobo water level recorders and Tidbit temperature loggers. At the start of the field season water level loggers and Tidbits were placed in the Powder River about 100m upstream and downstream of Burger Draw (stations Powder River above Burger Draw and *Powder River below Burger Draw*). These loggers were attached to concrete-filled steel anchors, which in turn were attached to bedrock outcrops in the river with expansion bolts and stainless steel cable. These bedrock outcrops, which were first misidentified as boulders in the Powder River at Burger Draw, were later identified as concretionary outcrops of a bedrock sandstone outcrop that underlies the shallow alluvium below the Powder River at this location. Detailed cross section surveys during the 2010-2011 field seasons revealed that the river can scour down to this bedrock layer around Burger Draw. A Tidbit was also attached to a staff gage about 40 m from the mouth of Burger Draw, in a position where it could not be affected by inflow from the Powder River (*Burger Draw at mouth*). On December 16, 2009 it was discovered that the ice cover had thickened and encased the Powder River above Burger Draw data loggers. The water level logger was removed at this time, and the TidbiT was returned to the river for remainder of the winter season. Removing the water level logger served two purposes: it protected the logger from damage caused by freezing and it freed up the logger to be used as an air pressure recorder, so the downstream water level recorder could be corrected for atmospheric pressure. On March 5, 2010 two more TidbiTs were placed in Burger Draw: *Burger Draw at discharge* was placed in the run-out of a CBM product water discharge point to record water temperatures at the point where the CBM product water entered Burger Draw. This discharge was located 1000 m upstream of *Burger Draw at Mouth*. The second TidBit, *Burger Draw at Schoonover Road*, was placed just upstream of the Schoonover Road culvert, upstream of the *Burger Draw at discharge* location, about 1200m from the Burger Draw/Powder River confluence.

In early February 2010, the investigators received permission to access Beaver Creek, a CBM discharge stream that enters the Powder River about 6km upstream of Burger Draw (USGS

Station 06313585). On February 9, 2010, a TidbiT was placed in Beaver Creek (*Beaver Creek upstream of mouth*), and regular visits were made to this site to record ice conditions in the creek and the adjacent Powder River. Table 2.1 lists the geographic coordinates and durations of record for all of the data loggers placed during this study.

Discharge measurements were made when the Beaver Creek and Burger Draw study reaches were visited. The discharge measurements were made with a Marsh-McBirney Flowmate electromagnetic current meter attached to a top-set wading rod using the standard 0.4-depth technique. However, both of these creeks are very small, so usually on 10 to 12 verticals were used to determine the discharge.

For the second study season, 2010-2011, it was decided to concentrate efforts on Beaver Creek and Burger Draw. Anchor ice and frazil ice phenomena are best observed early in the day, and the long commute between Prairie Dog Creek Acme and Burger Draw made it impossible to visit both sites on the same morning. This consideration, combined with the fact that Prairie Dog Creek was not CBM impacted, drove the decision to concentrate on the two Powder River locations. However, the 2009-2010 Prairie Dog Creek observations provide a baseline for small stream freeze up processes in the Powder River Basin.

Water level loggers and TidbiT loggers were placed in the Powder River locations listed in Table 2.1 for the 2010-2011 seasons. The following changes in logger positions were made in the fall of 2010:

1. Abandoning the *Burger Draw at discharge* point because the discharge was no longer active (the authors later learned it had been moved upstream of Schoonover Road);
2. Abandoning the "Burger Powder River above Burger Draw logger station;
3. Placing a water level logger with the TidbiT at "Beaver Creek near mouth";
4. Establishing a station, "Powder River at mouth of Beaver Creek" in the Powder River 6m downstream of the Powder River/Beaver Creek confluence. Unfortunately, this site was downloaded once in January 2010, after that the station was covered with thick ice and could not be recovered. When the ice broke up, the logger was gone; and,
5. Establishing a TidbiT temperature logger at *Beaver Creek at Road*, about 1200 m upstream of the confluence with the Powder. This logger became encased in ice early in the ice season and did not record useful data.

It became apparent during the first observations at Burger Creek and Beaver Creek that there were consistent open-water leads (large areas of open water) in the Powder River below the confluences with these creeks. The extents of the leads were "mapped" on several occasions using a GPS and estimating the lead width at a number of geo-referenced points along the lead length. These positions and widths, along with the position of the end of the open water lead, were recorded in the field notes, and the areas and lengths of the leads were calculated in the office.

A major objective for the winter season 2010-2011 was to determine if the open water leads affected channel cross section shape over the course of the winter season. Seven cross-section lines were established in early September 2010, four on the Powder River at Burger Draw (named BD1 to BD4 from downstream to upstream) and three on the Powder River at Beaver Creek (BC1 to BC3). The cross sections were surveyed with a total station on September 9, 2010 (no ice) and December 15-16, 2010 (ice and open water lead present). Endpoint benchmarks consisting of three feet of 12mm rebar capped with a plastic cap were established on both sides of the river during the September visits. The positions of these benchmarks are shown in Figures 2.2 and 2.3. Surveys were made by stretching a Kevlar tape between the benchmarks marking the cross section lines, moving the rod in approximately 1m increments along the tape, and recording easting, northing, and vertical displacements with the total station.

The cross-section data were plotted in the office after field work. The sites were surveyed again on January 21-22, 2011 (ice cover and open water lead) and on March 15-16, 2011 (immediately after ice out at the study reaches). For these surveys, a Lasermark LMH laser level system was used to establish vertical displacements along the cross sections. This system has a stated precision of ±2.4mm over a 30m range. The system was used over ranges up to 100m; the accuracy at this range degrades to about ±1cm. Inter-comparison of relative benchmark elevations confirmed this accuracy. Horizontal control for the 2011 surveys was established by measuring distances from the river-left benchmarks on each survey line. This was accurate to an estimated ±5cm. The largest detriment to horizontal and vertical accuracy in all surveys was holding the survey rod (and rod man) in position in the sometimes strong currents. Maintaining position was much easier when ice was present. When ice was present, 150mm-diameter holes were drilled through the ice at 1m intervals before the surveys were started. Cross sections were then surveyed through these holes in the ice. Project personnel were very careful not to run the ice auger into the river bed during ice-hole drilling. Contacting the bed with the auger teeth instantly dulled the auger teeth to the point where they would no longer cut ice.

When ice was present, ice thicknesses at survey holes were measured with a shortened carpenter's square. The end of the square was rotated around the ice hole, and an average ice thickness value for the hole was recorded. In addition, current velocities were measured at 0.4 of the water depth with the Marsh McBirney current meter. These data were used to establish ice thickness profiles and velocity profiles under the ice and in open water leads.

Table 2.1: Data logger locations, deployment dates, and measured parameters.

Site	UTM Coordinates (Zone 13)		Timeline of Data		Instruments*
	Easting	Northing	Date Set	Date Pulled	Measuring
Burger Draw at Mouth	408618	4888914	1/21/2010	3/16/2011	T
Burger Draw at Discharge	409281	4888770	3/5/2010	10/29/2010	T
Burger Draw at Schoonover Road	409372	4888608	3/5/2010	3/16/2011	T
Powder River above Burger Draw	408737	4888769	11/17/2009	3/5/2010	T
Powder River below Buger Draw	408524	4888865	11/17/2009	3/16/2011	T,P
Powder River at Mouth of Beaver Creek	408991	4885675	9/8/2010	1/22/2011	T
Beaver Creek upstream of Mouth	409032	4885595	2/9/2010	3/16/2011	T,P
Beaver Creek at Road	409366	4885577	1/21/2011	3/16/2011	T
Powder River Air temperature and pressure	408897	4888555	11/17/2009	3/16/2011	T,P
Prairie Dog Creek at Acme	354937	4982814	11/18/2009	3/5/2010	T,P

*T=temperature P=pressure

Table 2.2: Bench mark locations for Burger Draw and Beaver Creek cross sections.

Location	UTM Easting	UTM Northing	UTM Elevation
BC1R	408994.08	4885660.93	1208.93
BC1L	408985.79	4885711.06	1208.48
BC2R	408974.38	4885651.41	1209.05
BC2R	408974.26	4885656.59	1208.94
BC2L	408972.73	4885708.83	1208.60
BC3R	408929.96	4885652.59	1209.22
BC3R	408929.64	4885660.23	1209.22
BC3L	408927.92	4885712.62	1208.63
BD1R	408540.44	4888876.78	1203.60
BD1L	408537.90	4888831.10	1202.26
BD2R	408587.35	4888866.75	1202.97
BD2L	408578.78	4888824.79	1202.46
BD3R	408612.73	4888863.33	1202.86
BD3L	408598.16	4888819.07	1202.56
BD4R	408632.94	4888855.34	1203.45
BD4L	408617.00	4888814.07	1202.73

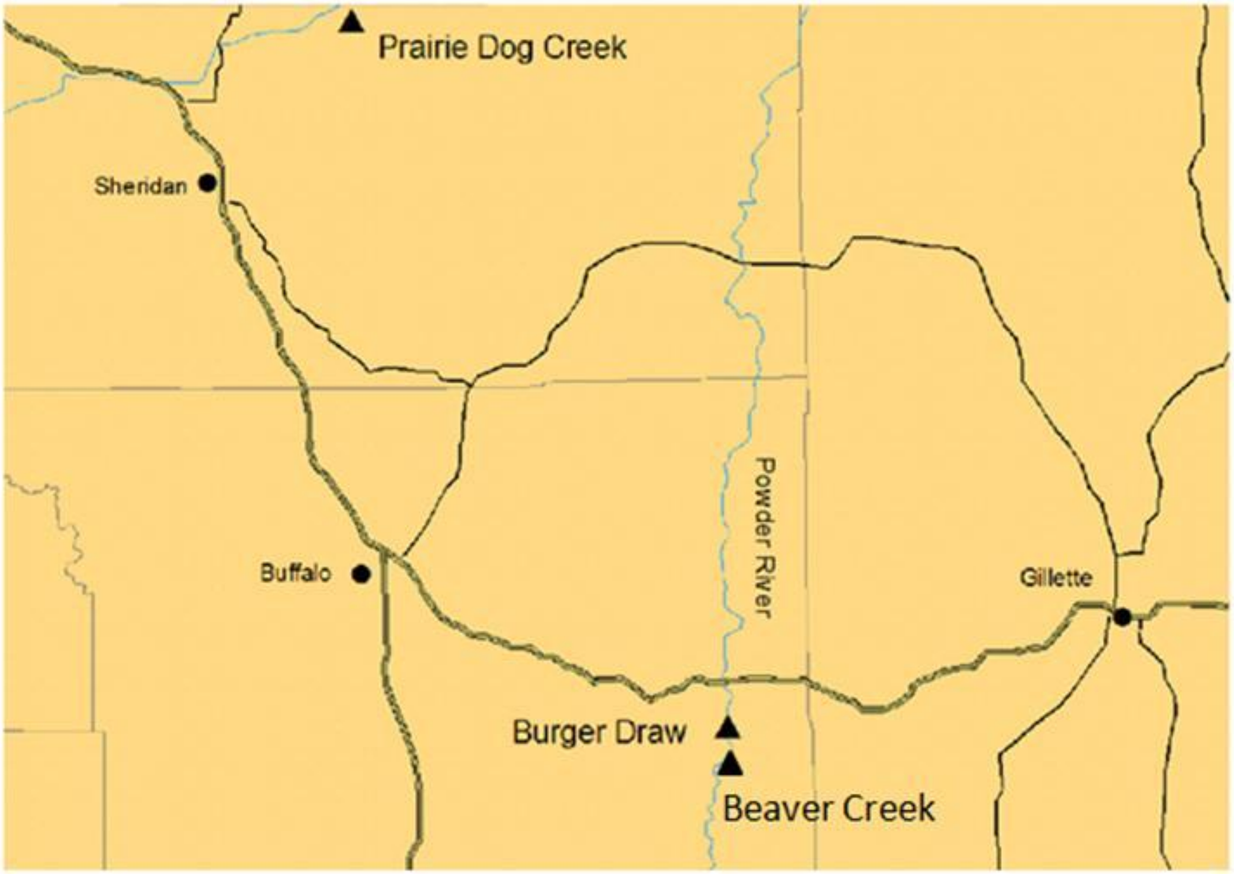

Figure 2.1. Map showing locations of study sites at Burger Draw, Beaver Creek, and Prairie Dog Creek.

Figure 2.2. Aerial image of the Beaver Creek—Powder River confluence showing the relative postions of the cross sections. Cross sections BC1 and BC2 are downstream of Beaver Creek while BC3 is upstream Beaver Creek. The arrow indicates flow direction of the Powder River. Distances (upstream or downstream) of the cross sections from the tributary confluence are: BC1: 30m, BC2: 10m, BC3: 40m.

Figure 2.3. Aerial image of the Burger Draw—Powder River confluence showing the relative positions of the Burger Draw cross sections. Cross sections BD1, BD2, and BD3 are downstream of Burger Draw while BD4 is upstream. The arrow indicates flow direction of the Powder River. Distances (upstream or downstream) of the cross sections from the tributary confluence are: BD1: 80m, BD2: 30m, BD3: 5m, BD4: 15m.

3. RESULTS

This chapter presents the principal findings from the field survey conducted over two winters. They comprise the following component aspects:

1. Water temperature and ice processes in response to air temperature variation;
2. Ice formation characteristics in the Powder River; and,
3. Powder River channel bathymetry responses to ice formation and the effects of CBM water.

The survey produced more data and observations than reported herein. Additional information is given by Stiver (2011).

3.1 Winter Water Temperatures and Ice Processes in Tributary Streams

This section presents the field survey's results regarding water flow and ice formation in the tributary streams to the Powder River – Prairie Dog Creek, Burger Draw, and Beaver Creek. The behavior of flow in these tributary streams bears upon ice conditions and flow in the Powder River over the reach studied. The wintertime behavior of Prairie Dog Creek was representative of streams that do not convey CBM water, whereas Burger Draw and Beaver Creek were CBM-water conveying streams. Prairie Dog Creek conveyed flow from 11 to 14cfs (0.28 to 0.40m^3s^{-1}) during the 2009-2010 ice season. Burger Draw conveyed a small amount of CBM water (0.19 to 1.6cfs; 0.005 to 0.5m^3s^{-1}) whereas Beaver Creek conveyed a much larger CBM flow (5 to 10cfs, 0.14 to 0.28m^3s^{-1}).

3.1.1 Prairie Dog Creek (No CBM Water Flow)

Prairie Dog Creek did not receive any CBM discharge water during the fall freeze up of 2009. As a result, the temperature record for *Prairie Dog Creek at Acme* (Figure 3.1) is typical for small Wyoming streams during freeze up. This sub-section of the report documents the main observations obtained from this site. The observations and associated data provide important, and relatively uncommon, insight into ice formation in small high-plains streams.

Cold air temperatures during late November lowered the water temperature to near freezing at night. However, during daylight hours, warmer air temperatures and incoming solar radiation warmed the water during daylight hours. During the night of November 29, the temperature record shows a short period of supercooling in Prairie Dog Creek; during this period ice was growing in the river, although daytime warming of the water to above 1^oC indicates that ice formed overnight probably melted during daylight hours. By the night of December 1, the water had cooled to very near the freezing point, and from December 2 onward daytime water temperatures did not exceed 0.3^oC. These small peaks in daytime temperature are indicative of a growing ice cover, and decreased in amplitude as the ice cover grew. Eventually they were no longer discernable in the temperature records. From early December until late February 2010, *Prairie Dog Creek at Acme* was completely covered by a continuous ice cover up to 30cm thick.

This ice cover was firmly attached to the Creek banks. The water beneath the ice cover remained stable at the freezing point during this period. As air temperatures warmed in February, the temperature record of is reversed; i.e. small temperature peaks show up in the water temperature record in mid-February during mid-day, and continue to increase in magnitude through early March. In addition, from March 1 to March 9, 2010, Prairie Dog Creek shows supercooling events at night (Figure 3.2), indicating that there was substantial open water upstream of the sampling site. The March 4 site visit confirmed that there was substantial open water, although significant portions of surface ice cover were still present. The large temperature spike on March 11, 2010, combined with the observation that water temperature never reached the freezing point after this date, suggests that there no more ice in the Creek after this date.

Weather conditions, particularly air temperatures and insolation, drive ice formation and melting on Wyoming streams. Depending on weather conditions, formation of a permanent ice cover may occur at any time between late October and late December. In addition, a cold snap followed by a warm spell may result intermittent formation and melting of the ice cover before the continuous ice cover is developed, as described above. This occurred at Prairie Dog Creek in late November 2009. Between November 18 and 24 there were four nights when creek water supercooled. This was followed by a five-day period when water temperatures never dropped below 0.2^{o}C, indicating there was no ice formation (and probably complete melting) of ice in the Creek. This warm spell soon transitioned into the cold snap that led to the seasonal ice cover development described above.

During the freeze up and ice-cover melt periods, when there is little or no floating ice cover and water supercools during the night, frazil and anchor ice form in the water column. Although frazil formation was not directly observed during this study, anchor ice (a derivative form of frazil) was observed in Prairie Dog Creek on three occasions. On November 18, 2009 there was a sparse anchor ice run in Prairie Dog Creek at Wakeley Siding (USGS sampling station 06306200, http://wy.water.usgs.gov/projects/qw/index.htm). Anchor ice covered 80% of the gravelly sand bed at this site at 7:38 AM. The anchor ice formed hard, sub-rounded masses up to 30 cm thick on the creek bed. Individual crystals in the anchor ice masses were sub-rounded to angular, flat plates 0.3 to 1.5cm in diameter. Two anchor ice samples were collected at this location, using the method described by Kempema et al. (2002). A floating anchor ice sample had a sediment concentration of $9.4gl^{-1}$, while an anchor ice sample recovered from the Creek bed had a sediment concentration of $73.1gl^{-1}$ (Table 3.1). All of the sediment in both samples was sand sized (i.e. 0.062 to 2mm diameter). At 9:45 AM on the same day an anchor ice run on Prairie Dog Creek was sampled near Acme (USGS sampling station 06306250, http://wy.water.usgs.gov/projects/qw/index.htm). The ice crystals forming the floating anchor ice mass were similar to the Wakeley Siding samples collected earlier in the day. This sample contained 6.4gl^{-1} of sand-sized sediment. The largest sediment particle in this sample weighed 0.7g (Table 3.1). In addition, there was a 20cm high anchor ice dam located about 100m downstream of the USGS Acme gaging station at this time.

The last observed occurrence of anchor ice in *Prairie Dog Creek at Acme* occurred on March 4, 2010. This anchor ice formed a dam downstream of the USGS Acme sampling site (Figure 3.3). The dam developed on top of an inundated piece of the floating ice cover, and created a backwater effect extending approximately 100m upstream of the dam. Based on the water level record at the Acme gaging station, it appears that the anchor ice dam, along with increased discharge associated with runoff, raised the upstream water level by up to 60cm over a four day period from March 1 to March 4, 2010. The ice making up the anchor ice dam were flat, dendritic or “christmas-tree” shaped crystals and up to 5cm in diameter. The anchor ice dam, along with the ice crystals making up the dam, had morphologies remarkably similar to features reported from the Laramie River in southeast Wyoming (Kempema et al., 2008). In fact, all of the ice phenomena observed on Prairie Dog Creek have been observed at other Wyoming streams (Kempema and Ettema, 2009; Kempema and Ettema, 2010; Kempema and Konrad, 2004).

3.1.2 Burger Draw (Small Discharge of CBM Water)

The November through December, 2009 water temperature history of Burger Draw, whose small discharge (averaging about 0.75cfd, 0.02m^3s^{-1}, Table 3.2) consisted entirely of CBM discharge water, is markedly different than Prairie Dog Creek (Figure 3.1). Instead of the water temperature asymptotically approached the freezing point over several days as the average daily air temperature droped below freezing in the fall, it cooled to a point but warmed several degrees during daylight hours. It was found that Burger Draw water cooled to 0^{o}C, or even supercooled during night time. However, unless the air temperature became very low, the water temperature always rose during the daylight hours. This pattern continued throughout the winter (Figure 3.4); water temperatures often reached several degrees centigrade during daylight hours throughout the winter. As a result, a continuous ice cover was not maintained over Burger Draw. During the coldest winter weather, a continuous floating ice cover often formed over Burger Draw, but the continuous flux of warm CBM product water melted this ice when air temperatures increased. However, as there is a direct connection between the water and the atmosphere in Burger Draw (i.e., no insulating ice cover), cold weather conditions evidently led to supercooling with the consequence of frazil and anchor ice formation at any time during the winter.

Warm CBM discharge water was discharged into Burger Draw throughout the 2009-2011 ice seasons. This discharge was not continuously measured during the ice season. Instead, discharge was measured during each visit to the study site, and was augmented with USGS discharge measurements made during this study (Table 3.2).

Burger Draw water temperatures remained relatively warm (i.e., above the freezing temperature) for several extended periods during the 2010-2011 ice season (Figure 3.5), even though the first major CBM discharge point was moved 500m upstream during the summer of 2010. Discharge during the 2010-2011 season was also similar to the 2009-2010 season (Table 3.2). However, the water temperature record at the mouth of Burger Draw for 2010-2011 shows a marked difference from the 2009-2010 temperature record. This difference shows up as temperature dips of up to -2^{o}C during late November, late December through mid-February, and late February through early March. These sub-freezing temperatures were measured because aufeis grew in the shallow channel where the temperature logger was placed early in the season (Figure 3.6). This ice grew to the channel bed, encasing the logger in ice, and shifting Burger Draw flow about 1m to the left of the data logger position. As a result, for much of the 2010-2011 ice season, the *Burger Draw at mouth* data logger recorded ice temperatures, rather than water temperatures. The influence of the water flowing near the logger is seen in fact that the temperature record never falls far below the freezing point, but this station cannot be used to determine the temperature of water entering the Powder River at Burger Draw. The *Burger Draw at Schoonover Road* data logger, located 500m below a major discharge point, shows that stream temperatures were commonly 2^{o}C to 5^{o}C above freezing 1,200m above the confluence, but a significant (and unknown) amount of this heat was lost to the atmosphere before the water discharged into the Powder River.

Although the *Burger Draw at mouth* temperature logger record was not useable for the 2010-2011 ice season, the Burger Draw at Schoonover logger recorded maximum daily water temperatures of between 1 and 5^{o}C on most days during the winter season. However, qualitatively, much more ice was observed in the lower portions of Burger Draw during the 2010-2011 season compared to the previous season. Aufeis near Burger Draw mouth reached a thickness somewhat in excess of 30cm in early January 2011, forcing water out of the creek channel (Figure 3.6). Continued warm water flow under the aufeis melted the ice from below, creating an insulating ice and air layer that protected Burger Draw from warming.

3.1.3 Beaver Creek (Substantial Flow of CBM Water)

Beaver Creek, like Burger Draw, is a perennialized stream consisting entirely of CBM water during the winter months. Measured discharges in Beaver Creek varied between 5 and 10cfs (0.142 to 0.283m^3s^{-1}, Table 3.2) during the two winter seasons of this study. Water temperatures measured near the creek mouth during the 2010-2011 ice season generally remained between 1^{o}C and 5^{o}C except for a week-long period near the end of February (Figure 3.7). Water temperatures at Beaver Creek were generally more stable that at Burger Draw (compare Figures 3.4, 3.5, and 3.7). This is attributed to the order-of-magnitude higher discharge of Beaver Creek (Table 3.2) and the deeper flow depth of Beaver Creek. Even though measured water temperatures remained well above freezing for most of the 2009-2010 ice season, ice covers still formed during cold snaps and melted during subsequent warmer periods. CBM water created open water leads in Beaver Creek during warm spells; these open water leads allowed water to cool rapidly when exposed to frigid air temperatures. As a result, a variety of ice types formed during frigid weather periods, including surface ice, anchor ice dams (Figure 3.8), and aufeis. Ice formation driven by cold air temperatures raised water levels significantly, at times completely filling the stream channel. When air temperatures warmed and ice melted, stage dropped, leaving hanging ice remnants (Figure 3.8). It is possible that dropping water levels left ice perched above the water surface, as was observed on Burger Draw. When this happens, it creates a dead air space that insulates the water from loosing heat to the atmosphere while at the same time insulating the perched ice from melting. The dynamic nature of ice formation in Burger Creek resulted in water level variations of up to 0.6m over the course of the winter. The water level tended to rise about 0.2m rather rapidly when temperatures dropped (Figure 3.7) and border ice and anchor ice dams retarded creek flow. Creek level would drop as air temperatures warmed and warm creek water thermally eroded the ice. The continuous flow of warm water down the creek created very dynamic changes in ice and flow conditions as weather conditions varied throughout the season.

3.1.4 Powder River (Recipient of CBM Inflow)

Powder River is a perennial (as opposed to perennialized) stream that has a natural discharge of around 100 to 200cfs (2.8 to 4.6m^3s^{-1}) at Burger Draw during the winter months (USGS, http://nwis.waterdata.usgs.gov/wy/nwis/measurements/?site_no=06313590; Table 3.2). As such, it should undergo a typical fall freeze up sequence consisting of cooling of river water to the freezing point and then initial formation of frazil, anchor ice, border ice, and congelation ice growth that amalgamate into a continuous surface ice layer that forms over several days. Once a continuous ice cover forms, it should continue to thicken as long as daily average air temperatures remain below freezing. However, perennialized CBM streams inject a significant quantity of heat into the Powder River. As a result, ice conditions below CBM-stream confluences are not fully natural for the Powder River below these discharge points. This sub-section assesses the quantity of heat injected into the Powder River at discrete CBM discharge points, and the effects that this heat has on ice conditions and cross section profiles in the Powder River.

Formation of Open-water Leads in the Powder River

A common consequence of warm water discharge into the Powder River was the formation of long, relatively narrow stretches of open-water flanking an incomplete ice cover in the river. Herein, these open-water stretches are termed “open water leads,” because their appearance has similarities to open-water leads observed in sea ice. The ice leads in the Powder River, however, formed by virtue of heat convected with tributary CBM flow entering the river, rather than by the action of wind or water current as is the case for sea ice.

During the two ice seasons, open-water leads developed at the confluences of Burger Creek and Beaver Creek with Powder River. They also were observed to occur at other locations where CBM water was discharged into the Powder River. Accordingly, they are a distinctive feature of CBM water discharge into the Powder River. Similar leads often develop in ice covers at rivers adjoining thermal power plants (Ashton 1986).

As described earlier in this report, Burger Draw and Beaver Creek discharge water above the freezing temperature at their confluence with the Powder River. The receiving flow in the Powder River at these confluences within 0.05^{o}C of the freezing temperature when the river is ice covered. On most winter days, the inflow temperature from the two streams varies diurnally, peaking at up to 8^{o}C during early afternoon on sunny days, and then cooling to about the freezing temperature during the night time (Figures 3.4, 3.5 and 3.7). As a result, the Powder River at the confluences received a more-or-less cyclic input of heat on a daily basis. The temperature of CBM water entering the Powder River was influenced by the distance between the discharge points in the tributaries and the confluences with the Powder River.

The influent discharges from Burger Draw and Beaver Creek flow as a form of density current along the Powder River, and do not immediately mix with water flow already in the river. Density currents maintain their form because gravity forces acting on the small difference in water density (between inflowing warmer water and Powder River water at 0^{o}C) inhibits instant dispersion of water. The streamwise flow of a density current in a river channel is greatly facilitated by gravity and drag from surrounding flow. CBM water at 4^{o}C is sufficiently denser (0.013%) than water at 0^{o}C that, bordered on one side by the channel bank, it can maintain itself as a thin density current in a lead extending over a very long distance. In contrast, CBM water introduced at 15^{o}C would be lighter (0.074%) than water at 0^{o}C, such that it would form a buoyant plume. Constrained on one side a channel bank (Figure 3.9 TOP and BOTTOM), such a plume also would form an open-water lead.

In due course, through the effects of heat loss to air and turbulent mixing generated by channel bed and bank features, a density current or buoyant plume weakens and disperses in a river. Eventually, the leads disappear, unless augmented by additional inflow of relatively warm water.

The width and streamwise extent of the Burger Draw and Beaver Creek open-water leads scaled approximately with the magnitude of heat convected with tributary water flow into the Powder River. The relationship for lead size can be related to a balance of heat influxes in terms of the following heat balance relationship between heat inflow and heat loss to frigid air above the Powder River (e.g., Ashton 1986, Dingman et al. 1968):

$$\frac{\partial(\rho C_p T_w)}{\partial t} + U\frac{\partial(\rho C_p T_w)}{\partial x} = \frac{\partial}{\partial z}\left[E_z\frac{\partial(\rho C_p T_w)}{\partial z}\right] - \frac{\emptyset}{Y} \qquad (1)$$

In which ρ = water density, C_p = specific heat capacity, T_w = water temperature, t = time, U = mean velocity, x = streamwise position, z = transverse position, E_z = transverse dispersion coefficient, Y = flow depth, and ϕ = heat flux from the water surface to air above. The terms in Eq. (1) are (left to right of the page): rate of heat loss from the flow, convection of heat in the flow, transverse dispersion of heat, and heat flux to air. The terms are expressed as relative unit volume of flow.

Equation (1) is written using the assumption that the water is fully mixed over its depth and that there is no transverse mixing due to transverse velocities generated by large-scale turbulence structures in the flow. Measurement of flow velocities through the leads, estimated as about $1ms^{-1}$, suggest that the flow is well mixed over their depth, thereby impeding thermal stratification, which could enable ice-cover growth over stationary water. The assumptions normally are sound for values of densimetric Froude number[3] associated with river flows during winter (Ashton, 1986).

The heat flux can be estimated from an energy budget analysis at the water surface. The budget is simply expressed as

$$\emptyset = H_{wa}(T_w - T_a) \quad (2)$$

Here, H_{wa} = heat transfer coefficient stemming from the heat-budget analysis, T_a = air temperature, and T_w = water temperature.

If warm tributary water is fully mixed across the river depth when it enters the Powder River and a Lagrangian approach is used (i.e., follow a parcel of water at Udt = dx), Eq. (1) simplifies to

$$\frac{dT_w}{dt} = -\frac{\emptyset}{\rho C_p Y} \quad (3)$$

This equation can be integrated to yield relationships for the length and area of open water lead; i.e.,

$$L = x - x_{(T_w = 0^oC)} = -\frac{\rho C_p q}{H_{wa}}\left[ln\left(\frac{-T_a}{T_{wo} - T_a}\right)\right] \quad (4)$$

If the average width of the open-water lead is taken into account, Eq. (4) adjust to

$$A = B(x - x_{(T_w = 0^oC)}) = -\frac{\rho C_p q B}{H_{wa}}\left[ln\left(\frac{-T_a}{T_{wo} - T_a}\right)\right] \quad (5)$$

In which unit discharge q = UY, B = average width of open water lead, and T_{wo} = the initial value of T_w at x = 0 and t = 0. The downstream end of the lead approximately corresponds to the

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[3] Densimetric Froude number = $U/(\Delta\rho/\rho[gY])^{0.5}$, where $\Delta\rho/\rho$ = normalized density difference of density current relative to river flow density, g = gravity acceleration, and Y = flow depth.

location where water in the lead has cooled to the freezing temperature as prevails in the Powder River. Values of B at the survey sites were influenced by several factors:

1. The relative unit discharges (discharge per unit width) of the flows in Burger Draw and Beaver Creek;
2. The manner whereby the flow is introduced into the Powder River (e.g., angle between confluent channels, pipe discharge, manifold discharge); and,
3. The bathymetry of the channel at the discharge location and immediately downstream of it.

The open water lead below the Burger Draw confluence always had a relatively uniform width along its downstream length. In comparison, the open water lead in the Powder River below Beaver Creek tended hug the right river bank and to have a consistent width for about 800m downstream of the confluence. Downstream of this, the open water lead widened and filled the center of the channel. This change in lead character probably resulted from the presence of braided point bars that appear at this location.

If the same values of T_a and T_{wo} are assumed,

$$\frac{A_{Beaver\ Creek}}{A_{Burger\ Draw}} = \frac{(qB)_{Beaver\ Creek}}{(qB)_{Burger\ Draw}} = \frac{Q_{Beaver\ Creek}}{Q_{Burger\ Draw}} = 6.5 \qquad (6)$$

In accordance with Eqs. (4) through (6), the surface area of downstream flow required to cool water from an initial relatively warm temperature of, say, 4^oC to 0^oC varies directly with the magnitude of the inflow rate. This tendency was reflected by the dimensions of the leads formed in the Powder River at Burger Draw and Beaver Creek, as summarized in Table 3.4. The greater discharge and heat input from Beaver Creek resulted in an open-water lead just over 3km in length and on average 7m wide; and open-water surface are of approximately 2 x $10^4 m^2$. The corresponding open-water area for the lead produced by CBM water discharged from Burger Draw was about 3 x $10^3 m^2$. The surface areas of the leads scale reasonably well with the average discharges of the two CBM water discharges.

The formulation Eqs (1) through (6) is useful for identifying ways whereby the discharge of CBM water could be managed so as to reduce significantly the formation of open-water leads. Section 4.3 subsequently discusses possible management options that facilitate CBM water discharge, but with minimal effect on the Powder River, other than adding to its overall flow of water.

Influence on Powder River Ice Cover Profiles

Upstream of the Burger Draw and Beaver Creek confluences, the ice cover on the Powder River averaged about 0.4m in thickness in January and February. The ice cover was reasonably uniform upstream of each site, with thickness variations at locations where drifting anchor ice or frazil may have accumulated to differing extents as the cover initially formed. The formation of open-water leads below the confluences affected the ice cover primarily by impeding its development in the area occupied by the lead, except during especially frigid weather conditions when the ice cover expanded laterally to envelop portions of the lead (see Appendix 2 for ice profiles). The open water lead at Burger Draw, being smaller, was more readily enveloped by ice.

The measurements of cross sections of the ice cover produced profiles of ice cover thickness at the survey sites. The profiles show that the ice cover thickened rapidly with distance transversely away from each lead. Within about 2m from the lead's edge at each site, the cover was at its average thickness (Appendix 2). This thickness variation reflected the very limited lateral spreading of flow within each lead. Water discharged from Burger Draw and Beaver Creek did not affect the ice-cover thickness over much of the cross-section widths below the confluences (Appendix 2). At most locations the ice cover extended to the top of sand bar bars or to the river bed near the banks (Appendix 2). The covers maintained their thickness and strength, such that during the surveys it was possible to walk across the ice cover right up to the edge of the lead. During one site visit, cattle were observed standing on the ice cover and drinking from the open water lead, attesting to the strength of the ice all the way to the lead edge (Figure 3.10).

When a lead froze over during an especially cold period, ice over the lead readily melted out by heat convected from warm water flowing underneath. Lead freeze-over occurred as so-called border ice growth at the edges of the lead caused the lead to contract in a cross-stream direction and as frazil and released anchor ice collected and froze at the downstream boundary of the leads.

Responses of the Powder River Channel

The onset of frigid weather for rivers such as the Powder River typically cause the formation of an ice cover, which imposes a solid boundary across the top of the river, increasing flow resistance (and thereby usually producing a stage rise), and a decrease in flow as watershed runoff substantially diminishes. Frigid weather also affects the strength of channel banks by means of freeze-thaw action on bank soils and halting vegetation growth. The discharge of relatively warm CBM water into the channel of the Powder River affects ice cover formation (as described in the preceding sections) and increases wintertime flow.

Currently, it is only possible to describe in conceptual terms how ice influences alluvial-channel bathymetry (Ettema, 2002). No quantitative evidence exists that ice hastens or slows large-scale changes, such as the migration of a series of meander loops. Such evidence is hard to obtain, since ice is one of several factors influencing the dynamic balance between flow, slope, and sediment in an alluvial channel. Some evidence was obtained from the Power River survey sites suggests that slight adjustments in channel thalweg occurred, but the adjustments were of lesser magnitude than those observed to occur overnight during Spring break-up of the ice cover at the BC1 and BC2 survey sites (Appendix 1). This section describes the channel responses observed at all the sites.

The sets of channel bathymetry cross sections recorded for the Burger Draw and Beaver Creek sites are presented in Appendix 1. Figures A1.3 and A1.4 in Appendix 1 show the BC1 and BC2 cross section surveys for the 2010-2011 winter season. The site at these cross sections is illustrated in Figures 3.9.

The main responses observed were as follows:

1. Thalweg shift toward the open water lead when the thalweg was not entrenched along a channel bend;
2. The channel thalweg, which coincided with the open water lead, deepened slightly, typically by about 0.25m. Because bedrock underlies the Powder River at Burger Draw channel at shallow (and presently unknown) depth below the sandy alluvium, it is unclear whether this depth represents an equilibrium erosion depth in alluvium, or whether deepening was limited by the presence of the bedrock. The bed of the Powder River in the vicinity of the cross sections contains sandstone bedrock that was exposed in the channel below the open water lead during winter;
3. The deepened flow along the open water lead, in combination with weakening of bank soil, resulted in bank erosion and approximately a 2m lateral shift of the channel below the confluences of both Beaver Creek and Burger Draw.

The changes measured at the Beaver Creek and Burger Draw cross sections are summarized in Table 3.5. The responses are indexed in terms of the maximum vertical motion of the channel bed, and the widening of the channel owing to bank erosion. The vertical motions were scour (downward displacement) or fill (upward displacement) of the bed at points on the channel cross-section.

Heat flux to the Powder River and Ice suppression

Direct discharge of CBM water into ephemeral tributaries delivers a continuous flux of heat to the Powder River during the winter months. This heat flux varies on daily and longer time scales (Figures 3.4, 3.5 and 3.7). CBM tributary water temperatures (and hence heat flux) vary in a quasi-sinusoidal fashion with a day-long period (Figures 3.1 and 3.11), with highest water temperatures occurring in early afternoon and lowest temperatures occurring during the nighttime. The lowest temperature that CBM discharge water can reach (like any natural water) is a slight supercooling of $<0.1^oC$ (Daly, 1994). The maximum possible water temperature of CBM discharge water is the temperature of the water at the discharge point. Average CBM water temperature at the well head is 20^oC (Rice et al., 2002). However, because CBM water is usually discharged into tributary channels, some distance upstream from the Powder River, the water cools as it flows down the channel. This effect can be seen in the last six days of the temperature record for Burger Draw in 2010 (Figure 3.4). During mid-March, average water temperatures in the Draw below a discharge point were 14-16^{o}C, while 1,200m downstream at *Burger Draw at mouth* the average water temperature was around 8^{o}C. A method for calculating cooling rate of a stream open to the atmosphere was discussed earlier. In this section a different approach, describing the amount of ice suppression caused by CBM tributary discharge into the Powder River, is discussed

The amount of heat delivered from Burger Draw for the 2009-2010 winter season, and for Beaver Creek during the 2010-2011 winter, to the Powder River can be can be determined with:

$$Q_h = C_p Q T_w t \qquad (7)$$

where Q_h is the total heat flux (kJ day^{-1}), C_p is the specific heat capacity of water (4187kJm^{-3o}C^{-1}), Q is discharge (flow of water from tributary to Powder River, m^{3}s^{-1}), T_w is the temperature of the incoming tributary water, measured near the mouth (^{o}C), and t is the time step. Water temperature was measured at 10 minute intervals, and discharge was measured at two to three week intervals (Table 3.2). By assuming constant discharge between discharge measurements, it was possible to calculate heat fluxes at 10-minute intervals. Summing the 10-minute intervals over the course of the day gave the daily CBM heat fluxes from Burger Draw and Beaver Creek into the Powder River. This daily heat flux was converted to an "ice suppression" value by dividing Q_h by the latent heat of fusion of ice (3.046X10^{5}kJm^{-3}). These daily ice suppression values are shown in Figure 3.12. Beaver Creek had consistently higher water temperatures and discharges compared to Burger Draw; as a result, the ice suppression values for Beaver Creek are consistently much higher than for Burger Draw. Beaver Creek ice suppression values ranged from 0 to 2450m^{3}day^{-1}, while Burger Draw had a maximum ice suppression value of 380m^{3}day^{-1}.

The term "ice suppression" is used herein to give a physical meaning to the heat that CBM-fed tributaries deliver to the Powder River. The term can be interpreted at least two ways: as the amount of excess heat that has to be removed by heat flux to air from the Powder River downstream of the tributaries before ice can form; and, as the amount of heat that is available to melt ice downstream of tributaries. Ice suppression applies only to excess heat delivered from CBM tributaries to the Powder River, and does not account for other heat fluxes to the river, for example, short wave solar radiation or conduction to the atmosphere on warm days. As noted earlier in this report, the temperatures of CBM tributary streams varies over several degrees on daily and longer cycles in response to air temperatures and insolation (Figures 3.4, 3.5 and 3.7). Ice suppression therefore varies on the same scale. However, the net flux of heat from Burger Draw and Beaver Creek maintains open water leads in the Powder River below these tributaries. For Burger Draw, the total potential ice suppression volume for the period of November 4, 2009 through March 15, 2010 was 20,800 m^3 of ice; for Beaver Creek between November 1, 2010 and March 15, 2011 the total potential ice suppression volume was 118,000

m^3. These numbers represent potential values, because air temperatures remained above freezing through mid-November during both seasons, and no ice formed until that time. However, as a result of the heat supplied by these tributaries, there were open water leads below both confluences in both the 2009-2010 and the 2010-2011 field seasons. The ice regimes in the Powder River were different below the confluences than above the confluences, as discussed below.

Effects of Open Water Lead on Ice Processes in the Powder River

The continuous flux of warm water from Burger Draw and Beaver Creek to the Powder River has a direct effect on Powder River water temperatures and ice regimes below these tributary confluences. The warm tributary water mixes with Powder River water. The *Powder River below Burger Draw* temperature logger was located 100m below the Burger Draw confluence and 6m from the right bank of the Powder River. During winter 2009-2010, the *Powder River below Burger Draw* recorded daytime warming less than 0.2^{o}C above the freezing point on most days (this shows up as a small saw tooth pattern in Figure 3.4). By contrast, during the 2010-2011 winter season, the same station shows repeated, long-term (up to 10 day) periods of temperatures of 0.2 to 0.4^{o}C above the freezing point. The warmest water temperatures measured at *Powder River below Burger Draw* correspond to the coldest air temperatures. In general, it appeared that the open water lead was less developed in 2010-2011 compared to 2009-2010. The authors interpret the long periods of relatively warm (0.2 ^{o}C to 0.4^{o}C) water observed in 2010-2011 to result from a thin ice cover forming over the Powder River between the confluence and the measuring site. This ice cover insulated the water from the atmosphere and allowed warm water temperatures to be maintained in the *Powder River below Burger Draw* for long relatively long time periods. Thus, the Powder River responded differently to the warm water flux from Burger Draw during the two seasons of this study. During 2009-2010, the Burger Draw heat flux maintained a relatively large open-water lead in the Powder River. As a result, the warm water from Burger Draw could be seen during the day, but at night, between mixing with Powder River water and heat loss to the atmosphere, the water cooled to the freezing point by the time it arrived at the logger location (~100m downstream of the confluence). By contrast, formation of even a thin ice cover between Burger Draw and the *Powder River below Burger Draw* logger site allowed the heat injected into the Powder River to be maintained for periods of up to 10 days (Figure 3.5). This heat was transported down steam under the ice, resulting in a thinning of the ice cover for some distance downstream. An important point highlighted by the temperature recordings in Beaver Creek, Burger Draw, and the Powder River during this study is that the presence of an ice cover on top of a stream does not necessarily mean that the water underneath is at the freezing point. The ice cover may act as an insulator, enabling warm water to move far downstream before it cools to the freezing point.

One consequence of maintaining an open water lead downstream of CBM tributaries is that there is a direct connection between the water surface and the atmosphere. This raises the possibility of frazil and anchor ice formation in the open water lead sections of the Powder River. As already noted, anchor ice was observed in Beaver Creek on several occasions during this project. Anchor ice was also observed in the open water leads below Burger Draw and Beaver Creek during this study. On February 9, 2010 and February 23, 2010 anchor ice was observed on boulders around the *Powder River below Burger Draw* logger station, and there was a moderate anchor ice run at the downstream end of the Burger Draw open water lead. This floating anchor ice was sampled on both occasions and found to have sediment concentrations less than $1gl^{-1}$ (Table 3.1).

February 9, 2010 was the first day of field work in and around Beaver Creek, which has about an order of magnitude greater flow than Burger Draw. Large accumulations of anchor ice, up to 50cm thick, composed of 2-3cm diameter crystals apparently formed regularly in the open water lead at distances of about 800 to 1600m from the Beaver Creek confluence. The large anchor ice masses at this site were unusual in that they formed on a sand bed (Kempema et al., 2008). On two occasions large volumes of anchor ice were observed (extending along 100m of the river, for the whole river width, with anchor ice 15-30cm thick) to rise to the water surface and drift downstream over about a 10-minute period. In addition, anchor-ice dams formed in this region.

Released anchor ice carried a noticeable amount of sediment, which consisted mainly of sand and pebbles. Sediment concentrations in collected, floating anchor ice sample ranged from 0.19 to $37.3gl^{-1}$ of sediment (Table 3.1). Two attached anchor ice samples contained 42.5 and 73.1g of sediment per liter. Both the absolute concentrations and the range of concentrations measured in Powder River anchor ice samples are similar to anchor ice concentrations reported from other rivers (Kempema and Konrad, 2004; Kempema and Ettema, 2009; Kempema and Ettema, 2010).

Even though the bed of the Powder River contains sediment ranging in size from fine sand to boulders, only relatively small sediment was observed in the collected anchor ice samples. The largest single sediment particle found in a Powder River anchor ice sample weighed 5 g and measured roughly 2.2cm by 1cm by 1cm (a pebble). Moody et al. (1999) studied the ontogeny of the Powder River floodplain near Moorhead, Montana over an 18-year period. They note the presence of ice rafted sand and gravel in fine-grained flood plain deposits. They attribute the presence of these coarse materials to ice rafting by blocks of ice that are carried downstream during breakup ice jams, and note that melting of the ice can deposit “decimeters” (1dm = 10cm) of sand and gravel on the floodplain. However, it is also possible that anchor ice is responsible for ice rafting this coarser material. Moody et al.’s (1999) observation suggests the possibility of anchor ice rafting of coarser material in the Powder River, but this was not confirmed in the present study. Kempema and Ettema (2010) note from the Laramie River that anchor ice rafting is capable of moving boulders weighing up to several kilograms.

At the *Powder River below Burger Draw*, it appears that frazil ice and anchor ice are not significant problems. No evidence of unusual ice thickening, hanging dams, or anchor ice dams were noted in the vicinity of the Burger Draw open water lead. This probably results from the fact that the Burger Draw open-water lead is relatively small, so there is not much chance for the water to supercool and underwater ice to form (Kempema et al., 2008).

By contrast, the open water lead below Beaver Creek appeared to be an anchor-ice factory. The open-water lead tended to hug the right river bank for about 800m downstream from the confluence with Beaver Creek as the Powder River made a large, left oxbow bend. Below this, the river straightens out. At this point, the lead melted the ice off the entire river surface for a distance of 300 to 500m (1,100 to 1,300m downstream of the Beaver Creek confluence). The large open water reach had the greatest the greatest volume of anchor ice. Anchor ice dams were seen in this area, along with hanging ice remnants up to 60cm above the normal water level that were indicative of larger dams in the past. Although these dams raised the water level for up to 150m upstream, they did not cause the water to rise out of the river channel.

Water above the freezing temperature maintains an open water lead, either in perennialized streams or in the main stem of the Powder River. If conditions get cold enough to form significant frazil and anchor ice, both the river and perennialized streams are subject to hanging dam formation, aufeis, and anchor ice. Although there is the potential for flooding when these ice types develop (Daly, 2002), there is relatively little risk posed by the flooding because of the undeveloped nature of the floodplain along the Powder River. However, relatively warm CBM water should probably not be discharged upstream of regions where the risk of flood damage to buildings or land exists.

The USGS regularly measures water quality, including discharge and water temperature, on several CBM-impacted drainages in the Powder River Basin. Table 3.3 presents the USGS discharge and instantaneous water temperatures for Barber Creek (USGS Station #06313750) and Pumpkin Creek (USGS Station #06313560), located downstream of Burger Draw and upstream of Beaver Creek, respectively. Using the method outlined above, and assuming that discharge and water temperatures remain constant between consecutive discharge measurements (dubious at best, based on the fact that USGS personnel make discharge measurements during daylight hours, when water temperatures are at their warmest), it is possible to calculate the daily and winter season potential ice suppression for these streams. Pumpkin Creek had potential ice suppression of 160 to 920m^3day^{-1}, and a total potential seasonal (November 1 to March 15) ice suppression of 58,000 m^3. Barber Creek, by comparison, had much higher water temperatures of 18.8 to 21^oC throughout the winter. As a result, daily calculated ice suppression for Barber Creek ranged from 1,800 to 3,700m^3day^{-1}, with a seasonal total ice suppression estimated at 390,000m^3. Access to the Powder River at either of these sites was not available during the study, but USGS personnel reported that the Powder River stayed "completely open for several miles below Barber Creek" throughout the winter (Eric Blajszczak, USGS, personal communication). The observations for Beaver Creek and Barber Creek reported here most probably apply to the environs around Barber Creek, Pumpkin Creek, and other CBM water discharge points that discharge directly into ephemeral tributaries of the Powder River, i.e. all of these locations are sites of open-water leads, frazil, and anchor ice formation throughout the winter.

Table 3.1. Anchor ice samples collected in the Powder River Basin

Sample date	Sample Location	Sample type	Largest sediment* (g)	Sediment concentration (gl^{-1})
11/18/09	Prairie Dog Creek Wakeley Siding	Floating	1.8	9.42
11/18/09	Prairie Dog Creek Wakeley Siding	Attached	Sand	73.1
11/18/09	Prairie Dog Creek Acme	Floating	Sand	6.4
2/9/10	Powder River below Burger Draw	Floating	Sand	0.19
2/9/10	Powder River below Beaver Creek	Floating	Sand	37.2
2/9/10	Powder River below Beaver Creek	Search for largest sediment particle	16.4 g	n/a
2/23/10	Powder River below Burger Draw	Floating	Sand	0.45
2/23/11	Powder River below Beaver Creek	Floating	5.5	14.6
2/23/11	Powder River below Beaver Creek	Floating, but just released	Sand	42.5

*The largest sedimentary particle was hand-picked from each dried sample and then weighed. If the largest particles were sand-sized, the largest particle size is recorded as "sand" (<2mm diameter).

Table 3.2. Discharge measurements in Burger Draw, Beaver Creek, and the Powder River during this study.

Date	Burger Draw Discharge (cfs)	Beaver Creek Discharge (cfs)	Powder River above Burger Draw Discharge (cfs)	Measuring Agency*
11/04/2010	0.81	8.1	166	USGS
11/17/2009	0.98	--	--	UWYO
12/3/2010	.72	6.4	32	USGS
12/16/2009	0.83	--	--	UWYO
1/13/2010	.81	8.3	69	USGS
1/21/2010	0.77	--	--	UWYO
2/4/2010	.53	6.8	115	USGS
2/9/2010	0.93	9.03	--	UWYO
2/23/2010	0.47	7.8	--	UWYO
3/3/2010	1.1	8.7	183	USGS
3/04/2010	1.1	6.8	--	UWYO
3/30/2010	0.76	5.00	--	UWYO
10/29/2010	0.63	6.5	--	UWYO
11/09/2010	0.52	7.9	133	USGS
11/28/2010	0.64	7.1	--	UWYO
12/8/2010	0.56	7.2	122	USGS
12/14/2010	0.64	10.1	--	UWYO
1/5/2011	0.19	7.2	71	USGS
1/21/2011	0.45	5.3	--	UWYO
2/10/2011	0.35	5.9	122	USGS
2/23/10	0.47	7.8	--	UWYO
3/9/2011	1.60	8.1	308	USGS
3/16/10	0.42	8.58	456	UWYO

*USGS data taken from http://wy.water.usgs.gov/projects/qw/index.htm

Table 3.3. Heat flux and potential ice suppression for Barber Creek and Pumpkin Creek based on USGS discharge measurements during winter 2010-2011.

Date	Discharge Period (days)	Water Temperature (°C)*	Discharge (cfs)*	Discharge (m^3s^{-1})	Heat Flux per Day (kJ day^{-1})	Ice Suppression (m^3day^{-1})
Barber Creek upstream of mouth						
2010/11/01 to 2010/11/22	22	20.5	3.9	0.11	8.19E+08	2700
2010/11/22 to 2010/12/20	28	19.5	2.8	0.079	5.59E+08	1800
2010/12/20 to 2011/01/09	20	18.8	5.1	0.14	9.82E+08	3200
2011/01/09 to 2011/02/22	38	21	5	0.14	1.08E+09	3500
2011/02/22 to 2011/03/15	21	21	5.3	0.15	1.14E+09	3700
Pumpkin Creek						
2010/11/01 to 2010/11/09	9	1.5	3.2	0.09	4.92E+07	160
2010/11/09 to 2010/12/08	29	9.4	2.9	0.082	2.79E+08	920
2010/12/08 to 2011/01/05	28	4.5	3.2	0.091	1.48E+08	480
2011/01/05 to 2011/02/10	33	3.1	2.3	0.065	7.30E+07	240
2/10/2011 to 2011/03/15	33	2.8	2.8	0.079	8.03E+07	260

*USGS data taken from http://wy.water.usgs.gov/projects/qw/index.htm

Table 3.4. Comparison of areas of open water to magnitudes of CBM water discharge

Confluence Site	Average Water Discharge (cfs)	Lead Length (km)	Average Width of Lead (m)	Approx. Area of Open-water (10^3m^2)
Burger Draw	0.75	Approx. 1	3	3
Beaver Creek	5.0	Approx. 3	7	21

Table 3.5. A summary of the maximum fill and scour depths, and change in width for all the cross sections over the two survey periods

Date:	9/8/2010-12/14/2010			12/14/2010-1/21/11			1/21/11-3/15/11		
Cross Section #*	**Max Fill Depth (m)**	**Max Scour Depth (m)**	**Δ Width (m)**	**Max Fill Depth (m)**	**Max Scour Depth (m)**	**Δ Width (m)**	**Max Fill Depth (m)**	**Max Scour Depth (m)**	**Δ Width (m)**
BC1	0.3	0.25	0.1	0.2	0.35	0.5	0.15	0.3	0.5
BC2	0.1	0.15	0	0.1	0.22	0.25	0.05	0.15	2
BC3	0.1	0.18	0	0.05	0.15	0	0.1	0.1	2
BD1	0.05	0.2	0.25	0.05	0.15	0.1	0	0.25	0
BD2	0.025	0.18	0	0.02	0.1	0.5	0.12	0.25	0
BD3	0.15	0.25	0.75	0.05	0	0.25	0.1	0.25	3
BD4	0.17	0.2	0	0.23	0.1	0.25	0.3	0.45	0.25

*BC is Beaver Creek, BD is Burger Draw

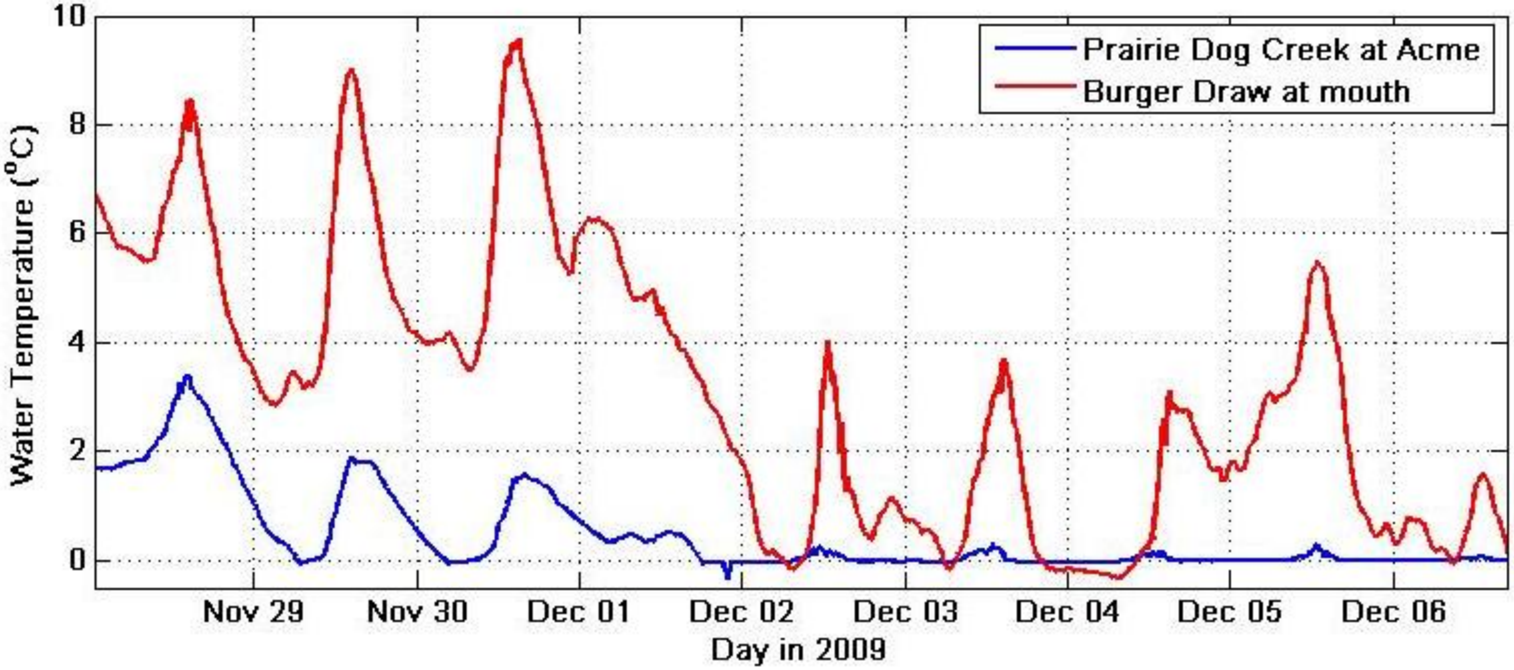

Figure 3.1. Plot of water temperatures in *Prairie Dog Creek at Acme* and *Burger Draw at mouth* during freeze-up in 2009. The Prairie Dog Creek temperature record is typical for the freeze up period for many small Wyoming streams. By contrast, the effect of warm CBM product water discharge into Burger Draw is indicated by the elevated temperatures in the temperature record for this stream.

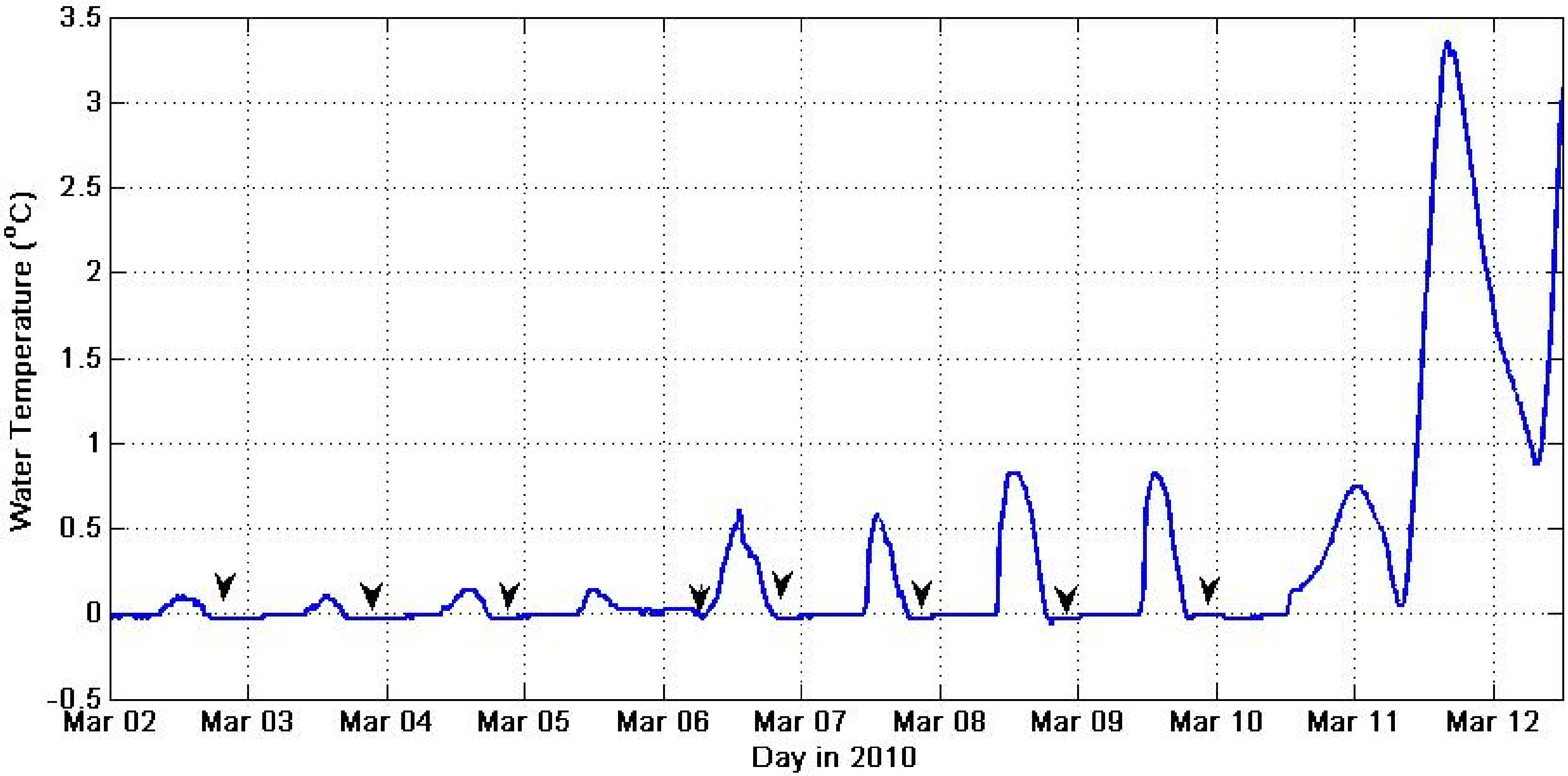

Figure 3.2. Temperature record for *Prairie Dog Creek at Acme* during the spring melt period. Water temperatures during the melt period are the mirror image of freeze-up temperatures; i.e., mid-day temperature peaks are small during the early part of the melt season, and increase in magnitude as air temperatures warm and ice melts. The black arrows mark supercooling periods, when the potential existed for frazil and anchor ice formation. Supercooling of the water column indicates significant amounts of open water and frigid night time air temperatures.

Figure 3.3. An anchor ice dam on Prairie Dog Creek, March 4, 2010. The vertical culvert pipe and cableway about 50 m in the background mark the position of the USGS gaging station, Prairie Dog Creek Acme (06306250). The anchor ice dam formed at night and was in place long enough for a thin layer of border ice to form on the backwater created by the dam.

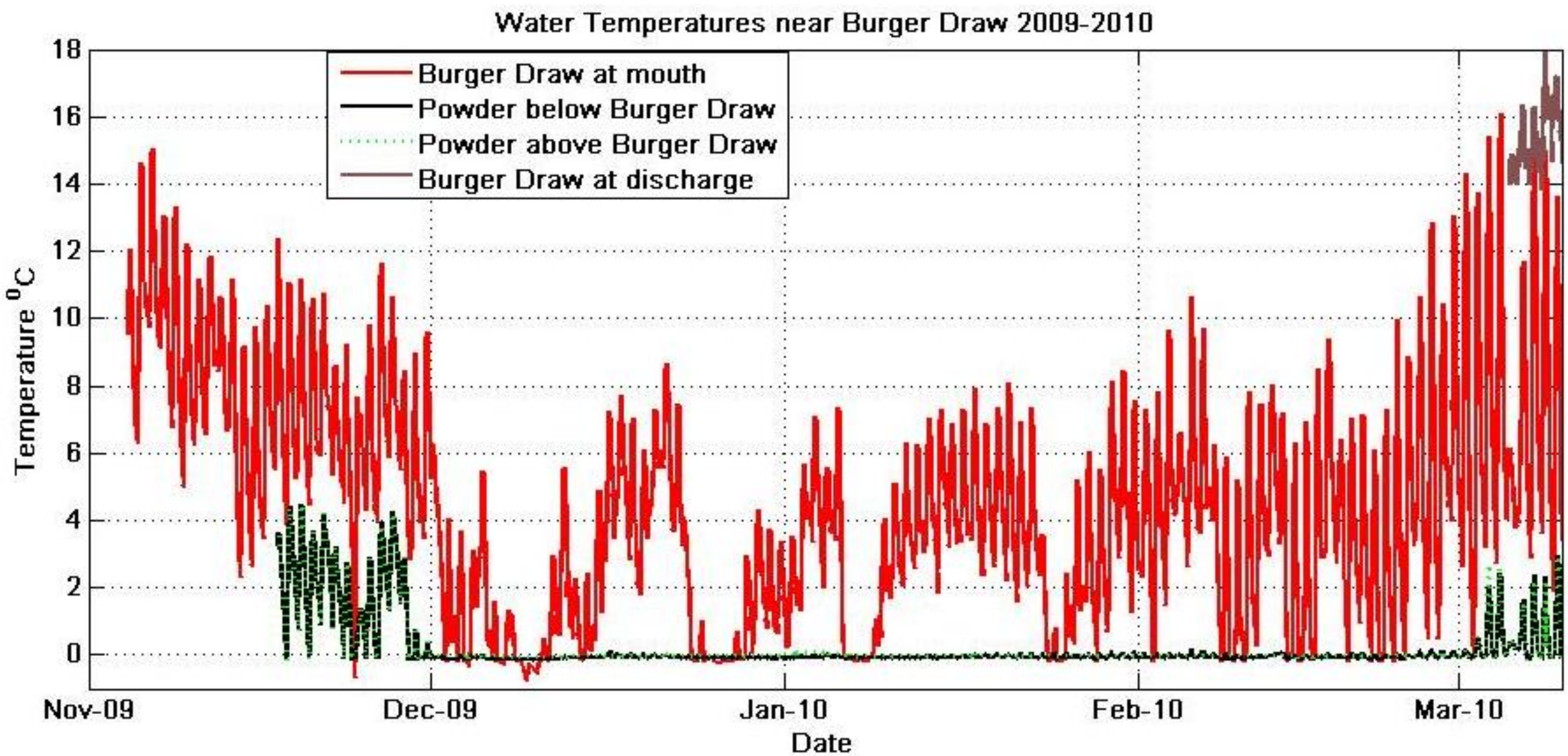

Figure 3.4. Water temperatures for Burger Draw and the Powder River near Burger Draw during the 2009-2010 ice season. The temperature record for *Burger Draw at mouth* (red) reached freezing several times during the winter, when air temperatures were very low. Generally, the Burger Draw water temperatures stayed well above freezing, and as a result this stream transmitted a significant amount of heat to the Powder River throughout the winter. Consequently, a series low-amplitude temperature spikes can be seen in the *Powder River below Burger Draw* temperature record from December through February, when ice was present on the Powder River. The *Burger Draw at discharge* temperature record, established on March 4, 2010, is a short record of the Burger Draw water temperature measured directly below a major discharge point, estimated to contribute >50% of the total flow to Burger Draw, located 1000m upstream of *Burger Draw at mouth*. Water temperatures at this discharge point remain well above 10^{o}C, but the water cools substantially during passage down Burger Draw.

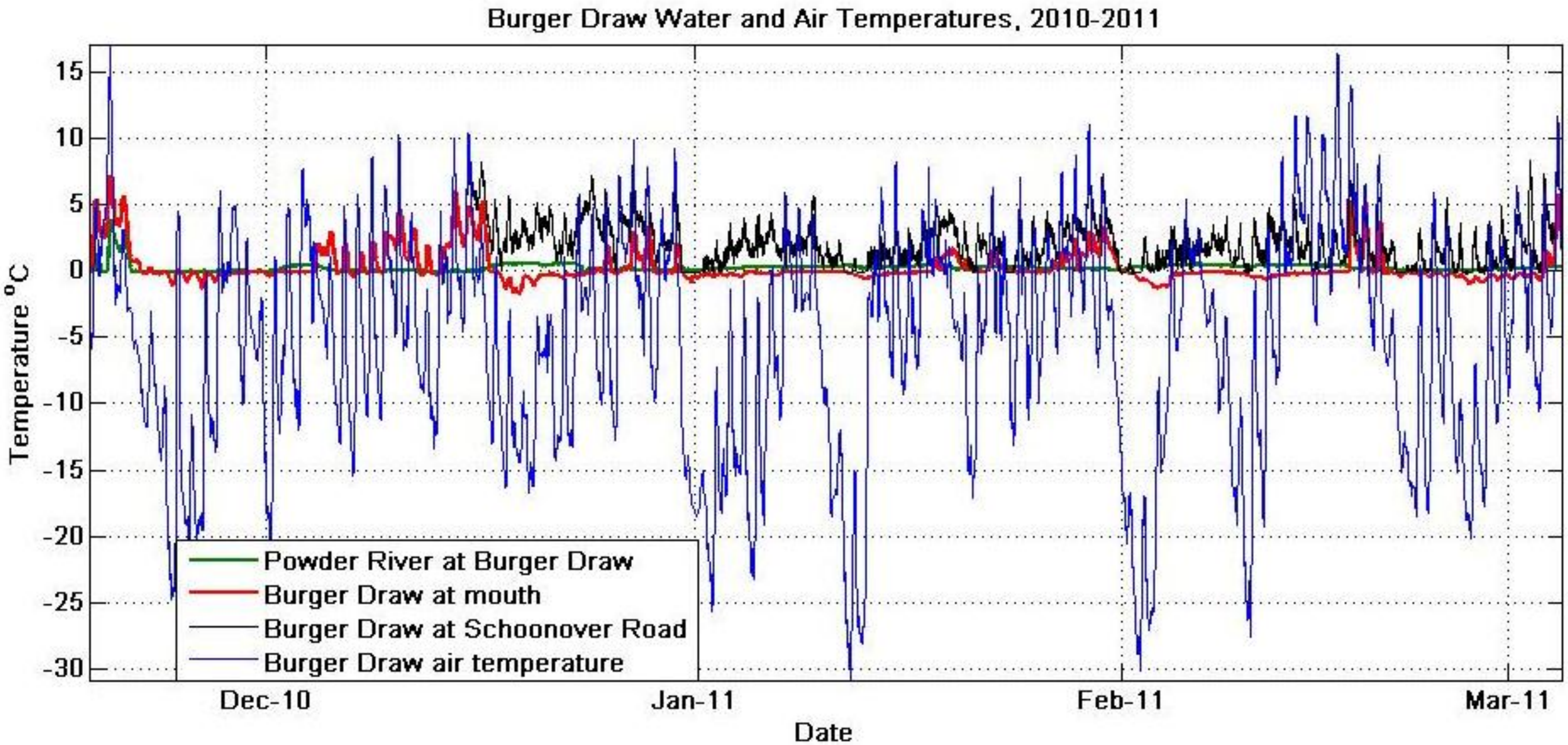

Figure 3.5. Winter water and air temperatures for Burger Draw and Powder River downstream of Burger Draw for the 2010-2011 ice season. During this season, the *Burger Draw at mouth* (red) data logger became encapsulated in ice near the start of the season. This ice grew to the stream bed at the data logger location, which caused the majority of Burger Draw flow to shift away from the data logger location, resulting in below-freezing temperature recordings during cold weather periods. As a result, it is not possible to calculate heat flux from Burger Draw to the Powder River for the 2009-2010 ice season. The *Burger Draw at Schoonover Road* sampling site is located 1200m above *Burger Draw at mouth*, and 500m below the first major discharge point on Burger Draw (which was moved during the summer of 2010).

Figure 3.6. The staff gage at *Burger Draw at mouth*, a water temperature logging station located 50 m from the mouth of Burger Draw. The ice accumulation (aufeis) shown here is exceeds 30cm in thickness, and extends outside the natural channel boundaries.

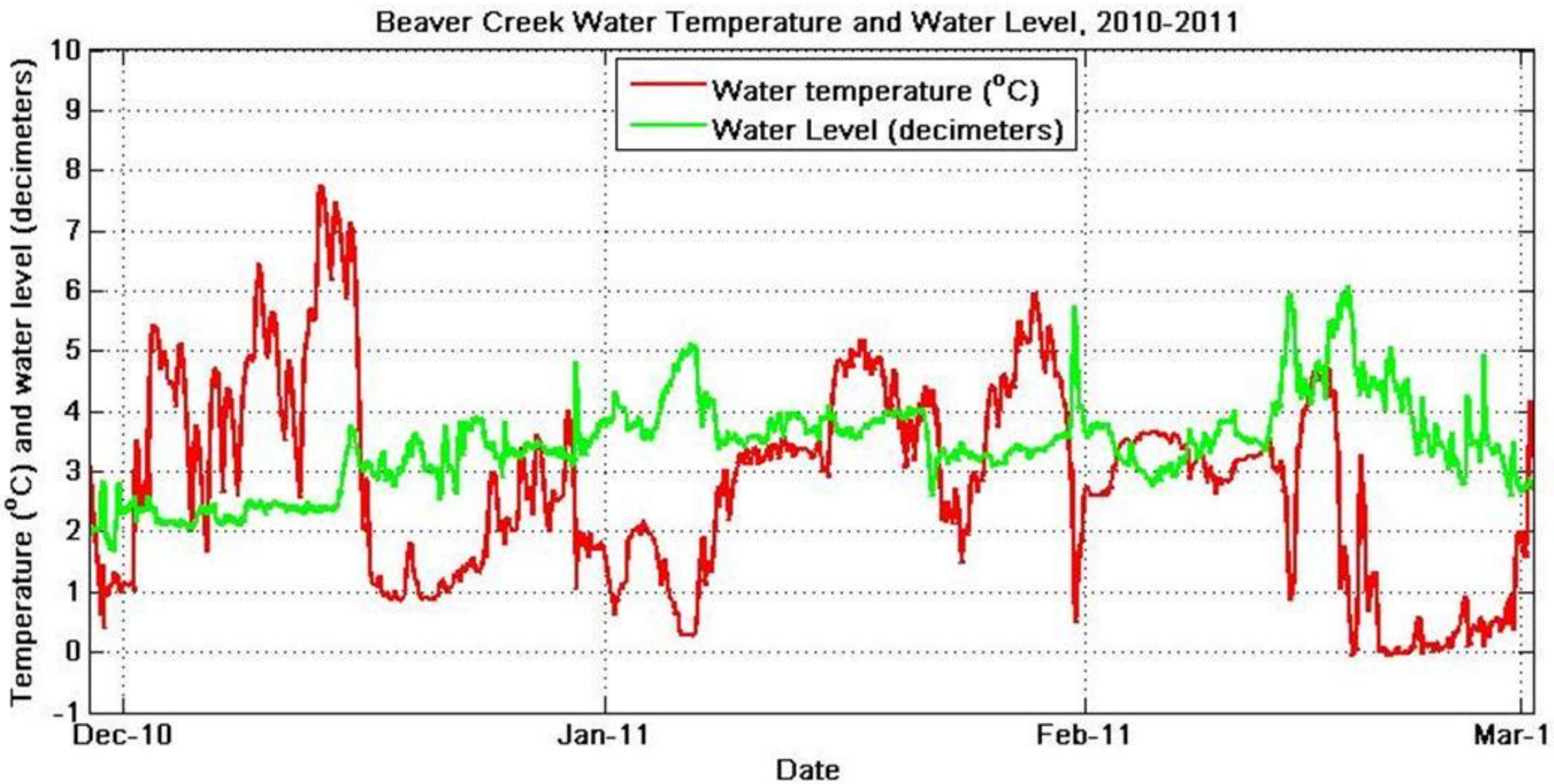

Figure 3.7. Beaver Creek water level and water temperature near the mouth of the Powder River during the 2010-2011 ice season. Water temperatures near the mouth of Beaver Creek stayed above freezing except for a 10-day cold snap at the end of February (see Figure 3.5 for local air temperatures). Water level generally rose during rapid temperature drops, indicating formation of surface ice covers and, potentially, anchor ice dams or over-flooding of the ice, which was observed during field visits in January and February.

Figure 3.8 TOP: Frozen surface of Beaver Creek on February 23, 2011. Water level along this stream section is reduced because of an anchor ice dam that formed by bluff in background of picture. BOTTOM: February 23, 2011 anchor ice dam about 50m upstream from the position where the top picture was taken. The anchor ice dam is creating a backwater. Evidence of water levels up to 25cm above the present water level is seen in the perched ice remnants along the right hand side of the creek. This higher water level completely filled the creek channel, as can be seen in the matted-down vegetation on the left side of the photograph. Flow is towards the viewer in both images.

Figure 3.9 TOP: Powder River below Beaver Creek January 21, 2011.The open-water lead visible along the (river) right bank of the Powder River is the result of warm CBM discharge from Beaver Creek, visible in the center of the picture. The researcher visible on the river ice is drilling holes for cross-section surveys, ice thickness measurements, and current meter measurements on cross section BC1. Cross sections BC1 and BC2 were located just downstream of the Beaver Creek/Powder River confluence (Figure A1.1), while BC3 was upstream of the confluence. The open water lead in this figure is about 6m wide; flow is toward the viewer.

Figure 3.9 BOTTOM: View of open water lead on Powder River downstream of Beaver Creek on January 21, 2011. This photograph was taken from the same positions 3.9 TOP, the photographer simply turned downstream to take this picture. This open water lead extended more than 1.1km downstream of the Beaver Creek confluence on this date.

Figure 3.10. Cattle using the open water lead on the Powder River below Burger Draw as a water source on February 23, 2010. The ice was thick enough right up to the edge of the lead to support the cattle.

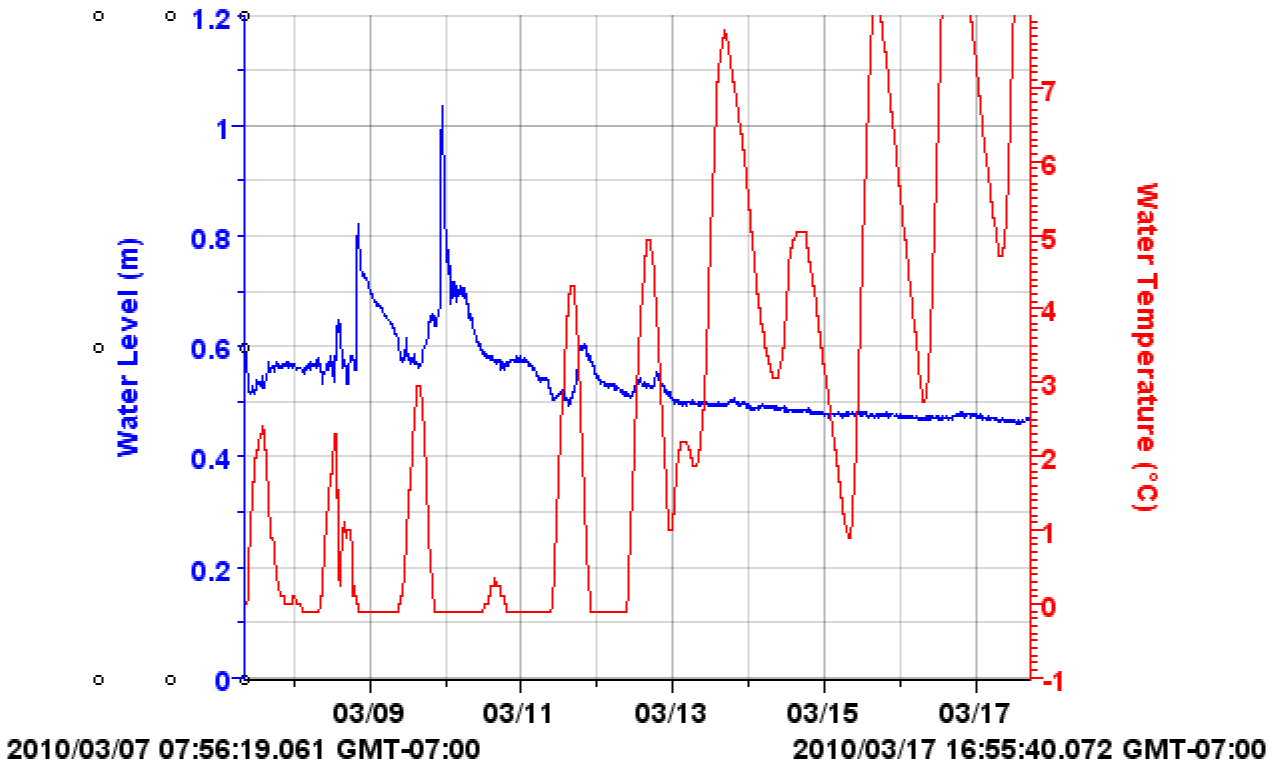

Figure 3.11. Water level and temperature for the *Powder River below Burger Draw* station, in early March, 2010. The steep rises in water level on during the nights of March 8 and 9 were probably driven by anchor-ice formation raising local stage or by formation of an anchor-ice dam downstream. By March 4 there was substantial melting of the ice cover from this location upstream to Beaver Creek, which would have enhanced night-time anchor ice formation. Powder River water at this site did not cool to freezing after the night of March 11, 2010, suggesting that all ice was off the river by this time.

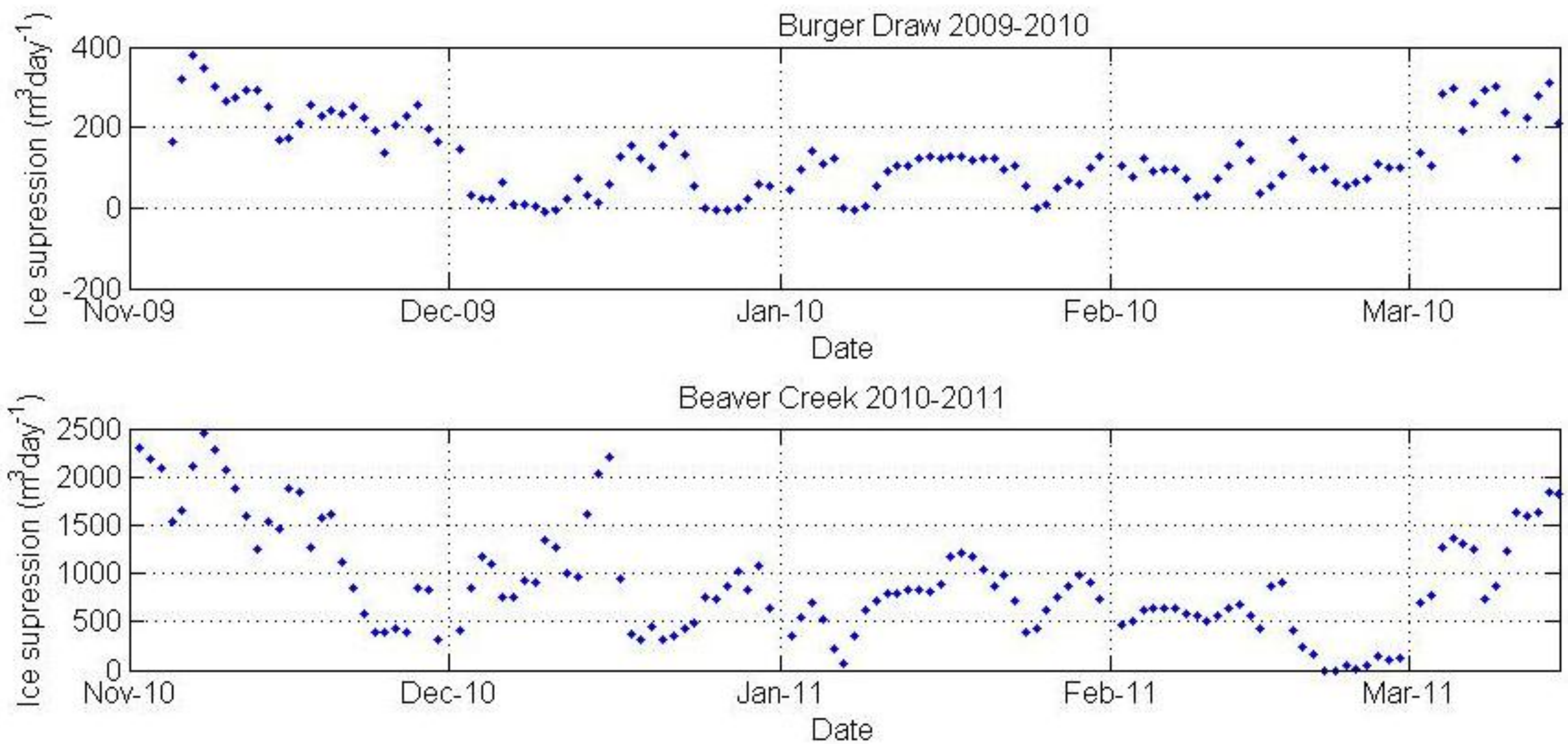

Figure 3.12. Daily ice suppression in Powder River caused by CBM product water heat delivered by Burger Draw (top) and Beaver Creek (bottom). The maximum ice suppression at Burger Draw was 380m^{3}day^{-1}, while Beaver Creek has a maximum ice suppression of 2450m^{3}day^{-1}. The large, almost continuous heat flux supplied by these drainages maintained open water leads downstream of confluences throughout the two winters of the study

4. DISCUSSION

To place the survey findings in an overall context of river ice formation in alluvial channels, it is useful to discuss them briefly in terms of ice effects on rivers and their banks, and relate the context to processes generally observed in the Powder River.

Channel response to ice-cover formation, and concomitantly with the inflow of relatively warm tributary water, soon becomes complicated, especially for a fully alluvial channel. Changes in channel thalweg alignment, channel width, the statistical properties of bedforms may occur in response to diverse changes in boundary resistance, flow rate and sediment supply. Some evidence exists that ice may influence mid-scale features of alluvial channels (e.g., Zabilansky et al. 2002). For example, ice jams may lead to meander-loop cutoffs. However, at this scale, ice effects are still subject to considerable hypothesis. At the local (or survey site) scale it is possible to identify several mechanisms whereby ice may hasten bank erosion and channel shifting. Two such mechanisms, for example, are flow concentration beneath an ice cover and bank/bed gouging by an ice run. Yet, questions remain as to whether these mechanisms prevail over other processes and conditions, and as to exactly how they work. Flow concentration was observed at the two study sites, especially along the open water leads (BC1, BC2, BD1, BD2 and BD3 cross sections, Appendix 1) when an open water lead was present. However, flow concentration was also seen on March 15, 2011 at cross section BC3, upstream of the Burger Draw confluence. This last flow concentration was caused by a rubble ice accumulation on the right portion of the river channel. All of these flow concentrations resulted in widening of the river channel at these locations through bank erosion.

The only prior study that examined how the seasonal appearance and disappearance of river ice perturbs the bathymetry, and thereby stability, of alluvial channels subject to frigid winters, is the survey study conducted by Zabilansky et al. (2002). It examined how the Missouri River downstream of Fort Peck Dam responded to the wintertime release of water from Fort Peck Dam. Their study reported similar observations to those noted for the present study. The literature regarding ice impacts on alluvial channels is sparse and rather inconclusive. A brief review of it ensues.

4.1 River Ice Effects on Channel Morphology

Several factors enable river ice to influence alluvial channel bathymetry. Most of them are explainable in terms of the ensuing functional relationship between a dependent variable, such as hydraulic radius of flow, R, and the typical set of independent variables for alluvial channels;

$$R = \mathrm{f}_R\left(Q, Q_s, \rho, \nu, d, \sigma_g, \rho_s, g\Delta\rho, B, S_o\right) \quad (8)$$

Here, Q and Q_s are inflow rates of water and bed sediment, respectively; d, σ_g, ρ_s, and $g\Delta\rho$ are bed sediment diameter, geometric standard deviation (a measure of sediment-size distribution), density, and submerged unit weight, respectively; B is channel width; S_o is channel slope; and, ρ and ν are water density and kinematic viscosity, respectively. Other dependent variables of practical interest are channel width, average depth, shape, sinuosity (ζ), flow-energy gradient (S), and sediment-transport capacity (Q_{sc}). Significant changes in any of the independent variables in Eq. 8 may alter R, ζ, or Q_{sc}, and may destabilize the alluvial reach. The greatest natural disturbances typically result from changes in Q, or Q_s, which usually vary seasonally.

The seasonal appearance and disappearance of river ice expands and modifies the set of hydraulic variables in Eq. (8) in a somewhat periodic manner, with the annual cycle of winter. The extents to which ice affects important dependent variables, such as R, ζ, or Q_{sc}, are unclear for alluvial channels. Several qualitative aspects of river ice are clear, however. River ice modifies flow resistance. It exerts hydraulic and geomechanic influences that act over a range of scales in space and time. And, as to be expected, influence impact increases with decreasing channel stability under open water conditions.

A relatively long, level ice cover, for instance, practically doubles the wetted perimeter of flow in a channel, thereby significantly increasing the boundary resistance exerted on the flow. Ice accumulated as an ice jam increases flow resistance by locally constricting flow. Increased flow resistance typically results in increased flow depth, altered flow distribution, and reduced flow drag on the bed - at least for fixed-bed channels. For a given channel, ice impacts on channel bed and banks increase in significance as water discharge, Q, increases. Sediment entrainment and transport increase with increased flow in an ice-covered channel as with an open-water channel. Increased flow also increases the velocity of moving ice and increases the possibility of over-bank flow. River-ice influences likely become more significant when water discharge fluctuates appreciably; then, the prospects for other adverse ice influences increase, such as ice-cover break up followed by ice jamming.

The variables in Eq. (8) suggest that river ice may exert the following hydraulic influences on a channel reach:

1. Through its effects on lateral distribution of flow resistance and, thereby, flow and boundary drag, river ice may modify channel cross-sectional shape developed under open water-flow conditions. This channel response was observed for the cross sections at Beaver Creek and Burger Draw;
2. By imposing additional flow resistance, river ice diminishes the effective gradient of flow energy available for sediment transport and alluvial-channel shaping. It may consequently alter channel-thalweg alignment. This study indicated a thalweg change,

though further field work over a longer channel reach is needed to confirm this response. Also, it is not clear whether the observed thalweg change is the result of ice-cover formation or maintenance of an open water lead downstream of the tributary channels during the ice season.

3. By reducing the sediment-transport capacity of a reach, river ice redistributes bed sediment along the channel. Whatever local-scale effects river ice may exert in accentuating erosion, river ice reduces the channel's overall capacity to convey the eroded sediment a significant distance from the erosion location. Consequently, bars may develop in response to flow conditions under river ice, and then be washed out shortly after the cover breaks up. In situations where a significant load of bed sediment enters a long reach, river ice may tend to cause mild aggradation[4] of the channel it covers. Although there was limited fill in some portions of some of the cross sections during the ice survey (Appendix 1) little or no aggradation was evident. The largest fill volume occurred between the afternoon of March 15 and the morning of March 16, 2011 on the BC2 cross section. The ice had essentially all melted at this point, and stage had risen. The surveyed Powder River cross sections (Appendix 1) indicate no aggradation, likely because flow magnitudes along the river were not of sufficient magnitude to convey sediment, except along the open water lead and in the outer bends of the channel. Moreover, because the flow had scoured the channel to exposed rock in several locations, the river was not conveying bed sediment at its capacity.
4. At times of ice-cover formation and break-up, congestion or jamming of ice at one channel (or sub-channel) location may divert flow into an adjoining channel, which then enlarges (channel anabranching[5] and thalweg avulsion), or over-bank, which may result in a channel cutoff (avulson[6]). This phenomenon was not observed to fully occur at the survey sites, but the propensity for it was inferred by the ephemeral accumulations of ice (e.g., anchor ice congestion at the Beaver Creek site, and ice-cover break-up at both study reaches). A small ice jam was observed at the location of BC3 on the morning of March 15. This jam covered about three quarters of the river channel from the right bank, concentrating flow along the left bank. This jam was gone by late afternoon the same day. Another small ice jam was observed about 10km downstream of the Beaver Creek confluence on March 16, 2011. This jam created a riffle, but its effect on channel morphology is not known. Moody et al (2009) report significant ice jam formation along a study reach on the Powder River located near the Montana border.

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[4] Aggradation refers to deposition of bed sediment in a manner that elevates the channel bed and steepens its overall slope.

[5] Anabranching refers to a sub-channel that diverts away from the main channel then merges with it.

[6] Avulsion refers to the cut-off of a tight channel loop or a meander bend.

4.2 River Ice and Thermal Effects on Channel Banks

River ice may influence channel bathymetry through several geotechnical influences it potentially exerts on channel riverbanks:

1. Freeze-thaw thermal weakening of riverbank soils. This was observed during the two winters of site survey as vertical cracks forming on the floodplain and on bluffs flanking the river. The riverbanks would later fail along the cracks, sloughing sediment into the river. No quantitative measurements were taken to document weakening, however;
2. Reduce riverbank strength by increasing pore-water pressure or by producing rapid drawdown of the riverbank water-table during dynamic ice-cover or ice-jam breakup. Survey measurements documented changes in stage associated with ice-cover formation and break-up. Relatively large stage changes occurred at the *Beaver Creek upstream of mouth* site, with rapid stage changes of up to 25cm (Figure 3.7) recorded during cold spells throughout the winter, but no evidence of bank failure was seen in this portion of Beaver Creek. At *Powder River below Burger Draw* water rose nightly over several days in early March, 2010, and dropped down again during daylight hours. These nightly rises peaked on the night of March 10, 2010, with a water level increase of 0.47m (Figure 3.11). The rapid rise at night, followed by drop during the daytime, suggests anchor ice formation backed up the flow in this region. Field notes for the March 6 visit indicate that there was already continuous open water channel about 10m wide from Beaver Creek to an unknown distance past Burger Draw on this day. This channel was bordered by ice attached to the banks. The fact that water no longer reached the freezing point after the night of March 11 suggests that all the ice was off the river by this date. The rapid rises and falls may have affected bank stability. However, it is important to note that this ice-associated water level rise is not directly associated with the discharge of warm CBM water from Beaver Creek 100m upstream. Anchor ice formation and ice jams both occur regularly in rivers without CBM input, so the water level rises seen here probably would have occurred regardless of warm-water input;
3. Tear and dislodge riverbank material and vegetation during collapse of channel-bank-fast ice. It was observed that ice cover break-up sometimes resulted in the removal of grass-cover along the channel bank;
4. Gouge and abrade channel-bank material and vegetation during an ice run. Ice break-up along the Powder River occurred fairly gradually over a several day period for the two winters of survey. Therefore, no significant gouging or abrasion of the channel banks was observed.

In general terms, the foregoing influences reduce channel-bank resistance to erosion, increase the local supply of sediment entering a channel, and can promote lateral shifting of channel. The first two influences are not well studied. The third and fourth have received a little attention, but the extents to which they affect channel morphology is unclear. The observations at the survey sites augment those reported by Zabilansky et al. (2002) for the Missouri River. For both studies, the channel banks flanking the river were formed of relatively weak, easily erodible sedimentary rock.

4.3 Approaches to Management of CBM Water Discharge

Besides augmenting water flow in the Powder River, the principal visible effect of CBM product water discharge into the river at the two sites surveyed, and at other sites informally observed, was the formation of open water leads immediately downstream of locations where CBM product water discharged into the Powder River. The surface area associated with each lead was found to scale in proportion to the magnitude of CBM water discharged into the river, for the same prevailing values of initial CBM water temperature and air temperatures; larger CBM water discharges result in larger open water leads. In a similar fashion, increased water temperatures at constant discharge also increases open water lead areas. Important questions to be considered are the significance of lead formation, and, if the effects are determined to be adverse, the options for minimizing lead formation.

The study shows that the formation of open water leads may influence the following aspects of the Powder River at the sites:

1. The formation and stability of the river's ice cover;
2. The alignment and stability of the river's largely alluvial channel (the channel is not fully alluvial in some reaches, because exposed sandstone bedrock is encountered at in some bed and bank locations); and,
3. The wintertime ecology of the river.

For the sites studied during the winters 2009-2010 and 2010-2011, the present study showed that lead presence locally affected ice-cover formation and channel bathymetry, but did not greatly disrupt them. The present study did not examine how an open water lead might influence the wintertime ecology of the sites, or river as a whole. The similar study by Zabilansky et al. (2002) also did not consider ecological effects resulting from the formation of open water regions along the Fort Peck reach of the Missouri River, but anecdotally noted that such regions seemed to attract fish and birds during winter.

The ecological effects associate with the thermal aspects of CBM product water discharge, lead formation, or mixing with river flow are largely unknown, or analytically substantiated. There appears to be no prior study that has examined these effects. Observations during the two winters noted that the open water leads served as places for animals (both domestic and wild) to drink. Geese and ducks were observed on the leads in February of both years, when the rest of the Powder River was frozen. Finally, small fish were regularly observed right at the confluence of Burger Draw throughout both ice seasons of this study. These admittedly anecdotal observations suggest wildlife might concentrate around leads during the winter months.

Should further consideration indicate the need to decrease the extent or number of open-water leads in the Powder River, Eqs (1) through (6) provide a theoretical framework for determining how to do so. These equations indicate that the following straightforward actions reduce lead size:

1. The length and width of the lead reduce in direct relationship with reductions in the amount of heat entering the river. Eq. (5) directly shows that the amount of heat diminishes when the initial water temperature (T_{wo}) of CBM water at the location of discharge into the river decrease. In frigid winter weather, two methods would decrease T_{wo}:

    a) Lengthen the flow path between the originating source for CBM water (e.g., a CBM discharge point) and the location of eventual discharge into the river.

    b) If feasible, release more CBM water during night time, when air temperatures are normally colder, there is no short wave radiation warming the water (insolation), and water cooling is enhanced by black-body radiation. As shown by Figures 3.4 and 3.5, air temperatures from late afternoon through early morning typically are especially cold (other factors that enhance cooling are also optimal at this time), and therefore cause greatest cooling of CBM water in tributary streams. If this strategy is adopted to control water temperatures entering the Powder River, careful monitoring will be required. It is possible that increased warm water flow at night would increase the potential for ice jams (caused by anchor ice dams or hanging frazil dams) that could increase the flooding potential. The situation in Flat Creek though Jackson, Wyoming as related by Daly (2002) is a cautionary tale in this regard. Warm groundwater was pumped from wells and discharged into Flat Creek to reduce frazil and anchor ice formation thorough the town. The well water did not supply enough heat to Flat Creek to protect the town; instead it just moved the freezing problem downstream.

    c) Increasing the heat flux to air for CBM water while it is flowing from the discharge point to the river. This enhanced cooling of CBM water can be achieved by aerating the flow in a manner that causes it to flow over a small drop-structure or a man-made rock riffle. The increased exposure to air increases the heat transfer coefficient, ϕ, and thereby causes more rapid cooling of CBM water. Some CBM product water is already discharged through a system like this to precipitate solids, increasing the length of the system would allow more heat to be lost to the atmosphere.

d) A combination of actions a) through c).

2. Enhanced transverse dispersion of discharged CBM water across the Powder River channel will result in more rapid mixing of CBM water with the river's flow, and thereby reduce lead size. The formulation of Eq. (1) indicates two ways for increasing mixing and dilution of CBM water:

   a) Increase the transverse-dispersion coefficient, E, in Eq. (1). The results of various laboratory and numerical studies (e.g., Fischer et al. 1979, Rutherford 1994, and Boxall et al. 2002) show that carefully locating discharge locations can maximize the mixing rates in rivers. A discharge located on the outside of a bend produces a faster rate of transverse mixing than does a discharge on the inside of a bend.

   b) Introduce transverse velocities, by means of secondary currents and large-scale turbulence structures. Inclusion of local structure in the channel can promote secondary currents and mixing across the channel.

There is a fine point to consider with option 2. The mixing of two streams of relatively hot and cold water changes the temperature of the combined water mass, but not the heat content. So, heat introduced at a CBM-influenced tributary must still be removed before ice can form. The result of mixing water is to spread the heat out over a larger volume. If the river is ice-free, the larger open water area will efficiently lose heat to the atmosphere. However, if CBM-water supplied heat mixes and spreads out over a large area under the ice cover, the result will be slight melting of the bottom side of the ice cover that comes in contact with the heat-laden water. The Beaver Creek open water lead apparently shows that mixing can have unexpected effects. On most days when surveying the Beaver Creek site during the ice season, a uniformly wide open water lead hugged the right side of the channel. The lead extended about 800m downstream of the creek's confluence with the Powder River. Depending on weather conditions, the lead was 2m to 7m wide and remarkable for its uniform width. Between 800 and 1,000m downstream of the confluence, where the river transitioned from a long-radius left hand meander bend through a short straight reach, the open water lead consistently widened to cover most of the channel width. The straight section of the channel has several large bars that apparently enhance cross-channel mixing and widen the open channel lead. However, the influence of warm Beaver Creek water at this point is still enough to melt essentially all of the ice in the channel for several hundred meters more downstream. This wide open channel area is the zone where the greatest accumulations of anchor ice occurred; it had the greatest amount of anchor-ice rafting and the largest anchor ice dams observed in the study area. Other streams with comparable discharges and heat fluxes, like Barber Creek or Pumpkin Creek (Table 3.3) probably have similar large, wide open water reaches that act as anchor ice factories throughout the winter.

4.4 Impact of Open Water on Winter Fluvial and Ice Processes

The most important outcome of this study is the documentation of long, continuous open-water reaches of water in perennialized tributary streams and in the main stem of the Powder River during winter. This open water is associated with CBM product water discharge points. Considered here are the impacts of such leads.

River reaches without a floating ice cover respond differently to freezing air temperatures than do reaches with an ice cover. Ice-covered river reaches respond by slow thickening of the ice cover. As the ice cover thickens, its insulation value increases, so eventually an equilibrium ice thickness forms on the river surface, ice growth stops, and conditions under the ice become stable. In contrast, when there is a direct connection between the river water and atmosphere (i.e., no ice cover), river water supercools causing frazil and anchor ice form. These ice types can create anchor ice dams (Figures 3.3 and 3.8), raise stage significantly (Figures 3.7 and 3.11), and increase ice-rafting erosion of coarse-grained sediment from the reach's channel bed (Table 3.1). In addition, in small, shallow perennialized streams cold snaps can lead to aufeis formation and local flooding (Figure 3.6). In short, formation of a floating ice cover leads to stable conditions in a river, whereas inhibiting ice cover formation creates very dynamic conditions. The present study documents two types of dynamic conditions observed in the Powder River and its tributaries.

1. The formation of frazil and anchor ice; and,
2. The dynamic nature of the ice cover forming on both the Powder River and its tributary streams.

The dynamic nature of the surface ice cover is seen in the expansion and contraction of open water leads with fluctuating weather conditions (primarily air temperature). Very cold conditions eventually result in closing of open water leads and even growth of ice covers in tributary streams (possibly with local flooding when the ice cover forms). Ironically, the same conditions that close leads also promote dynamic ice frazil and anchor ice formation that result increased stage and ice rafting. When the weather warms, the flux of CBM-supplied heat quickly re-establishes large open water areas, resulting once again in dynamic frazil and anchor ice formation. It should be stressed that CBM-generated open-water leads do not create un-natural ice types. Frazil and anchor ice occur commonly in many Wyoming streams, as illustrated by Prairie Dog Creek. Instead, the maintenance of substantial open water leads throughout the winter creates conditions that cause frazil and anchor ice to form through the entire winter, rather than their normal occurrence during a few days in the spring and fall.

This study focused on ice conditions and channel responses around Burger Draw and Beaver Creek. However, there are at least five CBM discharge points between Pumpkin Creek and Barber Creek, a distance of about 40 river kilometers, encompassing the four creeks and a direct discharge point about 9km below Burger Draw that maintains an open water lead for more than 1km downstream. Table 3.4 shows measured discharges and water temperatures for Barber Creek and Pumpkin Creek during the 2010-2011 winter season. Both creeks contribute significant heat to the Powder River. Barber Creek, in particular, with measured temperature near the mouth consistently above 18°C (Table 3.4) transports significant heat to the Powder River throughout the entire winter season. Based on the scaling laws discussed in Section 3 (Formation of open water leads in the Powder River), the open water lead downstream of the Powder River/Barber Creek confluence should be significantly larger than the one observed on Beaver Creek, with a concomitant increase in persistent frazil and anchor ice formation. The large size of the Barber Creek open water lead was confirmed by observations from USGS personnel (Eric Blajszczak, USGS, personal communication). The presence of so many warm water discharge points over a relatively short river stretch may have multiplicative effects not recognized in this study.

This study documented changes to the channel bathymetry associated with open-water leads, and finds that the changes are hard to distinguish from effects attributable to ice jams and large, ice-free flows in the channel. It is noted, though, that flooding caused by anchor ice formation can be a serious problem in developed areas (Daly 2002).

It was beyond the scope of this study to address biological impacts. However, there is a growing body of literature indicating that the dynamic conditions associated with frazil and anchor ice create harsh conditions for fish that may lead to increased mortality (Brown et al. 2011, Lindstrom and Hubert 2004, Simkins et al. 2000, Stickler et al., 2008). (The authors highly recommend Brown et. al., 2011 for an informative review ice processes and stream-dwelling fish.) Based on the unique assembly of fish found in the Powder River and the environmental stresses they are exposed to in summer (Senecal 2009), the results of the present study strongly indicate the need for further study of the effects of CBM-product-water generated open-water leads on the biological community in the Powder River.

5. CONCLUSIONS AND RECOMMENDATIONS

The present study examined the extent to which the discharge of warm CBM water into the Powder River drainage during winter flow conditions influenced the Powder River. Its principal objectives were to:

1. Determine if discharge or relatively warm CBM product water had any effect on ice conditions in the Powder River Basin
2. Determine the effects of CBM water discharge on local ice conditions in the Powder River at two representative sites during winter; and,
3. Evaluate if CBM water discharge, by virtue of influencing ice conditions, affects channel morphology in the Powder River.

The first year of the study was entailed a preliminary survey of the area and ice conditions. Two streams, Burger Draw, which consisted entirely of CBM product water discharge, and Prairie Dog Creek, which had no CBM influence, were chosen for the first year of the study. Prairie Dog Creek was examined to gain insight into the winter regime of small, natural stream in the

Powder River basin. These streams were relatively far apart (about a 1.5 hour commute), making it very difficult to visit both sites in one morning. During the second year of the study, two streams were again chosen for more detailed study. The Burger Draw and Beaver Creek sites were chosen because they were located accessibly close to each other, flows in both creeks consisted of CBM product discharge water, and they differed in discharge by about one order of magnitude.

5.1 Conclusions

The study's conclusions provide useful information addressing its objectives. Though limited to site surveys conducted at three sites during two winters, 2009-2010 and 2010-2011, they provide information of use to agencies and industries involved in CBM recovery and managing CBM water discharge. The insights have direct relevance to all rivers subject to frigid winter conditions.

The study's main conclusions are:

1. Besides adding to the flow of water in the Powder River, the most visible influence of CBM product water discharge is the formation of open water leads extending along a channel bank typically for the order of one or more kilometers along the Powder River. The observed leads were, on average, three to seven meters in width, and formed because of heat conveyed by CBM water entering the river. For constant values of air temperature and CBM water temperature discharged, the surface area of the open water leads scales with the discharge rate and temperature of CBM water.
2. The open water leads comprise a form of density current when the discharging CBM water has greater density than the water flowing in the Powder River. For example, this situation prevails when CBM water is at $4^{o}C$. The leads comprised essentially a buoyant current when CBM water is lighter than water flowing in the river. For example, this situation prevails when CBM water is at $15^{o}C$. For both currents, the leads maintain their form in part because the leads are flanked by a channel bank. At some locations along the river where the channel thalweg crosses from one side of the channel to another, notably when the thalweg switches from one outer bend to another, the current may pass under an ice cover, emerging a short distance downstream.
3. When an open water lead passed by a bank irregularity such as a rock outcrop or bar, the local flow structure at the irregularity created secondary currents that disrupted and dispersed the lead, which caused widening of the lead.
4. The presence of an open-water lead caused small adjustments in the Powder River channel bed that eroded the bed and at times also resulted in channel bank failure. The maximum depth of winter bed scour was about 0.25m, and bank erosion at most caused a 2m lateral shift of the channel. Presently, it is unclear whether deeper bed scour

would have occurred had flow in the Beaver Creek open water lead not eroded the bed down to the sandstone bedrock. The banks directly downstream of the Burger Draw and Beaver Creek confluences are did not have plant covers, indicating recent deposition of the sediment. These unvegetated banks experienced the greatest erosion measured in the cross section surveys.

5. With the upstream movement of the lower-most Burger Draw discharge point during the summer of 2010, the amount of time CBM product water had to cool down effected the amount of open water it created on the Powder River. A possible approach to control the amount of open water that direct CBM water discharges have on the Powder River (or any other river) would be to increase the time CBM product water is exposed to the atmosphere before it is discharged into the main river. This approach could be achieved by increasing CBM product water transit time in tributary drainages or by holding water in settling ponds before discharging in the perennialized drain channels.
6. The discharge of CBM water predominantly along the observed open water leads resulted in an incomplete ice cover formation over the Powder River at the survey sites. The cross-channel ice cover thickness was little affected by flow along the lead, though some thinning occurred very close to the lead. The cover did end abruptly at the edge of the lead. This finding adds credence to the supposition that the leads comprise a density or buoyancy current that undergoes little transverse mixing. The CBM discharge did not affect the overall thickness of the ice cover; the ice cover near the lead was as thick as upstream of the lead. Saraaf (1990), for example, modeled thermal effluent discharged into a river. The model results, confirmed with field studies in the Mississippi River, showed that warm water can be transported long distances under an existing ice cover at the downstream ends of open water lead, resulting in thinning of the ice in this region.
7. The open water leads were observed to be places where wildlife drink and feed during winter.
8. The influences of warm CBM water discharge into small tributary drainages in the Powder River basin is striking. The CBM water provides a warm perennial flow to many such streams, and thereby dramatically alters ice formation in them. CBM product water also significantly increases the total average Powder River discharge during winter months.
9. A framework for identifying how to manage lead formation readily is evident from the formulation of heat loss in open-water flow, as indicated by Eqs (1) through (6). Lead size can be reduced by several actions that decrease inflow water temperature and promoting greater transverse mixing across the river.

5.2 Recommendations for Further Research

The present study, essentially an exploratory survey, prompts several recommendations for further research:

1. An effect only casually observed during the site surveys concerns the biological aspects of warm CBM water discharge into the Powder River. The open water leads formed by CBM discharge evidently attracted animals for drinking and possibly feeding. As CBM-induced open water leads appear to be a major wintertime ecological feature of the Powder River, a useful further research will be to ascertain the ecological implications of such leads;
2. It will be useful to determine the overall extent and frequency of open-water lead formation along the Powder River during winter. The present study focused particularly on two sites having CBM discharge. Casual observation of the river at other sites indicated that leads consequent to CBM-water discharge are frequent features of the middle portion of the Powder River during winter and are a significant feature of winter fluvial and ice processes along the river. If CBM water discharge adds about 33cfs to the rivers erstwhile flow of 100cfs, open water lead formation is likely to be substantial;
3. Casual observations of CBM water discharge at a few sites identified late in the present study indicate larger lead formation than observed at the two survey sites. Useful additional research will be to more closely study CBM water discharge at those sites; and,
4. At a site where CBM water is currently is quite warm (say about 10^{o}C or warmer) when entering the Powder River, it will be useful to implement a simple pilot test to confirm the performance of one or more methods this report proposes for reducing CBM water temperature or enhance mixing with flow in the Powder River.
5. A growing body of literature suggests that frazil and anchor ice stress fish. Extending frazil and anchor ice formation events through the entire winter in CBM-heat-impacted reaches of the Powder River may have negative impacts of native fish populations. A combined, detailed physical/biological study of processes in Powder River is warranted.

6. PUBLICATIONS

- Stiver, J.J., (in preparation, expected completion in Summer 2011), Effects of CBM Water Discharge on Fluvial and Ice Processes in Powder River Basin, Wyoming Streams, M.S. Thesis, Civil and Architectural Engineering, University of Wyoming, Laramie, WY.
- Kempema, E.W., Stiver, J.J. and Ettema, R., (accepted, in preparation), Effects of CBM water discharge on fluvial and ice processes in Powder River Basin, Wyoming Streams; in: Conference Proceedings, CRIPE 2011 Workshop on River Ice, Winnipeg, Canada, September 2011.
- Ettema, R. and Kempema, E.W., (invited, in press), Ice effects on gravel-bedded channels, 7th Gravel-Bedded River Conference 2010, Tadoussac, Quebec, Canada, September 6-10 ,2010, 22 p.
- Kempema, E.W. and Ettema, R., 2011. Anchor ice rafting: observations from the Laramie River. River Research and Applications: doi:10.1002/rra.1450 (published online in 2010).

7. PRESENTATIONS

- Kempema, E.W., Stiver, J.J. and Ettema, R., (September, 2011), Effects of CBM water discharge on fluvial and ice processes in Powder River Basin, Wyoming Streams; at: CRIPE 2011 Workshop on River Ice, Winnipeg, Canada, September 2011.
- Stiver, J.J., April 7 2011, Presentation to Class: Water Resources Seminar, REWM 5250, Instructor: KJ Reddy.
- Stiver, J.J April 20 2011, Presentation to Class: Spatial Analysis, RNEW 5200, Instructor: Scott Miller.
- Kempema, E.W., Ettema, R, and Stiver, J. May 25, 2010. Effects of Coalbed Methane Product Water on Winter Flow in the Powder River; Energy Resources and Produced Waters Conference: Laramie, WY.
- Stiver, J.J., April 7, 2010, Presentation to Class: Watershed H_20 Quality, REWM 5710, Instructor: KJ Reddy.
- Stiver, Jared, March 5, 2010. Effects of CBM waters in the Powder River Basin, invited presentation to RNEW 5710 class taught by KJ Reddy.
- Kempema, E.W. and Ettema, R. November 2009. Progress Report to the Wyoming Water Development Commission, Cheyenne, WY.
- Stiver, J.J., October 6 2009, Presentation to Class: Principles of Water Quality, REWM 5640, Instructor: KJ Reddy.

8. STUDENT SUPPORT

- Jared Stiver, a Civil Engineering student, worked on this projected since it started. Mr. Stiver worked on this project as an undergraduate during the Fall Semester 2009. In January 2009, Mr. Stiver enrolled as a graduate student in Civil Engineering. He plans to finish his thesis on CBM heat impacts on Powder River sstreams during winter during summer, 2011.

- Casey Valkenburg, an undergraduate in Mechanical Engineering, worked with the project during the 2010-2011 winter season as a field helper. Mr. Valkenburg received training in laser-level surveying techniques and discharge measurement techniques, and learned how to drill holes in river ice on this project.

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10. APPENDICES

Appendix 1 contains cross sections of the Powder River collected at Beaver Creek and Burger Draw during the 2010-2011 field season.

Appendix 2 contains the ice thickness profiles collected at Beaver Creek and Burger Draw during the 2010-2011 field seasons.

10.1 Appendix 1: Powder River Cross Sections, 2010-2011

Figure A1.1. Aerial image of the Beaver Creek—Powder River confluence showing the relative positions of the cross sections in the Powder River. Cross sections BC1 and BC2 are downstream of Beaver Creek while BC3 is upstream Beaver Creek. The arrow indicates flow direction of the Powder River. Distances (upstream or downstream) of the cross sections from the tributary confluence are: BC1: 30m, BC2: 10m, BC3: 40m.

Figure A1.2. Aerial image of the Burger Draw—Powder River confluence showing the relative positions of the cross sections in the Powder River. Cross sections BD1, BD2, and BD3 are downstream of Burger Draw while BD4 is upstream. The arrow indicates flow direction of the Powder River. Distances (upstream or downstream) of the cross sections from the tributary confluence are: BD1: 80m, BD2: 30m, BD3: 5m, BD4: 15m

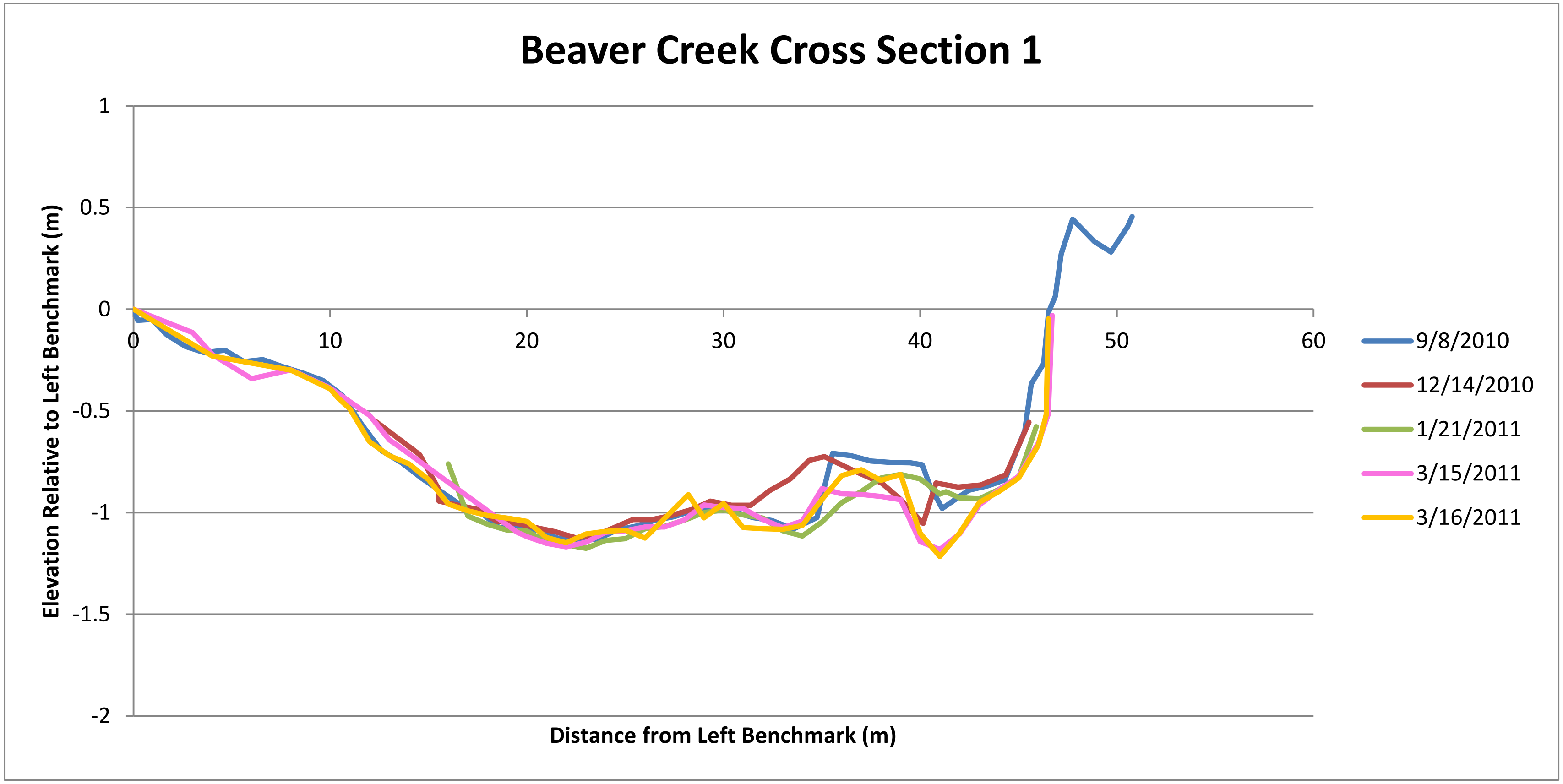


Figure A1.3. Beaver Creek Cross Section 1 (BC1).

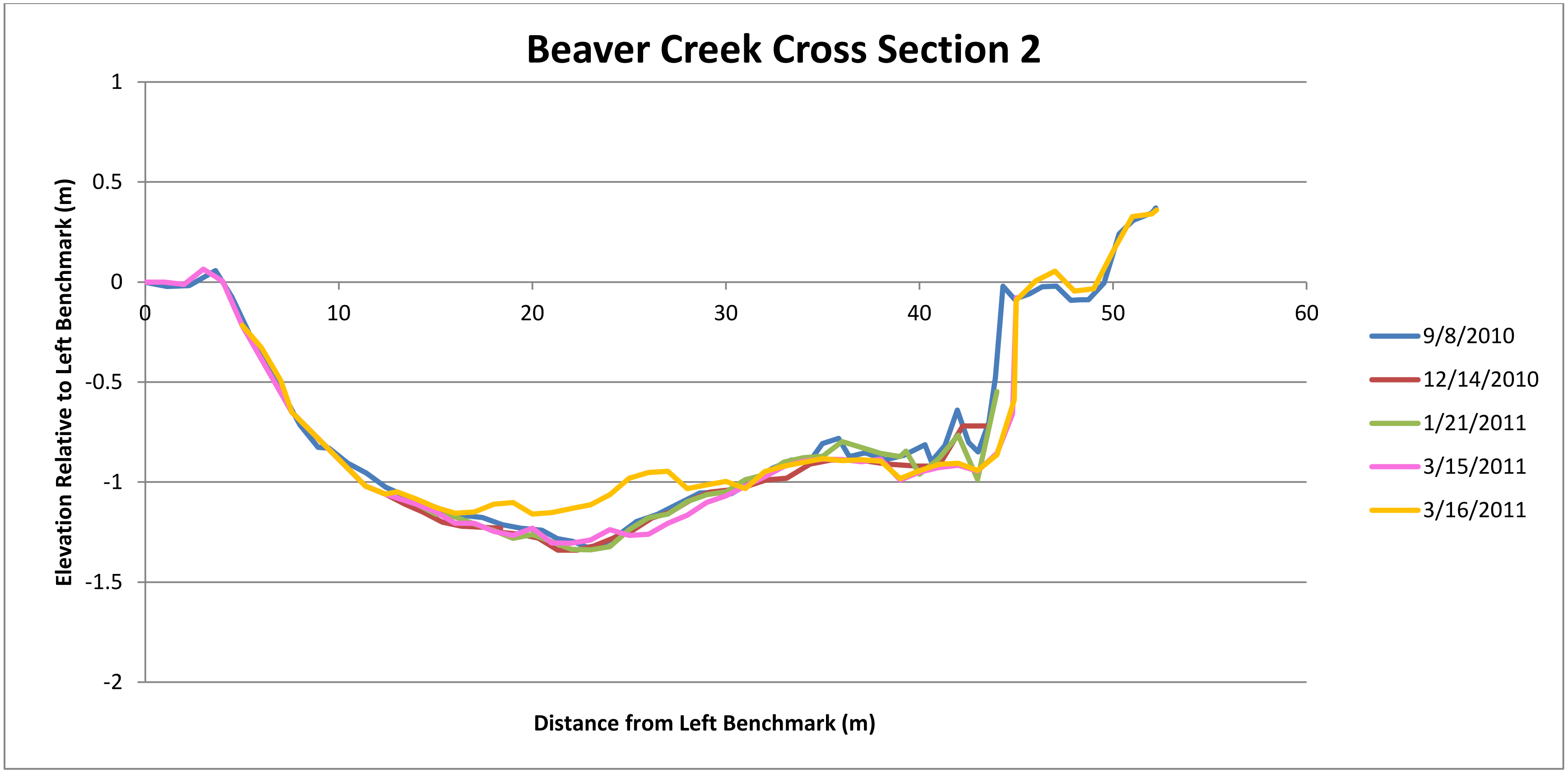


Figure A1.4. Beaver Creek Cross Section 1 (BC2).

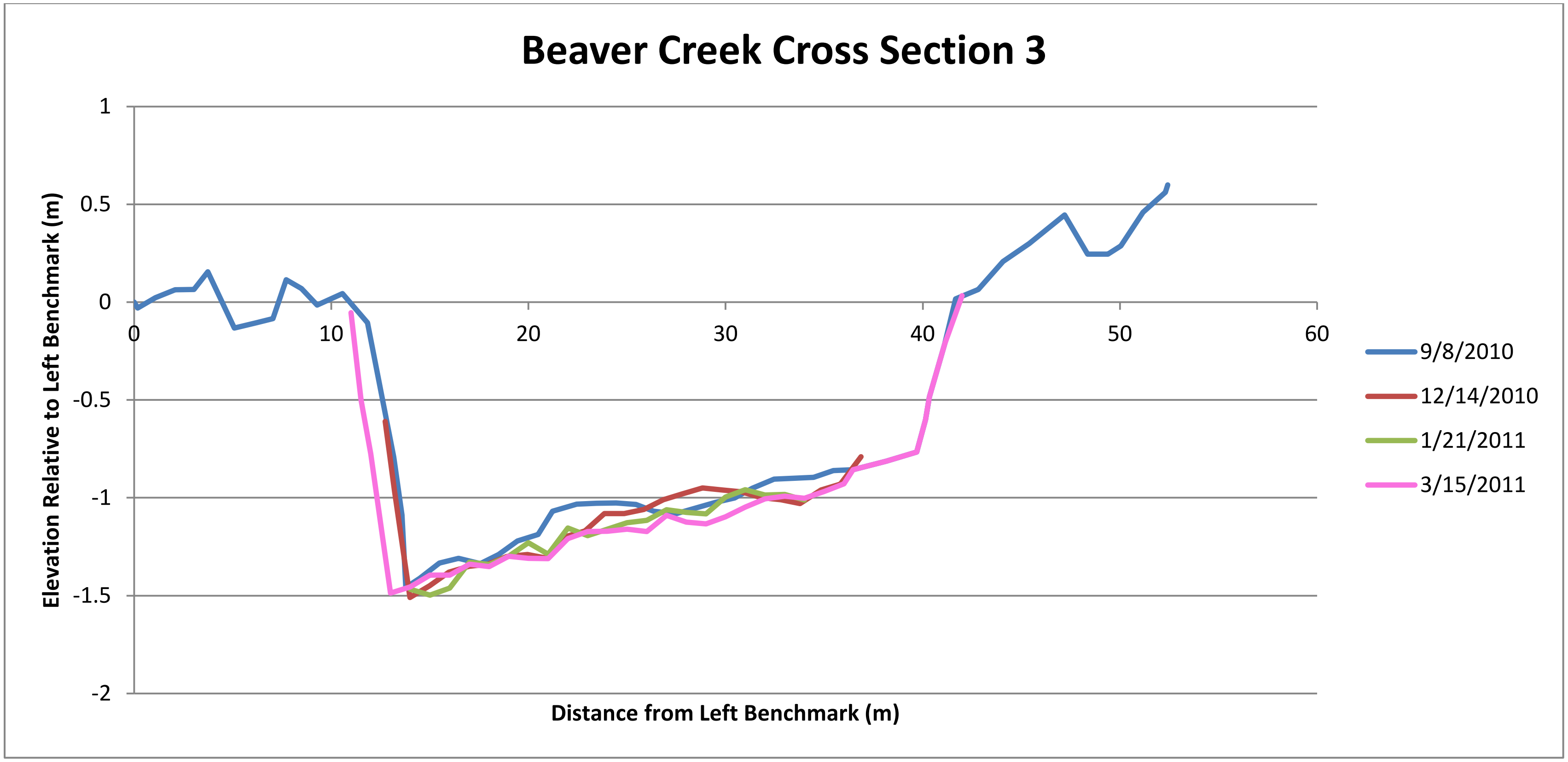


Figure A1.5. Beaver Creek Cross Section 3 (BC3).

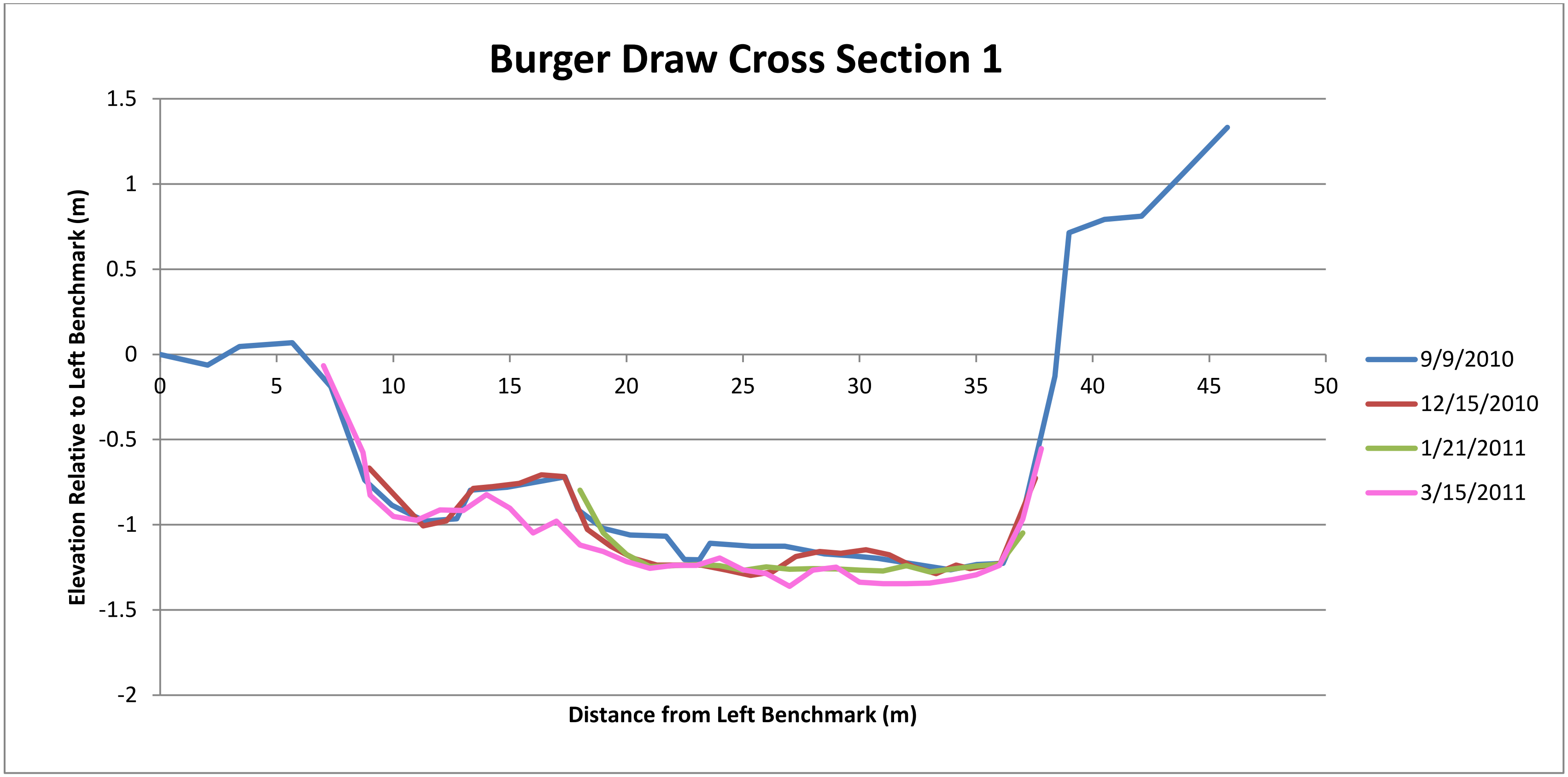


Figure A1.6. Burger Draw Cross Section 1 (BD1).

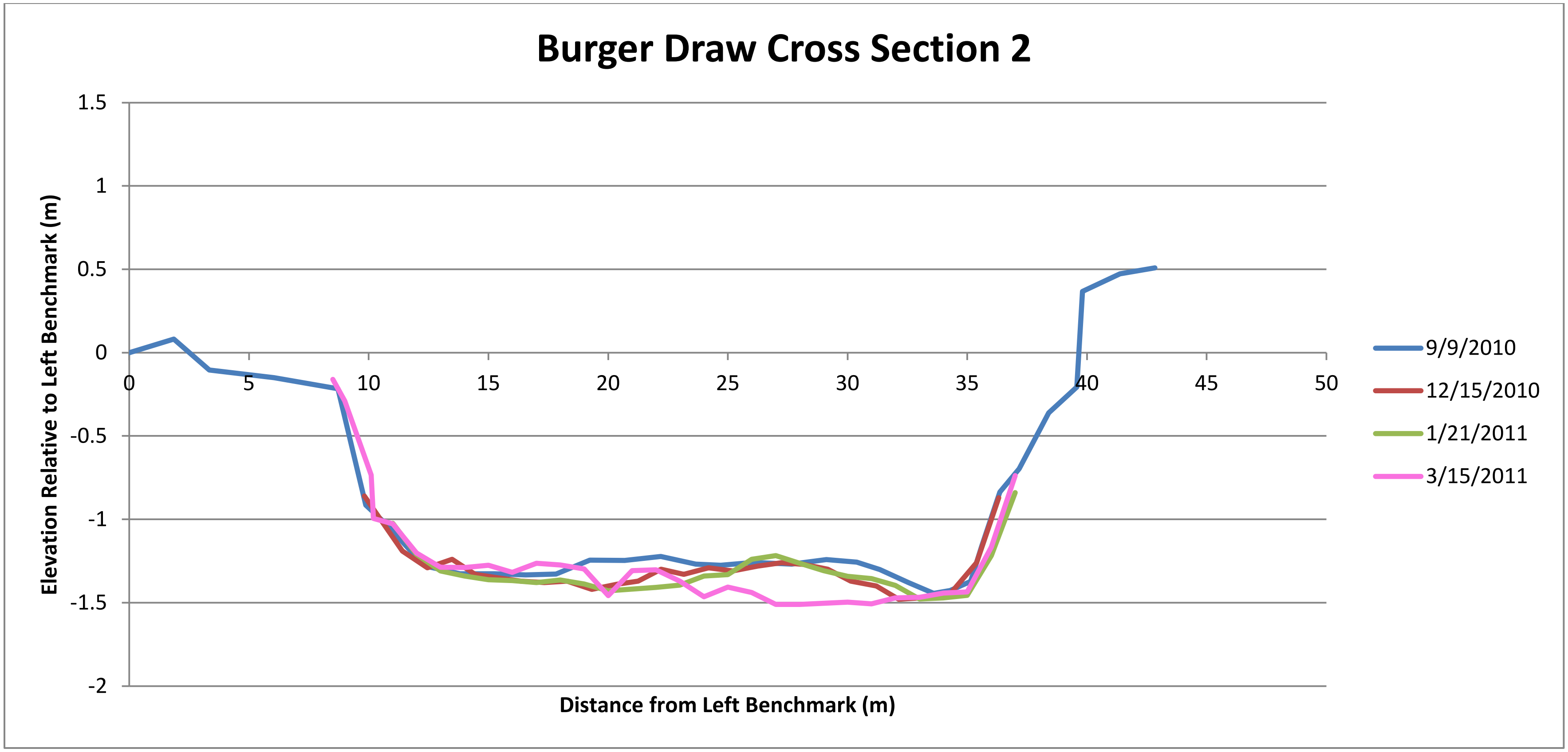


Figure A1.7. Burger Draw Cross Section 2 (BD2).

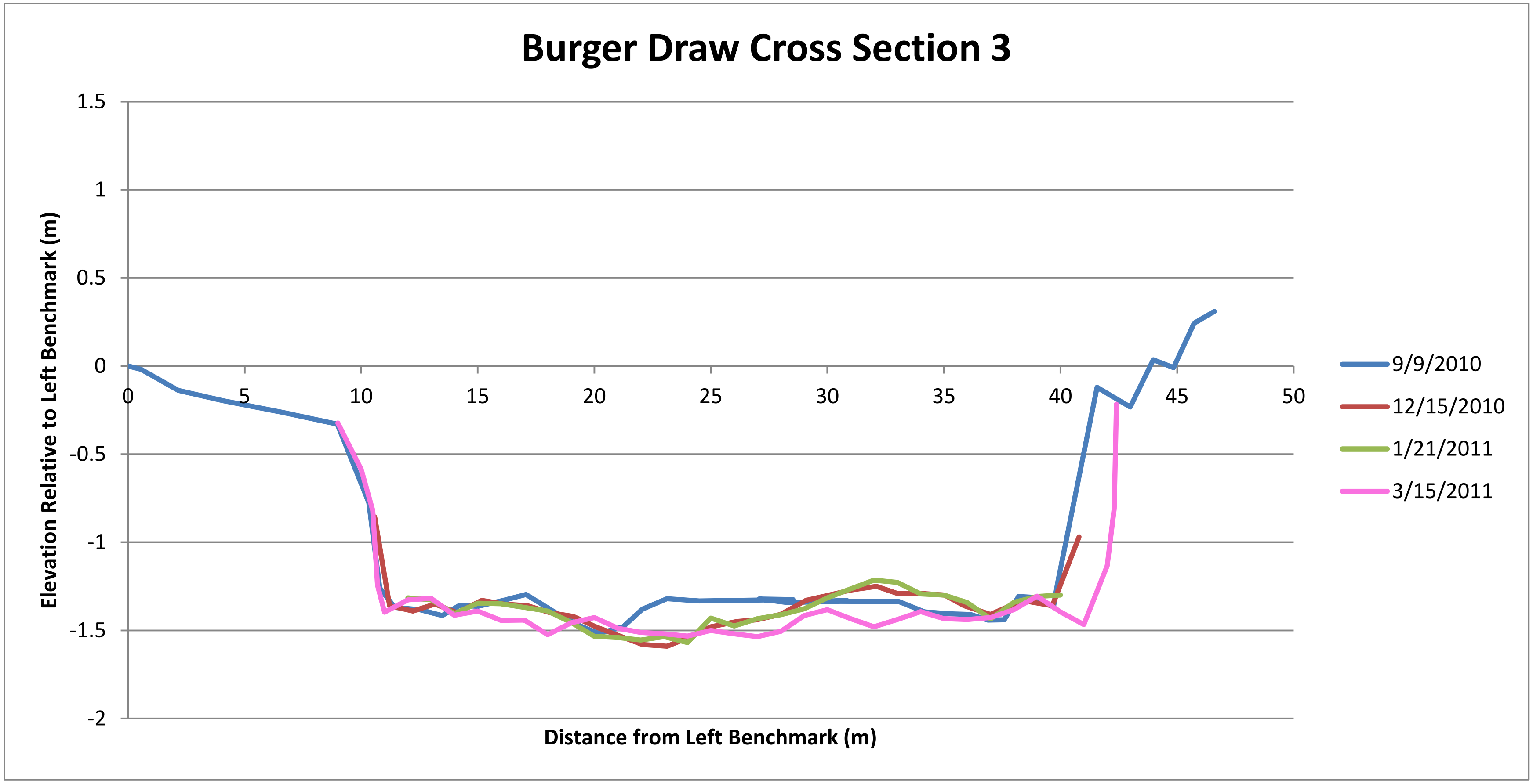


Figure A1.8. Burger Draw Cross Section 3 (BD3).

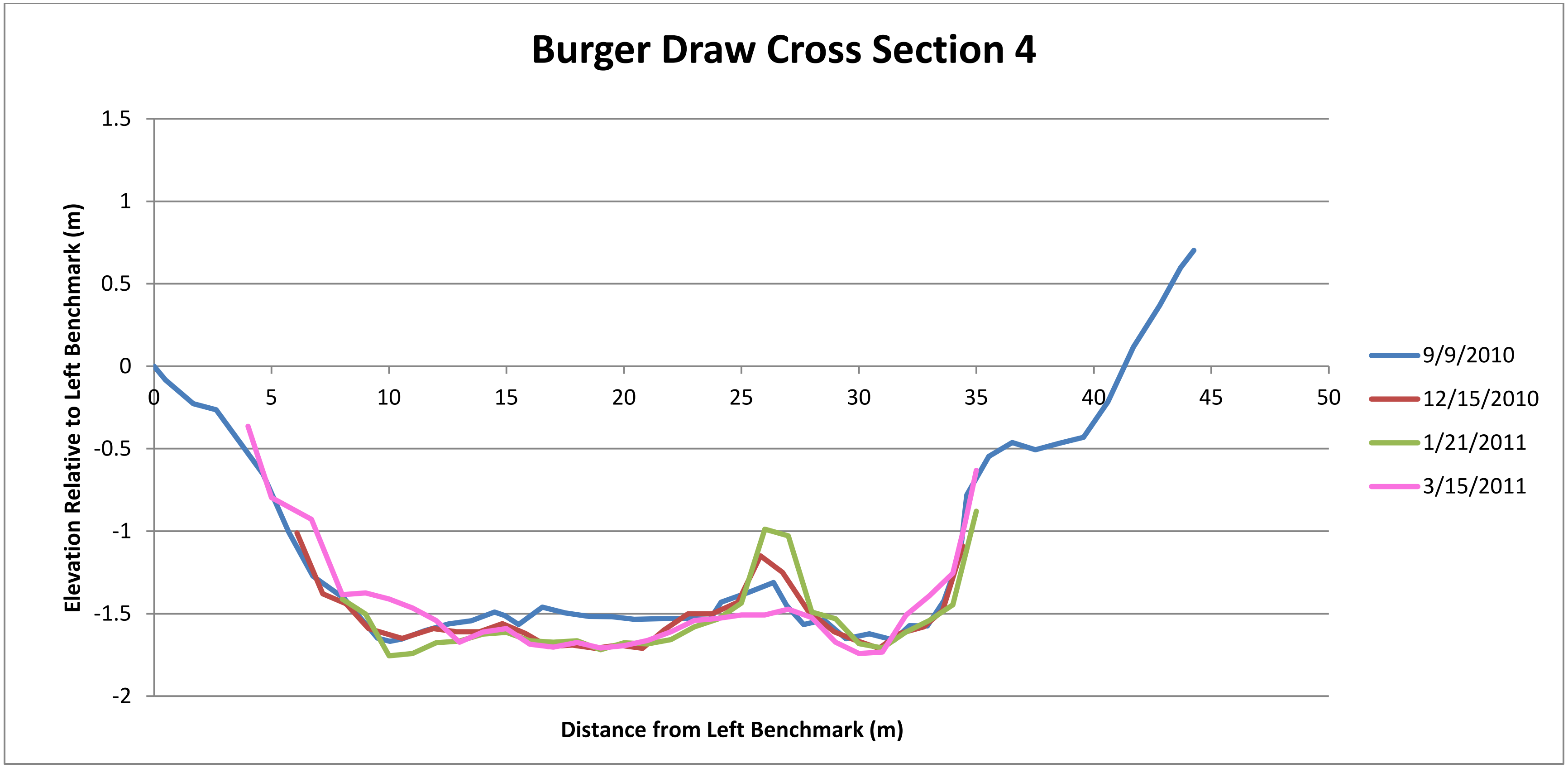
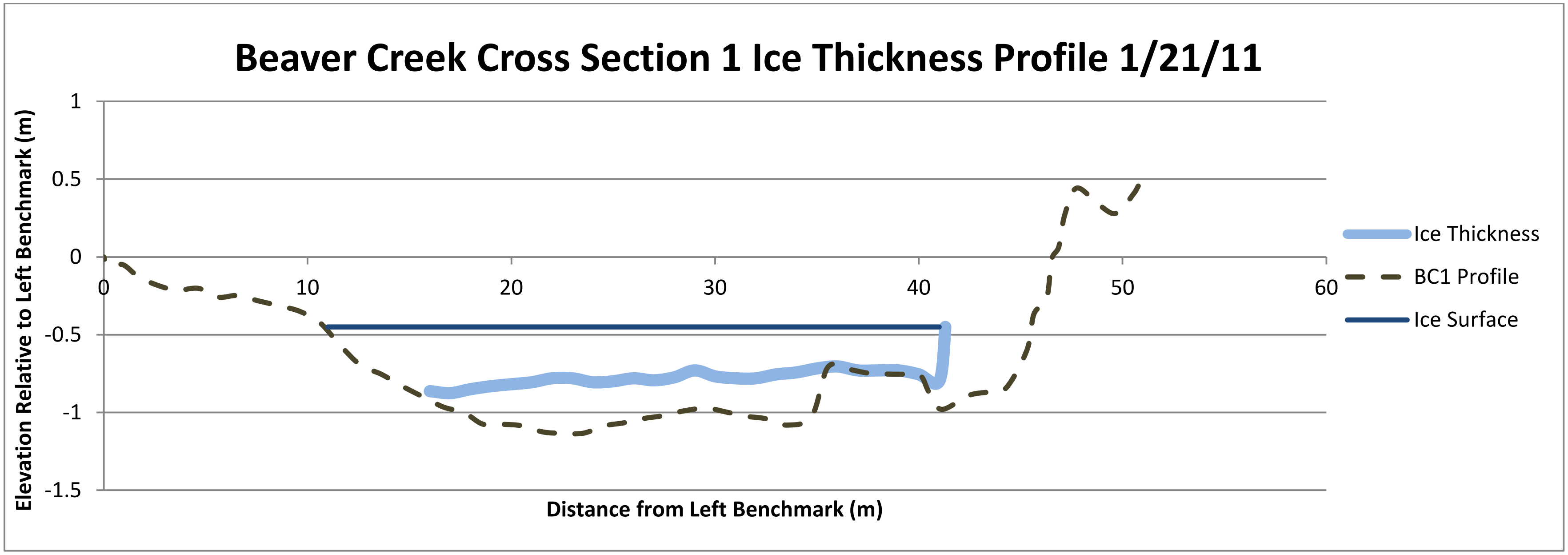


Figure A1.9. Burger Draw Cross Section #4 (BD4)

10.2 Appendix 2. Powder River Ice Thickness Profiles



FigureA2.1: Beaver Creek Cross Section 1 Ice Thickness Profile, surveyed on January 21, 2011. BC1 has an open water lead on the right end of the profile that is roughly 5 meters wide. The Ice thickness is continuous throughout the profile till the open water lead. BD1 is 25 meters downstream of the mouth of Beaver Creek.

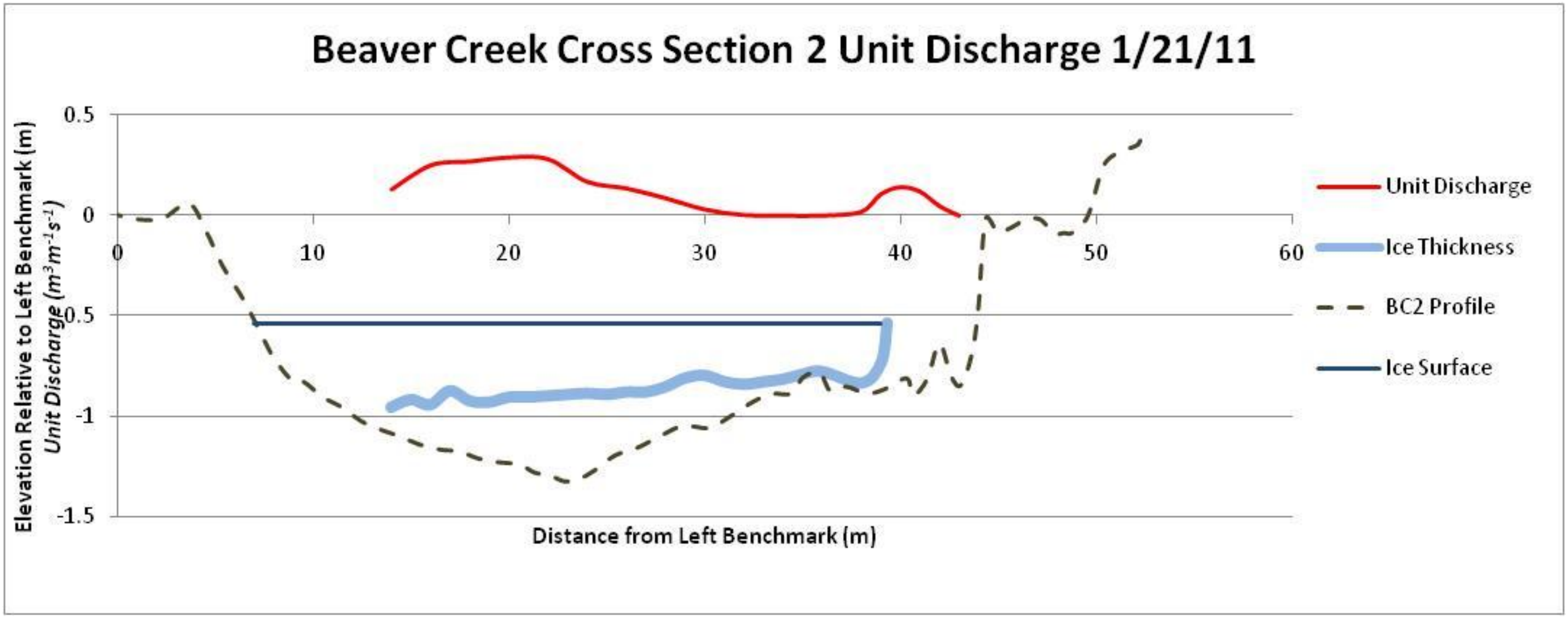


Figure A2.2: Beaver Creek Cross Section 2 Ice Thickness Profile was surveyed on January 21, 2011. BC2 is the cross section closest to the mouth of Beaver Creek and directly downstream of Beaver Creek. There is an open water lead that has formed on the right side of the Powder River. In addition to the cross section and ice-thickness profile, this figure shows the unit discharge per cross sectional area on January 21. Highest unit discharges are concentrated in the profile thalweg and in the open water lead.

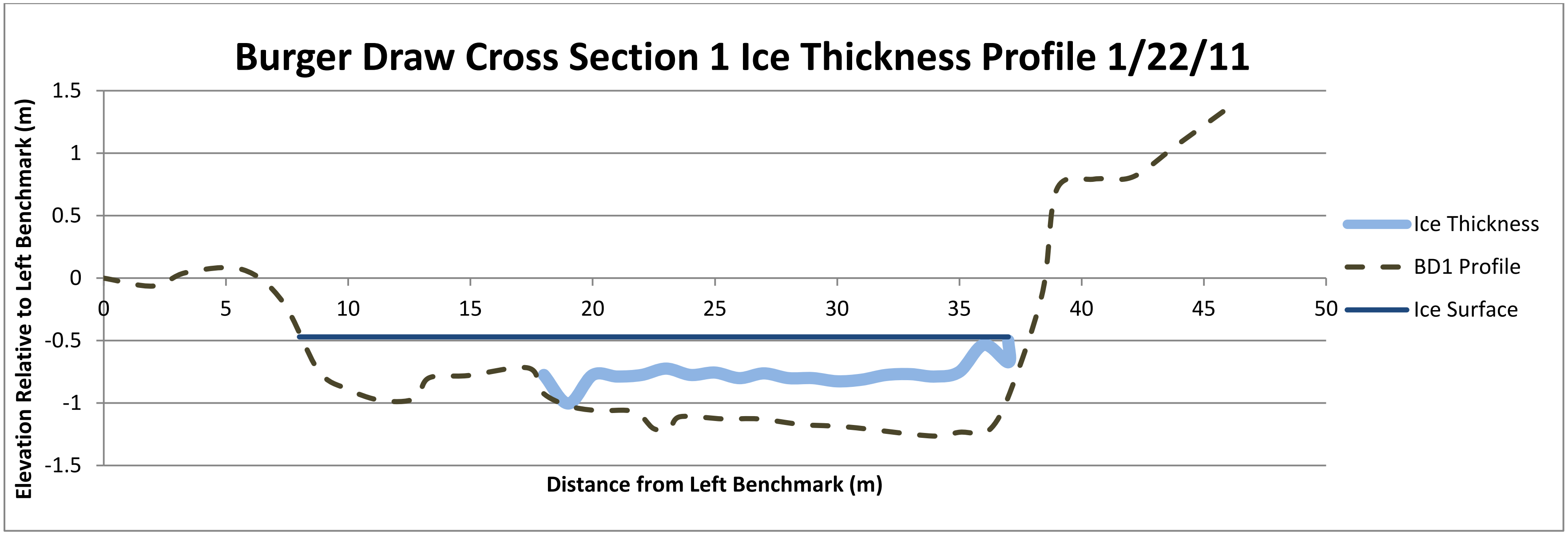


Figure A2.3. Burger Draw Cross Section 1 Ice Thickness Profile was surveyed on January 21, 2011. BD1 has a 1 meter wide open water lead on the right end of the profile. BD1 is 80 meters downstream the mouth of Burger Draw. Ice froze to the bed from left water edge to about 17 meters from the left benchmark.

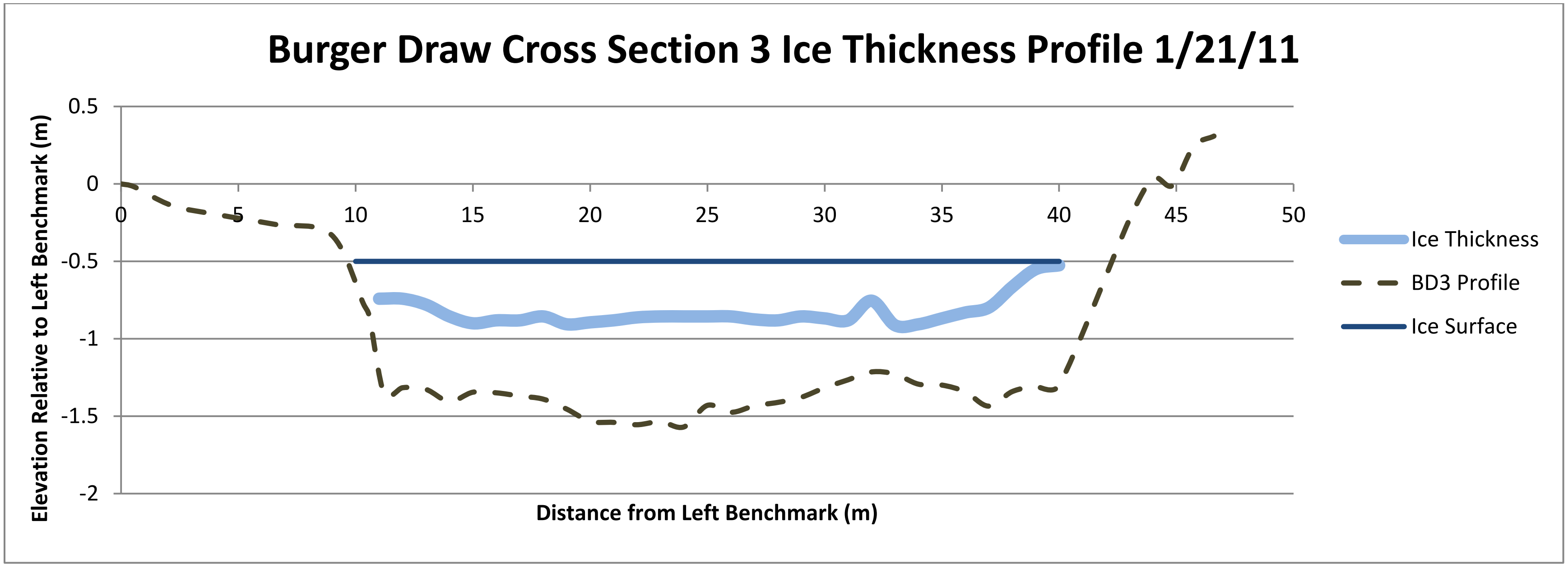
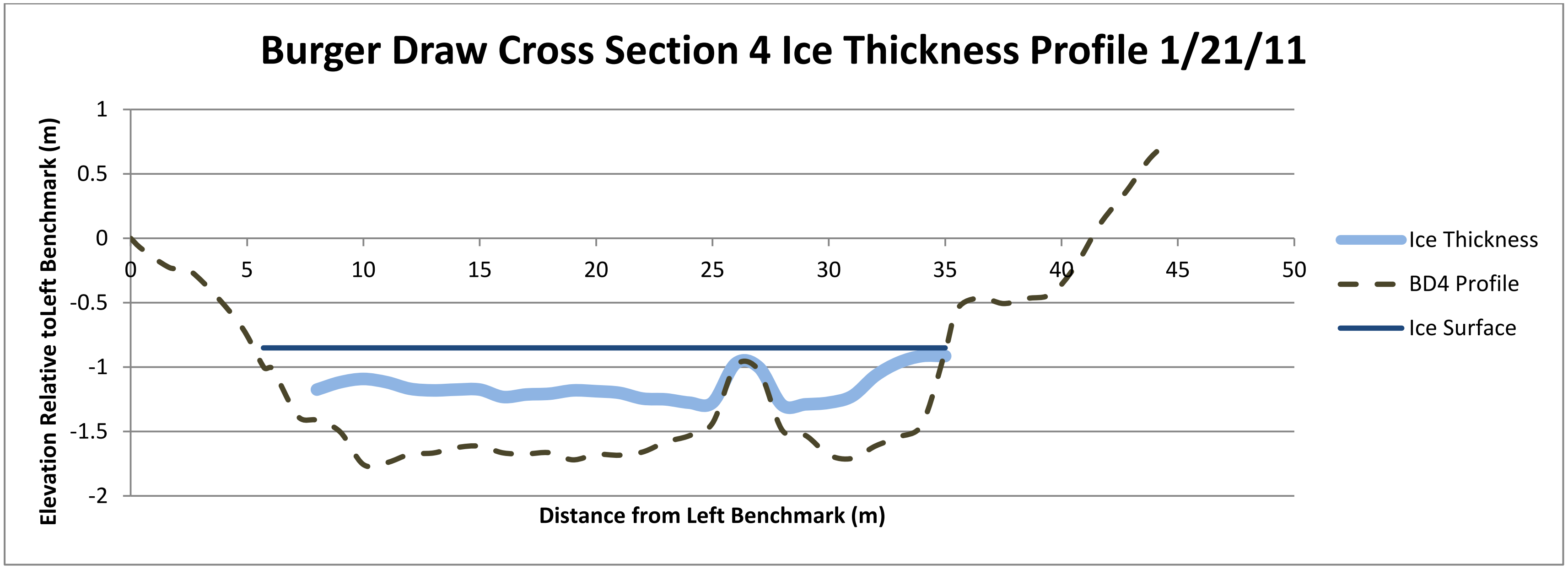


Figure A2.4: Burger Draw Cross Section 3 Ice Thickness Profile, surveyed on January 21, 2011. BD3 is the cross section closest to the mouth of Burger Draw and is directly downstream of the confluence. A small open water lead formed on the right side of the river. The ice thickness is fairly consistent throughout the profile till it draws near the open water lead end and thins rapidly.



FigureA2.5: Burger Draw Cross Section 4 Ice Thickness Profile; surveyed on January 21, 2011. BD4 is upstream of Burger Draw on the Powder River, and has a continuous ice cover. The underside of the ice profile ends before the left end of the ice cover because field personnel feared driving the ice auger into the bed at that location.

Characterization of Algal Blooms Affecting Wyoming Irrigation Infrastructure: Microbiological Groundwork for Effective Management

Basic Information

Title:	Characterization of Algal Blooms Affecting Wyoming Irrigation Infrastructure: Microbiological Groundwork for Effective Management
Project Number:	2009WY48B
Start Date:	3/1/2009
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	1
Research Category:	Biological Sciences
Focus Category:	Ecology, Management and Planning, Water Quality
Descriptors:	Algal blooms, Algae-associated bacteria, Eutrophication, Irrigation
Principal Investigators:	Naomi Ward, Blaire Steven

Publications

There are no publications.

Characterization of Algal Blooms Affecting Wyoming Irrigation Infrastructure: Microbiological Groundwork for Effective Management

Final Report

(For a two-year project: March 2009 – February 2011)

Naomi Ward, Assistant Professor, Department of Molecular Biology, University of Wyoming and Blaire Steven, Postdoctoral Associate, Department of Molecular Biology, University of Wyoming

Abstract:

Eutrophication, resulting from increased nutrient input into a water body, is one of the most pervasive water quality problems in the United States, affecting lakes, estuaries, streams, and wetlands. Eutrophication is often driven by human activities such as agriculture, where fertilizer run-off and soil erosion are major sources of the nutrient load. The effects of eutrophication include algal/cyanobacteria blooms, leading to hypoxia of the water column and subsequent decline in submerged vegetation, and fish kills. Locally, management of algal blooms represents a significant cost to maintaining the irrigation infrastructure in Wyoming. The effectiveness and environmental impact of these algae treatment strategies are not well understood. It is very difficult to estimate or monitor the total amount of algaecides released into the environment, and the full range of species affected remains unknown. Development of more effective algae treatment strategies is hampered by a *knowledge gap*: we have not identified the key algal and bacterial species and processes involved in establishing, maintaining, and degrading algal blooms in Wyoming lakes. *We are working to address this knowledge gap and thus provide a sound microbiological foundation for long-term development of more targeted, effective algae treatment strategies*. In order to achieve this objective, we are (1) Characterizing algae/cyanobacteria species responsible for blooms, (2) Characterizing the role of bloom-associated bacteria, and (3) Developing model systems to test bacterial/algal interactions. Our long-term goal is to anticipate the type and severity of the bloom and propose predictive management strategies (as opposed to the reactive treatment protocols currently employed).

Progress:

Objectives:

(1) Characterize algae/cyanobacteria species responsible for blooms,
(2) Characterize the role of bloom-associated bacteria, and
(3) Develop model systems to test bacterial/algal interactions.

Methodology:

A. Field Work. We have worked at two sites: Labonte Lake in Laramie (impacted urban lake), and Rock Lake (impacted agricultural lake). Sample types included the lake sediment, water column, and any macroscopically observed algal bloom material. Samples were subdivided for water quality analysis, microscopy, and DNA extraction.

B. Laboratory Work. Water quality analyses included total nitrogen, total phosphorus, dissolved oxygen, and dissolved organic carbon (DOC). Phase-contrast light microscopy was used to monitor the development of blooms. Profiling of the microbial community was performed by ribosomal RNA gene 454 FLX pyrosequencing. Sequencing was performed by Research and Testing Laboratories LLC (Lubbock, TX). We are performing separate analyses of bacterial, archaeal, and algal populations. Small-subunit (16S) rRNA genes were analyzed for Bacteria and Archaea, and large-subunit (23S) rRNA genes for algae. This very large amount of sequencing was achieved by multiplexing the 454 runs with the use of bar-coded PCR primers. We were able to simultaneously sequence 16S/23S rRNA genes from all samples on a PicoTiter plate, yielding approximately 5,000 sequence reads per sample. Low-quality sequences were removed and primer sequences trimmed and de-coded using in-house Perl scripts. DOTUR was used to assign sequences to OTUs (Operational Taxonomic Units) at 96% identity, then one sequence representing each of the resulting OTUs was selected for inclusion in a multiple sequence alignment from which a phylogenetic tree was constructed (RaxML). This tree was used to cluster the samples with UniFrac. BLAT, the BLAST-like alignment tool, was used to compare sequences against sequence databases obtained from one of the publicly available rRNA sequence resources. Matches with weak homologies were filtered out, and then each read assigned to a specific taxonomic group, resulting in a weighted phylogeny.

Algal microcosms were established in Year 2 to study specific interactions between algae and bacteria under controlled conditions. Four microcosm types were set up: three in which we simulated eutrophication events by addition of different amounts of extra nitrogen and phosphorus, and a control untreated microcosm. We ran the microcosms in triplicate for 4 weeks and sampled weekly, yielding samples on which pyrosequencing has been performed. We also determined biomass dry weight and total chlorophyll, as indicators of overall growth, and phototroph growth, respectively. Analysis of these data is still underway. Comparison of the lake and microcosm data will allow us to determine whether the algal-bacterial interactions observed in our microcosms reflect the natural relationships occurring in the lake.

Principal Findings:

We collected samples over the course of 2009 bloom development and collapse in Labonte Lake. This involved monthly sampling in May and October, with bimonthly sampling during the intervening 4 months, resulting in a total of 10 time points. We also collected peak bloom samples from Rock Lake. Analysis of water quality (Table 1) in LaBonte Lake indicated that dissolved oxygen increased until peak algal bloom (mid July), and then decreased during bloom decay. Total organic carbon displayed an inverse relationship to dissolved oxygen, while total nitrogen and phosphorus exhibited smaller fluctuations. Water quality data for samples taken at Rock Lake at peak bloom (mid July to early August) fairly closely resembled LaBonte Lake data from the same time period (Table 1).

We have generated 141,155 bacterial 16S rDNA sequences, and 133,371 algae 23S rDNA plastid sequences. Archaeal 16S rDNA sequencing has also been performed, but we experienced problems with non-specificity of the archaeal primers. This limited the usefulness of the data obtained. Analysis of algal sequences is still underway, and the results described in the remainder of this section refer only to bacterial sequences. Changes in bacterial populations were compared between sediment, water, and algal mat samples from LaBonte Lake. Different time-points for these three sample types shared broad similarities in phylum-level composition, but each sample type displayed different shifts in composition over time (Figure 1). For example, the most variably abundant phylum in the water appeared to be the Actinobacteria, while this phylum remained relatively low in abundance in the sediment, where greater shifts in Chloroflexi were observed. At deeper levels of taxonomic classification, there was more variation in composition over time within one type of sample and across sample types. This was most evident at the level of species-equivalents, where few operational taxonomic units (OTUs) were found consistently throughout the sampling regime (Table 2). The OTUs that persisted throughout the sampling never accounted for more than 2% of the total sequences, and were represented by only a single sequence when all sequence libraries were compared. These data suggest that LaBonte Lake contains temporally and spatially diverse microbial communities, with a 'core' bacterial population often present in low abundance. Peak bloom bacterial populations in this lake were also compared with those recovered from Rock Lake. Taxonomic analysis (Figure 2) and similarity clustering (Figure 3) indicated that communities from the same sample type (sediment, water, or algal mat) in different lakes were more alike than communities from different sample types within the same lake, indicating strong ecotype differentiations in the freshwater systems under study.

Significance:

The microbial community sequencing performed in our project has resulted in the most exhaustive description of the bacterial community in a eutrophic lake performed to date. It will provide an excellent foundation for selection of bacterial species and functions most relevant to bacteria-algal interactions, for further study. Lastly, it will serve as a reference point for future comparison of microbial communities associated with algal blooms in other lakes. Such comparative analysis will be important to future determination of the most effective management strategies that can be applied in lakes and reservoirs where algal blooms adversely affect irrigation.

Student support:

Undergraduate researcher Sage McCann was supported and trained by this project during the summer of 2009. He was also included as a co-author on an abstract presented at the 2010 International Symposium on Microbial Ecology (see below). Sage (graduated Spring 2009, Molecular Biology) was previously an INBRE Transition Scholar, i.e. a Wyoming community college student supported by NIH INBRE funds to participate in research after transfer to UW. Therefore WRP support for Sage allowed further research training for a community college transfer student. Sage is currently pursuing graduate studies in Pharmacy at UW. An additional student (Kristie Capson, Molecular Biology) was supported in Summer 2010. Postdoctoral fellow Blaire Steven also received training for the duration of the project.

Publications (student and postdoc names underlined):

1. **<u>Steven, B</u>., S. E. Dowd, <u>K. H. Schulmeyer</u>, and N. L. Ward**. Diversity and abundance of planctomycete populations associated with an algal bloom in a eutrophic lake. In press at <u>Aquatic Microbial Ecology</u>.
   ***** Note**: the work described in this paper was performed prior to obtaining WRP funding, but the results informed the conduct of our project and therefore the paper is included here.
2. **<u>Steven, B.</u> and N. L. Ward.** Pyrosequencing-based characterization of bacterial, archaeal, and algal population dynamics in a freshwater algal bloom. In preparation for The ISME Journal (Nature Publishing Group).

Presentations (student names underlined):

1. **Steven, B., and N. Ward.** Deep sequencing of ribosomal RNA genes during an algal bloom in a eutrophic lake: a primer for metagenomic sequencing. DOE Joint Genome Institute 5th Annual User Meeting: Genomics of Energy & Environment. Walnut Creek, CA. March 24-26, 2010.
2. **Steven, B., S. McCann, K. H. Schulmeyer, and N. L. Ward.** Characterization of the microbial diversity associated with algal blooms in a eutrophic freshwater lake. 13th International Symposium on Microbial Ecology. Seattle, WA. August 22-27, 2010.

Funding:

We submitted a proposal ('Metatranscriptomic analysis of bacterial-algal interactions: an ecological foundation for enhancing algal biofuel and geoengineering initiatives') that was selected for funding support in 2010 by the US Department of Energy's Community Sequencing Program (CSP), **PI: Naomi Ward**. This is not a traditional award mechanism in which funds are distributed to the University, but rather a peer-reviewed program that allows researchers to compete for access to the high-throughput sequencing resources of the DOE's Joint Genome Institute. We leveraged the support provided by USGS/WRP to obtain this funding, which will help us to establish a program that uses both bioinformatic and experimental approaches to characterize algal-bacterial interactions.

Table 1 Physical and chemical parameters of study sites

	Sample Date	Water Temp. (°C)	pH	Dissolved Oxygen mg l^{-1}	Total Nitrogen mg l^{-1}	Total Phosphorus mg l^{-1}	Total Organic Carbon mg l^{-1}	Algal bloom status
Labonte Lake	May 12	15.6	8.9	3.7	2.8	0.3	14	Pre-bloom
	June 2	12.7	8.7	2.8	1.5	0.2	13	
	June 16	17.0	9.0	4.8	1.2	0.2	18	Algal bloom
	July 16	24.9	9.3	11.2	1.3	0.2	10	
	July 28	21.1	9.2	8.3	1.8	0.2	14	
	June 28	24.4	9.7	10.4	1.8	0.2	14	
	August 3	21.8	8.7	4.4	1.6	0.4	13	
	August 17	15.9	7.9	2.2	1.4	0.4	13	
	August 31	18.4	7.4	5.0	4.0	0.5	20	
	September 14	12.8	7.2	1.2	2.5	0.6	18	
	September 28	11.8	8.4	4.3	1.9	0.4	23	Post-bloom
Rock Lake	July 9	20.6	8.5	8.2	1.1	0.1	10	Algal bloom
	July 21	31.9	8.4	8.4	3.3	0.1	15	
	August 4	16.3	8.0	4.3	3.5	0.1	12	

Table 2 Operational Taxonomic Units (OTUs) shared between lakes and across sampling time points

Sample	Comparison	Shared OTUs
LaBonte Lake		
	Rock Lake	693
LaBonte Lake algal mat	Rock Lake algal mat	182
LaBonte Lake water	Rock Lake water	187
LaBonte Lake sediment	Rock Lake sediment	255
LaBonte algal mat (all time points)	-	7
LaBonte water (all time points)	-	0
LaBonte sediment (all time points)	-	0
Rock Lake algal mat (all time points)	-	40
Rock Lake water (all time points)	-	28
Rock lake sediment (all time points)	-	18

Figure 1. Taxonomic diversity of 16S rRNA gene sequences in LaBonte Lake over the development of an algal bloom. A). Phylum level taxonomic assignments. B). Family level taxonomic assignments. Only relative abundances of the dominant groups are plotted, so the bars do not sum to 100%.

Steven et al.
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Figure 1

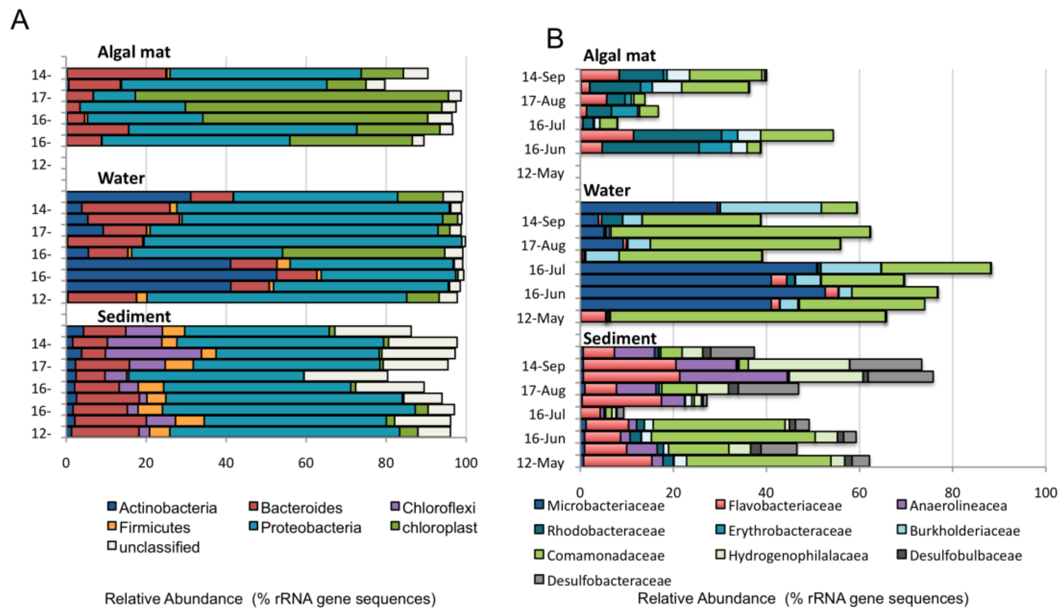

Figure 2. Comparison of LaBonte Lake and Rock Lake microbial communities. Each chart represents a lake environment where the outside ring represents LaBonte Lake and the inside ring represents Rock Lake. Relative abundances (percent of sequence libraries) of the dominant groups are indicated either inside the ring or with the phylum label.

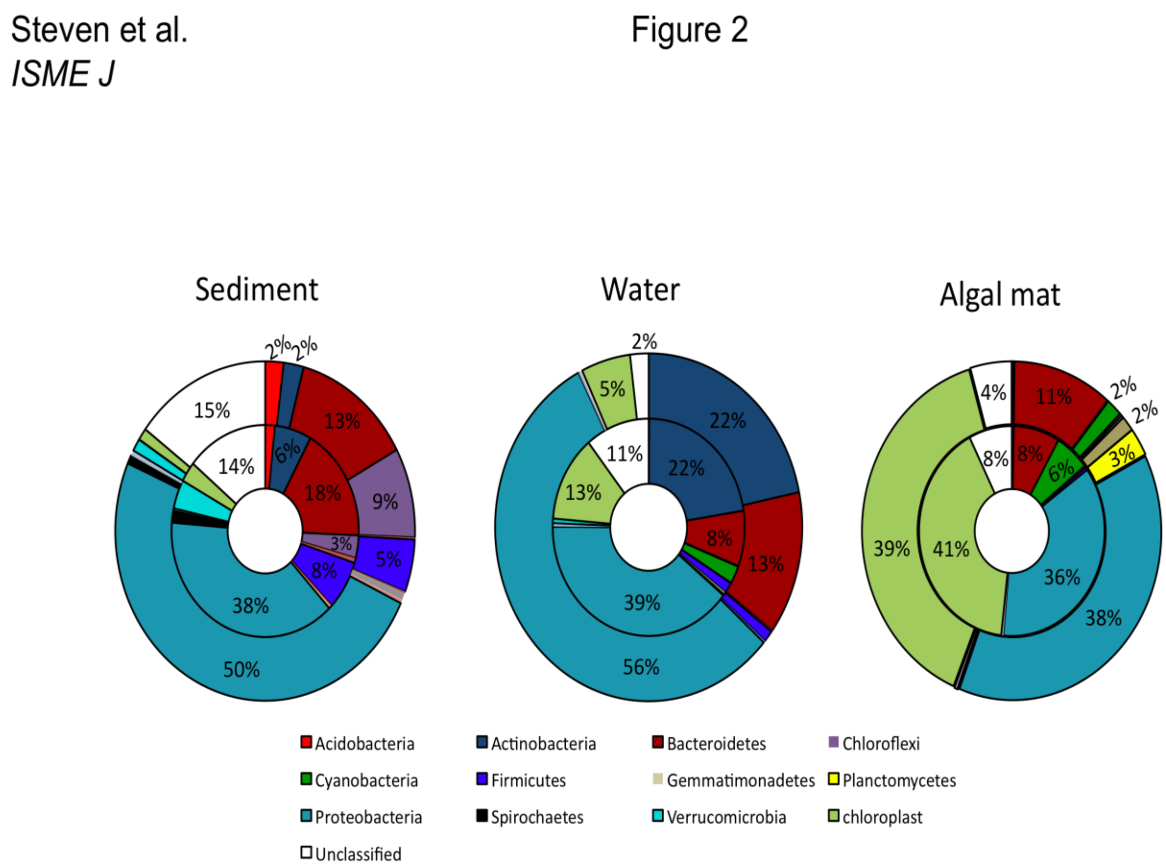

Figure 3. Clustering of sequence libraries. Similarity in community structure was determined using the abundance based similarity index and plotted as a dendogram. Branch lengths are proportional to the fraction of individuals that belong to shared OTUs.

Is the Muddy Creek Food Web Affected by Coalbed Natural Gas Inputs?

Basic Information

Title:	Is the Muddy Creek Food Web Affected by Coalbed Natural Gas Inputs?
Project Number:	2010WY54B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	1
Research Category:	Biological Sciences
Focus Category:	Ecology, Groundwater, Surface Water
Descriptors:	Food web, Coalbed natural gas, Bioaccumulation
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Publications

There are no publications.

Is the Muddy Creek Food Web Affected by Coalbed Natural Gas Inputs?
Final Report

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Abstract

The Muddy Creek watershed is a unique ecosystem because the stream contains a distinctive fish assemblage, is physically degraded, and will soon be influenced by oil and gas development. Separating the effects of multiple stressors can be challenging; however, having prior data can be very useful in determining the influence of different stressors. In our study, we attempted to separate the effects of physical degradation, and oil and gas development by sampling prior to most energy development. To extract oil and gas, groundwater must be pumped to the surface; groundwater associated with oil and gas resources can contain detectable concentrations of trace elements. The produced groundwater is often discharged into streams or ponds. Trace elements in produced water can be taken up into food resources (e.g., algae) and transferred to higher trophic levels in the food web through predation. We collected animals from each trophic level in the Muddy Creek food web above and below the current coalbed natural gas (CBNG) input, and measured their tissue for trace element concentrations and $\delta^{15}N$ (trophic position). As a result, we regressed trophic position ($\delta^{15}N$) against trace element concentration for each organism (e.g., µg Se/g tissue) to measure how trace elements moved through the food web. Al and Zn concentrations in Muddy Creek exceeded chronic standards for aquatic life. We found that only Se and Hg bioaccumulated in the Muddy Creek food web, but other trace elements biodiminished, peaked at intermediate trophic levels, or concentrations remained similar in the food web (Be, B, Mg, Al, v, Cr, Mn, Fe, Ni, Cu, Zn, As, Sr, Mo, Cd, Ba, and Pb). By understanding the Muddy Creek ecosystem now, land managers and developers can make informed decisions about management needs and potential mitigation efforts. This study will record baseline (pre-CBNG) influences on the Muddy Creek food web. We plan to repeat this study in 3-5 years after CBNG development has occurred to determine if trace metals are accumulating differently in the food web.

Objectives

1. *Are trace elements detectable in water and biota before most energy development in Muddy Creek?* We collected and analyzed water, aquatic food sources, invertebrates, birds, frogs, and fish for trace element concentrations (Be, B, Mg, Al, v, Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Sr, Mo, Cd, Ba, Hg, and Pb) at 2 sites along Muddy Creek (above and below the current coalbed natural gas well).
2. *What does the food web at Muddy Creek look like?* We collected aquatic food sources, aquatic invertebrates, spiders, birds, frogs, and fish at 2 sites along Muddy Creek and analyzed these samples for $\delta^{15}N$ and $\delta^{13}C$. $\delta^{15}N$ describes trophic position of each group, because ^{15}N accumulates in biota at higher trophic levels. $\delta^{13}C$ describes carbon sources.
3. *Do trace elements bioaccumulate in the Muddy Creek food web?* To estimate how each trace element behaves in the food web, we regressed trace element concentration (e.g., µg Se/g tissue) against $\delta^{15}N$ (trophic position).

Study Sites

Muddy Creek is located south of Rawlins, Wyoming in the Colorado River Basin. Muddy Creek originates by the continental divide near the Atlantic Rim and Bridger Pass at ~2500 m elevation (Figure 1). The stream flows across high desert prairie dominated by sagebrush (*Artemisia* sp.) and greasewood (*Sarcobatus* sp.). Several tributaries empty into Muddy Creek within the watershed, including Wild Cow Creek and Dry Cow Creek. Finally, Muddy Creek joins the Little Snake River by the Colorado boarder near Baggs, Wyoming.

We collected samples at 2 sites along Muddy Creek. The upper site was used as a reference site, because the site was located above the current input of CBNG. The lower site was below the current CBNG input; however, produced water was not being discharged during our study. The upper and lower sites shared several characteristics, such as stream width (1-2 m wide after runoff), fine sediments, dominant vegetation, and stream morphology. One difference between sites was that the upper site had more riparian vegetations (*Salix* and *Carex*) compared to the lower site (*Salix*, *Juncus*, and *Equisetum*).

The Muddy Creek watershed is a unique ecosystem because the stream contains a distinctive fish assemblage, is physically degraded, and will soon be influenced by oil and gas development. First, Muddy Creek contains fish species not known to coexist elsewhere (Quist et al. 2006). Four fish within Muddy Creek (flannelmouth sucker (*Catostomus latipinnis*), bluehead sucker (*Catostomus discobolus*), roundtail chub (*Gila robusta robusta*), and Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*)) are considered sensitive species by Bureau of Land Management and the Wyoming Game and Fish Department. The populations of these fish have declined because of habitat degradation, dams, introduced competitors, introduced predators, and hybridization. The survival of these fish depends on intermittent flows in late summer and early fall (Bower et al. 2008). Second, Muddy Creek is on the EPA's impaired stream list due to physical degradation and steps have been taken to reduce erosion (Ellison et al. 2008). Finally, oil and gas development is beginning in the area. Currently, coalbed natural gas (CBNG) development is occurring and CBNG product water is being discharged into Muddy Creek. Therefore, Muddy Creek has multiple stressors. Because physical impairments and sensitive species are known in Muddy Creek, a prior investigation of the food web may provide developers and managers (e.g., BLM-Rawlins Field Office, Wyoming Department of Environmental Quality, and Wyoming Game and Fish) with more information about the watershed.

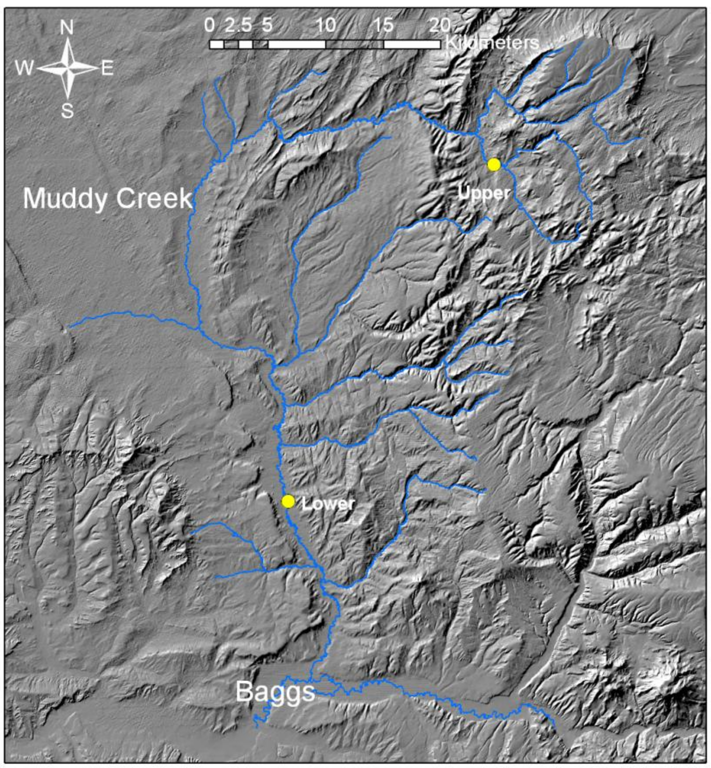


Figure 1. Map of Muddy Creek watershed located south of Rawlins, Wyoming.

Methods

To estimate how trace elements moved through the food web of Muddy Creek, we collected water, food, and biota at 2 sites along Muddy Creek, and analyzed them for trace elements (Be, B, Mg, Al, v, Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Sr, Mo, Cd, Ba, Hg, and Pb), $\delta^{15}N$ (trophic position) and $\delta^{13}C$

(carbon source). All samples were collected using trace element clean techniques with acid washed utensils and bottles. Samples were analyzed for trace element concentrations at Dartmouth Toxic Metals Superfund Research Program (inductively coupled plasma mass spectrometry), and $\delta^{15}N$ and $\delta^{13}C$ at University of Wyoming Stable Isotope Facility (Finnigan Delta Plus XP).

To measure the constituents of stream water, we collected water samples at each site between May and July 2010. Water was collected in 125 mL Nalgene HDPE bottles that were acid washed in trace element grade nitric acid. Water samples were filtered (0.45 µm) and preserved by adding trace element grade nitric acid. Additionally, we measured basic water quality parameters at both sites using a YSI Professional Plus Multiprobe.

We measured basal food resources (i.e., algae, sediment, and suspended organic matter (SOM)) for trace element concentrations to estimate how trace element moved through the food web. Stream algae was collected from tiles placed in Muddy Creek for at least 3 weeks and ambient rocks. Stream sediments were collected using a plastic corer. Finally, we collected suspended organic matter (eaten by filter feeding invertebrates) by filtering stream water through filters for analysis.

To estimate how trace elements moved through animals, we collected invertebrates, amphibians, and birds. We collected aquatic invertebrates using a dip net, and sorted invertebrates according to functional feeding groups (Merritt et al. 2008). Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies; EPT) are orders of insects that tend to be sensitive to water quality. Spiders were hand collected by searching after dark with flashlights and identified using Kaston (1953). Boreal Chorus Frogs (*Pseudacris maculate*) were collected using dip nets after locating frogs via their calls at dawn and dusk. Frogs were euthanized by immersing them in a 4g/L solution of tricaine methane sulfonate (MS-222) for 10 minutes. Although we planned to sample Boreal Chorus Frog tadpoles, none were observed at our study sites. We measured whole invertebrates and frogs (no gut clearance), because these measurements represent what a predator consumes (Farag et al. 1998).

We collected samples from riparian nesting birds to measure the concentration of trace elements in terrestrial animals adjacent to the stream. Adult birds were captured using mist nets (Bub 1995; Braun 2005; Fair et al. 2010). Mist nets were checked every 15 minutes to minimize time in nets and predation risk. We collected blood samples from adult birds by puncturing the brachial vein with a 26 gauge needle and collecting blood directly into microhematocrit capillary tubes (Fair et al. 2010). The volume of blood collected was restricted to less than 1% of the birds body mass (McGuill and Rowan 1989; Fair et al. 2010). We also collected feather samples from nestlings because feathers of chicks have been shown to reflect local contaminant concentrations (Becker et al. 1994). All sampling procedures for vertebrate species were approved by the University of Wyoming Animal Care and Use Committee.

Fish samples were provided by the United States Fish and Wildlife Service (USFWS), which is conducting a concurrent multi-year study monitoring water quality throughout the Muddy Creek drainage. We worked with the USFWS to obtain whole fish samples from white suckers and creek chubs (non-native fish with very similar feeding habits to the native suckers) and muscle plugs from roundtail chub, bluehead suckers, and flannelmouth suckers. Most fish samples are currently being analyzed for trace elements; however, all fish samples have been analyzed for $\delta^{15}N$ and $\delta^{13}C$.

Principle findings

Basic water quality parameters were similar between the 2 sites, except the lower site had higher conductivity (Table 1). B, Mg, Cu, Sr, and Ba had higher concentrations at the lower site, but As, Se, and Mo had higher concentrations at the upper site (2 sample t-tests, $p < 0.05$; Table 2). Al and Zn exceeded the chronic water quality standards for aquatic life at the lower site and both sites, respectively (Table 2).

Table 1. Water quality parameters at both sites along Muddy Creek in late July. We measured temperature, dissolved oxygen (DO), specific conductivity (SP conductivity), conductivity, pH, and oxidation-reduction potential (ORP) using an YSI Professional Plus Multiprobe.

Parameter	Upper	Lower
Temperature (°C)	22	25
DO (% saturation)	130	123
DO (mg/L)	8.8	8.1
SP conductivity (µS/cm)	645	1198
Conductivity (µS/cm)	611	1205
pH	8.63	8.45
ORP (mV)	227.8	202.7

Table 2. We compared trace element concentrations in water from the upper and lower sites against the EPA and Wyoming chronic water quality standards for aquatic life. NS indicates that there are no standards for the element. Six water samples were collected between May and July 2010, and the standard errors (SE) were calculated. The limit column shows if the concentrations measured in Muddy Creek were above (Y) or below (N) the aquatic life standards. Water quality standards for chromium are based on the species (III vs. VI); however, we did not determine the species of chromium in Muddy Creek.

Element	EPA Chronic (µg/L)	WY Chronic (µg/L)	Upper			Lower		
			Mean (µg/L)	SE	Limit	Mean (µg/L)	SE	Limit
Be	NS	NS	0.0	0.0		0.0	0.0	
B	NS	NS	47.0	4.6		170.0	2.2	
Mg	NS	NS	21,493.1	1433.5		44,007.2	3475.7	
Al	87	87	20.3	6.8	N	136.1	66.9	**Y**
V	NS	NS	1.6	0.1		2.2	0.3	
Cr	11 (VI) 74 (III)	11 (VI) 210 (III)	0.4	0.1	N	0.5	0.1	N
Mn	NS	1462	22.3	1.7	N	11.5	2.2	N
Fe	1000	1000	113.8	13.6	N	161.5	77.8	N
Ni	52	160	7.7	1.7	N	7.2	0.7	N
Cu		12	3.0	0.6	N	5.3	0.9	N
Zn	120	110	127.9	27.3	**Y**	125.1	13.1	**Y**
As	150	190	2.5	0.2	N	1.3	0.1	N
Se	5	5	3.4	0.3	N	1.0	0.1	N
Sr	NS	NS	506.3	2.6		746.5	59.9	
Mo	NS	NS	12.0	0.5		9.8	0.6	
Cd	0.25	1.1	0.1	0.0	N	0.1	0.0	N
Ba	NS	NS	39.9	0.5		50.7	0.8	
Hg	0.77	0.012	0.001	0.0	N	0.001	0.0	N
Pb	2.5	3.2	1.6	0.5	N	1.4	0.2	N

The trophic arrangement differed between upper and lower Muddy Creek, however, this may have been due, in part, to different species sampled. Although we aimed to sample the same species at both the upper and lower sites, we were not always able to do this. For example, frogs were rare in this system and we were only able to sample one Boreal Chorus Frog at the upper site. Of the species sampled at the upper site, cliff swallows, roundtail chub, and boreal chorus frogs were the top predators (Figure 2). At the lower site, mountain blue birds and creek chub were the top predators. Basal food resources also varied. SOM probably contained a higher percent of animal matter compared to soil and algae at the upper site compared to the lower, because the $\delta^{15}N$ value of SOM was higher at the upper site. Also, maximum $\delta^{15}N$ values were higher at the lower site. Filterer and predatory invertebrates had the highest $\delta^{15}N$ at the upper site, and *Ephemera* and omnivores had the lower. Conversely, spiders, crayfish, and predatory insects had the higher $\delta^{15}N$ at the lower site, and filterers, scrapers, and collector-gatherers had the lowest $\delta^{15}N$ values. The $\delta^{13}C$ values for each group were similar between sites.

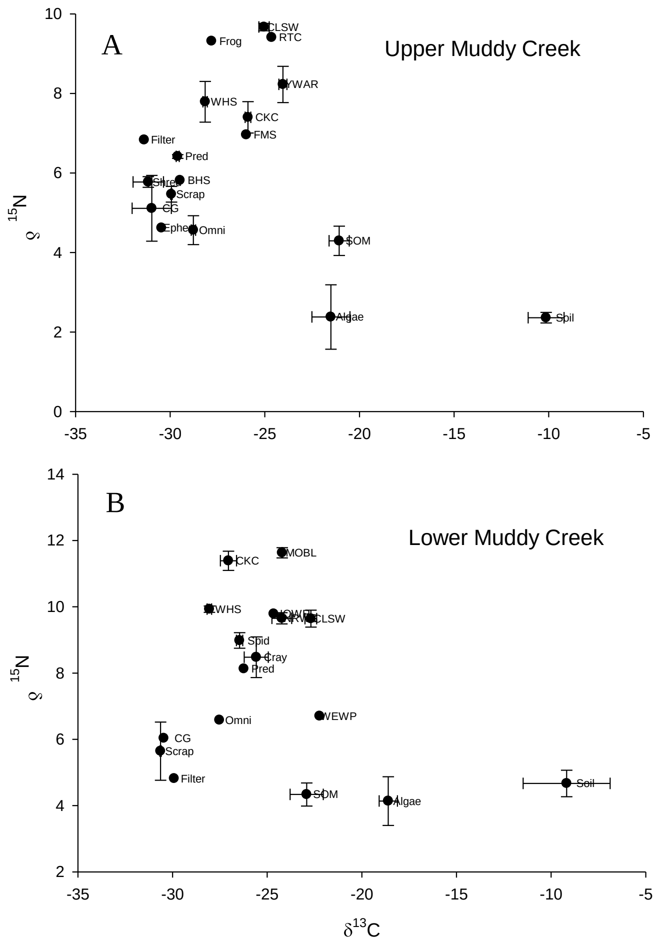


Figure 2. Plot of δ15N vs. δ13C for A. upper and B. lower Muddy Creek sites. Larger δ15N values indicate a higher trophic position. δ13C represents carbon sources. CLSW is cliff swallow, YWAR is yellow warbler, HOWR is house wren, MOBL is mountain blue bird, WEWP is western wood pee-wee, RTC is roundtail chub, CKC is creek chub, FMS is flannelmouth sucker, WHS is whitehead sucker, BHS is bluehead sucker, spid is spider, cray is crayfish, pred are predatory invertebrates, shred are shredding insects, filter are filtering insects, scrap are scraping insects, CG are collector-gatherer insects, Ephem is Ephemera, omni are omnivorous invertebrates, and SOM is suspended organic matter.

Concentrations of trace elements either biodiminished, bioaccumulated, peaked at intermediate trophic levels, or remained similar as they moved through the food web (Figure 3). Concentrations of Be, Mg, Al, V, Cr, Mn, Fe, Ni, As, Sr (upper), Mo, Ba, and Pb all biodiminished in the food web (Least Squares Regression, $p < 0.05$). Conversely, concentrations of Se (upper) and Hg (upper) bioaccumulated in the food web (Least Squares Regression, $p < 0.05$). The concentration of B, Se (lower), Sr (lower), and Hg (lower) remained similar as these elements moved through the food web (Least Squares Regression, $p > 0.05$). Finally, concentrations of Cu, Zn, and Cd were highest at intermediate trophic levels.

Aquatic food sources tended to have the highest concentrations of elements, because most elements biodiminished. Of the food sources, algae generally had the highest concentration of trace elements and SOM had the lowest concentration. One exception was that SOM had the highest B concentration at both sites. Additionally, algae and soil often contained similar concentrations of elements at the upper site. Algae at the lower site contained the highest concentration of Be, Al, V, Fe, Ni, Ba, and Pb.

Aquatic invertebrates contained fairly high concentrations of trace elements. We collected 24 taxa of aquatic invertebrates at the upper site, but only 8 taxa at the lower site. Of these taxa 10 were EPT taxa at the upper site, and only 2 were EPT taxa at the lower site. *Ephemera*, a burrowing mayfly that is a collector-gatherer, filterer, and predator, often had high concentrations of trace elements. Insects in the functional feeding groups scraper, collector-gatherer, and omnivore often contained high concentrations of trace elements. At the upper site, snails in the family Physidae were the dominant scrapers, but the mayfly *Heptagenia* was the dominant scraper at the lower site. *Plauditus* (Baetidae), *Caenis* (Caenidae), *Sigara* (Corixidae), Elmidae, and non-Tanypodinae chironomids were the collector-gatherers at the upper site, while *Acentrella* (Baetidae) and non-Tanypodinae chironomids were the collector-gatherers at the lower site. Omnivores at the upper site were Amphipoda, and Amphipoda and crayfish (Decapoda) were at the lower site. Filterers contained high concentrations of Mn, Ni, Se, and Mo. *Ceratopsyche*, *Hydropsyche* (Hydropsychidae), Spheariidae, and Simuliidae were the filterers at the upper site, and *Simulium* (Simuliidae) were the only filterers we collected at the lower site. Shredders contained high concentrations of Mn, Ni, Zn, Se, Mo, and Ba. At the upper site, *Limnephilus*, *Homophylax*, *Eocosmoecus* (Limnephilidae), *Microsema* (Brachycentridae), *Lepidostoma* (Lepidostomatidae), and Tipulidae were the dominant shredders, but we did not collected shredders at the lower site. The concentrations of Mn, Zn, Se, and Cd were high in predaceous insects. *Cultus* (Perlodidae), *Ambrysus* (Naucoridae), *Anax* (Aeshnidae), *Gomphus* (Gomphidae), *Coenagrion/Enallagma* (Coenagrionidae), *Ambrysus* (Nauicoridae), *Gerris* (Gerridae), *Susphisellus* (Noteridae), *Agabus* (Dytiscidae), Acari, and Hirudinidae were the predaceous insects we collected at the upper site, and *Gyrinus* and *Trepobates* (Gerridae) were the predators we collected at the lower site. Finally, spiders had high concentrations of Zn, Se, and Cd. We collected *Pachygnatha* (Tetragnathidae) and *Dictyna* (Dictynidae) at the upper site, and *Haplodrassus* (Gnaphosidae) and *Pachygnatha* (Tetragnathidae) at the lower site.

Birds and amphibians had high concentrations of some trace elements. We collected an adult boreal chorus frog at the upper site. The frog had high concentrations of Zn, Cr, Se, and Hg. Birds also had high concentrations of Se and Hg, probably because these elements bioaccumulated. Blood from Yellow warblers and cliff swallows had high concentrations of Se. Similarly, Brewer's blackbirds and cliff swallows had high concentrations of Hg. Feathers from cliff swallow hatchlings always had higher concentrations of trace elements compared to blood from adult cliff swallow, except for Fe and Se. Yellow warbler, cliff swallow (adult blood, hatchling feathers), and Brewer's blackbird had the highest concentrations of Se at the upper site in decreasing order. At the lower site, northern rough-winged swallow, cliff swallow (adult blood, hatchling feathers), western wood pee-wee, house wren, and mountain blue bird had the highest concentration of Se at the lower site in decreasing order. Brewer's blackbirds, cliff swallows (hatchling feathers), yellow warbler, and cliff swallow (adult blood) at the upper site contained the highest concentrations of Hg in decreasing order. At the lower site, cliff swallow (hatchling feathers), western wood pee-wee, northern rough-winged swallow, house wren, cliff swallow (adult blood), and mountain bluebirds had the highest Hg concentrations in decreasing order.

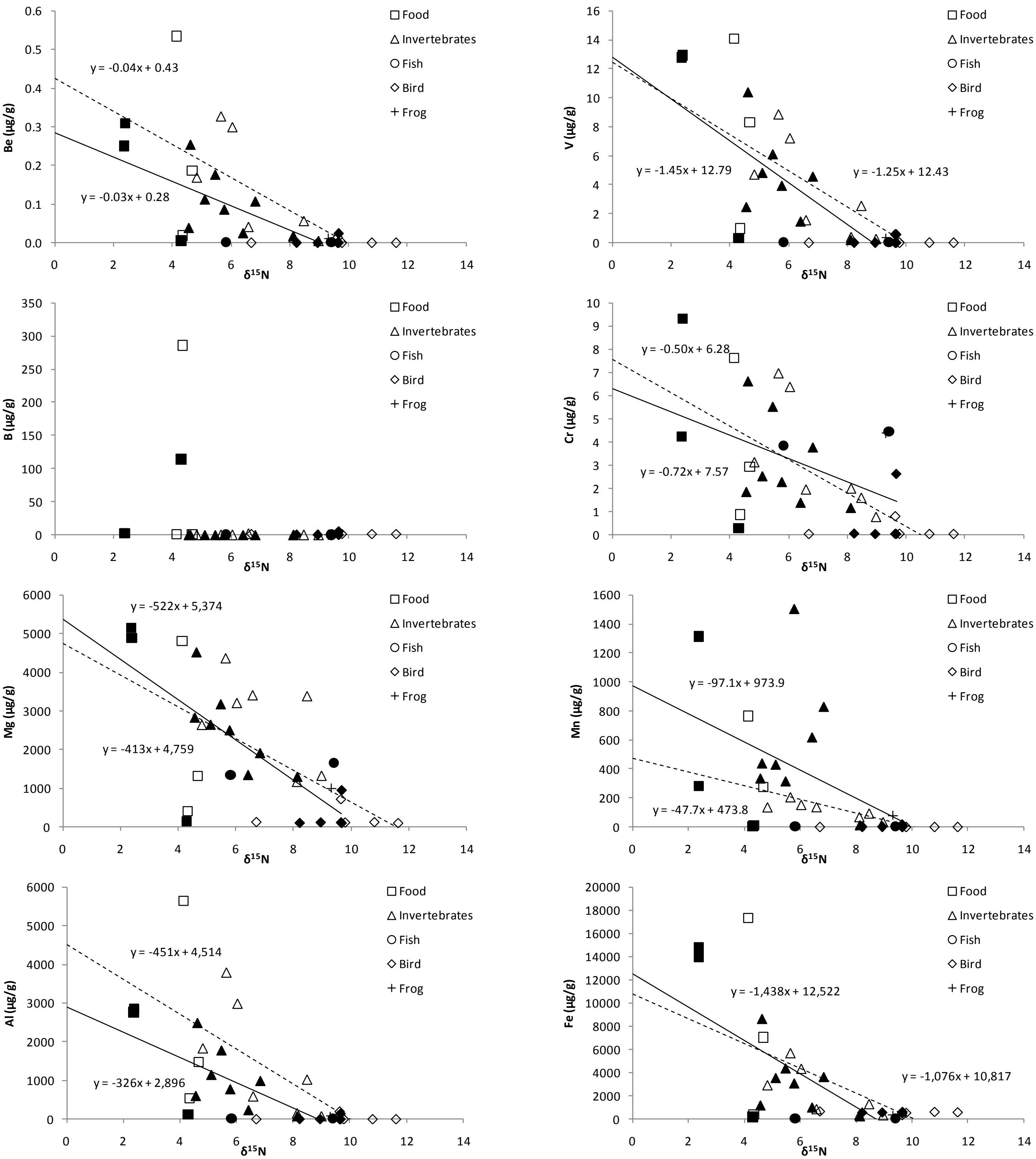
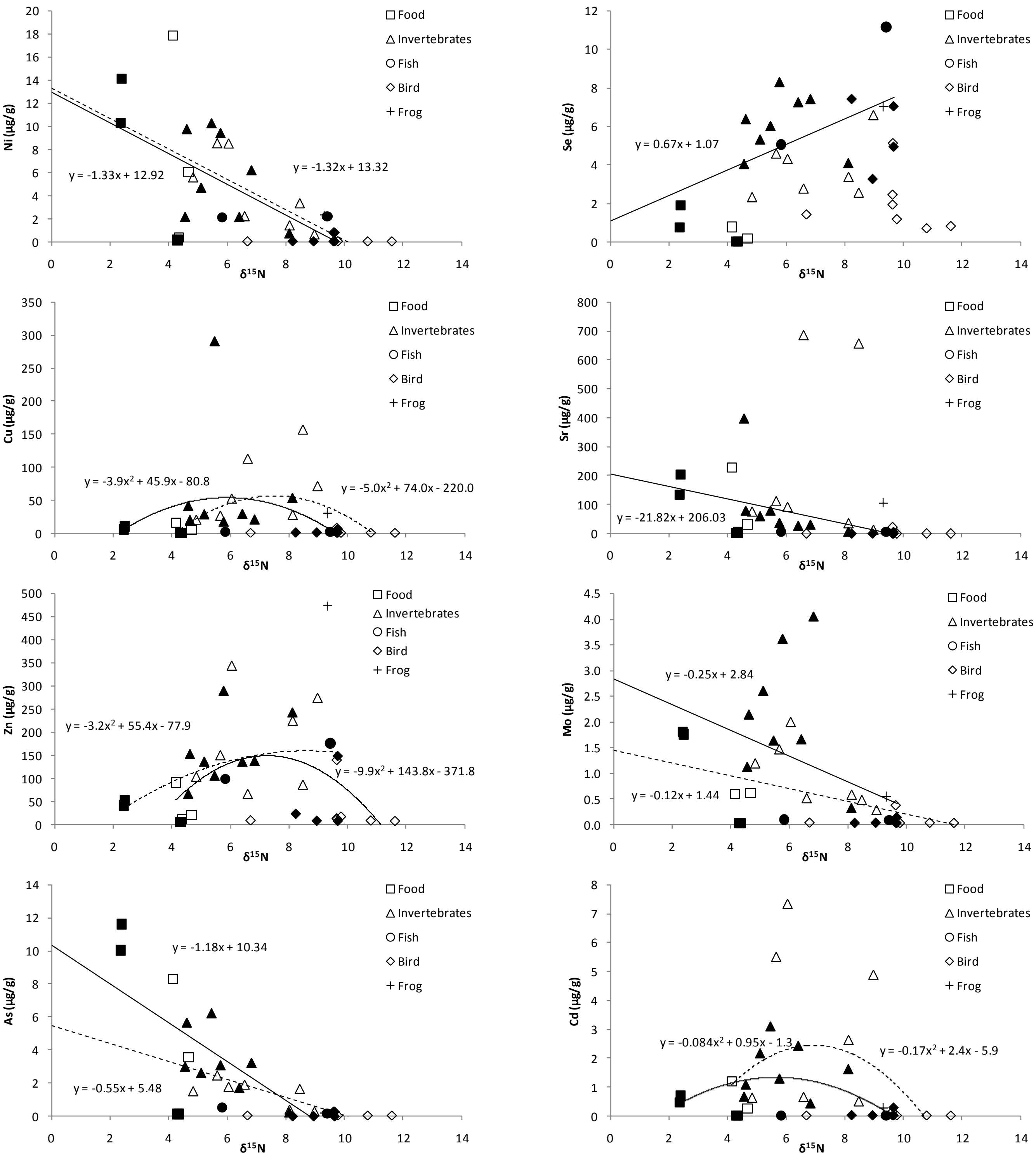


Figure 3. Elements in the Muddy Creek food web either bioaccumulated, biodiminished, peaked at intermediate trophic levels, or concentrations remained similar. Solid symbols and lines represent the upper site, and clear symbols and dotted lines represent the lower site. Aquatic food sources were algae, suspended organic matter, and sediment. Each invertebrate symbol represents a different functional feeding group or terrestrial spiders. Both adult bird blood and hatchling feathers are represented on the plots for birds. The frog was captured at the upper site.



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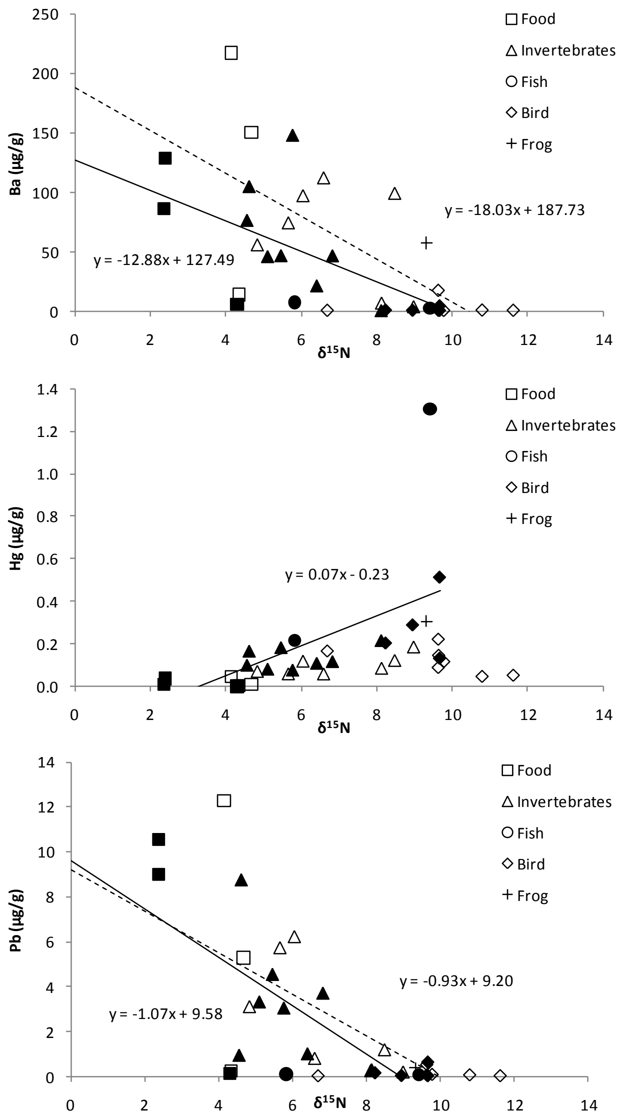

Figure 3. Continued.

Significance

Trace elements were detectable in water and biota in the Muddy Creek watershed. Trace elements in the water were taken up by algae and transferred to higher trophic levels. Algae often contained the highest concentration of trace element, because most elements biodiminished in the food web. Therefore, concentrations of trace elements decreased as they moved through the food web and were less likely to cause major environmental impacts. However, Hg and Se appeared to bioaccumulate at the upper Muddy Creek site. These elements have been observed to bioaccumulate in other ecosystems (e.g., Cabana and Rasmussen 1994; Ikemoto et al. 2008). According to our results, Hg and Se that originated in Muddy Creek can move to riparian animals, such as northern rough-winged swallows. Many such birds are known to feed heavily on adult insects that emerge from the stream. Trace elements can move beyond riparian habitats; Cristol et al. (2008) noted that Hg moved from a river-ecosystem to terrestrial-feeding birds and resulted in higher Hg concentrations due to bioaccumulation.

Trace elements in the environment come from both anthropogenic and natural sources. Anthropogenic activities, such as mining (e.g., Valenti et al. 2005) and manufacturing (e.g., Chen and Folt 2000) can lead to high concentrations of trace elements in the environment. Additionally, groundwater can be naturally high in certain trace elements, such as the Mekong Delta region of Vietnam, which is naturally high in arsenic, manganese, and barium (Ikemoto et al. 2008). Trace elements that we measured in the current study in the Muddy Creek watershed were probably naturally occurring; however, oil and gas development could potentially increase concentrations depending on geology. Groundwater produced in association with oil and gas development can contain trace elements and the concentration of trace elements depend on the geology of the aquifer (Rice et al. 2000). By releasing ground water into surface waters, oil and gas development can increase the concentrations of certain trace elements in rivers and streams.

The fate of trace elements in the environment is largely unknown. However, trace elements may be taken up by algae (Kiffney and Clements 1993), deposited in sediments (Lee et al. 2000), or incorporated into decaying organic matter (Sundberg et al. 2006) before being ingested by stream inhabitants. Once trace elements enter the food web, they can be transferred to higher levels through predators. The concentration of trace elements can behave differently depending on the element, the organism, and the specific conditions at the site. For example, invertebrates that eat sediment (collector-gatherers), such as burrowing mayflies, midges, or worms, can have higher trace element concentrations than invertebrates with other feeding habits (Smock 1983). Similarly, we found that collector-gatherers and *Ephemera* often contained high concentrations of trace elements. Additionally, smaller invertebrates tend to have higher concentrations (Van Hattum et al. 1991), which means juvenile fish may ingest higher concentrations of trace elements (Farag et al. 1998). We look forward to investigating how size may affect trace element concentration of fish in Muddy Creek.

Results of this project provide an understanding of baseline concentrations of trace metals in the Muddy Creek food web. These baseline data were collected before significant expansion of oil and gas development in the watershed. It is currently unknown whether water produced during oil and gas development significantly impacts local watersheds. By comparing the baseline concentrations of trace metals detected in this study to data collected in 3 to 5 years after oil and gas development has expanded in this area, we hope to assess any potential impacts energy development might have on the Muddy Creek ecosystem.

Publication and Presentation citations

We plan to present our results at for the WRP Priority and Selection Committee in July 2011. We also hope to present these results at the Wyoming-Colorado Chapter of the American Fisheries Society meetings during spring 2012. Finally, we plan to publish our results in a peer-reviewed journal.

Student support info

The project gave 2 students field and laboratory experience that will help them gain employment or enter into a graduate degree program. The project benefited the students by becoming familiar with an array of techniques used in stream ecology, vertebrate ecology, and toxicology. One student is currently a junior in Rangeland Ecology and Watershed Management at the University of Wyoming. The other student graduated from Clemson University with a degree in Wildlife and Fisheries Biology and is currently applying to graduate programs.

Products

We plan to publish the study. However, we are waiting for results from the majority of fish samples analyzed for trace elements.

Acknowledgements

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Using Voluntary Arrangements to Reduce Diversions and Improve Stream Flows for In-Channel Benefits in Wyoming

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Enhancing Stream Flows in Wyoming

Final Report

PI: Lawrence J. MacDonnell, Professor, University of Wyoming College of Law

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Abstract

Restoration of stream flows for fishery and other instream benefits often requires reduction of historical diversions under existing water rights. With growing interest in enhancing flows in critical locations, especially during low-flow periods, many states now provide legal mechanisms under which diversions may be reduced so that flows can remain in-channel. This project examined the relevant laws in Colorado, Idaho, Montana, Oregon, and Washington that allow such reduced diversions. It identified examples in each of these states to illustrate how the law enabled such reduced diversions to stay instream for fishery and other benefits. The project also examined existing Wyoming water law relating to instream flow protection. Based on the evaluation of what had worked well in other study states, recommendations were made for ways Wyoming might allow holders of water rights to reduce diversions for instream flow benefits while still retaining ownership of the water right.

Objectives

To evaluate legal approaches followed in other states to encourage reduced diversions under existing water rights for instream benefits.

To evaluate how these approaches work in practice through case studies.

To examine existing Wyoming water law related to instream flow protection.

To recommend ways Wyoming law might be adapted to enable holders of water rights to reduce diversions for instream flow benefits.

Methodology

Read literature examining instream flow water rights.

Examine state statutes and regulations governing the appropriation of water for instream flow benefits.

Telephone interviews with state personnel charged with implementation of instream flow laws.

Telephone interviews with members of NGOs working to enhance stream flows.

Analysis of information and preparation of a written report.

Revising draft report based on comments from outside reviewers.

Principal Findings and Significance

At least five western states now allow the change of use of an existing appropriative water right to instream flow use.

In some cases, only the state may acquire and change the use of a water right; in other states, non-governmental entities also are allowed to acquire a water right and make the change of use.

In most cases, these changes are temporary; the holder of the original right maintains ownership.
There are a variety of approaches used to enable the appropriator to reduce diversions; in some cases, the reduction is only seasonal.
Such transactions are increasing.
They are producing measurable benefits for fisheries and other instream values.
They often produce efficiency benefits for the diversionary water user.
They occur with no injury to other existing water rights.
Water right holders are more interested in temporary arrangements than in permanent sale of the right; they want to maintain ownership of the right and often are themselves interested in being to use a portion of their right to improve stream flows on their property.
To facilitate such temporary changes it is important to protect the right from forfeiture so it is not lost because of non-diversion.
Another important incentive is provided by not reducing the historic consumptive use associated with the original use during the period of instream flow use.
Allowing NGOs to participate increases the funding available to facilitate the transactions.
Wyoming law presently only allows the State to acquire a water right and change its use to instream flow protection.
There is substantial interest in Wyoming to allow holders of water rights to temporarily change their use to instream flows; flow enhancements are desired to complement the habitat improvements being made by some landowners to improve the fishery on their property.

Student Support
Project funds were used entirely to support student research and writing. Most of the research and writing summarizing state laws and case studies was performed by Curran Trick, Class of 2012, University of Wyoming College of Law. Assistance with citations was provided by Janna Wittenberg, Class of 2012, University of Wyoming College of Law.

Table of Contents

Enhancing Stream Flows in Wyoming **5**
- I. Introduction 5
- II. Background 6
- III. Proposal 11
- IV. Summary and Conclusion 16

Appendix One: Colorado **17**
- I. Instream Flow Appropriations 17
- II. Water Acquisitions 20
- III. Temporary Loans of Water 22
- IV. Instream Flow Monitoring 23
- V. Project Example: Pitkin County 23
- VI. Project Example: Blue River 26

Appendix Two: Idaho **28**
- I. Filing on Unappropriated Waters 29
- II. Changing Existing Appropriative Rights to Instream Use 31
- III. Water Banks in Idaho 31
- IV. Project Example: Fourth of July Creek 34

Appendix Three: Montana **37**
- I. Water Reservations 38
- II. Leases and Temporary Transfers 40
- III. Project Example: Mannix Bros. Ranch 44

Appendix Four: Oregon **47**
- I. Instream Water Right Act 47
- II. Minimum Perennial Streamflows 48
- III. Permanent Transfers, Leasing, and Time-Limited Transfers 49
- IV. Allocation of Conserved Water 52
- V. Project Example: Austin Ranch 54
- VI. Project Example: Lower Rudio Creek 57

Appendix Five: Washington **60**
- I. The Watershed Planning Process 63
- II. Water Markets, Water Banks, and the Trust Water Rights Program 64
- III. Project Example: Salmon Creek 67

Appendix Six: Wyoming **70**

Appendix Seven: Columbia Basin Water Transactions Program **74**

Enhancing Stream Flows in Wyoming

I. Introduction

Wyoming streams and rivers provide many important benefits including serving as sources of water for out-of-stream uses. They also still support valuable fisheries, especially at higher elevations. In some cases, these fisheries could be measurably improved if some existing diversions were reduced, especially during critical flow periods. Some owners of water rights have expressed an interest in modifying their traditional water use practices to benefit fish, but they are concerned about what would happen to their water rights. At present, Wyoming law does not allow a water right owner to temporarily change the use of a water right to maintain instream flows.[1] Failure to divert water can result in forfeiture of the right.[2] Diverting and consuming less water diminishes the amount of water that can be changed to a different use, reducing its value.[3]

This report explores modifications needed in existing law to enable holders of valid water rights in Wyoming—either on their own initiative or with support from other interested parties—to not divert water historically beneficially used out of the stream channel so that flows of water beneficial to fisheries and other in-channel values can be maintained.[4] It begins with examples of how people in Wyoming and elsewhere are

[1] Wyo. Stat. Ann. § 41-3-1001 (2011). Only the State of Wyoming is allowed to hold a water right for the protection of instream flows of water. Wyo. Stat. Ann. § 41-3-1002(e) (2011). While the State may be able to temporarily change use of a water right it owns to instream uses, other water rights owners are not presently allowed to do this.

[2] Wyo. Stat. Ann. § 41-3-401(a) (2011). Non-diversion under a permit based on diversion would probably be considered non-use of the right. After five years, such non-diversion could result in loss of the right.

[3] Wyo. Stat. Ann. § 41-3-104 (a) (2011). A change of use may not result in the increase in the amount of water historically consumed under the original water right. By not diverting water and applying it to a consumptive use for some period of time, the historical average consumption would be reduced.

[4] Similarly, the owner of a storage right would be permitted not to divert and use the water but to release and leave the water instream to and beyond its historical point of diversion.

making changes in their traditional water use practices to enhance stream flows for fishery benefits. The report then discusses how neighboring states have adapted their laws to help facilitate such outcomes. Finally it offers suggestions for ways Wyoming law could be adapted to allow such modifications of historical uses to go forward without impairing the status of the water rights or injuring the rights of others. An appendix provides summaries of the laws of Colorado, Idaho, Montana, Oregon, Washington, and Wyoming related to protection of instream flows, with special attention to ways the laws in these states (other than Wyoming) permit at least temporary shifts of diversionary and storage rights to instream flow use.

II. Background

Public interest in protecting some portion of remaining unappropriated water to maintain stream flows has grown markedly in recent decades.[5] In response, Wyoming and many other states have modified their laws to provide for such protection.[6] Wyoming allows the Water Development Commission, acting on behalf of the State, to obtain a water right from the State Engineer to maintain or improve flows for fish.[7] Since 1986, the State has applied for over 110 permits protecting specified unappropriated flows in more than 300 miles of stream.[8] Such appropriations are made within the priority system so there are no effects on existing water rights.

[5] DAVID M. GILLILAN & THOMAS C. BROWN, INSTREAM FLOW PROTECTION: SEEKING A BALANCE IN WESTERN WATER USE (1997); INSTREAM FLOW COUNCIL, INSTREAM FLOWS FOR RIVERINE RESOURCE STEWARDSHIP 5–6 (rev. ed. 2004).
[6] INSTREAM FLOW PROTECTION IN THE WEST (LAWRENCE J. MACDONNELL & TERESA A. RICE, eds) (rev. ed. 1993); Cynthia F. Covell, *A Survey of State Instream Flow Programs in the Western United States*, 1 U. OF DENVER WATER L. REV. 177 (1998); Lawrence J. MacDonnell, *Environmental Flows in the Rocky Mountain West: A Progress Report*, 9 WYO. L. REV. 225 (2009) (hereafter "*Environmental Flows*").
[7] Wyo. Stat. Ann. § 41-3-1003 (2011). The State is authorized to acquire an existing water right and change its use to instream flows as well. Wyo. Stat. Ann. § 41-3-1007 (2011).
[8] Instream Flow Filings, Water Resources Data System, http://www.wrds.uwyo.edu/, December 2010.

While the work to identify stream reaches with important fisheries that still contain unappropriated water continues, interest has increased in ways to enhance flows in stream reaches with little or no unappropriated water but that still support or have the potential to support viable fisheries.[9] In some cases, this interest emerges from the desire of a landowner to improve fishing on his land, a city to improve fishing on streams within its limits, or a conservation group wanting to restore populations of native species. In some cases, stream restoration is driven by legal requirements.[10]

Trout Unlimited in Wyoming has been working with landowners and public entities to improve fisheries and their habitat in the Gros Ventre River and Spread Creek near Jackson, in the Smiths Fork and Thomas Fork of the Bear River in Wyoming and Idaho, and with broad programmatic efforts in the North Platte, Upper Green, and Bighorn river basins.[11] Many of these projects have streamflow components but can only occur on smaller tributaries with simple water rights systems. This was the case for flow restoration projects like Grade Creek (Smiths Fork drainage) and the Francs Fork of the Greybull River where only one water right holder exists, and TU was able to work directly with the private landowner to mutually benefit agricultural and fishery interests.

Trout Unlimited has identified water right owners interested in using at least a portion of their water rights to enhance stream flows to benefit fisheries and for other instream benefits. For example, the Laramie River Guest Ranch grows forage on approximately

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9 INSTREAM FLOW COUNCIL, *supra* note 5; *Environmental Flows*, *supra* note 6.
10 *See, e.g.*, John M. Volkman, *Endangered Species Act and the Ecosystem of the Columbia River Salmon*, 4 HASTINGS NORTH-NORTHWEST J. ENVT'L LAW & POLICY 51 (1997). Flow restoration can help address water quality concerns as well.
11 Personal communication with Scott Yates, Western Water Project Director, Trout Unlimited (Feb. 14, 2011.)

1,600 acres, irrigated from the Laramie River near Wheatland.[12] The Ranch considered taking certain lands out of production late-season to provide additional flows and bolster the wild brown and rainbow trout fishery. They have seen neighbors use the existing temporary change statute to move groundwater rights to Basin Electric in exchange for substantial financial benefits but are unable to temporarily change their water right to protect trout.

TU has also worked closely with ranchers along Rock Creek, a Wyoming tributary to Twin Creek in the Bear River Basin, to enhance the Bonneville cutthroat trout fishery. Project components have included new diversion structures and fish screens to ensure fish passage and reduce entrainment and the installation of gated pipe to use less water, supported by Federal Farm Bill funding made available through the Natural Resources Conservation Service. The families also are interested in eliminating water use during the late-season over a term of years to ensure adequate stream flows for the fish in exchange for funding from sources such as the federal farm bill that could be use to support other ranch operations.

A primary concern of many interested water right owners is their desire to retain ownership of the right. Water rights are property rights.[13] These owners would like more freedom to use their rights, including the ability to choose not to divert at least some of

[12] *Wyoming Water, Wyoming Solutions: Partnering for Streamflow Restoration*. Trout Unlimited Wyoming Water Project. 2009.

[13] A water right represents the legally protected ability to use a specified portion of water from a particular source for a beneficial use. Its priority date determines its ability to divert and use water physically available in the source, with more senior rights able to use water when supplies are limited. Rights are defined in terms of points of diversion, maximum rates of diversion, purpose of use, and place of use. Irrigation rights in Wyoming are tied to the land on which they are used. Wyo. Stat. § 41-3-101: "Water being always the property of the state, rights to its use shall attach to the land for irrigation, or to such other purposes or object for which acquired in accordance with the beneficial use made for which the right receives public recognition, under the law and the administration provided thereby." Ownership of the right is freely transferable, but changes of use are subject to review to ensure no injury to existing water rights. Wyo. Stat. § 41-3-104. Temporary changes of use are authorized under Wyo. Stat. § 41-3-110.

their rights, without fear of their loss to forfeiture—subject always to the no injury requirement.

Efforts in other states have led to identification of opportunities in some cases to reduce diversions from an especially critical stream reach while either finding alternative sources of water supply or reducing the amount of water that needs to be diverted through conservation to achieve the beneficial use. Thus, for example, Montana Trout Unlimited facilitated the replacement of a leaky ditch conveyance system with pumps and piping at a critical reach in the North Fork of the Blackfoot River, cutting diversions by more than 18 cubic feet per second (cfs) and enabling bull trout to move through this reach that was previously impassable in late summer and early fall.[14] In Oregon, Kevin Campbell switched from a direct flow diversion system to a pump and changed from flood irrigation to a pressurized wheel line, enabling him to reduce diversions by two cfs from Rudio Creek, a tributary of the North Fork of the John Day River while maintaining his hay production.[15] In Cache Valley, Utah an irrigator moved his point of diversion from Little Bear Creek to the South Fork of Bear Creek to increase flows needed by cutthroat trout in Little Bear.[16] By shifting from flood to center pivot irrigation, the irrigator was able to halve his diversion rate while maintaining his production. Similarly, an Idaho irrigator shifted his point of diversion from Badger Creek downstream to the Little Lost

[14] Private Water Leasing: A *Montana* Approach. *Restoring Stream Flows in Key River Basins*, Trout Unlimited, http://www.tu.org/conservation/western-water-project/montana (last visited February 7, 2011). See also, *In Montana... Heading to Greater Efficiency*, Columbia Basin Water Project. 2005 (describing the North Fork Project, http://cbwtp.org (last visited February 7, 2011); *Big Blackfoot Chapter of Trout Unlimited: A Watershed Initiative to Restore Native Fish Populations*, U.S. Fish and Wildlife Service. http://www.fws.gov/mountain-prairie/pfw/montana/mt5b.htm (last visited February 7, 2011).
[15] *See* Appendix 4, Oregon.
[16] http://www.tuutah.org.

River, enabling bull trout to move up Badger Creek to spawning habitat.[17] Again, by shifting from flood to pivot irrigation he was also able to reduce his rate of diversion while maintaining his production. A variety of federal, state, and private funding sources are used to pay much or all of the costs of these changes.

Oregon allows use of what are called "split season" agreements.[18] Using this approach, the Austin Ranch irrigates with its water right up to July 20th and then ceases diversion for the remainder of the irrigation season to benefit the fishery.[19] In Montana, the Mannix Ranch entered into a lease with Montana Trout Unlimited under which diversions will cease whenever flows in Wasson Creek drop below a specified minimum level.[20]

The Wyoming Game and Fish Department (WGFD) has recently succeeded in obtaining a permanent change of use to instream flow for a storage water right it acquired in Fremont Lake.[21] This is the first time the State has acquired and changed a water right for the purpose of enhancing instream flows.[22] According to Tom Annear, Instream Flow Coordinator for WGFD, "there are many stream reaches around the state with fisheries that could benefit from reduced diversions and improved flows, especially in low-flow periods."[23] While the state's focus has been and remains protecting available unappropriated flows on important streams on public land, there are as many or more

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[17] *Bull Trout Recovery in the Little Lost Basin: Proving Partnerships Can Make the Difference*. Trout Unlimited, Idaho Water Project. 2008 (describing a variety of on-the-ground projects with private landowners and state and federal resource agencies, including the Badger Creek Reconnect, to restore ESA-listed bull trout).
[18] *See* Appendix 4, Oregon, for a discussion of this approach.
[19] *Id.*
[20] *See* Appendix 3, Montana.
[21] Wyoming Board of Control Order, Record No. 76, p.495-510, Dated January 21, 2011.
[22] In 2008, WGFD successfully obtained from the State Board of Control a change of use permit for a water right held by the State to provide water to a fish hatchery. *Environmental Flows*, *supra* note 5 at 375 (citing Telephone interview with Tom Annear, Instream Flow Supervisor, Wyoming Department of Game & Fish (April 29, 2008)).
[23] Personal Communication, Feb. 17, 2011.

opportunities to restore flows on private lands. According to Mr. Annear, "these opportunities are strictly the business of private property owners, and the state has no desire to acquire or hold water rights for instream flow on private lands."[24] As he notes, "the benefits from such use would accrue to landowners so logically they should be the ones holding those rights – especially if they already hold them and use them for other purposes like irrigation. To require that existing water rights be held only by the state if changed temporarily to instream flow is both discriminatory and counter to recognizing and respecting the rights of private property owners."[25]

III. Proposal

Our review of approaches in other states suggests the most straightforward method for reducing diversions to enhance stream flows is to authorize the water right holder to simply choose not to divert water available in priority under the water right. This approach is widely used in Lemhi River in Idaho to reduce diversions at critical times when salmon are returning to spawn.[26] Agreements not to divert at such times help ensure the sufficiency of flows needed for the fish to make their way upstream. The State of Idaho manages the process, but no formal change of use proceeding is involved. Agreements are totally voluntary; the water right remains the property of the original owner. We would encourage Wyoming to consider authorizing holders of water right, either on their own initiative or under agreement with another party, to decide not to divert water if such non-diversion would benefit a fishery. As we envision such

[24] *Id.*
[25] *Id.*
[26] The legislature established a special bank in the Lemhi River Basin to facilitate transfers of irrigation water to instream flows to enable salmon to reach upstream spawning habitat in the watershed. *See* Appendix 2, Idaho; *see also Environmental Flows*, *supra* note 6 at 341, n.20 (citing Idaho Code Ann. §§ 42-1506; 1765A.)

agreements, they would be short-term and might even apply only for a portion of the irrigation season (split-season arrangements). Given their short-term nature, we would suggest a presumption of no-injury should apply.[27]

As mentioned, a change of use is subject to review by the Board of Control to ensure no injury to other water rights. The primary focus of such a review is to ensure the change does not result in an increased demand on the water source that would interfere with the ability of other diverters to enjoy their rights.[28] A decision not to divert leaves water in the channel that otherwise would have been diverted. A portion of that water, approximately 50% if the use was irrigation, would have been lost to evaporation or evapotranspiration by the crop.[29] All of the water that would have been diverted stays in the channel so none is lost. The instream benefit is the higher level of stream flow between the point of diversion and the place where unconsumed water would otherwise return to the stream (or to the headgate of the next appropriator downstream). Thus downstream appropriators benefit from improved flows. For short-term arrangements, especially if diversions only cease in the late season, the timing of the water in the stream will be little affected. Upstream junior appropriators cannot complain of injury since they would not have otherwise been able to consume water obligated to the downstream senior's headgate. For these reasons we believe a presumption of no injury is entirely

[27] The presumption would be overcome if the agreement is protested by another water right holder.
[28] *See, e.g.,* Leonard Rice & Michael D. White, ENGINEERING ASPECTS OF WATER LAW 78 (1987): "Making a change is an exercise in balancing depletions. … A junior priority holder cannot be said to be injured if the change of a senior priority imposes no greater or different burden on the stream than existed before the change."
[29] Wyoming follows a presumption that an irrigation right consumes half of the water diverted from the stream. Wyo. Stat. Ann. § 41-3-110(c) (2010).

warranted for short-term decisions not to divert. Longer-term changes to instream flow use would be expected to go through the usual, more extended injury analysis.[30]

State laws in Colorado, Montana, Idaho, Nevada, Oregon, Utah, and Washington have been changed in recent years to specifically provide a means whereby existing water rights can be temporarily made available for use instream.[31] Most commonly, these statutory provisions anticipate a lease of the existing right, followed by a change of use to instream flow purposes.[32] Several states authorize non-governmental as well as governmental parties to engage in leasing the water right for instream flow uses.[33] In

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[30] Often, this analysis will be considerably simpler than for a change of use to another consumptive use. *See, e.g., Hohenlohe v. State Dep't Natural Res. & Cons.*, 240 P.3d 628 (2010) (department's requirement for detailed return flow analysis not warranted by the facts).

[31] The **Colorado** Water Conservation Board may acquire an instream flow right by "grant, purchase, bequest, devise, lease, exchange or contractual agreement," from any person, including a government entity, as long as the rights acquired are not on the division engineer's abandonment list. COLO. REV. STAT. § 37-92-102(3) (2010). **Idaho** allows instream flow leases mostly through its water banks, which were codified by the legislature in 1979. Idaho Code Ann. § 42-1761 (2010); Idaho has essentially two systems of water bank or market, one for "natural flow" rights (i.e. surface and groundwater) operated directly by the Water Resource Board (Rule 1.02, IDAPA 37.02.03) and one for stored water (called a "rental pool") at specific storage locations, operated by local committees appointed by the IWRB. (Rule 010.09, IDAPA 37.02.03). *see also,* Sasha Charney, *Decades Down the Road: An Analysis of Instream Flow Programs in Colorado and the Western United States* 84 (2005). **Montana** has two statutory programs that allow for the conversion of consumptive water rights to instream flow purposes: one for private parties and one that is available to the Montana Department of Fish, Wildlife and Parks only; both utilize the Montana change of use statute. MONT. CODE ANN. § 85-2-402 (2010). In Montana, "appropriate" is defined as: (e) temporary changes or leases for instream flow to maintain or enhance instream flow to benefit the fishery resource in accordance with 85-2-408. Mont. Code Ann. § 85-2-102(1).In **Nevada**, in 2007 the legislature authorized the temporary conversion of irrigation rights to wildlife purposes or to improve the quality or flow of water. NEV. REV. STAT. § 533.0243 (2009). **Oregon's** Instream Leasing program allows a water right holder to temporarily lease their water for instream use. ORS § 537.348 (2009). The **Utah** legislature in 2008 authorized "fishing groups" to file a change of use to instream flows for an existing right for up to 10 years to protect or restore habitat for native trout. H.B. 117, codified at Utah Code Ann. § 73-3-30(3) (2009). In **Washington**, water-right holders who participate in the Trust Program can sell, lease or donate all or part of their right to the state, on a temporary or permanent basis. WASH. REV. CODE § 90.42.005 & § 90.42.080(3) (2010). Washington also created a water bank along with the Trust Program as a means to "facilitate the voluntary transfer of water rights established through conservation, purchase, lease, or donation…and to achieve a variety of water resource management objectives throughout the state," including improving stream flows. WASH. REV. CODE § 90.42.005 (2010).

[32] *See* references in preceding footnote.

[33] For example, Nevada, Oregon, and Montana allow non-governmental parties. In Nevada, there is no state program for protection of environmental flows. Nevada law, however, authorizes appropriation of water for recreational uses, a provision that has been interpreted by the state's Supreme Court to include wildlife, and does not limit who may file for such appropriations. *State v. Morros*, 766 P.2d 263 (Nev. 1988). In Oregon,

general, such leases require a formal change of use review to ensure no injury to other water rights. For emergency or short-term uses, several states provide an expedited review process. Temporary leases in Oregon are given an expedited approval process, where approval can occur in as little as 30 days after receipt of the application.[34] Colorado authorizes the "loan" of an agricultural water right for instream flow purposes for no more than 120 days on an emergency basis.[35] It authorizes the State Engineer to determine whether any injury will result, rather than requiring the normal Water Court review process.[36] Colorado also has clarified its law to ensure that the historic consumptive use associated with water rights temporarily used for instream flows is not reduced while the right is being used instream.[37] Colorado also authorizes sale of the historic consumptive use during the lease period to a downstream user at the option of the

"Any person may purchase or lease all or a portion of an existing water right or accept a gift of all or a portion of an existing water right for conversion to an in-stream water right." ORS § 537.348. In Montana, Mont. Code Anno., § 85-2-408(2)(a) notes that a "temporary change authorization under the provisions of this section is allowable only if the owner of the water right voluntarily agrees to: (i) change the purpose of a consumptive use water right to instream flow for the benefit of the fishery resource; or (ii) lease a consumptive use water right to another person for instream flow to benefit the fishery resource." Also, (b) notes that "for the purpose of this subsection (2), "person" means and is limited to an individual, association, partnership, or corporation."

[34] Because of this expedited review allowance, there is potential for unobserved injury to other users, but according to the Oregon Water Resources Department, "if injury to another water right is found, the lease can be modified or terminated to prevent the injury." Oregon Water Resources Dept., *Oregon's Flow Restoration Toolbox,* http://www.oregon.gov/OWRD/mgmt_instream_tools.shtml (last visited Feb. 5, 2011).

[35] Colo. Rev. Stat. § 37-83-105 (2)(a).

[36] *Id.* at 105 (2)(a) III.

[37] *Id.* at 105 (2)(c); Colo. Rev. Stat. § 37-92-102 (3): "The board shall file a change of water right application or other application with the water court to obtain a decreed right to use water for instream flow purposes under a contract or agreement for a lease or loan of water, water rights, or interests in water pursuant to this subsection (3). The resulting water court decree shall quantify the historical consumptive use of the leased or loaned water right and determine the method by which the historical consumptive use should be quantified and credited during the term of the agreement for the lease or loan of the water right. Said method shall recognize the actual amount of consumptive use available under the leased or loaned water right and *shall not result in a reduction of the historical consumptive use of that water right during the term of the lease or loan*, except to the extent such reduction is based upon the actual amount of water available under said rights (emphasis added)."

lessor.[38] Several states make clear that the nondiversion of water by leased rights being used for instream purposes is not a basis for forfeiture of the right.[39]

Based on our examination of these approaches, we suggest Wyoming allow the holder of a valid diversionary or storage right (permitted or certificated and applied to beneficial use) to temporarily or permanently change the use to instream flow use. To provide some additional incentives we would encourage enabling other parties as well as the State to either purchase or lease a water right and change its use to instream flow. We would suggest specifically allowing so-called split season arrangements as well as changes that would entirely shift the right to instream flows for some specified period of time or permanently. To provide water right holders with the security they seek, Wyoming's forfeiture provisions should not apply to such transactions. Moreover, the historic consumptive use established in the change of use proceeding should be preserved and not reduced because of non-consumption during its use for instream flow purposes.

The owner, or a party leasing the right, would file an application with the State Engineer stating his intention not to divert water, when water will not be diverted (e.g., beginning and ending dates during the irrigation season, for a year, for a period of years), the purpose of non-diversion (the fisheries' benefit it would provide), evidence of historic

[38] Colo. Rev. Stat. § 37-92-102(3). Thus an entity leasing the water right can generate income to pay for the lease by renting the water to a downstream user.

[39] Colorado tolls its period of nonuse for an abandonment proceeding during such time as a water right has been loaned to the CWCB for instream flow use under Colo. Rev. Stat. § 37-83-105 (a) or allows the CWCB to use all or a part of the right for instream flows under 37-92-102 (3). Colo. Rev. Stat. § 37-92-103 (2)(V), (VI). Oregon tolls the calculation of nonuse (five years) under the statutory forfeiture provision for temporary water transfers. Oregon Rev. Stat. § 540.530(1)(f) (2009); Washington protects water rights in the Trust Water Rights program as exempt from relinquishment. Wash. Rev. Code § 90.42.040(6) (2010); In Idaho, water rights credited to the water supply bank are not subject to forfeiture for nonuse while retained in or rented from the water supply bank. Idaho Code Ann. § 42-1764(2) (2011); Montana protects instream flow leases held by the Department of Fish, Wildlife, and Parks from abandonment, as well as instream flow leases that utilize temporary change procedures. Mont. Code Ann. § 85-2-404(4) (2010).

beneficial use under the right, and evidence that non-diversion will not injure other water rights. The application could resemble temporary water use agreements now used to enable other consumptive uses of water for relatively short periods of time.[40]

IV. Summary and Conclusion

Wyoming fisheries could benefit by reducing or eliminating existing diversions in some instances. Many states now provide mechanisms by which holders of water rights can choose to modify diversions to benefit a fishery. Wyoming law authorizes the State to acquire a water right and change its use to instream flow, but it does not allow the water right holder to make such a change, even temporarily. We suggest Wyoming consider allowing water right holders to make such changes while retaining ownership of the right. We would also suggest allowing the holders of water rights to lease their rights to others who would go through the change of use process. Temporary changes should be protected against forfeiture. The historic consumptive use of the right in its original use should be preserved while the right is temporarily used for instream flows. All such changes of use would be subject to the traditional no injury requirement, though simple non-divert agreements for less than one year would be given a presumption of no injury. The recent adoption of such approaches in other states illustrates the growing interest in enabling reduced diversions where desired by the water right holder and beneficial to fish. We encourage Wyoming to consider allowing such voluntary changes so long as no other water users are harmed.

[40] The Wyoming State Engineer authorizes such temporary water user agreements under Wyo. Stat. § 41-3-110.

APPENDIX ONE: INSTREAM FLOWS IN COLORADO

Colorado is a prior appropriation state,[41] and the only prior appropriation state that uses a water court system to govern the appropriation, use, transfer, and loss of water rights.[42] The Colorado General assembly enacted Colorado's instream flow law in 1973 under Senate Bill 97,[43] when they declared preservation of the natural environment as a beneficial use of water, and eliminated the need to divert water in order to gain a water right.[44] The driving factor behind the initial enactment of the instream flow law was the protection of aquatic habitat.[45] The constitutionality of the bill was affirmed by the Colorado Supreme Court in 1979 with the "Crystal River" decision.[46] The law is currently codified under Colorado Revised Statute Section 37-92-102(3) (2010). There are two predominant ways to put water to instream flow use in Colorado, by new appropriation and by water right acquisition. As of October 2010, the CWCB has appropriated minimum flows in 1,500 stream segments covering 8,500 miles of stream, established minimum level protection for approximately 477 lakes, and has completed over 20 voluntary water acquisition transactions.[47]

I. Instream Flow Appropriations

Instream flow rights exist as a part of the established prior-appropriation system in Colorado, in order of priority date, and are subject to senior decreed rights and

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[41] Colo. Const. art. XVI, § 6.
[42] A. DAN TARLOCK, ET AL., WATER RESOURCE MANAGEMENT 158 (6th ed. 2009).
[43] Steven J. Shupe, *The Legal Evolution of Colorado's Instream Flow Program*, THE COLORADO LAWYER, May 1988, at 861.
[44] *Id.* at 861-2.
[45] *Id.*; *see generally* Steven O. Sims, *Colorado's Instream Flow Program: Integrating Instream Flow Protection Into A Prior Appropriation System, in* INSTREAM FLOW PROTECTION IN THE WEST, REV. ED., 12-1 (Lawrence J. MacDonnell and Teresa A. Rice, Eds., 1993) (discussing concerns over the adverse environmental effects of the 1950s Fryingpan-Arkansas project).
[46] Sims, *supra* note 45 at 12-2.
[47] Colo. Water Conservation Bd., *Instream Flow Program*, http://cwcb.state.co.us/environment/instream-flow-program/Pages/main.aspx (last visited Feb. 22, 2011).

"present uses or exchanges of water being made by other water users pursuant to appropriation or practices in existence on the date of such appropriation."[48] Colorado's instream flow law provides that the Colorado Water Conservation Board (CWCB) (state agency with governor-appointed board members representing each major water basin)[49] is the only entity that may hold an instream flow right on behalf of the public.[50] No other entity is allowed to hold an instream flow right in the state.[51] Instream flow rights may be appropriated for either minimum stream flows or minimum lake level protection, to preserve the natural environment to a reasonable degree.[52] The measuring stick for preserving the environment is usually fishery health, whether cold or warm water fishery, but also includes waterfowl habitat, salamander habitat, and endangered native fish habitat.[53] The Colorado Division of Wildlife is usually the entity responsible for quantifying and/or verifying the amount of water necessary to maintain the environmental value protected.[54] The appropriation process is outlined in the Board's adopted instream flow (ISF) rules.[55] The Board has the authority to adopt instream flow rules pursuant to Colorado Revised Statute Section 37-60-108 and 37-92-102(3) (2010).[56] The CWCB adopted new rules concerning the instream flow program in March of 2009.[57]

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[48] COLO. REV. STAT. § 37-92-102(3)(b) (2010).
[49] Colo. Water Conservation Bd., *The CWCB Board*, http://cwcb.state.co.us/about-us/cwcb-board/Pages/main.aspx (last visited Feb. 22, 2011).
[50] COLO. REV. STAT. § 37-92-102(3) (2010).
[51] *Id.*
[52] *Id.*
[53] Colo. Water Conservation Bd., *Instream Flow Program*, *supra* note 47.
[54] Lawrence J. MacDonnell, *Environmental Flows in the Rocky Mountain West: A Progress Report*, 9 WYO. L. REV. 335, 347 (2009).
[55] 2 COLO. CODE REGS. § 408-2 (2011); *see generally* Colo. Water Conservation Bd., *Instream Flow Appropriations*, http://cwcb.state.co.us/environment/instream-flow-program/Pages/InstreamFlowAppropriations.aspx (last visited Feb. 22, 2010).
[56] COLO. REV. STAT. § 37-60-108 (2010); COLO. REV. STAT. § 37-92-102(3) (2010); *see also* 2 COLO. CODE REGS. 408-2(3) (2011).
[57] Colo. Water Conservation Bd., *Rules*, http://cwcb.state.co.us/legal/Pages/Rules.aspx (last visited Feb. 22, 2011).

ISF Rule 5 outlines the board process for ISF appropriations, and sets out the annual schedule for initiating, processing, and appropriating instream flow rights.[58]

Each February, the CWCB Board holds a Workshop to request recommendations for proposed stream and lake protections.[59] The Workshop is open to the public, and notice is provided through the CWCB website and by mailing list.[60] Any person or entity may submit recommendations (in writing) to the Board.[61] From February through the remainder of the first year, the Board provides public notice, and CWCB staff "analyzes the information provided by the recommending entities in order to provide the Board with accurate information to make the required findings as outlined in Instream Flow (ISF) Rule 5i."[62] The Board takes public input during this time.[63] In March of the second year, the proposed stream reaches that the Board intends to adopt (which were recommended in the previous year) are compiled and the Board gives notice to the public.[64] Also in the second year, the CWCB staff works with the Board members and the public to identify problems and concerns through a formal hearing process for contested appropriations.[65]

Before making an appropriation, the board must find that 1) there is a natural environment that can be preserved to a reasonable degree, 2) that the necessary water to preserve the natural environment is available, and 3) that there is no material injury to

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[58] 2 COLO. CODE REGS. § 408-2(5)(c) (2011).
[59] Colo. Water Conservation Bd., *Instream Flow Appropriations*, *supra* note 55.
[60] *Id.*
[61] *Id.*
[62] Colo. Water Conservation Bd., *Instream Flow Recommendation Process*, http://cwcb.state.co.us/environment/instream-flow-program/Documents/Appropriations/ InstreamFlowRecommendationProcedures.pdf.; *accord* 2 COLO. CODE REGS. § 408-2(5i) (2011) (required findings include water availability and injury to other users).
[63] Colorado Water Conservation Bd., *New Appropriation Processing Timeline*, http://cwcb.state.co.us/ environment/instream-flow-program/Documents/Appropriations/NewAppropriationsTimeline.pdf.
[64] *Id.*
[65] *Id.*

other water rights.[66] If objections are resolved and the Board decides to adopt the recommendation in the latter part of the second year, the appropriation goes through the Water Court process for decree.[67] The Board has the authority to modify a previously decreed instream flow by decreasing its appropriation if necessary, as long as the Board follows the proper public review and court proceeding processes.[68]

II. Water Acquisitions

The CWCB may acquire an instream flow right by "grant, purchase, bequest, devise, lease, exchange or contractual agreement," from any person, including a government entity, as long as the rights acquired are not on the division engineer's abandonment list.[69] Before the acquisition is approved, the CWCB must obtain confirmation from the division engineer that the right will be capable of being administered.[70] If the right cannot be administered, it will not be granted.[71] The CWCB may not exercise eminent domain to acquire water rights for instream flow purposes.[72] In 2009, the Colorado Legislature allocated up to one million dollars per year from the CWCB's construction fund to the CWCB strictly for water acquisition purposes, prioritizing the money for instream flow water rights that preserve the natural environment to a reasonable degree.[73] This funds allocation allows the state to acquire water rights without having to rely solely on charitable donations. In 2010, the

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66 COLO. REV. STAT. § 37-92-102(3)(c) (2010); 2 COLO. CODE REGS. § 408-2(5i) (2011).
67 MacDonnell, *supra* note 54.
68 COLO. REV. STAT. § 37-92-102(4)(b) (2010).
69 COLO. REV. STAT. § 37-92-102(3) (2010).
70 *Id.*
71 *Id.*
72 *Id.*; *e.g.*, Colo. Water Conservation Bd., *Water Acquisitions*, http://cwcb.state.co.us/environment/instream-flow-program/Pages/WaterAcquisitions.aspx (last visited Feb. 22, 2011).
73 COLO. REV. STAT. § 37-60-123.7 (2010); Email from Linda J. Bassi, Chief, Stream and Lake Protection Section, Colorado Water Conservation Board, Department of Natural Resources, to author (March 4, 2011, 4:36 pm MST)(on file with author).

Legislature added a provision whereby the CWCB, if it has already expended the initial one million dollar allocation, may apply to the wildlife commission for additional moneys under the habitat stamp program.[74] The CWCB must report to the General Assembly at the end of the fiscal year as to how this spending authority was exercised.[75]

Colorado Revised Statute Sections 37-60-108 and 37-92-102(3) (2010) give the CWCB the authority to adopt criteria for evaluating proposed contracts or agreements for leases or transfers of water.[76] ISF Rule 6 outlines the additional procedures and considerations for acquiring water rights or interests in water for instream flow purposes.[77] The Board must determine within 120 days (from the first day the board considers the contract or agreement) what terms and conditions the Board will accept in a contract or agreement for the acquisition.[78] Rule 6e requires the board to consider the appropriateness of any acquisition of water, including "stacking,"[79] and the effect of the transaction on any relevant interstate compact issue.[80] The Board is directed to give consideration to donations before considering purchase acquisitions.[81]

ISF Rule 6 also states that under all contracts or agreements for acquisitions of water, including leases and loans, the Board shall file a change of water right application or other application with the water court to obtain a decreed right to use water for ISF purposes.[82] This will take the form of a joint application to the water court including the

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[74] COLO. REV. STAT. § 37-60-123.7(1.5) (2010).
[75] COLO. REV. STAT. § 37-60-123.7(2) (2010).
[76] COLO. REV. STAT. § 37-60-108 (2010); COLO. REV. STAT. § 37-92-102(3) (2010).
[77] 2 COLO. CODE REGS. § 408-2(6) (2011).
[78] 2 COLO. CODE REGS. § 408-2(6b) (2011).
[79] 2 COLO. CODE REGS. § 408-2(6c) (2011). "As used in Rule 6, the terms "stack" or "stacking" refer to an instance in which the Board holds more than one water right for the same lake or reach of stream and exercises the rights independently according to their decrees." 2 COLO. CODE REGS. § 408-2(4o) (2010).
[80] 2 COLO. CODE REGS. § 408-2(6e)(7) (2011).
[81] 2 COLO. CODE REGS. § 408-2(6f)(3) (2011).
[82] 2 COLO. CODE REGS. § 408-2(6i) (2011).

Board and the "Person from whom the Board has acquired the water or a Person who has facilitated the acquisition, if requested by such Person."[83]

III. Temporary Loans of Water

In 2005, the Colorado Legislature passed HB 05-1039, which allows water right owners to loan water to the CWCB on a temporary basis (not to exceed 120 days per year, and cannot be done more than three years in a ten-year period), for instream flow purposes pursuant to an already decreed instream flow water right held by the CWCB.[84] Prior to acceptance, the CWCB must compile information about the duration of the loan, the original points of diversion, as well as any other information needed for the State Engineer to determine that the loan will not injure existing decreed water rights.[85] The CWCB Director must provide a response to an offer of a temporary loan of water within five working days of receipt of the offer.[86] If accepted, the CWCB staff works with the proponent to provide public notice and to prepare the necessary documentation for the State Engineer's Office to perform an injury analysis.[87] As with other instream flow rights, the CWCB is the only entity allowed to accept the loan and hold the right.[88] During the time period of the loan, contract, or agreement with the CWCB in which the Board uses all or part of a water right for instream flow purposes, any period of nonuse is tolled and that water right is protected from abandonment.[89]

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[83] *Id.*
[84] COLO. REV. STAT. § 37-83-105(2)(a) (2010).
[85] *Id.*
[86] 2 COLO. CODE REGS. § 408-2(6k)(1) (2010).
[87] *Id.*
[88] COLO. REV. STAT. § 37-83-105(2)(a)(II) (2010).
[89] COLO. REV. STAT. § 37-92-103(2) (2010).

IV. Instream Flow Monitoring

The CWCB has an active ISF protection program. The CWCB staff must review the monthly resumes of all water divisions for possible injury to an ISF right.[90] The CWCB is responsible for reviewing all new water right applications, and will file a Statement of Opposition if an ISF right will be injured.[91] The CWCB can file objections to new appropriations, plans for augmentation, changes of water rights, and/or place calls on junior rights to enforce instream flow appropriations.[92] Most of the Board objections involve augmentation plans and changes of water rights.[93]

V. Project Example: Pitkin County

In 2009, the Colorado Water Conservation Board (CWCB) completed a voluntary transaction to restore streamflows in the Roaring Fork Valley of Colorado in partnership with Pitkin County, facilitated by the Colorado Water Trust (a nonprofit organization that supports voluntary streamflow efforts in Colorado).[94] The Colorado Water Trust, Colorado Water Conservation Board, and Pitkin County utilized a revocable trust agreement ("Trust") in which Pitkin County agreed to a long-term loan of water rights to the CWCB for Colorado's Instream Flow Program.[95] This was the first long term loan of a water right offered to the CWCB since the Colorado General Assembly passed HB 08-1280.[96] Pitkin County loaned senior water rights totaling 4.3cfs/119.25af with an

[90] 2 COLO. CODE REGS. § 408-2(8a) (2011).
[91] Colo. Water Conservation Bd., *Monitoring and Enforcement*, http://cwcb.state.co.us/environment/instream-flow-program/Pages/MonitoringEnforcement.aspx (last visited Feb. 22, 2011).
[92] MacDonnell, *supra* note 54 at 348.
[93] Email from Linda J. Bassi, *supra* note 73.
[94] Colorado Water Trust, http://www.coloradowatertrust.org/ (last visited Feb. 28, 2011).
[95] Memorandum from Linda J. Bassi, Chief, Stream and Lake Protection Section, Colorado Water Conservation Board, Department of Natural Resources, to Colorado Water Conservation Board Members (January 20, 2009) (on file with author).
[96] *Id.* HB 08-1280 was passed in 2008, and specified that the time during which the CWCB uses water rights for instream flow purposes pursuant to a contract shall not be considered as abandonment of the

appropriation date of 1904 (decree date of 1933) to the CWCB from the Stapleton Brothers Ditch to be utilized for instream flow purposes in Maroon Creek and the Roaring Fork River.[97] The rights were historically used for irrigation purposes.[98] The Stapleton Brothers Ditch historically diverted water from Maroon Creek, two miles upstream of its junction with the Roaring Fork River.[99] The predominant purpose of the instream flow transaction is to enhance the habitat of fish and aquatic species.[100] In addition to the long-term loan of the 4.3 cfs/119.25af senior water right from the Stapleton Brothers Ditch, the Trust contemplates the addition of 34 other water rights owned by Pitkin County for future ISF purposes.[101]

The CWCB and Pitkin County chose the Trust arrangement because of how the water rights were acquired by Pitkin County. Some of the water rights were acquired through the County's Open Space and Trails Department; others through the County's Airport Enterprise Fund. The rights purchased with Open Space and Trails dollars were purchased with restricted funds that necessitate voter approval and replacement of the water rights if they are to be sold and converted.[102] The water rights purchased with the Airport Enterprise Fund require compliance with Taxpayers' Bill of Rights (TABOR) restrictions if they are to be sold or leased.[103] The trust arrangement allowed a long-term loan of the water rights that avoided these restrictions, by providing the flexibility

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water right, and that the lessor or donor of the water may bring about the historic consumptive use as fully consumable reusable water downstream of the instream flow reach. H.B. 08-1280, 66th Gen. Assemb., 2nd Reg. Sess., §§ 1-3 (2008).

[97] Application for Change of Water Right, Colorado Water Conservation Board, Dist. Ct., Water Div. No. 5., June 30, 2010 at 2-3 (on file with author).

[98] *Id.*

[99] Bassi, Memo, *supra* note 95.

[100] Colorado Water Trust, *Pitkin County*, http://www.coloradowatertrust.org/acquisitions/detail/pitkin-county/ (last visited Feb. 22, 2011).

[101] Bassi, Memo, *supra* note 95.

[102] *Id.*

[103] *Id.*

necessary to address the restrictions while allowing the CWCB to use the water rights in the state's instream flow program.[104]

The Trust term is perpetual unless terminated by Pitkin County, although it may only be terminated after ten years from creation of the Trust agreement.[105] First, Pitkin County and the CWCB will apply to Water Court within six months of the Trust execution to change the Stapleton Brothers Ditch water right to add instream flow use as a beneficial use.[106] In the first phase of the arrangement, one of the County's water rights will be adjudicated.[107] Then other water rights will be changed in a later case.[108] If any other water rights are added to the agreement, they must be evaluated according to the previously mentioned procedures under the CWCB's ISF Rule 6.[109] An additional boon to the transaction is a recently passed sales tax in Pitkin County of 0.1%, called the Healthy Rivers and Streams Fund, which may generate additional funds to protect the quality and quantity of water in the Roaring Fork Basin, as well as enable acquisition of additional water rights for that purpose.[110]

The CWCB, as part of the trust agreement, committed to being responsible for administration, monitoring, and measurement of the ISF water right, and shall provide annual updates to Pitkin County.[111] The board and Pitkin will each bear their own costs and expenses in Water Court cases and each shall bear ½ for consulting engineers.[112]

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[104] *Pitkin County*, *supra* note 100.
[105] Bassi, Memo, *supra* note 95.
[106] Linda J. Bassi, Chief, Stream and Lake Protection Section, Colorado Water Conservation Board, CWCB Staff Presentation: Stapleton Brothers Ditch Water Acquisition (November 16-18, 2009) (on file with author).
[107] *Pitkin County*, *supra* note 100.
[108] *Id.*
[109] Bassi, Staff Presentation, *supra* note 106.
[110] *Pitkin County*, *supra* note 100.
[111] Bassi, Staff Presentation, *supra* note 106.
[112] Bassi, Memo, *supra* note 95.

Pitkin County may add or withdraw all or part of the water rights in the Trust Estate by delivering an instrument in writing to the board.[113]

VI. Project Example: Blue River

In 2004, the Colorado Water Trust CWT donated nearly 800 acre feet (af) of 1904 and 1915 senior water rights to the Colorado Water Conservation Board (CWCB) for use in Boulder Creek and the Blue River in Summit County, Colorado.[114] The instream flow will benefit and improve habitat conditions in Boulder Creek for brook trout, and the Blue River for rainbow and brown trout. Boulder Creek was suffering from low flows in the late summer months (3 to 5 cfs) before the transaction.[115]

The Colorado Water Trust purchased the Peabody Ditch irrigation water from the Mosers, owners of Slate Creek Ranch in Summit County, Colorado, for $130,000.[116] The transaction was funded in part by the Colorado Conservation Trust and the Gates Family Foundation.[117] Then CWT donated the water to the CWCB as per the authority provided to the Board by Section 37-92-102(3) of Colorado's Revised Statues (2010). The CWCB approved the donation at its regular board meeting in September of 2004.[118] However, although it was a straightforward donation, a fairly new idea was brought to fruition as part of this transaction: after the water flows through the designated instream flow reach (after which it will end up in the Colorado River), the historic consumptive use (HCU) will be purchased and used by the Colorado River Water Conservation District.[119] CWT

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[113] *Id.*
[114] Colorado Water Trust, *Moser/Blue River*, http://www.coloradowatertrust.org/acquisitions/detail/moser-blue-river/ (last visited Feb. 28, 2011).
[115] Bob Berwyn, *Water Trust Finalizes First Sale*, SUMMIT DAILY NEWS, June 3, 2005.
[116] Jerd Smith, *Water deal will benefit nature, People*, ROCKY MTN. NEWS, May 28, 2005.
[117] Berwyn, *supra* note 115.
[118] *Moser/Blue River*, *supra* note 114.
[119] Email from Amy Beatie, Executive Director, Colorado Water Trust, to author (Feb. 15, 2011, 1:15pm MST) (on file with author).

was able to complete this HCU sale because of the newly passed legislation that allowed the sale of HCU downstream of an instream flow reach.[120] By selling the HCU, CWT was effectively reimbursed for the original purchase price of the water, and was able to allow a downstream user to put the water to use instead of letting it flow out of the state.

Finally, the CWT submitted a change of use application to water court to finalize the transaction.[121] The change of use decree is still pending at this time and all objectors are out of the case.[122] As for the Mosers, the sale of the water right will not affect the ability to grow hay on the ranch, since they still have other water rights in Slate Creek that the ranch can use for irrigation.[123]

Confluence of Boulder Creek and Blue River
Photo by Colorado Water Trust

[120] HB 08-1280, *Supra* note 96.
[121] Email, *supra* note 119.
[122] Colo. Water Conservation Bd., *Completed Transactions*, http://cwcb.state.co.us/environment/instream-flow-program/Pages/CompletedTransactions.aspx (last visited Feb. 28, 2011).
[123] Berwyn, *supra* note 115.

APPENDIX TWO: INSTREAM FLOWS IN IDAHO

Idaho is a prior appropriation state, declared by Article 15, Section 3 of the Idaho Constitution.[124] Around 1965, Idaho passed a "State Water Plan," creating an agency responsible for state water planning, partly in response to threats from California and other downstream states to appropriate Idaho water.[125] The State Water Plan paved the way for the current statutory instream flow program (approved in 1978 as the Minimum Stream Flow Act),[126] codified in Idaho Code, Title 42, Sections 1501 – 1508 (2011). Under Idaho law, minimum stream flows are declared a beneficial use of water, for the protection of "fish and wildlife habitat, aquatic life, recreation, aesthetic beauty, transportation and navigation values, and water quality."[127]

Furthermore, the maintenance of instream flow values is declared to be beneficial for the purpose of "protecting such waters from interstate diversion to other states or by the federal government for use outside the boundaries of the state of Idaho."[128] To protect in-state waters, Idaho has also specifically declared that: "Minimum stream flows as established [under Idaho Code Title 42, Chapter 15] shall be prior in right to any claims asserted by any other state, government agency, or person for out of state diversion."[129] To date, Idaho has 297 licensed or permitted water rights for minimum stream flows, and 4 for minimum lake levels, covering 1,577 miles of stream, and comprising 2 percent of the total stream miles in the state.[130]

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[124] Idaho Const. art. XV, § 3 (2011).
[125] Josephine P. Beeman, *Instream Flows in Idaho, in* INSTREAM FLOW PROTECTION IN THE WEST, REV. ED., 13-1 (Lawrence J. MacDonnell and Teresa A. Rice, Eds., 1993).
[126] IDAHO CODE ANN. § 42-1501 (2011).
[127] *Id.*
[128] *Id.*
[129] *Id.*
[130] Idaho Water Resource Board, *Minimum Streamflows*, http://www.idwr.idaho.gov/waterboard/WaterPlanning/Minimum%20Stream%20Flow/minimum_stream_flow.htm (last visited Feb. 12, 2011).

I. Filing on Unappropriated Waters

The Idaho Water Resource Board (IWRB) is the agency authorized to file for and hold an instream flow right (which they hold in trust for the people of the state); though any person, association, county, municipality, or state agency can request that the board file for instream flow rights to unappropriated waters.[131] The IWRB consists of eight governor-appointed members serving four-year terms representing four geographical districts within the state of Idaho.[132] When the Water Resource Board wishes to appropriate a minimum stream flow on unappropriated waters, the Board files an application with the Director of the Idaho Department of Water Resources (IDWR), listing the name of the stream, minimum flow amount proposed, purpose for the minimum flow, and period of time or season for which the flow is proposed.[133] The Department of Fish and Game, Environmental Quality, Parks and Recreation, and any other public entity with an interest in the matter is given copies of the proposed instream flow by the Director of the IDWR, who also prepares the statutorily required public notice.[134] The IWRB holds a hearing, where concerned parties can testify in support of or in opposition to the proposed minimum stream flow.[135] The Water Resource Board may ask the Departments of Fish and Game, Parks and Recreation, or the Department of

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[131] IDAHO CODE ANN. § 42-1504 (2011); *see generally,* Bureau of Land Management, *Western States Water Laws,* http://www.blm.gov/nstc/WaterLaws/idaho.html (last visited Feb. 12, 2011).
[132] IDAHO CODE ANN. § 42-1732 (2011).
[133] IDAHO CODE ANN. § 42-1503 (2011).
[134] *Id.*
[135] *Id.*; *see generally* Idaho Department of Water Resources, *Idaho Minimum Stream Flow Program,* (2010), http://www.idwr.idaho.gov/waterboard/WaterPlanning/Minimum%20Stream%20Flow/PDFs/MSF_Brochure.pdf.

Environmental Quality to review and give an assessment of minimum stream flow applications.[136]

After the public hearing and notice procedures, the Director of IDWR will issue an order denying or approving the application, and may issue approval for the right as a whole, in part, or with conditions attached.[137] Aggrieved parties (who were formal parties at the hearing) have the right to judicial review of the Director's decision.[138] Approval of the application must be based upon a finding that the instream flow right: 1) will not interfere with any vested senior right, 2) is in the public interest, 3) is necessary for the preservation of the beneficial use for which it is declared, 4) is the minimum (not ideal) flow necessary for the beneficial use, and 5) is capable of being maintained and administered.[139] As a final step, the Idaho legislature gives final approval for an instream flow permit,[140] which is one major difference between Idaho and other Western states concerning minimum streamflows. Once the legislature affirms by "concurrent resolution," the minimum streamflow water right is deemed approved.[141] If the legislature fails to act or approve the permit by the end of the regular session, the application is considered approved.[142] The priority date for filing on unappropriated waters for minimum stream flows is the date the completed application was received and

[136] SASHA CHARNEY, DECADES DOWN THE ROAD: AN ANALYSIS OF INSTREAM FLOW PROGRAMS IN COLORADO AND THE WESTERN UNITED STATES 84 (JULY 2005).
[137] *Idaho Minimum Stream Flow Program, supra* note 135.
[138] IDAHO CODE ANN. § 42-1503 (2011).
[139] *Id.*
[140] *Id.*
[141] *Id.*; *see generally Idaho Minimum Stream Flow Program, supra* note 135.
[142] IDAHO CODE ANN. § 42-1503 (2011).

filed in the IDWR Director's office.[143] The new instream flow right is administered within the existing priority system, like any other water right.[144]

II. Changing Existing Appropriative Rights to Instream Use

Idaho's change of use and forfeiture laws are found in Idaho Code, Title 42, Section 222 (2011). In Idaho, anyone who wishes to change the period of use, place of use, point of diversion, or nature of use of an appropriative water right is required to gain approval from the Department of Water Resources.[145] Processing requirements include an application, a fee, and notice to other water users.[146] The Director of the IDWR is responsible for examining the proposed change of use for injury, enlargement, and public interest concerns, and to approve or deny accordingly (possibly with conditions attached).[147] Currently it is not possible for a water user to *permanently* change the place and type of use on their consumptive water right certificate or decree to an instream flow purpose.[148] In Idaho, the preferred mechanism for private parties to transfer their water to an instream flow purpose or place of use is through an established water bank.

III. Water Banks in Idaho

All instream flow leases in Idaho are accomplished by utilizing the Water Bank. The Water Banking program in Idaho was codified by the legislature in 1979,[149] although rental pools were used for many years prior to formalization of the program.[150] Water Banking is a tool for making dormant and unused water rights available for use by others

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143 IDAHO CODE ANN. § 42-1505 (2011).
144 *Idaho Minimum Stream Flow Program*, *supra* note 135.
145 IDAHO CODE ANN. § 42-222 (2011).
146 *Id.*
147 *Id.*
148 Telephone Interview with Morgan Case, Staff Biologist, Idaho Department of Water Resources (July 13, 2010).
149 IDAHO CODE ANN. § 42-1761 (2011); *see, e.g.*, CHARNEY, *supra* note 136.
150 Idaho Water Resource Board, *History of the Water Supply Bank*, http://www.idwr.idaho.gov/WaterManagement/WaterRights/WaterSupply/history_of_bank.htm (last visited Feb. 12, 2011).

through lease and/or rental, and is a way to circumvent formal change-in-use or point of diversion procedures under Title 42, Section 222, Idaho Code (2011).[151] Water rights in use by the bank are protected from forfeiture,[152] since any "nonuse" calculation is suspended while the water right is in the bank.[153] The Water Banking program is found in Idaho Code, Title 42, Section 1761-65 (2011). Its principal purpose is to "make use of and obtain the highest duty for beneficial use from water, provide a source of adequate water supplies to benefit new and supplemental water uses, and provide a source of funding for improving water user facilities and efficiencies."[154]

Idaho has essentially two systems of water bank or market, one for "natural flow" rights (i.e. surface and groundwater) operated directly by the Water Resource Board,[155] and one for stored water (called a "rental pool") at specific storage locations, operated by local committee appointed by the IWRB.[156] There are rental pools on the upper Snake River, Boise River, and Payette River.[157] It is the responsibility of the Idaho Water Resource Board (IWRB) to operate the water supply bank,[158] as well as to adopt rules for its operation (in accordance with the Idaho Administrative Procedure Act).[159] Applications to lease and rent water are processed by the IDWR.[160]

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[151] IDAHO CODE ANN. § 42-1764(1) (2011); *see generally* Idaho Department of Water Resources, *Overview of the Idaho Water Supply Bank*, (2010), http://www.idwr.idaho.gov/WaterManagement/WaterRights/WaterSupply/PDFs/BankOverviewFAQ.pdf.
[152] The statutory period for forfeiture is five years in Idaho. IDAHO CODE ANN. § 42-1764 (2011).
[153] IDAHO CODE ANN. § 42-1764(2) (2011); However, "The five (5) year period of nonuse shall continue to accrue if a period of nonuse occurred prior to the effective date of acceptance of the right into the bank and the right was not beneficially used while in the bank." *Id.*
[154] IDAHO CODE ANN. § 42-1761 (2011).
[155] IDAHO ADMIN. CODE r. 37.02.03.010.02 (2010).
[156] IDAHO ADMIN. CODE r. 37.02.03.010.09 (2010).
[157] *Overview of the Idaho Water Supply Bank*, *supra* note 151.
[158] IDAHO CODE ANN. § 42-1761 (2011).
[159] IDAHO CODE ANN. § 42-1762 (2011).
[160] *Overview of the Idaho Water Supply Bank*, *supra* note 151.

Rentals from the Board's water bank must be approved by the Director of the IDWR, who may reject approval, or partially approve rentals with a lesser quantity of water or with conditions attached.[161] The director must also consider various factors outlined by statute[162] when considering water rentals outside the state of Idaho, such as in-state water demands.[163] The Board is allowed to "purchase, lease, or otherwise obtain decreed, licensed or permitted water rights to be credited to the water supply bank," as well as to act as an intermediary between parties to the rental.[164] Water right rentals can be authorized without having to undertake formal transfer proceeding requirements (i.e. change in point of diversion, place, or nature of use), but the authorization is usually only temporary in nature (rentals less than five years).[165] The IDWR is required to publish notice and obtain Board review for rentals of water lasting more than five years.[166] The owner of the water right may not use the right for their own use while it is leased to the Board's Bank, even if the water right is not rented at that time.[167]

The Water Resource Board is authorized by statute to appoint local committees to market and facilitate rentals of stored water (from the local Rental Pools) under rules and regulations adopted by the board.[168] There are currently six committee-operated (and Board-appointed) rental pools in Idaho, four designated for the rental and lease of storage water, and two special rental pools: one in Water District 74 on the Lemhi River,[169] and one in the Wood River Basin (the only rental pools managing the exchange of natural

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161 IDAHO CODE ANN. § 42-1763 (2011).
162 IDAHO CODE ANN. § 42-401(3) (2011).
163 IDAHO CODE ANN. § 42-1763 (2011).
164 IDAHO CODE ANN. § 42-1762(2) (2011).
165 IDAHO CODE ANN. § 42-1764(1) (2011); *see, e.g., Overview of the Idaho Water Supply Bank, supra* note 151.
166 *Overview of the Idaho Water Supply Bank, supra* note 151.
167 *Id.*
168 IDAHO CODE ANN. § 42-1765 (2011).
169 *Overview of the Idaho Water Supply Bank, supra* note 151.

flow water rights).[170] One additional rental pool is operated independently by the Shoshone-Bannock Tribe.[171] The Lemhi Rental Pool was created by special legislation to authorize a committee to lease and rent natural flow rights to satisfy the IWRB's minimum streamflow water right on the Lemhi River (as opposed to having to operate through the Board's water supply bank).[172] In fact, the legislation mandates that the Lemhi River minimum stream flow be met through this water bank.[173] This special rental pool was formed to prevent a call on water rights under the Endangered Species Act in the lower 7.5 mile reach of the Lemhi River.[174] The Wood River Rental Pool was established in a similar manner to the Lemhi River Rental Pool after the success of that program; however, the Wood River pool will only allow *donations* of water rights to supply the bank.[175] The Wood River Rental Pool authorizing legislation is scheduled to sunset on December 31, 2012, unless the legislature renews that provision.[176]

IV. Project Example: Fourth of July Creek

Fourth of July Creek is a tributary of the Salmon River in Idaho's Stanley Basin, and provides quality habitat for spawning, migration, and rearing to ESA-listed bull trout and juvenile chinook salmon.[177] In 2004, the Idaho Water Resource Board began leasing 1916 and 1927 irrigation water rights from William and Anne Vanderbilt on an annual basis, to restore aquatic habitat on Fourth of July Creek during the summer months when the creek became flow-limited. The Vanderbilts would lease half of their water right to

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[170] IDAHO CODE ANN. §§ 42-1765A, -1765B (2011).
[171] *Overview of the Idaho Water Supply Bank, supra* note 151.
[172] IDAHO CODE ANN. § 42-1506 (2011); *see, e.g., Overview of the Idaho Water Supply Bank, supra* note 151.
[173] IDAHO CODE ANN. § 42-1506(2) (2011).
[174] *Overview of the Idaho Water Supply Bank, supra* note 151.
[175] IDAHO CODE ANN. § 42-1765B (2011).
[176] *Id.*
[177] Memorandum from Morgan Case, Staff Biologist, Idaho Department of Water Resources, to Idaho Water Resource Board (January 23, 2009) (on file with author).

the Water Supply Bank, and the Idaho Water Resource Board (IWRB) would rent that water for minimum streamflow deliveries to the Salmon River at its confluence with Fourth of July Creek.[178] As a consequence, the Vanderbilts refrained from irrigating about 43 acres, and flows in Fourth of July Creek increased by approximately 2.9 cubic feet per second (cfs) during the irrigation season.[179] What started as a series of one-year leases turned into a 20-year lease, lasting from May 1 to Oct 31 of each year, signed in 2009 and ending in 2028.[180]

The Vanderbilts will receive an annual payment of $1,185 over 20 years, totaling $23,705.[181] The project was funded through the IWRB and the Columbia Basin Water Transactions Program.[182] The Water Supply Bank receives a ten percent surcharge for facilitating the transaction, for a total cost of $26,338 for the lease.[183] The lease contract includes an option to apply the lease payments toward any future option for IWRB to buy the water rights permanently.[184] The IWRB has an active monitoring and stream gauge program to keep tabs on the instream effects of the lease, and will compile annual data reports.[185] The Vanderbilts still maintain a portion of the water rights for other habitat use on the ranch.[186] The Vanderbilts are satisfied that their partnership with IWRB will

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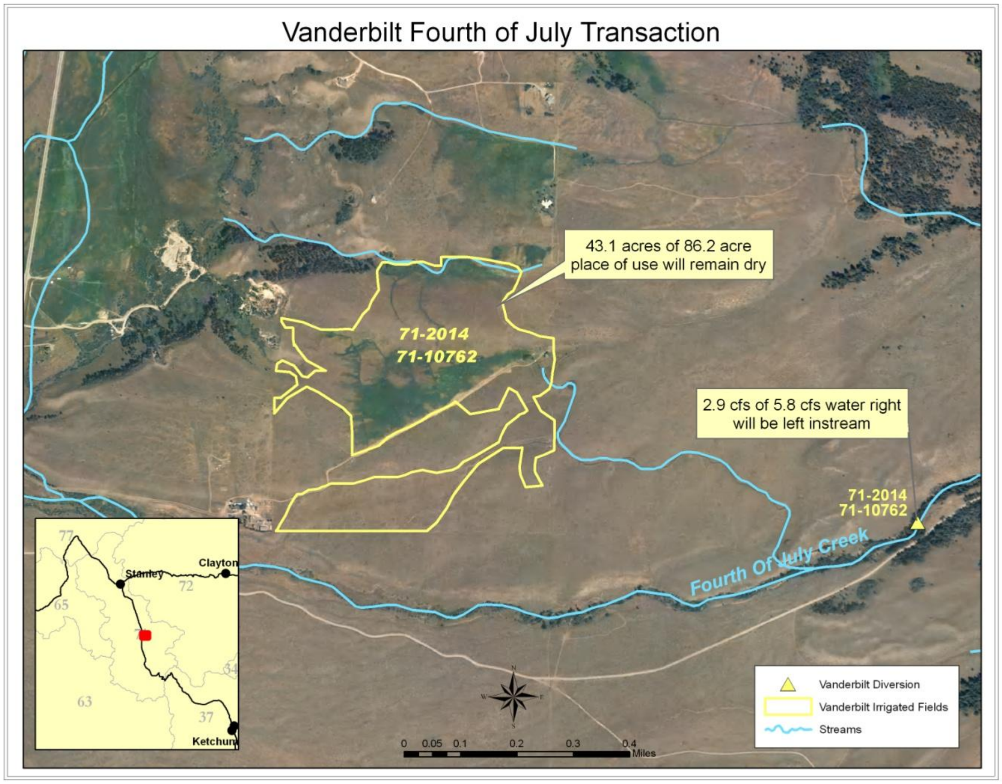
[178] Idaho Water Resource Board, *Idaho Water Transactions Program*, http://www.idwr.idaho.gov/waterboard/WaterPlanning/Water%20Transaction%20Program/PDFs/WaterTransactionProgram.pdf.
[179] *Id.*
[180] *Id.*
[181] Case, Memo, *supra* note 177.
[182] *Id.* For background information on the Columbia Basin Water Transactions Program, see Appendix 7, *infra*.
[183] *Id.*
[184] *Id.*
[185] Idaho Water Resource Board, *Stream Gauges*, http://www.idwr.idaho.gov/waterboard/WaterPlanning/Water%20Transaction%20Program/streamgages/stream_gages.htm (last visited Feb. 26, 2011).
[186] Telephone interview with Morgan Case, *supra* note 148.

enable them to help a threatened species in the Salmon River by leaving half of their water in Fourth of July Creek.[187]



Map by Idaho Department of Water Resources

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[187] *Idaho Water Transactions Program*, *supra* note 178.

APPENDIX 3: INSTREAM FLOWS IN MONTANA

Montana is a prior appropriation state that operates on a permit system.[188] Montana began an instream flow program in 1969 in an effort to protect twelve of the state's "blue ribbon" trout streams, whereby the Fish and Game Commission was allowed to file on unappropriated waters to maintain minimum flows for the preservation of fish and wildlife habitat.[189] These became known as "Murphy Rights."[190] The state legislature subsequently passed the Montana Water Use Act,[191] which significantly changed the state's water right laws, including the following: 1) establishing a permit system for new water rights, 2) mandating an adjudication process for all water rights existing prior to July 1, 1973, 3) establishing an authorization system for changing water rights, 4) establishing a centralized records system, and 5) establishing a reservation system for future consumptive uses in order to maintain minimum instream flows for water quality and wildlife habitat.[192]

Montana recognizes the following uses of water as a beneficial use: 1) "agricultural, stock water, domestic, fish and wildlife, industrial, irrigation, mining, municipal, power, and recreational uses," 2) water appropriated by the Department of Natural Resources and Conservation (DNRC) under the state water leasing program, 3) use of water by the Department of Fish, Wildlife and Parks (FWP) "through a change in an appropriation right for instream flow to protect, maintain, or enhance streamflows to benefit the fishery resource," 4) use of water for aquifer recharge or storage, and 5) a

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[188] SASHA CHARNEY, DECADES DOWN THE ROAD: AN ANALYSIS OF INSTREAM FLOW PROGRAMS IN COLORADO AND THE WESTERN UNITED STATES 91 (JULY 2005).
[189] Cynthia F. Covell, *A Survey of State Instream Flow Programs in the Western United States*, 1 U. Denv. Water L. Rev. 177, 182 (1998).
[190] Charney, *supra* note 188.
[191] MONT. CODE ANN. Title 85, Chapter 2 (2010).
[192] Montana Department of Natural Resources and Conservation, et. al., *Water Rights in Montana*, 2-3 (2009), http://leg.mt.gov/content/Publications/Environmental/2009waterrightshandbook.pdf.

temporary change of use in an appropriation right "to enhance instream flow to benefit the fishery resource."[193]

I. Water Reservations

The reservation process is one way an instream flow may be established in Montana; however, this option is not available to private parties. The 1973 Water Use Act established a process allowing both federal and state agencies (including political subdivisions of the state) to request a water reservation (of unappropriated waters) on any stream for minimum flow purposes.[194] Reservations have already been established in the Yellowstone River Basin and the Missouri River Basin.[195] The Department of Natural Resources and Conservation (DNRC) is the agency responsible for establishing reservations, and does so by a procedural process similar to the consumptive permit process.[196] The state or federal agency applies to the DNRC, which then processes it through procedures outlined in Montana Code Annotated (2010), Section 85-2-307 through 85-2-309 (DNRC also performs the required public notice procedures).[197] In order to receive a permit, the applicant must show that the reservation is in the public interest, as well as the purpose, need, and amount of water necessary for the reservation.[198] Permits are issued by the Montana Department of Natural Resources and Conservation.[199]

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[193] MONT. CODE ANN. § 85-2-102(4) (2010).
[194] MONT. CODE ANN. § 85-2-316; *see, e.g.*, Covell, *supra* note 189.
[195] *Water Rights in Montana*, *supra* note 192 at 40.
[196] Covell, *supra* note 189.
[197] Matthew J. McKinney, *Instream Flow Policy In Montana: A History And Blueprint For The Future, in* INSTREAM FLOW PROTECTION IN THE WEST, REV. ED., 15-1, 15-3 (Lawrence J. MacDonnell and Teresa A. Rice, Eds., 1993).
[198] Covell, *supra* note 189.
[199] *Id.*

The quantity of water of a reservation is limited to "a maximum of 50% of the average annual flow of record on gauged streams."[200] Ungauged streams are not limited.[201] The priority date of appropriation for new filings on unappropriated waters is the date of the receipt of the filing of the application with the DNRC.[202] Instream flow reservations in Montana (except for those subject to the Department of Agriculture/Forest Service - Montana Compact[203]) are subject to review at least once every ten years, to "ensure that the objectives of the reservations are being met."[204] If the objectives of the reservation are not being met, the department may "extend, revoke, or modify the reservation."[205] A new appropriation for instream flow may not adversely affect any right already in existence, and may be subject to any "terms, conditions, restrictions, and limitations" the department deems necessary.[206] An instream flow may be reallocated to another qualified reservant, following notice and a hearing, if the new reservant shows that their need outweighs the need of the original reservant,[207] and if the total amount of the instream flow reservation is no longer needed.[208] The reservation retains its original priority date, "despite reallocation to a different entity for a different use."[209] However, this type of reallocation may not occur more than once every five years.[210] A state water reservation may also be voluntarily transferred from one qualified reservant to another.[211]

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[200] MONT. CODE ANN. § 85-2-316 (6) (2010).
[201] *Id.*
[202] MONT. CODE ANN. § 85-2-316 (7) (2010).
[203] MONT. CODE ANN. § 85-20-1401 (2010).
[204] MONT. CODE ANN. § 85-2-316(10) (2010).
[205] *Id.*
[206] MONT. CODE ANN. § 85-2-316(9) (2010).
[207] MONT. CODE ANN. § 85-2-316(11) (2010).
[208] McKinney, *supra* note 197 at 15-5.
[209] MONT. CODE ANN. § 85-2-3169 (11) (2010).
[210] MONT. CODE ANN. § 85-2-316(11) (2010).
[211] MONT. CODE ANN. § 85-2-316(13) (2010).

II. Leases and Temporary Transfers

Montana has two statutory programs that allow for the conversion of consumptive water rights to instream flow purposes, one for private parties and one that is available to the Montana Department of Fish, Wildlife and Parks only. Both of these programs utilize the Montana Change of Use statute, found in Section 85-2-402 of the Montana Code (2010).[212] This section recognizes the right to make a temporary change in a permit, an existing water right, or a state reservation.[213] Essentially there are three basic options for the private water user to convert an appropriative right to an instream flow: 1) Employ the change of use statute[214] to convert all or part of a consumptive right to an instream flow (usually without a lease), 2) lease the right to the Montana Department of Fish, Wildlife, and Parks for an instream flow purpose, or 3) lease the right to a private entity for an instream flow purpose.[215] In each instance, the applicant must file the proper application with the DNRC for a change in their appropriative right.[216] Applicants must also prove by a preponderance of the evidence that "the amount of water for the proposed use is needed to maintain or enhance instream flows to benefit the fishery resource."[217] Water rights that are leased for instream flow purposes or changed to an instream flow purpose through the change of use procedures are protected from abandonment.[218]

As a general rule, changes in use must have the prior approval of the Department of Natural Resources and Conservation, and in some instances, the legislature.[219] As with

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212 *Id.;* MONT. CODE ANN. § 85-2-402 (2010).
213 MONT. CODE ANN. § 85-2-402(1)(a) (2010).
214 MONT. CODE ANN. § 85-2-402 (2010).
215 Stan Bradshaw, *A Buyer's Guide To Montana Water Rights*, http://www.tu.org/atf/cf/%7B0D18ECB7-7347-445B-A38E-65B282BBBD8A%7D/TU%20WATERRIGHTS%20CORRECTED%20web.pdf.
216 *Water Rights in Montana*, *supra* note 192 at 37.
217 MONT. CODE ANN. § 85-2-408(3) (2010).
218 MONT. CODE ANN. § 85-2-404(4) (2010).
219 MONT. CODE ANN. § 85-2-402(1)(a) (2010).

most states, approval of all types of changes of use requires the applicant to prove that the change of type of use or place of use will not adversely affect other water rights.[220] As an additional protection, if a water right is leased, other water right holders are allowed to object to the change even after the DNRC has approved it, if those other water rights holders did not anticipate an adverse effect before the lease was in place.[221]

Private individuals are allowed to change an appropriative right to an instream flow use, consecutively or intermittently, for a period not to exceed ten years.[222] The DNRC is responsible for approving or denying the change.[223] The priority date remains the same as the original appropriative right.[224] The temporary change may be renewed at the end of the initial ten year period, for an additional period of a maximum of ten years, with no limit on the number of renewals allowed.[225] If the temporary change of the right is not renewed, it automatically reverts back to the original "purpose, place of use, point of diversion, or place of storage after the period for which a temporary change was authorized expires."[226] All renewals are subject to a notice process performed by the DNRC, whereby any other appropriators (holding permits before the original change of use application) potentially affected by the temporary change renewal have 90 days to submit evidence of their injury to DNRC.[227] If another appropriator is adversely affected by the renewal, the DNRC may not allow it.[228] In fact, any appropriator with a permit in

[220] MONT. CODE ANN. § 85-2-402 (2)(a) (2010); *see, e.g.*, *Water Rights in Montana*, *supra* note 192 at 35.
[221] MONT. CODE ANN. § 85-2-407(4)(b) (2010); *see, e.g.*, Stan Bradshaw and Laura Ziemer, *Water Leasing in Montana Through Trout Unlimited's Eyes*, PERC REPORTS, Vol. 25, No. 2, Summer 2007, at 15. http://www.perc.org/pdf/june07.pdf.
[222] MONT. CODE ANN. § 85-2-407(2) (2010).
[223] MONT. CODE ANN. § 85-2-407 (2010).
[224] MONT. CODE ANN. § 85-2-407(5) (2010).
[225] MONT. CODE ANN. § 85-2-407(2),(3) (2010).
[226] MONT. CODE ANN. § 85-2-407(6) (2010).
[227] MONT. CODE ANN. § 85-2-407(3) (2010).
[228] *Id.*

place before the change of use application may object to the initial temporary change application, the renewal process, or may object once during the term of the temporary change permit.[229]

Section 85-2-436 of the Montana Code authorizes the Department of Fish, Wildlife, and Parks (DFWP) to change the purpose of use and the place of use of an appropriative right, whether the right is leased or owned, to an instream flow purpose "to protect, maintain, or enhance streamflows to benefit the fishery resource."[230] This statutory provision sunsets on June 30, 2019.[231] The Commission of the Department of Fish, Wildlife, and Parks must consent to any lease of water from existing appropriative rights to the DFWP.[232] To be approved, the change in purpose of use or place of use by Fish & Wildlife must not injure other appropriators, and must comply with the procedures used in the normal permitting process,[233] priority date procedures,[234] and normal change of use proceedings.[235] This includes filing an application with DNRC, using proper public notice proceedings, and resolving possible objections to the filing of an instream flow permit.[236] The application must include specific information on the reach of stream that is protected, maintained, or enhanced, and must also provide a detailed measuring plan for that stream.[237] The priority date of the original appropriation

[229] MONT. CODE ANN. § 85-2-407(4)(b) (2010).
[230] MONT. CODE ANN. § 85-2-436(1) (2010).
[231] MONT. CODE ANN. § 85-2-436 (2010).
[232] MONT. CODE ANN. § 85-2-436(3)(a) (2010).
[233] MONT. CODE ANN. § 85-2-307-309 (2010).
[234] MONT. CODE ANN. § 85-2-401 (2010).
[235] MONT. CODE ANN. § 85-2-402 (2010).
[236] MONT. CODE ANN. § 85-2-436(3)(b) (2010).
[237] MONT. CODE ANN. § 85-2-436(3)(c) (2010).

is preserved in the change proceeding and/or in the lease transaction, and sticks with the new instream flow purpose.[238]

Leases for instream flows by the DFWP can last for up to ten years, with no limit on number of renewals, as long as the renewals only last ten years each.[239] Leases of water made available by conservation or storage projects may last for an amount of time equal to the expected life of the project, but may not exceed 30 years.[240] The maximum quantity of water that can be changed to instream flow use is the amount historically diverted.[241] And only the historical consumptive use (or a smaller amount) may be used "to protect, maintain, or enhance streamflows below the point of diversion that existed prior to the change in appropriation right."[242] The Department of Fish, Wildlife, and Parks is responsible for the costs associated with gauging and monitoring the instream flow.[243]

The Department of Natural Resources and Conservation reserves the right to modify or revoke a change in appropriation right authorization at any time.[244] This is allowed up to ten years after approval, if a senior water rights holder submits "new evidence not available at the time the change in appropriation right was approved that proves by a preponderance of evidence that the appropriator's water right is adversely affected."[245]

The DFWP is responsible for submitting to the DNRC, the Fish, Wildlife, and Parks Commission, and the Environmental Quality Council, a biennial progress report in

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238 MONT. CODE ANN. § 85-2-436(g) (2010).
239 MONT. CODE ANN. § 85-2-436(3)(e) (2010).
240 *Id.*
241 MONT. CODE ANN. § 85-2-436(3)(d) (2010).
242 *Id.*
243 MONT. CODE ANN. § 85-2-436(3)(j) (2010).
244 MONT. CODE ANN. § 85-2-436(3)(f) (2010).
245 *Id.*

December of odd-numbered years, which includes a summary of all rights they have changed from appropriative to instream flow purposes in the previous two years.[246] This includes information on each length of stream reach, including the volume of water needed to protect the streamflow, steps taken to minimize harm to other appropriators, and monitoring methods.[247] Most importantly, if the legislature does not renew the statutory provision after 2019, the DFWP "may not enter into any new lease agreements pursuant to [Section 85-2-436] or renew any leases that expire after that date."[248]

III. Project Example: Mannix Brothers Ranch

As part of the Montana Water Project, Trout Unlimited (TU) has restored streamflows in Montana through voluntary transactions since 1998.[249] In 2006, TU partnered with the Mannix Brothers Ranch in Montana to enter into a ten year lease of pre-1900 irrigation rights on Wasson Creek for instream flow purposes.[250] Wasson Creek is located in the Blackfoot River Valley, near Helmville Montana, and is habitat for a pure-strain of westslope cutthroat trout (WSCT). It is a tributary to Nevada Spring Creek, which is a tributary to the Middle Blackfoot. The Mannix Ranch is the primary landowner on Wasson creek. The Mannix Ranch has historically relied on the waters of Wasson Creek for irrigation purposes for pasture grass for their cattle.[251]

This lease transaction was key to restoring native westslope cutthroat trout populations in Wasson Creek and the middle reach of the Blackfoot River.[252] TU had

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[246] MONT. CODE ANN. § 85-2-436(4)(a) (2010).
[247] MONT. CODE ANN. § 85-2-436(4)(b) (2010).
[248] MONT. CODE ANN. § 85-2-436(7) (2010).
[249] Trout Unlimited, *Montana Water Project*, http://www.tu.org/conservation/western-water-project/Montana (last visited Feb 25, 2011).
[250] Columbia Basin Water Transactions Program, *Transaction Proposal Form*, (2006), http://www.cbwtp.org/jsp/cbwtp/checklist_pdf/checklist_pdf.jsp?project_id=52&transaction_id=214.
[251] Bradshaw, *supra* note 215.
[252] *Id.*

already completed a significant amount of channel and riparian restoration work on Wasson creek, and securing the lease from the Mannix Ranch was a major component in the overall restoration plan.[253] The transaction began with three years of one-season agreements not to divert when the flow of Wasson Creek dropped to 0.5 cubic feet per second (cfs), and the immediate restorative results of the short term leases evolved into a ten-year lease.[254] The ten-year lease will provide 0.75cfs throughout the entire irrigation season, and will address both base flow conditions of the creek, as well as channel maintenance flows.[255] The flows will improve WSCT habitat by improving temperature throughout the stream reach, and provide migration opportunity in July/August for the WSCT to migrate to Nevada Spring Creek.[256] The Mannix Ranch received $75,000 for the ten-year lease, funded in part by the Columbia Basin Water Transactions Program, Northwestern Energy, and the Chutney Foundation.[257] The payment calculation was based on the lost hay and forage value to the Mannix Brothers Ranch.[258]

To effectuate the change, the Mannix Brothers Ranch and TU applied to the Department of Natural Resources and Conservation (DNRC) for a temporary change in use of the water right, allowed under Montana Law for instream flow leases.[259] The Mannix lease retained its original priority date, and because of the Montana leasing statute, the Mannix Ranch still owns the water right, and that right is protected from abandonment.[260] TU will actively monitor the flows of the stream for the duration of the

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[253] *Id.*
[254] *Id.*
[255] *Transaction Proposal Form*, *supra* note 250.
[256] *Id.*
[257] *Id.* For background information on the Columbia Basin Water Transactions Program, see Appendix 7, *infra*.
[258] *Id.*
[259] *See supra*, Appendix 3, Section II, “Leases and Temporary Transfers.”
[260] MONT. CODE ANN. § 85-2-404(4) (2010); Bradshaw, *supra* note 215.

lease.[261] The Montana Department of Fish, Wildlife, and Parks will monitor the benefits to the fish population at monitoring sites on Wasson Creek and Nevada Spring Creek.[262]

In determining the proper location for a water lease transaction, each stream is unique. But according to Stan Bradshaw and Laura Ziemer of TU, "Just the right combination of seniority of the water right, location of the diversion, the amount of water to be left instream, the condition of the stream itself, and the willing participation of the irrigator all play a part in a successful water lease."[263] The Mannix transaction is an example of such a combination of factors for the benefit of an instream flow.

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[261] *Transaction Proposal Form*, *supra* note 250.
[262] *Id.*
[263] Bradshaw and Ziemer, *supra* note 221.

APPENDIX FOUR: INSTREAM FLOWS IN OREGON

Oregon is a prior-appropriation state with riparian vestiges,[264] and operates on a permit system.[265] The Oregon Water Resources Department (ORWD) is the state agency with the authority to administer the state's water supplies, overseen by the Water Resources Commission ("Commission"), a governor-appointed, senate-confirmed body comprised of seven members who serve four-year terms.[266] The ORWD and the Commission generally manage the state's water by basin, and set comprehensive policies for managing the river systems in each of the state's eighteen (18) basins.[267] The basin planning process may include instating basin "closures," where new appropriations of water are not allowed in that basin, or are greatly restricted by administrative rule or order.[268] Oregon declares that beneficial uses of water are any "Public Uses,"[269] which include recreation, pollution abatement, navigation, and conservation or enhancement of fish and wildlife habitat, including "any other ecological values."[270]

I. Instream Water Right Act

Oregon's Instream Water Right Act was adopted in 1987, and since that time, the State of Oregon has worked with a variety of water users and organizations to restore streamflows for "fish and wildlife, recreation, and pollution abatement."[271] Since 1987, the OWRD has converted "more than 500 of the state's minimum perennial stream flows

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[264] SASHA CHARNEY, DECADES DOWN THE ROAD: AN ANALYSIS OF INSTREAM FLOW PROGRAMS IN COLORADO AND THE WESTERN UNITED STATES 110 (JULY 2005). For a definition of the riparian doctrine, see *infra* note 360.
[265] Oregon Water Resources Dept., *Water Rights in Oregon: An Introduction to Oregon's Water Laws*, 7 (2009), http://www.oregon.gov/OWRD/PUBS/docs/Centennial_Aquabook.pdf.
[266] *Id.* at 5.
[267] *Id.* at 13.
[268] OR. REV. STAT. § 536.410 (2009); *Water Rights in Oregon, supra* note 265 at 13.
[269] OR. REV. STAT. § 537.334 (2009).
[270] OR. REV. STAT. § 537.332 (2009).
[271] Oregon Water Resources Dept., *Flow Restoration in Oregon,* http://www.oregon.gov/OWRD/ mgmt_Instream.shtml (last visited Feb. 5, 2011).

to instream water rights, and has issued more than 900 state agency-applied instream water rights."[272] Oregon leads the country in flow restoration, with "more than 1,100 individual instream leases, instream transfers, and allocations of conserved water."[273] Oregon has restored nearly double the amount of instream flow of Washington, Idaho, and Montana combined, placing about 900 cfs instream, compared to Washington (400 cfs). Idaho (100 cfs), and Montana (14 cfs based on a 2006 survey).[274] In fact, it is the policy of the state of Oregon that "establishment of minimum perennial streamflows is a high priority of the Water Resources Commission and the Water Resources Department."[275] According to the OWRD, more than 70 percent of water put instream on a permanent basis is senior water, with certificates pre-dating Oregon's 1909 water law.[276] Oregon has one of the most abundant toolboxes for converting water to instream flow use, by: (1) instream lease and time-limited transfer, (2) permanent transfer, and (3) allocation of conserved water.[277]

II. Minimum Perennial Streamflows

The Instream Flow Provision for the State of Oregon is codified in Section 537.332 through 537.360, Oregon Revised Code (2009). Under this provision, certain state agencies may establish minimum streamflows by administrative rule. The procedures for doing so are outlined in Oregon Administrative Rules, Division 690-076 and 690-077 (2011). The State Department of Fish and Wildlife may request an instream flow certificate from the Commission for the purposes of "conservation, maintenance and

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[272] *Id.*
[273] *Id.*
[274] *Id.*
[275] OR. REV. STAT. § 536.235 (2009).
[276] Oregon Water Resources Dept., *2009 Instream Accomplishments,* http://www1.wrd.state.or.us./pdfs/ 2009_Instream_Accomplishments.pdf.
[277] *Flow Restoration in Oregon, supra* note 271.

enhancement of aquatic and fish life, wildlife and fish and wildlife habitat."[278] The Department of Environmental Quality may request an instream flow certificate from the Commission to "protect and maintain water quality standards."[279] State Parks and Recreation may do so for recreation and scenic attraction purposes.[280] Once the proper application is submitted, ORWD must provide an opportunity for public comment and review, and conduct a hearing on the proposed action.[281] If approved, the Water Resources Commission will issue a certificate for an instream right, in the name of the Water Resources Department as a trustee for the public.[282] The new instream flow right functions within the established prior appropriation system, and does not affect the rights of senior users.[283] The priority date is the date the application is submitted to the Commission by the appropriate state agency.[284] Also, the legislature approved provisions whereby any minimum perennial streamflow established before June 25, 1988 was converted to an instream flow right by the Commission, and issued a certificate.[285]

III. Permanent Transfers, Leasing, and Time-Limited Transfers

Oregon allows private water right owners to sell, lease, or donate water rights for instream flow purposes, and allows any person to "purchase or lease all or a portion of an existing water right or accept a gift of all or a portion of an existing water right for conversion to an in-stream water right."[286] Essentially there are three options available to private water users: permanent transfer, time-limited transfer, or lease. Transfers of all

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278 OR. REV. STAT. § 537.336 (1) (2009).
279 OR. REV. STAT. § 537.336 (2) (2009).
280 OR. REV. STAT. § 537.336 (3) (2009).
281 OR. ADMIN. R. 690-076-0020 (2011).
282 OR. REV. STAT. § 537.341 (2009).
283 OR. ADMIN. R. 690-076-0015 (2011); *see, e.g.*, *Water Rights in Oregon, supra* note 265.
284 OR. ADMIN. R. 690-076-0015 (2011).
285 OR. REV. STAT. § 537.346 (2009).
286 OR. REV. STAT. § 537.348 (2009); *see Water Rights in Oregon, supra* note 265 at 23.

types involve changing the point of diversion or appropriation, the place of use, the beneficial use of the water right, or a combination thereof.[287] The relevant statutory authority to make any transfer by changing the place of use, type of use, or point of diversion is found in Section 540.505 - 540.587, Oregon Revised Statues (2009). To complete the lease or donation transaction, the water right holder must complete the proper application and obtain prior approval from the Water Resources Department. The OWRD then provides notice to the public and conducts a non-injury analysis.[288] If the transfer is approved, OWRD issues a certificate,[289] and the underlying water right is protected from forfeiture of the water right for the duration of the transfer.[290]

The Instream Leasing program is the most flexible tool allowed under Oregon law, whereby a water right holder can voluntarily lease their water temporarily for instream use.[291] The owner can lease surface water, storage water, or water saved through conservation measures.[292] Leases may last for an initial period of up to five years, with renewal options at the lease holder's discretion.[293] The water converted to instream use by lease retains its original priority date.[294] When leased, the water is unavailable for the original owner's use.[295] Temporary leases in Oregon are given an expedited approval process, whereby approval can occur in as little as 30 days after

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287 Oregon Water Resources Dept., *Water Right Transfers*, http://www.oregon.gov/OWRD/mgmt_transfers.shtml (last visited Feb. 5, 2011).
288 OR. REV. STAT. § 540.520 (2009); *e.g.*, *Water Right Transfers*, *supra* note 287.
289 OR. REV. STAT. § 537.348 (2009).
290 OR. REV. STAT. § 540.530(1)(f) (2009).
291 Oregon Water Resources Dept., *Oregon's Flow Restoration Toolbox,* http://www.oregon.gov/OWRD/mgmt_instream_tools.shtml (last visited Feb. 5, 2011).
292 Oregon Water Resources Dept., *Instream Leasing Program*, http://www.oregon.gov/OWRD/mgmt_leases.shtml (last visited Feb. 5, 2011).
293 OR. REV. STAT. § 540.523 (1) (2009); *e.g.*, *Oregon's Flow Restoration Toolbox, supra* note 291.
294 OR. REV. STAT. § 537.348 (2009).
295 OR. REV. STAT. § 540.523(7) (2009); *e.g.*, *Oregon's Flow Restoration Toolbox, supra* note 291.

receipt of the application.[296] Because of this expedited review allowance, there is potential for unobserved injury to other users, but according to the OWRD, "if injury to another water right is found, the lease can be modified or terminated to prevent the injury."[297] At the end of the lease term, the water right reverts back to its original place of use and conditions of use.[298]

A special kind of lease, a Split Season Instream Lease, allows the water right owner to use the water during one part of the irrigation season and then lease their water right instream during the other part of the season.[299] This type of lease works well with partial fallowing.[300] For example, the landowner may use the water right from April through June for one cutting of hay, then lease the right for an instream flow from July through September when streamflows are critical for salmon in Oregon.[301]

Permanent transfers are another means of putting water instream. Permanent transfers result in the issuance of an instream water right, held in trust by the Water Resources Department.[302] As of 2009, ORWD has completed 57 permanent transfers totaling more than 280 cubic feet per second (cfs).[303] A Time-Limited transfer, on the other hand, is a semi-permanent tool which is similar to a permanent transfer, but allows a water right holder to change their water to an instream use for a specified period of years.[304] Time-Limited transfers are similar to leases in function; the main differences are that a Time-Limited transfer can last for any length of time (as opposed to the five

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[296] *Oregon's Flow Restoration Toolbox, supra* note 291.
[297] *Id.*
[298] OR. REV. STAT. § 540.523 (3) (2009); *e.g.*, *Oregon's Flow Restoration Toolbox, supra* note 291.
[299] *Oregon's Flow Restoration Toolbox, supra* note 291.
[300] *Id.*
[301] *Id.*
[302] *Id.*
[303] *2009 Instream Accomplishments, supra* note 276.
[304] *Oregon's Flow Restoration Toolbox, supra* note 291.

year limit on leases), and cannot be later "unwound" if injury to another water right holder is discovered.[305] For example, the Time-Limited transfer can last 10, 20, or 50 or more years.[306] Because of its length and permanency, the Time-Limited transfer is subject to a more rigorous review process than a lease.[307] Additionally, Time-Limited transfers can be customized to terminate upon the occurrence of a condition (such as a change in land ownership).[308]

Since the inception of the leasing program, Oregon has restored flow through over 1,000 instream leases.[309] According to the OWRD, "The instream leasing program [in Oregon]...depends on active partnerships with the Klamath Basin Rangeland Trust (30% of flow during 2008), Deschutes River Conservancy (30%), and the Oregon Water Trust (8%)."[310]

IV. Allocation of Conserved Water

The Allocation of Conserved Water Program in Oregon was officially authorized by the Legislature in 1987.[311] It is a declared policy of the state of Oregon to aggressively promote water conservation, and to allow the sale or lease of the right to use conserved water.[312] The Conserved Water Program is a voluntary program that allows the use of conserved water to augment and enhance streamflows.[313] "Conserved Water" is defined for this purpose as the difference between "the smaller of the amount stated on the water right or the maximum amount of water that can be diverted using the existing

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[305] *Id.*
[306] *Id.*
[307] *Id.*
[308] *Id.*
[309] *Id.*
[310] *Flow Restoration in Oregon, supra* note 271.
[311] Oregon Water Resources Dept., *Allocation of Conserved Water*, http://www.oregon.gov/OWRD/mgmt_conserved_water.shtml (last visited Feb. 5, 2011).
[312] OR. REV. STAT. § 537.460(2) (2009).
[313] OR. REV. STAT. § 537.463 (2010); *e.g., Oregon's Flow Restoration Toolbox, supra* note 291.

facilities," and "the amount of water needed after implementation of conservation measures to meet the beneficial use under the water right certificate."[314] Conservation can be achieved by "improving the technology or method for diverting, transporting, applying or recovering the water or by implementing other approved conservation measures."[315] Moving physical points of diversion, lining canals, and changing from flood to drip irrigation are common conservation practices.[316]

The OWRD uses an application process outlined under O.R.S. § 537.465(2) (2009), where applicants must describe the conservation measures proposed, the amount of water expected from the implementation of the measures, choice of priority dates, and intended use for the conserved water.[317] Water users are also allowed to apply for allocations of conserved water if they have implemented the conservation measure within five years prior to the application.[318] The applicant does not need to apply for a separate change of use or transfer approval.[319] If the ORWD approves the conserved water application, new water right certificates are issued for the original water right (with priority date intact) and the new water right to which the conserved water is allocated (with priority date assigned either the same as the original right or one minute junior).[320]

Although it is not required, water users who implement efficiency measures have a significant incentive to work with the OWRD instream flow program, since the absence of Department approval means that the user is not allowed to "re-use" their conserved

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[314] OR. REV. STAT. § 537.455(2) (2009).
[315] OR. REV. STAT. § 537.455(1) (2009).
[316] *Oregon's Flow Restoration Toolbox, supra* note 291.
[317] OR. REV. STAT. § 537.465(2) (2009).
[318] OR. REV. STAT. § 537.465(1)(b) (2009).
[319] OR. REV. STAT. § 537.470(5) (2009).
[320] OR. REV. STAT. § 537.470(6) (2009).

water to meet new needs.[321] Instead, the water becomes available to the next appropriator.[322] In fact, according to the OWRD:

> In exchange for granting the user the right to "spread" a portion of the conserved water to new uses, the law requires allocation of a portion to the state for instream use. After mitigating the effects on any other water rights, the Water Resources Commission allocates 25 percent of the conserved water to the state and 75 percent to the applicant, unless the applicant proposes a higher allocation to the state or more than 25 percent of the project costs come from federal or state non-reimbursable sources. A new water right certificate is issued with the original priority date reflecting the reduced quantity of water being used with the improved technology. Other certificates are issued for the applicant's portion of the conserved water and for the state's instream water right. The priority dates for these certificates are either the same as the original right, or one minute junior.[323]

The first allocation of conserved water was approved in 1996.[324] As of 2009, the OWRD has approved at least 43 applications for allocation of conserved water, adding up to almost 80 cfs of instream flow protection.[325]

V. Project Example: Austin Ranch

In 2006, The Freshwater Trust (FWT),[326] a nonprofit organization that works to restore freshwater ecosystems in Oregon, reached an agreement with Pat and Hedy Voigt, third generation ranchers and owners of the Austin Ranch on the Middle Fork of the John Day River. The agreement was for the FWT to compensate the Voigts in exchange for them not to divert their senior irrigation water rights[327] for Alfalfa production past July

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[321] *Allocation of Conserved Water*, *supra* note 311.
[322] *Id.*
[323] *Id.*
[324] Oregon Water Resources Dept., *20th Anniversary of Instream Water Right Act: Milestones,* http://www.oregon.gov/OWRD/mgmt_instream_milestones.shtml (last visited Feb. 5, 2011).
[325] *Flow Restoration in Oregon, supra* note 271.
[326] The Freshwater Trust was formerly known as the Oregon Water Trust. The Oregon Water Trust was the first water trust in the United States. The Freshwater Trust, *History,* http://www.thefreshwatertrust.org/who-we-are/about-us (last visited Feb. 25, 2011).
[327] The priority dates for the rights were 1892, 1895, 1898, 1960, and 1962. Columbia Basin Water Transactions Program, *Transaction Proposal Form*, (2005), http://www.cbwtp.org/jsp/cbwtp/checklist_pdf/checklist_pdf.jsp?project_id=13&transaction_id=156.

20th of each year, in order to preserve and restore critical aquatic habitat.[328] The transaction was funded in part through the Columbia Basin Water Transactions Program (CBWTP).[329] This permanent agreement will preserve a flow of 10 cubic feet per second (cfs) in the John Day river system for wild fish runs of summer steelhead, spring chinook salmon, and bull trout.[330] The Voigts wanted to be able to protect the environmental resource while still keeping their ranch operational, and a split season agreement allows them to achieve that goal.[331]

The John Day River is a tributary of the Columbia River System in Northeastern Oregon. It is the longest undammed river in the Pacific Northwest.[332] The Middle Fork of the John Day, where the Austin Ranch is located, supports as much as one-third of the spawning salmon and steelhead in the river basin.[333] The Voigts raise Alfalfa and run cattle, and through this agreement, instead of yielding two cuttings of Alfalfa in a season, they only yield one.[334] After July 20th of each year, they stop diverting water for Alfalfa production and graze cattle on the pasture.[335] The water then restores flows in the Middle Fork of the John Day, and two of its tributaries: Vinegar Creek and Clear Creek. In exchange for the loss of income from the second cutting of Alfalfa, the Voigts received $700,000 from the Freshwater Trust; money they are using to update their existing irrigation system.[336] The Voigts feel that the transaction is working beneficially for them,

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[328] The Freshwater Trust, *Austin Ranch*, http://www.thefreshwatertrust.org/conservation/stream-flow/projects/austin-ranch (last visited Feb. 25, 2011).
[329] For background information on the Columbia Basin Water Transactions Program, see Appendix 7, *infra*.
[330] *Austin Ranch*, *supra* note 328.
[331] *Id.*
[332] ROBERT GEROME GLENNON, UNQUENCHABLE: AMERICA'S WATER CRISIS AND WHAT TO DO ABOUT IT 287 (2009).
[333] *Id.* at 288.
[334] *Id.* at 289.
[335] *Id.*
[336] *Id.*

as well as for The Freshwater Trust.[337] Pat Voigt said of the Freshwater Trust after the transaction: "[T]hey displayed a great deal of respect for agriculture."[338]

To achieve this transaction legally, the Voigts submitted an affidavit to the Oregon Water Resources Department (OWRD) to "abandon" the water right for the latter part of the summer irrigation season beginning July 20, under the authority of Oregon Revised Statute § 540.621 (2005).[339] The OWRD approved the "water right diminishment" and issued new certificates.[340] This is what makes the transfer permanent, as opposed to an annual leasing option or time-limited transfer option. The FWT and the Voigts did not actually employ a change of use method or a split season lease method under Oregon law.

The "diminishment" was an option that worked well for the Voigts and the FWT, since there will be no downstream appropriation of the Austin Ranch water below the instream flow reach (because the John Day Basin is closed to new appropriations, and the next nearest consumptive user is twenty miles downstream).[341] Possible injury to other water users was minimal in this transaction, as the OWRD does not need to regulate other water users to put the 10cfs back in the stream.[342] The Austin Ranch project is an example of a creative solution to put water back in the stream (by essentially reducing "demand" on the stream) without actually having to issue "formal" instream flow rights. As with most instream flow leases, a combination of circumstances unique to that particular stream reach resulted in a workable project for both parties.

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[337] *Austin Ranch*, *supra* note 328.
[338] *Austin Ranch*, *supra* note 328.
[339] Robert David Pilz, *At The Confluence: Oregon's Instream Water Rights Law in Theory and Practice*, 36 Envtl. L. 1383, 1416 (2006).
[340] *Transaction Proposal Form*, *supra* note 327.
[341] Pilz, *supra* note 339.
[342] *Id.*

VI. Project Example: Lower Rudio Creek

As part of a comprehensive restoration plan for the John Day Basin, the Freshwater Trust secured a permanent Water Use Agreement for a point of diversion (POD) change to put a minimum of 2 cubic feet per second (cfs) back instream on Lower Rudio Creek, a tributary to the John Day River in northeastern Oregon. In 2007, the Freshwater Trust began working with Kevin Campbell, owner of Campbell Crossing and an 1885 senior irrigation right on Lower Rudio Creek, which he uses for irrigation of hay and pasture.[343] Rudio Creek is an important salmon and steelhead habitat and passage area, and historically the lower two miles of the creek would go dry in the late summer months.[344]

The current irrigation diversion is a dam structure on Rudio Creek. As part of the agreement, Kevin Campbell will stop diverting water from the existing structure when one of two conditions is triggered: either flows of the creek reach 2 cfs, or the date reaches July 1, whichever comes first.[345] Then, after implementing new efficiency measures, Campbell Crossing will use a new pumping station located downstream (on the North Fork of the John Day River) to provide water to their pastures and hay meadows, thereby restoring flows to Rudio Creek.[346] The old 1885 priority date is kept intact for the new POD.[347] Some lands that were previously flood irrigated will have sprinklers and center pivot systems, and will get water from the new pumping station downstream,

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343 Telephone Interview with David Pilz and Natasha Bellis, Flow Restoration Managers, The Freshwater Trust (July 20, 2010).
344 Columbia Basin Water Transactions Program, *Transaction Proposal Form*, (2007), http://www.cbwtp.org/jsp/cbwtp/checklist_pdf/checklist_pdf.jsp?project_id=56&transaction_id=274.
345 *Id.*
346 *Id. See also* "Rudio Creek Simple Project Model," *infra.*
347 Telephone Interview, *supra* note 343.

therefore not taking any lands out of production.[348] Additionally, some of the areas along Rudio creek will be fenced off from livestock.[349]

This project did not create a "traditional" instream flow right on Rudio Creek. To implement the change legally, Campbell Crossing only had to file for an additional point of diversion approval with Oregon Water Resources Department (OWRD).[350] Technically Campbell Crossing could still divert from the old POD. However, the instream flow transaction is adequately secured for the future because Campbell Crossing will be monitored by OWRD: Campbell Crossing will only be able to use water out of the new POD when measurements show that the required instream flows are present in Rudio Creek, thereby effecting a water "exchange" between Rudio Creek water and John Day water.[351] Flow metering on Rudio Creek will provide the means to implement the monitoring, but will also protect others users on the North Fork of the John Day from injury.[352] This exchange will operate as a "condition" on the ranch's water rights, and will attach to any possible future owners.[353] Although the transaction does not result in a formal instream water right, in practice the project will essentially operate as an instream flow right for the lower two miles of Rudio Creek.[354]

Although this project is unique and site-specific (like most water projects), for the Freshwater Trust and Campbell Crossing, it was hard to find a downside.[355] Rudio Creek and the John Day will become a model for habitat improvements, and Kevin Campbell received $140,000 in compensation, along with the added benefit of improving irrigation

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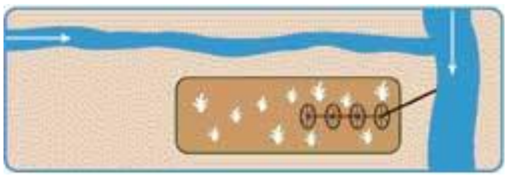
348 *Transaction Proposal Form*, *supra* note 344.
349 *Id.*
350 Telephone Interview, *supra* note 343.
351 *Transaction Proposal Form*, *supra* note 344.
352 Telephone Interview, *supra* note 343.
353 *Transaction Proposal Form*, *supra* note 344.
354 *Id.*
355 Telephone Interview, *supra* note 343.

efficiency on the ranch, which was a goal of his for the last few years.[356] There were many funding partners for this project, including the Columbia Basin Water Transactions Program, the Oregon Watershed Enhancement Board, and the Wild Salmon Center.[357]

Rudio Creek Simple Project Model:[358]

Change in point of diversion from tributary stream to main river

Old point of diversion



New point of diversion

Diagrams by Oregon Water Resources Department

[356] *Id.*

[357] *Id.* For background information on the Columbia Basin Water Transactions Program, see Appendix 7, *infra*.

[358] *Oregon's Flow Restoration Toolbox, supra* note 291.

APPENDIX FIVE: INSTREAM FLOWS IN WASHINGTON

Washington is a "dualistic" water state,[359] possessing both prior-appropriation and riparian[360] aspects. In 1917, the Washington Legislature passed the State Water Code,[361] which established prior appropriation as the exclusive means for creating new rights to surface water in Washington State,[362] and also established a centralized permitting system and procedures for adjudicating existing water rights.[363] Riparian rights that were recognized prior to the enactment of the 1917 State Water Code and put to a beneficial use before December 31, 1932 are still recognized.[364]

The State of Washington began enacting legislation concerning minimum stream flows in 1949,[365] mainly for the protection of salmon and steelhead trout fisheries.[366] In 1949, the Washington Legislature amended the Fisheries Code to allow the Washington State Department of Ecology ("Ecology") to protect fish habitat by attaching a "condition" to new water rights (whereby diversion is curtailed when streamflow falls below a specified level).[367] Ecology is a state environmental regulatory agency with a director (also the administrative and executive head) who is appointed by the governor

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[359] Kenneth O. Slattery and Robert F. Barwin, *Protecting Instream Resources in Washington State, in* INSTREAM FLOW PROTECTION IN THE WEST, REV. ED., 20-1, 20-2 (Lawrence J. MacDonnell and Teresa A. Rice, Eds., 1993).
[360] "The *riparian doctrine* of water law allows for the historic reasonable use of water on land adjacent to a water source. The priority of water rights established under the riparian doctrine was based on the date action was first taken to separate the land from federal ownership. In times of water shortage under the riparian doctrine, all users were to curtail their water uses proportionally." Wash. St. Dept. of Ecology, *Washington Water Law, a Primer,* (2006), http://www.ecy.wa.gov/pubs/98152.pdf.
[361] Now codified as WASH. REV. CODE § 90.03 (2011).
[362] SASHA CHARNEY, DECADES DOWN THE ROAD: AN ANALYSIS OF INSTREAM FLOW PROGRAMS IN COLORADO AND THE WESTERN UNITED STATES 125 (JULY 2005).
[363] *Water Law, a Primer, supra* note 360.
[363] *Id.*
[364] CHARNEY, *supra* note 362; *see, e.g., Washington Water Law, a Primer, supra* note 360.
[365] Cynthia F. Covell, *A Survey of State Instream Flow Programs in the Western United States*, 1 U. Denv. Water L. Rev. 177, 182 (1998).
[366] Slattery and Barwin, *supra* note 359 at 20-1.
[367] Wash. Env. Council, *Instream Flow Toolkit*, 10 (2003), http://wecprotects.org/issues-campaigns/water-for-washington/streamtoolkit.pdf; *see, e.g.,* Slattery and Barwin, *supra,* note 359 at 20-3.

and approved by the Senate.[368] Ecology is the entity vested with the exclusive authority to "establish minimum flows and levels or similar water flow or level restrictions for any stream or lake of the state."[369] No other entity or person may establish or hold instream flow rights.[370] The current (and rather comprehensive) statutory laws governing the instream flow process are found in the Revised Code of Washington (RCW), Chapter 90 (2011). There are three pieces of legislation that became the current statutory scheme relating to instream flows in Washington: the 1967 Minimum Water Flows and Levels Act,[371] the 1971 Water Resources Act,[372] and the 1991 Water Resources Management Act.[373]

The 1967 Minimum Water Flows and Levels Act provided that the Washington State Department of Ecology may establish minimum flows by administrative rule,[374] acting under its own volition or by the recommendation of the Department of Fish and Wildlife.[375] The 1967 Act is codified in RCW, Section 90.22 (2011), which outlines the current procedures for establishing minimum flows by rule.[376] The Department of Ecology may establish minimum stream flows for the purposes of "protecting fish, game, birds or other wildlife resources, or recreational or aesthetic values of said public waters whenever it appears to be in the public interest to establish the same."[377] Ecology may

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[368] WASH. REV. CODE § 43.21A.050 (2011); *see generally*, Wash. St. Dept. of Ecology, *Homepage*, http://www.ecy.wa.gov/ (last visited Feb. 27, 2011).
[369] WASH. REV. CODE § 90.03.247 (2011).
[370] *Id.*
[371] Now codified as WASH. REV. CODE §§ 90.22 (2011).
[372] WASH. REV. CODE § 90.54 (2011).
[373] *See generally, Washington Water Law, a Primer, supra* note 360.
[374] Ecology is vested with rulemaking power as per its statutory mandate: WASH. REV. CODE § 43.21A.064 (2011).
[375] WASH. REV. CODE § 90.22.010 (2011); *see also, Washington Water Law, a Primer, supra* note 360.
[376] WASH. REV. CODE § 90.22.010-060 (2011).
[377] WASH. REV. CODE § 90.22.010 (2011).

also establish a minimum stream flow to protect water quality.[378] In fact, the state of Washington recognizes a wide variety of water uses as beneficial:

> domestic, stock watering, industrial, commercial, agricultural, irrigation, hydroelectric power production, mining, fish and wildlife maintenance and enhancement, recreational, and thermal power production purposes, and preservation of environmental and aesthetic values, and all other uses compatible with the enjoyment of the public waters of the state, are declared to be beneficial.[379]

Before establishing or modifying minimum stream flows, Ecology must hold a public hearing and post notice by publication (in the county in which the affected stream is located).[380] The notice must include: "1) The name of each stream, lake, or other water source under consideration; 2) The place and time of the hearing; [and] 3) A statement that any person, including any private citizen or public official, may present his or her views either orally or in writing."[381] Notice of the hearing must be given to the departments of health, social services, natural resources, fish and wildlife, and transportation.[382] When stream flows are established by rule, the priority date is thirty days after the date of rule adoption.[383] An instream flow in Washington set by rule functions within the established prior-appropriation system. The new instream flow right does not affect existing surface water or storage rights, but water rights issued after the rule adoption are junior to the instream flow right in priority.[384] All minimum stream flow levels set by Ecology are filed in the "Minimum Water Level and Flow Register."[385]

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[378] *Id.*
[379] WASH. REV. CODE § 90.54.020 (2011).
[380] WASH. REV. CODE § 90.22.020 (2011).
[381] *Id.*
[382] *Id.*
[383] Wash. St. Dept. of Ecology, *Instream Flow Laws and Rules*, http://www.ecy.wa.gov/programs/wr/instream-flows/isfrul.html (last visited Feb. 27, 2011).
[384] WASH. REV. CODE § 90.22.030 (2011); *see, e.g., Instream Flow Laws and Rules, supra* note 383.
[385] WASH. REV. CODE § 90.22.030 (2011).

I. The Watershed Planning Process

The Water Resources Act of 1971 was codified in RCW Chapter 90.54 (2011), and recognized that a comprehensive state planning process was necessary to meet the competing water needs of Washington State.[386] The Act mandated Ecology to engage in water resources data collection,[387] as well as pilot the development and management of comprehensive basin plans, or Water Resource Inventory Areas (WRIAs).[388] The legislature declared that, "through comprehensive planning, conflicts among water users and interests can be reduced or resolved."[389] As a result of the WRIA planning process, the state of Washington is now divided into 62 watersheds,[390] five of which can be monitored online.[391] The WRIA process allows local citizens and local governments to join together with state agencies and tribal groups to form planning units to develop watershed management plans for their respective basins.[392]

WRIA planning units may set instream flows (sometimes called "baseflows"), in collaboration with the Department of Ecology.[393] This involves setting minimum instream flow levels basin-wide before issuing any new water rights. The stakeholders convene to assess each WRIA's water supply and use, and recommend strategies for satisfying minimum instream flows and other water supply needs.[394] This statewide planning process addresses all beneficial uses of water in each basin, including instream

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386 WASH. REV. CODE § 90.54.010 (2011).
387 WASH. REV. CODE § 90.54.030(1) (2011).
388 WASH. REV. CODE § 90.54.045 (2011); *see also,* Wash. St. Dept. of Ecology, *Water Resource Inventory Area (WRIA) Maps*, http://www.ecy.wa.gov/services/gis/maps/wria/wria.htm (last visited Feb. 27, 2011) (providing background information and map of WRIA areas in the state).
389 WASH. REV. CODE § 90.54.010 (2011).
390 WASH. ADMIN. CODE § 173-500-040 (2010).
391 Wash. St. Dept. of Ecology, *Instream Flow Data*, http://www.ecy.wa.gov/programs/wr/instream-flows/irpp_wrp.html (last visited Feb. 27, 2011).
392 WASH. REV. CODE § 90.54.010 (2011).
393 *Washington Water Law, a Primer, supra* note 360.
394 *Id.*

flows.[395] The legislature supplied funding to support these local planning efforts.[396] RCW Chapter 90.54 (2011) states that base flows must be maintained in the state's rivers and streams to "provide for preservation of wildlife, fish, scenic, aesthetic and other environmental values, and navigational values," and only when "overriding considerations of the public interest" are present can a withdrawal of water conflict with that purpose.[397] If data is lacking to make sufficient planning decisions, Ecology is given the authority to "set aside" certain waters in a particular basin, preventing additional appropriations until better data becomes available.[398] RCW Chapter 90.54 (2011) also states that Washington officially recognizes the interrelationship between groundwater and surface water (known as hydraulic continuity).[399]

The Watershed planning process was further refined in the 1997 Watershed Planning Act,[400] which designated a more precisely defined process for local groups to conduct watershed planning, receive agency assistance, and receive grant funding for WRIA formation and management.[401]

II. Water Markets, Water Banks, and the Trust Water Rights Program

Ecology has three programs to implement an active water market: the Trust Water Rights Program, the Water Acquisition Program, and Water Banking.[402] However, the Trust Water Rights Program is the central facilitation mechanism for both the Water

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395 Slattery and Barwin, *supra* note 359 at 20-4.
396 WASH. REV. CODE §§ 90.54.035, 060 (2011).
397 WASH. REV. CODE § 90.54.020 (2011).
398 WASH. REV. CODE § 90.54.050 (2011).
399 "Full recognition shall be given in the administration of water allocation and use programs to the natural interrelationships of surface and groundwaters." WASH. REV. CODE § 90.54.020 (2011).
400 WASH. REV. CODE § 90.82 (2011).
401 *Id.*
402 Wash. St. Dept. of Ecology, *Water Market*, http://www.ecy.wa.gov/programs/wr/market/market.html (last visited Feb. 27, 2011).

Banking and Water Acquisition programs.[403] The Washington Legislature established the Trust Water Rights program as part of the Water Resources Management Act of 1991.[404] The initial focus was to increase stream flow in 16 watersheds in Washington that were experiencing chronic water shortages.[405] A Water Bank was created along with the Trust Program as a means to "facilitate the voluntary transfer of water rights established through conservation, purchase, lease, or donation…and to achieve a variety of water resource management objectives throughout the state," including improving streamflows.[406] Water-right holders who participate in the Trust Program can sell, lease or donate all or part of their water right to the state,[407] on a temporary or permanent basis.[408] People who donate water rights to the Trust Program may specify that the rights be used for instream flow purposes,[409] and may receive a federal tax deduction for doing so.[410]

Water rights acquired through the Trust program are managed by the Department of Ecology, which holds the rights in trust and may use them for instream flows, irrigation, municipal, or other "beneficial uses consistent with applicable regional plans…or to resolve critical water supply problems."[411] Before establishing a Trust water right, Ecology must post a general notice in the applicable county's newspaper, as well as give direct notice to the appropriate state agencies, local governments, and tribal

[403] WASH. REV. CODE § 90.42.100 (2011); *see also*, Wash. Dept. of Ecology, *Trust Water Rights Program*, http://www.ecy.wa.gov/programs/wr/market/trust.html (last visited Feb. 27, 2011).
[404] WASH. REV. CODE § 90.42.005 (2011).
[405] Wash. St. Dept. of Ecology, *Washington Water Acquisition Program Strategy*, http://www.ecy.wa.gov/programs/wr/instream-flows/wacqstra.html (last visited Feb. 27, 2011).
[406] WASH. REV. CODE § 90.42.005 (2011).
[407] *Id.*
[408] WASH. REV. CODE § 90.42.080(3) (2011).
[409] CHARNEY, *supra* note 362 at 126.
[410] WASH. REV. CODE § 90.42.080(7) (2011).
[411] WASH. REV. CODE § 90.42.040(1) (2011).

governments affected.[412] For shorter-term transactions, Ecology is allowed to use its website and/or email to publish proper notice.[413] Before exercising a Trust right (acquired for more than a five year period), Ecology must ensure that neither existing water rights nor the public interest are harmed.[414] If injury is present, Ecology will alter the right to eliminate the impairment.[415] For permanent Trust Water Rights, Ecology issues a water right certificate in the name of Washington State, which includes quantity, reach of stream intended for the place of use, and the use type.[416] For non-permanent conveyances, Ecology issues a certificate or other instrument reflecting change of use information, such as place of use or point of diversion.[417] Trust water rights retain the priority date from the originating water right,[418] and the trust water right is considered as "exercised" while it is in the Trust program.[419] Trust water rights are not subject to relinquishment for nonuse.[420] If a water right is leased to the Trust Water Rights Program, the amount available for use by the state is limited to the historic consumptive use, calculated using the five years directly preceding the lease; nor may the lease result in enlargement of the underlying water right.[421]

The State may also provide financial assistance to a water right holder for the expense of implementing conservation measures, with the requirement that, in exchange for the state funding, the water right holder convey the "conserved" portion of their water

[412] WASH. REV. CODE § 90.42.040(5) (2011).
[413] *Id.*
[414] WASH. REV. CODE § 90.42.040(4)(a) (2011); WASH. REV. CODE § 90.42.040(8) (2011).
[415] WASH. REV. CODE § 90.42.080(4) (2011).
[416] WASH. REV. CODE § 90.42.040(2) (2011).
[417] *Id.*
[418] WASH. REV. CODE § 90.42.040(3) (2011).
[419] WASH. REV. CODE § 90.42.040(4)(c) (2011).
[420] WASH. REV. CODE § 90.42.040(6) (2011).
[421] WASH. REV. CODE § 90.42.080(8) (2011).

right to the Trust Water Rights program.[422] Ecology issues a water right certificate, as well as a "superseding" certificate that specifies the amount of water the water right holder is still entitled to use after the conservation project.[423]

III. Project Example: Salmon Creek

Salmon Creek is a tributary of the Okanogan River, located in north central Washington's and southern British Columbia's vast Okanogan Basin (part of the Columbia River system).[424] The Okanogan Basin is home to the ten thousand acre Okanogan Irrigation District (OID), as well as a Bureau of Reclamation (BOR) dam and diversion system to provide water for its users and their hayfields, pasture, and fruit orchards.[425] The Okanogan River Basin is also critical ESA-listed salmon and steelhead habitat.[426] Salmon Creek is typically dry during the irrigation season, preventing migration for salmon and steelhead species.[427]

Endangered Species concerns combined with limited water supplies in the basin led to a conflict between the Confederated Tribes of the Colville Reservation, the Okanogan Irrigation District, and the Bureau of Reclamation.[428] Litigation seemed imminent until the parties, along with the Washington Water Trust (WWT),[429] facilitated a solution: a memorandum of agreement between the parties that was signed in 2006, and

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422 WASH. REV. CODE § 90.42.030 (2011); *see also*, CHARNEY, *supra* note 362 at 126.
423 WASH. REV. CODE § 90.42.040(2) (2011).
424 Columbia Basin Water Transactions Program, *Stories From The Field,* http://www.cbwtp.org/jsp/cbwtp/stories/stories.jsp (last visited Feb. 26, 2011).
425 *Id.*
426 *Id.*
427 *Id.*
428 Telephone Interview with Greg McLaughlin, Project Manager, Washington Water Trust (Feb. 25, 2011).
429 The Washington Water Trust was established in 1998, and works to improve and protect stream flows and water quality throughout Washington using market-based transactions and cooperative partnerships. Washington Water Trust, http://washingtonwatertrust.org/ (last visited Feb. 26, 2011).

a long term water leasing arrangement.[430] The WWT requested funding through the Columbia Basin Water Transactions Program (CBWTP) in 2006 for a temporary out-of-court solution to the problem.[431] The WWT started working with the OID to obtain non-diversionary agreements for 2007 and 2008 (because many of the users in the OID were initially distrustful of Washington's Trust Water Rights program), while WWT worked on a long-term solution to the issue.[432] This "pilot agreement" between OID and WWT restored flows of 25 cubic feet per second (about 700 acre-feet, or "af") during steelhead spawning season in spring and early summer.[433] This project reconnected the Okanogan River with pristine summer steelhead habitat above the OID diversion point for a 4.6 mile stretch that has been dry (except during spring runoff) since the 1930s.[434]

However, there was a problem: if OID continued to do non-diversion agreements every year, they were in danger of losing their water rights by Washington's forfeiture statute. But because of the success of the short-term agreements, and some negotiations between the WWT, the OID, and the Bureau of Reclamation, a long-term solution was finally reached to sustain the 700af flow enhancement in Salmon Creek until 2018.[435] The long-term project was funded 75% through CBWTP and 25% through the Department of Ecology, with the Bureau of Reclamation providing an additional 500af of water under a cost share plan to bring the project total to 1200af and 30cfs.[436] The new agreement is funneled through Washington's Trust Water Rights program, resulting in a win-win situation for the OID, the Tribe, the BOR, the WWT, and the ESA-listed salmon

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[430] Telephone Interview, *supra* note 428.
[431] *Id.*
[432] *Id.*
[433] *Stories From The Field*, *supra* note 424.
[434] Washington Water Trust, *Salmon Creek*, http://washingtonwatertrust.org/projects/salmon-creek (last visited Feb. 27, 2011).
[435] Telephone Interview, *supra* note 428.
[436] *Id.*

and steelhead.[437] The OID received a payment of about $800,000 for the lease and can still provide irrigation water to their members, the BOR is relieved from a Section 7 consultation under the Endangered Species Act, the Tribe can protect their rights without having to initiate litigation, and the salmon can re-populate areas where they historically had habitat.[438]

Finally, there is a lease-to-purchase clause written into the lease, whereby WWT can apply lease payments already made to any future permanent purchase acquisition with OID, should the district choose to sell the water right.[439] Because of the legal protections of the Trust Water Rights program and the initiative of the parties involved, a workable non-litigation solution was reached in Washington for the protection of two ESA-listed species.

Picture of Okanogan Basin by Wikipedia

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[437] *Id.*
[438] *Id.*
[439] *Id.*

APPENDIX SIX: INSTREAM FLOWS IN WYOMING

Wyoming is a prior appropriation state, and the waters within its boundaries are declared property of the state, as recognized by the Wyoming Constitution.[440] Wyoming operates on a permit system, administered through the State Board of Control (BOC). The State Engineer (a governor-appointed position) is designated as the president of the Board of Control.[441]

Wyoming recognizes the following uses of water as a beneficial use: domestic, stockwatering, transportation, steam power plant, hot water heating plant, ice manufacture, industrial, municipal, and irrigation.[442] Wyoming also recognizes the storage of water "for the purpose of providing a recreational pool or the release of water for instream flows to establish or maintain new or existing fisheries" as a beneficial use of water.[443] The appropriation of unappropriated waters (on a case-by-case basis and approved by the State Engineer) to maintain or improve fisheries, as long as it doesn't injure other water users in the state, is declared a beneficial use.[444] Wyoming allows water for "existing rights not preferred" to be condemned to supply water for preferred uses, with certain limitations.[445] Designated aesthetic and recreational uses are not considered a beneficial use under the current law, only the use of sustaining fisheries is allowed (but other public values may be protected by default).

In Wyoming, water rights "for the direct use of the natural unstored flow of any stream cannot be detached from the lands, place or purpose for which they are

[440] Wyo. Const. Art. VIII § 1, 3 (2011); *e.g.*, Bureau of Land Management, *Western States Water Laws*, http://www.blm.gov/nstc/WaterLaws/wyoming.html (last visited Feb. 28, 2011).
[441] Wyo. Const. Art. VIII, § 5 (2011)
[442] WYO. STAT. ANN. § 41-3-102 (2011).
[443] WYO. STAT. ANN. § 41-3-1001(a) (2011).
[444] WYO. STAT. ANN. § 41-3-1001(b) (2011).
[445] WYO. STAT. ANN. § 41-3-102 (2011).

acquired,"[446] except in a few specific circumstances, such as when the Board of Control deems "a preferred use is to be made," and/or the proper change of use procedures are followed.[447] In Wyoming, the water right is "attached to and defined by the place of use, not the point of diversion."[448] Additionally, Wyoming limits each permit allotment "for the direct use of the natural unstored flow of any stream" to one (1) cubic foot per second (cfs) for each seventy (70) acres of land.[449]

The Wyoming instream flow program was enacted by statute in 1986.[450] It is codified in Title 41, Section 3, Subsections 1001-1014 of the Wyoming Statutes, 2011. Wyoming allows for the use of unappropriated water and/or storage water for an instream flow purpose to establish, maintain, or improve fisheries.[451] The flow available is limited to the minimum amount necessary for the fisheries purpose, and is confined to the designated reach of stream granted.[452] The Wyoming Water Development Commission ("Commission") is responsible for filing applications for permits to appropriate water for instream flows in the State's name.[453] Once the water has been allocated to and passes through its instream location, it becomes available for "reappropriation, diversion, and beneficial use" downstream.[454]

Wyoming also allows the conversion of existing water rights to an instream flow purpose, but the rights may only be acquired by the State, by transfer or gift, and can only

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[446] WYO. STAT. ANN. § 41-3-101 (2011).
[447] WYO. STAT. ANN. § 41-3-103 (2011).
[448] *Western States Water Laws*, *supra* note 440.
[449] WYO. STAT. ANN. § 41-4-317 (2011).
[450] Pat Tyrell, Green River Basin Plan, *Instream Flows in Wyoming,* (2001).http://waterplan.state.wy.us/plan/green/techmemos/instream_lores.pdf.
[451] WYO. STAT. ANN. § 41-3-1001(a),(b) (2011).
[452] WYO. STAT. ANN. §§ 41-3-1001(c),(d), -1002 (2011).
[453] WYO. STAT. ANN. § 41-3-1003 (2011).
[454] WYO. STAT. ANN. § 41-3-1002(b) (2011).

be held or owned by the State.[455] The original owner must comply with the Change of Use requirements, and the Game and Fish Commission is responsible for filing the change of use petition for this purpose.[456] The intended change of use to an instream flow must not interfere with or impair existing rights.[457] The original priority date is transferred to and preserved in the new instream flow use.[458] Once changed to an instream flow purpose, the right may subsequently be conveyed, sold, or transferred to another purpose (as long as the owner complies with the change of use proceedings[459] and the BOC holds the required public hearing).[460]

The Game and Fish Commission is responsible for 1) constructing measuring devices for the administration of an instream flow right, 2) reporting to the Commission annually those stream segments that Game and Fish considers to have the most critical need for instream flows, 3) identifying the stream reaches (beginning and end points) as well as time of year and minimum amount of water necessary for the recommended reaches, 4) filing change of use applications in the name of the State for the recommended reaches (for transfer of existing rights only), and 5) paying fees and costs of the Commission associated with permit applications and adjudication of water rights.[461]

The Wyoming Water Development Commission is responsible for 1) filing applications for permits to appropriate water for instream flows based on the

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[455] WYO. STAT. ANN. § 41-3-1007(e) (2011).
[456] WYO. STAT. ANN. § 41-3-1007 (2011).
[457] *Id.*
[458] *Id.*
[459] WYO. STAT. ANN. § 41-3-104 (2011).
[460] WYO. STAT. ANN. § 41-3-1002(c) (2011).
[461] WYO. STAT. ANN. § 41-3-1003 (2010).

recommendations of Game and Fish,[462] 2) conducting a feasibility study for recommended stream segments from unappropriated waters or storage facilities, which shall include "a determination of [the amount of] water necessary to maintain or improve existing fisheries" or to establish fisheries.[463] Finally, the Commission is required to make a report of its findings to Game and Fish and the Legislature.[464]

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462 WYO. STAT. ANN. § 41-3-1003(c) (2010).
463 WYO. STAT. ANN. § 41-3-1004 (2010).
464 *Id.*

APPENDIX SEVEN: COLUMBIA BASIN WATER TRANSACTIONS PROGRAM

Since 2002, the Columbia Basin Water Transactions Program (CBWTP) has worked to restore streamflows and habitat using voluntary water acquisitions, leases, and efficiency programs in Washington, Oregon, Idaho, and Montana.[465] The program is managed by the National Fish and Wildlife Foundation, with the majority of funding from the Bonneville Power Association (BPA) and the Northwest Power and Conservation Council.[466] The Bonneville Power Association is the U.S. Department of Energy agency that manages dams on the Columbia River System.[467]

The Program was started in 2001, when BPA issued a request for help with implementing an operations plan formulated under the National Marine Fisheries Service's (NMFS) 2000 Biological Opinion on the Operation of the Federal Columbia River Power System.[468] The National Fish and Wildlife Foundation (NFWF) was selected as the regional entity for the CBWTP, and the NFWF accessed their established Pacific Northwest Regional Office to develop partnerships with federal and nonfederal entities as part of the CBWTP.[469] This regional office "currently manages over 250 projects in the Northwest worth over $35 million."[470]

According to its website, the CBWTP "works with qualified local and state program partners [called "Qualified Local Entities" or QLEs] who join with irrigation

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[465] Columbia Basin Water Transactions Program, *Overview*, http://www.cbwtp.org/jsp/cbwtp/program.jsp (last visited Feb. 28, 2011).
[466] *Id.*
[467] ROBERT GEROME GLENNON, UNQUENCHABLE: AMERICA'S WATER CRISIS AND WHAT TO DO ABOUT IT 289-90 (2009).
[468] Columbia Basin Water Transactions Program, *Program History*, http://www.cbwtp.org/jsp/cbwtp/program/history.jsp (last visited Feb. 28, 2011).
[469] *Id.*
[470] *Id.*

districts, landowners, producers and others on projects to enhance stream flows."[471] QLEs can submit proposals for water transactions at any time to the Program.[472] NFWF "receives, evaluates, and ranks innovative water proposals submitted by local entities, and facilitates the implementation of projects and individual water transactions with funding from BPA, NFWF and other sources."[473] NFWF makes funding recommendations on the proposals and obtains BPA approval to fund projects.[474] NFWF ensures effective implementation of funded projects and compliance with the National Environmental Policy Act, and also "develops outreach information, issues transaction solicitations," and approves QLEs.[475]

The Columbia Basin Water Transactions Program is an important funding source for water banks, water markets, and instream flow project implementations in Oregon, Washington, Idaho, and Montana. Without this source, it is likely that many of the successful instream flow transactions in these states would not otherwise be possible.

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[471] Columbia Basin Water Transactions Program, *Partners*, http://www.cbwtp.org/jsp/cbwtp/program/partners.jsp (last visited Feb. 28, 2011).
[472] Columbia Basin Water Transactions Program, *Applying for Funds*, http://www.cbwtp.org/jsp/cbwtp/program/apply.jsp (last visited Feb. 28, 2011).
[473] *Program History*, *supra* note 468.
[474] *Id.*
[475] *Id.*

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

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

Progress Report, Year 1 of 2

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ABSTRACT

Aquifer storage and recovery (ASR) involves the storage of water in an aquifer, when water is available, and recovery of water from the well when it is needed. Accordingly, water injection could represent an important method for solving water shortages in semi-arid hydro-climatic regions such as Wyoming. However, water injection might also result in the contamination of ASRs due to the fractionation of heavy metals. In order to predict the potential mobility of those metals, is critically important to investigate and develop model ASR technologies for Wyoming and other states in the U.S. Part of this study focuses on factors that might contribute or enhance the mobility of metals, including pH, water injection flow rate, and temperature variation.

PROGRESS

1. Objective

The primary objective of this study is to design and provide a solution to the universal issue facing potential customers of ASR, a technology based on the physical and chemical properties of relevant rock formations and water resources analyzed through the kinetic theories of chemical engineering. Two models—batch and continuous—are used in this study. The purpose of developing the batching model is to obtain the kinetic parameters needed to develop a continuous-flow leaching model. The continuous models for multiple species will not be developed, but will be tested under various contaminant-leaching conditions.

2. Introduction

The state of Wyoming is considered part of a semi-arid hydro-climatic region, with water levels that vary throughout the year. In general, the state has limited sustainable surface water available for use. Furthermore, Wyoming is one of the largest fossil fuel suppliers in the country [1], with large quantities of water generated during production released either onto land or into nearby lakes or rivers with no beneficial use. Accordingly, an environmentally friendly and relatively inexpensive method is needed to store this co-produced water. An aquifer storage and recovery (ASR) injection method could be a feasible technology for conserving water that would otherwise be wasted. However, prior to implementation, any ASR method should address potential contamination that might occur during water injection and storage as a result of the leaching of toxic metals.

This project considers two models—continuous and batch leaching [2]—that can be modified to predict the potential leaching of contaminants into aquifers. Furthermore, the effects of varying certain parameters on the mobility of heavy metals through rocks, including pH and temperature, will be studied using both leaching processes, with the variation of flow rate studies applied to the continuous process as well. This work seeks to study mobility and investigate the kinetics of a number of heavy metals individually that may be present in "sandstone" rock types. Sandstone varieties are arenaceous sedimentary rocks composed mainly of feldspar and quartz, and exhibit a wide color palette of grey, yellow, red and white. They are broadly divided into three groups: arkosic sandstones, which have a high (>25%) feldspar content; quartzose sandstones, such as quartzite, which have a high (>90%) quartz content; and argillaceous sandstones, such as greywacke, which have a significant fine-grained element.

The term “heavy metal” refers to any metallic element that has a relatively high density, and typically refers to the group of metals and metalloids with atomic densities greater than $4g/cm^3$ [3]. Heavy metals are well known to be toxic to human beings and most other organisms when present in high concentrations in the environment [3]. Table 1 lists the standard levels of

Table 1: WHO/EU drinking water standards

Element	WHO standard (mg/L)	EPA standards (mg/L
Arsenic (As)	0.01	0.01
Barium (Ba)	0.3	2
Beryllium (Be)	No guideline	0.004
Boron (B)	0.3	N/A
Cadmium (Cd)	0.003	0.005
Chromium (Cr)	0.05	0.1
Copper (Cu)	2	1.3
Iron (Fe)	No guideline	N/A
Lead (Pb)	0.01	0.015
Manganese (Mn)	0.5	N/A
Nickel (Ni)	0.02	N/A
Selenium (Se)	0.01	0.05
Silver (Ag)	No guideline	N/A
Zinc (Zn)	3	N/A

these elements considered safe in water, according to World Health Organization (WHO) [4] and the United States Environmental Protection Agency (EPA) [5]. The leaching of heavy metals occurs naturally, as in the case of sulphide minerals in rocks that are oxidized upon contact with water and atmospheric oxygen, resulting in the formation of sulfates that generate so-called "acid rock drainage" and "metal leaching" (ARD-ML). ARD-ML is usually characterized by high concentrations of metals and sulfates in solution, which lower pH values to between 2-4. The literature has documented that low pH levels enhance the release of certain metals into aquifers [6-7].

The mobility of arsenic (As) as a toxic elements in the presence of pyrite in ASR has been reported in various studies as an example of such leaching, and geochemical modeling has examined the stability of pyrite in limestone during the injection into wells of surface water containing known mineralogy and water chemistry [8]. The goal of these modeling studies was to stabilize pyrite under certain conditions in order to alter the high leaching of As levels into ASRs. Another leaching model investigated interactions among immobilization reactions and transport mechanisms affecting the overall leaching of contaminants [9], and a characteristic leaching procedure for assessing the toxicity of soils contaminated with heavy metals has been reported elsewhere [10]. In addition, several reports have been cited for the release or mobility to groundwater of heavy metals from sources as diverse as fly ash [11], water springs [12], soil [13], mine waste material (i.e., tailings) [14], acidic sandy soil amended with dolomite phosphate rock (DPR) fertilizers [15], and contaminated calcareous soil [16].

All of these reports indicate the mobility of heavy metals in soil to some extent under various amendment conditions. Further, it has been reported that the addition of organic material could result in the fixation of metals such as zinc (Zn) and lead (Pb) in soil, which in turn might help to reduce leaching of these metals into aquifers [16]. The study of metal leaching from different fly ash samples [11] showed differing behavior patterns that were dependant on the element, the type of material and the method of extraction. The chemical partitioning of lead (Pb) and zinc (Zn) in soils, clays and rocks has been documented [17], with their migration showing an increase under low pH conditions. In the present study, we found it both necessary and useful to design and develop leaching models to study the kinetics of each individual contaminant species; to investigate the potential leaching of some of these heavy metals from sandstone rocks using both continuous and batch leaching processes; and to measure the effects of varying parameters such as pH and temperature of the leachate on both leaching processes, as well as the effects of flow rate on the continuous leaching process.

3. Methods

3.1 Sample collection and preparation

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

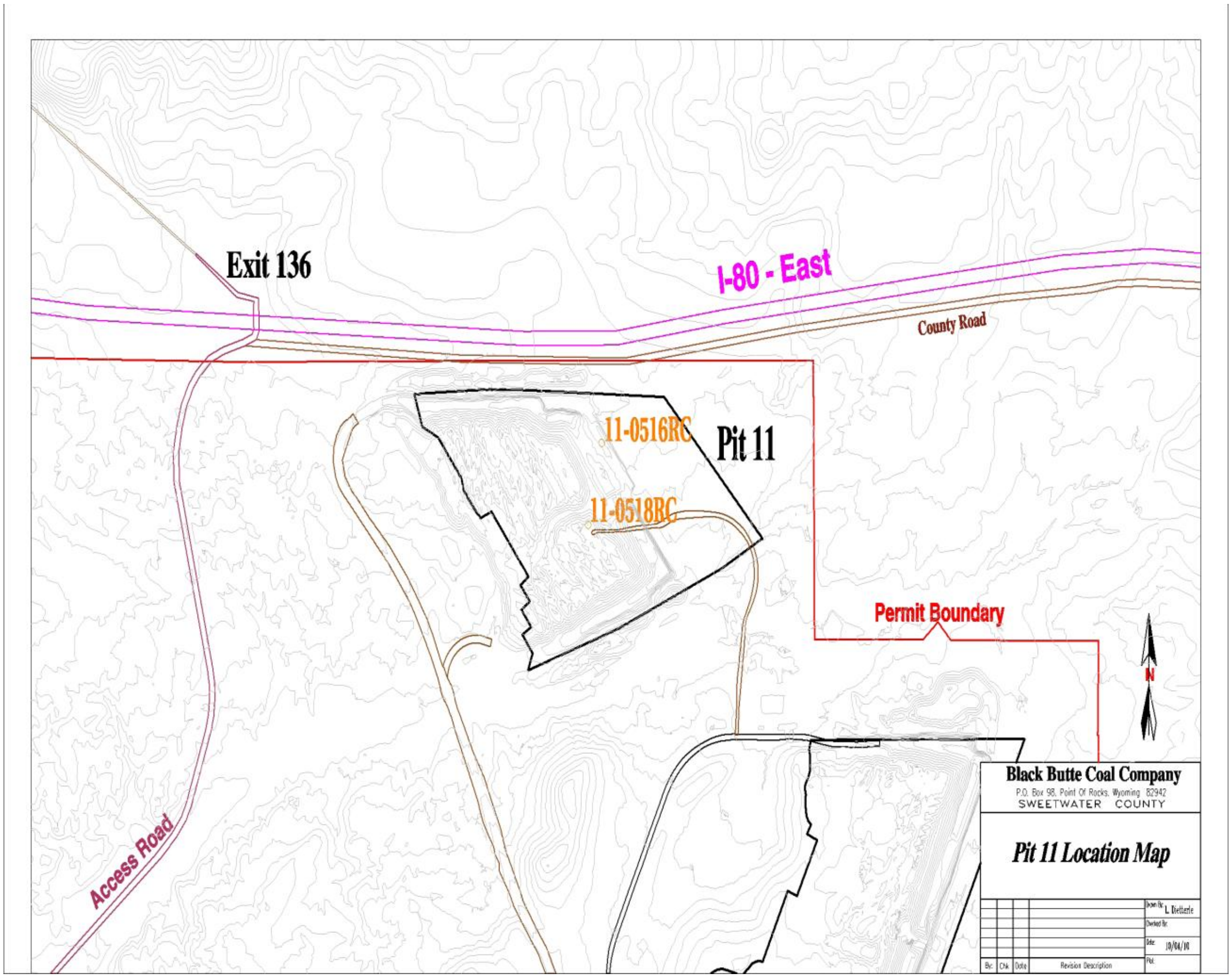

Figure 1: Rock Sample collection location (source: Black Butte Company)

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

Raw depths (feet)	Adjusted depths (feet)	Lithology type	Color
0.00-5.00	0.00-5.05	Soil	Yellowbrown
5.00-22.00	5.05-22.21	Sandstone	Greybrown
22.00-25.00	22.21-25.24	Siltstone	Brown
25.00-29.00	25.24-29.27	Sand	Grey
29.00-56.00	29.27-56.53	Siltstone/mudstone	Grey
56.00-61.00	56.53-61.58	Siltstone	Grey
61.00-74.00	61.58-74.70	Mudstone	Grey
74.00-83.00	74.70-83.78	Siltstone	Grey
83.00-85.00	83.78-85.80	Mudstone	Grey
85.00-93.00	85.80-93.88	Siltstone	Grey
93.00-98.00	93.88-98.92	Mudstone	Grey

98.00-129.00	98.92-130.22	Siltstone	Grey
129.00-135.00	130-22-136.27	Mudstone	Grey
135.00-143.00	136.27-144.35	Siltstone	Grey
143.00-144.00	144.35-145.36	Mudstone	Grey
144.00-150.00	145.36-151.42	Sandstone	Grey
150.00-153.20	151.42-154.65	Mudstone	Grey
153.20-155.00	154.65-156.46	Coal	Black
155.00-158.70	156.46-160.20	Carbonaceous mudstone	Brown
158.70-160.00	160.20-161.51	Coal	Black
160.00-168.00	161.51-169.58	Mudstone	Grey
168.00-212.00	169.58-214.00	Sandstone	Grey
212.00-240.20	214.00-241.20	Coal	Black
240.20-245.00	241.20-245.68	Carbonaceous mudstone	Brown
245.00-247.50	245.68-248.01	Coal	Black
247.50-255.00	248.01-255.00	Sandstone/mudstone	Grey

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

3.2 Reference sample

3.2.1 Quantitative analysis

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

3.2.2 Apparatus

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

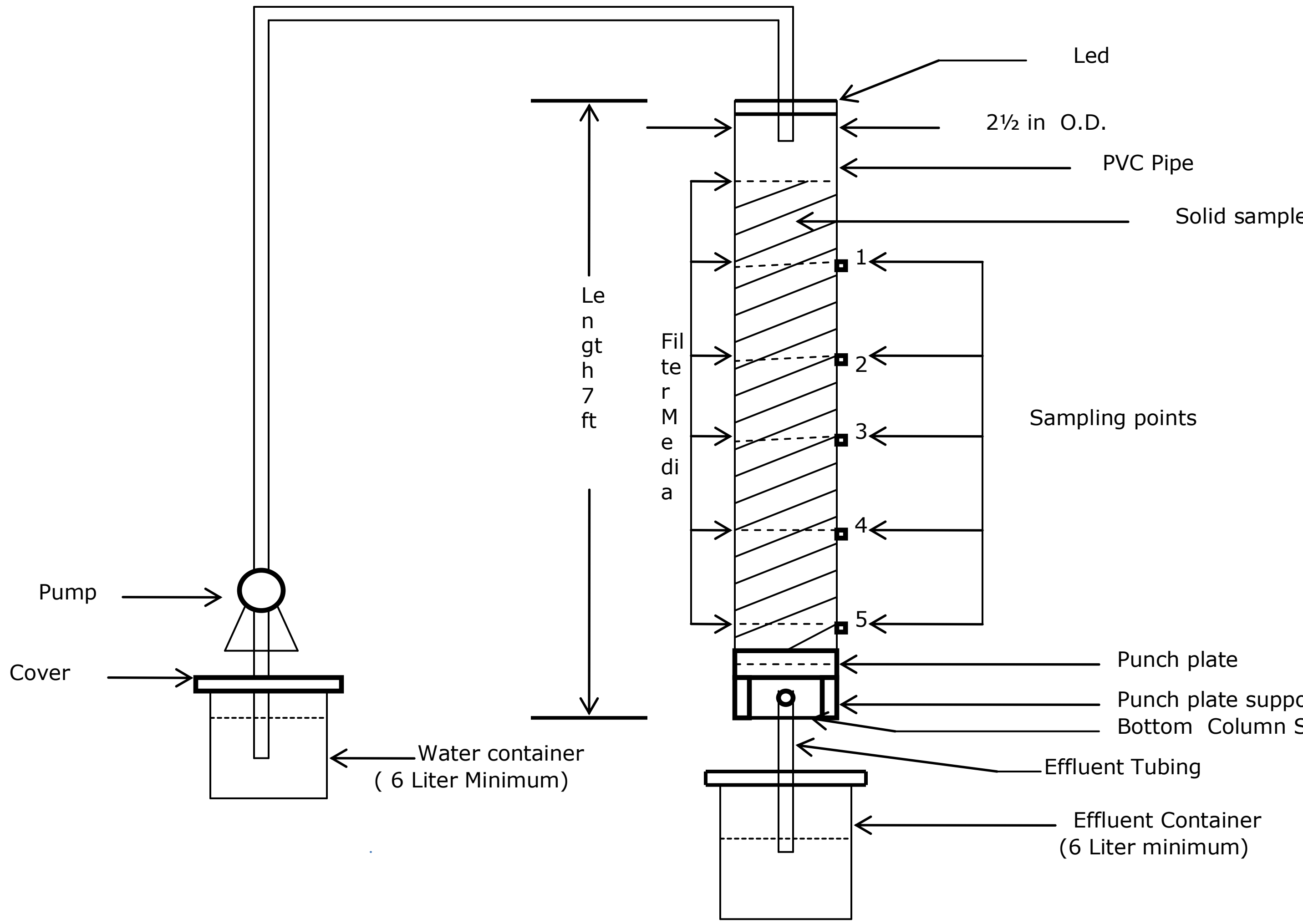

Figure 2: Schematic setup diagram for continuous leaching

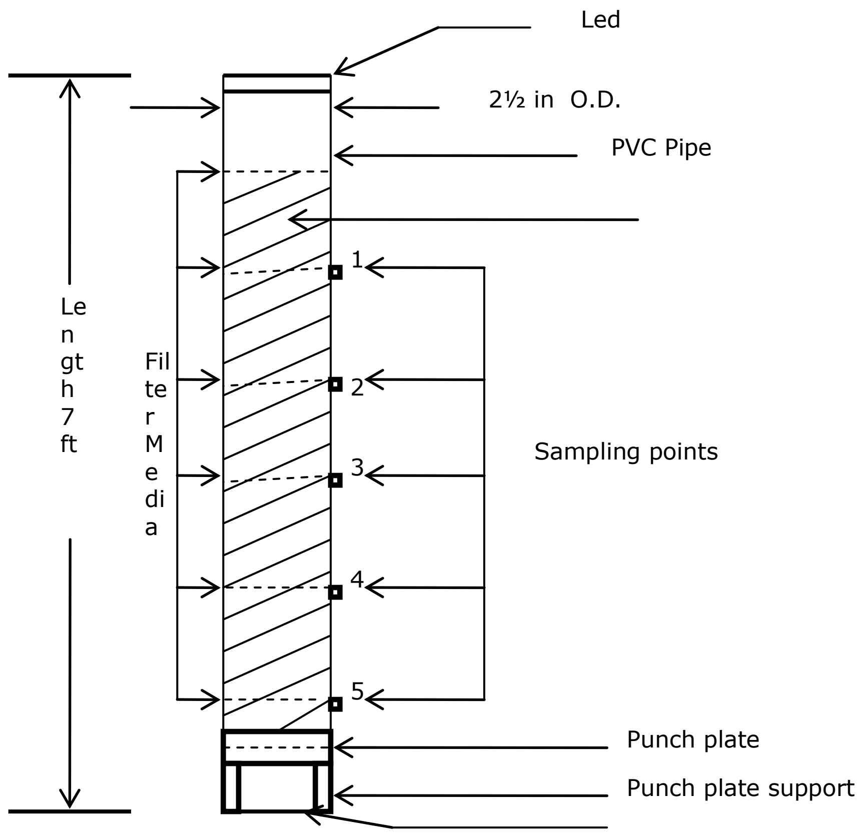

Figure 3: Schematic setup diagram for batch leaching

Figure 4: photo of continuous and batch apparatus

constant flow rate of extraction fluid (water). In the continuous leaching model, containers to hold both influent and effluent liquids were used during extraction.

3.2.3 Operation Procedure

Continuous leaching method

A 5kg dry rock sample was loaded in increments into the PVC column. In order to minimize particle segregation and compaction, the sample increments were carefully loaded without shaking or tamping. Cotton filter media were inserted into the column near each sampling point in order to withdraw sample effluents using a syringe during the extraction process. Deionized water (DI) was pumped from a container holding a minimum of 10l into the column at a specified flow rate using a diaphragm-type metering pump (series 100/150). The initial temperature and pH of the leachate water, as well as the date and starting time of the leaching process, were recorded in accordance with ASTM D 1293[19]. Two extraction samples of about 10ml were collected in plastic vials from sampling points 3 and 5 every 8 hours over a 40-hour period. Collected leachate samples were then analyzed for leachable metals using an ICP-OES Spectrometer (ICAP 6000 series, Thermo Scientific). The same procedure was used under different experimental conditions, including flow rate, pH and temperature.

Batch leaching method

With the exception of the use of a metering pump, a procedure largely similar to method 2.4.1 was used to assess the batch leaching method. A set volume of DI water (~1800ml) was added to the column at the start of the leaching process, and small aliquot samples (10ml) were withdrawn and collected in 15ml vials every 8 hours over a period of 40 hours from sampling points 3 and 5.

4. Findings/Results and discussions

4.1 Reference sample analysis

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

Table 3: Metal concentrations in rock sample (sandstone)

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

in sandstone rock samples. Because of the chemical composition, matrix complexity, and insolubility of the rock type in mild acidic media (due mainly to a high silica content of approximately 95-97% and various other resistant mineral constituents), the fine powder sample was treated under harsher acidic conditions to ensure complete elemental extraction into the aqueous solution. The method used for the sample dissolution is outlined in section 2.2. In order to minimize errors due to the varying distribution of elements within different rocks, the concentrations shown in Table 3 are based on an average of three representative sandstone samples. The reported data are based on the average of three independent runs with a calculated relative standard deviation of ~2%. The sandstone samples were found to contain a total of thirteen heavy metals at various concentrations, all within the calibration curve and the ICP detectable range. Compared to the remaining elements, barium (Ba) and manganese (Mn) concentration levels were observed to be highest. However, Ba and Mn are considered less harmful contaminants, and their levels in the sample were far below the allowable limits set by the WHO and EPA for standard potable water. Other more toxic elements such as Cd, As, Be, Co, Cu, Ni, Pb and Se were present as well, but with lower ppm-range concentrations. The remaining elements (Cr, Zn and V) showed moderate ppm concentration levels. Iron appeared to be present in high quantities but showed inconsistency (possibly from the jaw crusher's blades) among the samples, so was not included in this study. Actual Fe concentrations will be included in the next report.

4.2 Effect of flow rates on metal leaching

Variations in flow rate were examined in order to determine any effects they might have on the fractionation of metals from the sandstone rocks. Aliquots were collected every 8 hours from two column depths over a period of 40 hours and analyzed by ICP. Other experimental parameters such as temperature and pH were kept constant at 21^{o}C and 6, respectively. Water was introduced from the top of the column and percolated downward through the sandstone particles at four specified constant flow rates. The water flow rates used in the study ranged from 11.67ml/min to 33.33ml/min. Figures 5 to 9 represent (in ppb) concentrations of soluble metals in the leachate tending toward mobilization through the sandstone particles at various flow rates from the bottom column's sampling point 5; these were collected at the specified sampling periods. The results obtained were generated from the average of three independent experiments. Regardless of the flow rate applied, only five of thirteen elements were observed to have any desorption capability through rocks under the specified conditions. Their easy fractionation might be attributed to their weak physical or chemical adsorption bonding, or might instead be due their solubility relative to the other heavy elements.

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

Figures 5 to 9 also show desorption of these metal species with respect to sampling time. It can be observed that prolonged water contact with the particles' surfaces significantly impacted the metals' mobility. Maximum concentration levels of leached metals occurred at the first sampling collection time (8hrs); leachate collected at later sampling times (i.e., 16, 24, 32 and 40 hours) showed lower concentrations of leachable metals. Prolonged contact with the water flow caused desorption within shorter time periods, due either to solubility or the weak physical bonding of these species with the rock surface. These leached metals showed similar behaviors at different column depths (sampling point 3). Leachate concentrations of B obtained at other sampling time periods showed nearly the same trend at sampling point 5, with the exception that the amounts leached were at lower concentrations. It is worth noting that all of the leached metals' concentrations at all flow rates were observed to be below the WHO/EPA drinking water standard limits (Table 1). From these findings, it was determined that to complete

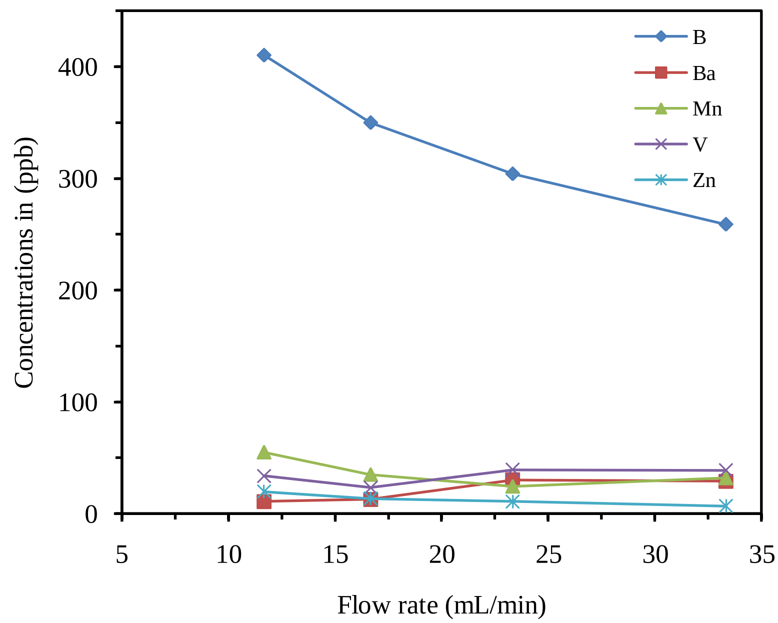

Figure 5: Effect of flow rate on metal leaching (sampling point 5, collection time 8 hours)

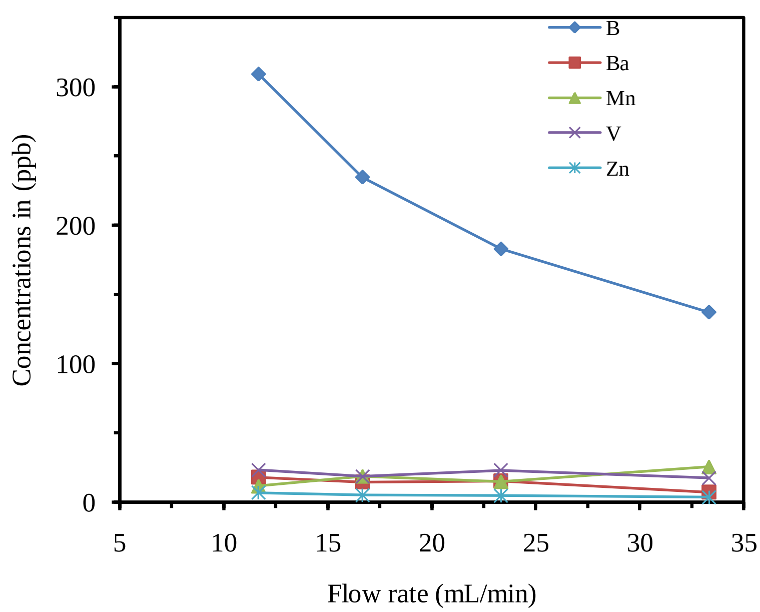

Figure 6: Effect of flow rate on metal leaching (sampling point 5, collection time 16 hours)

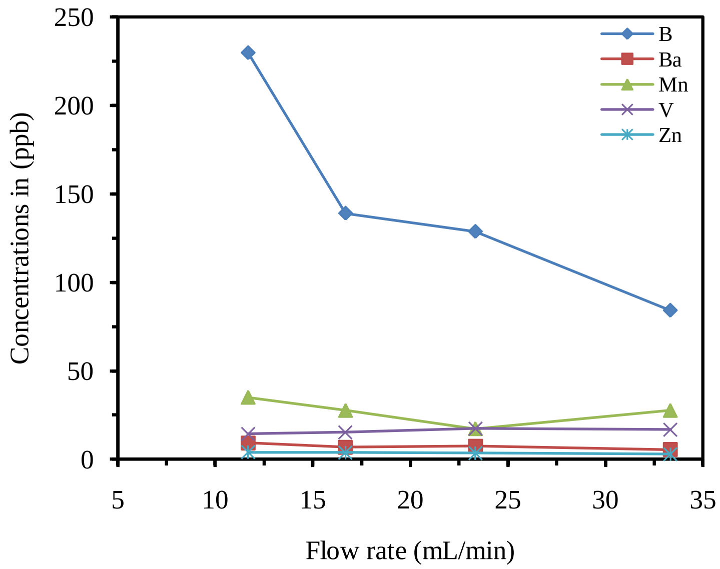

Figure 7: Effect of flow rate on metal leaching (sampling point 5, collection time 24 hours)

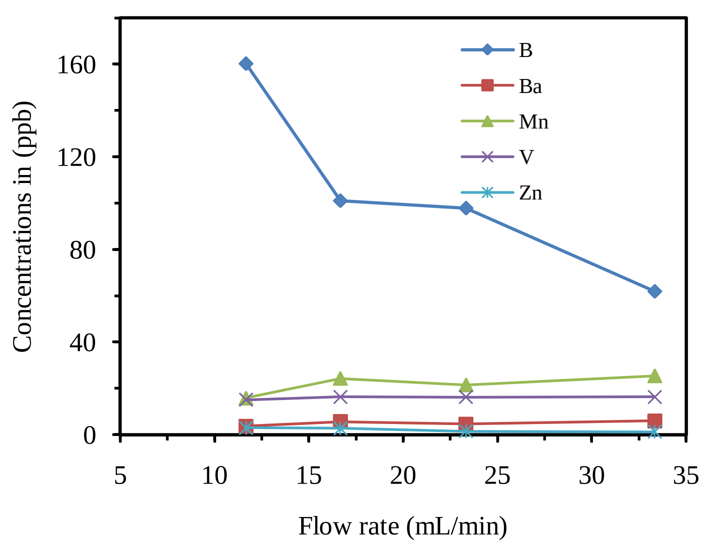

Figure 8: Effect of flow rate on metal leaching (sampling point 5, collection time 32 hours)

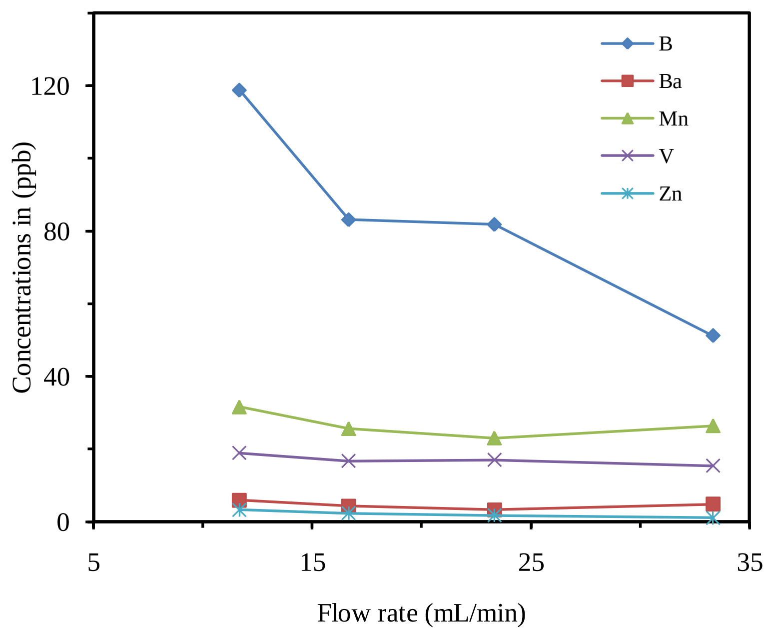

Figure 9: Effect of flow rate on metal leaching (sampling point 5, collection time 40 hours)

the remaining task of determining the effects of other parameters (e.g. pH and temperature) on metal leaching, a lower flow rate would be recommended in order to minimize desorption of the leachable metals (especially B and Mn).

4.3 Continuous vs. batch leaching

A comparison of continuous and batch processes for the leachable heavy metals is presented in Figures 10 and 11, with levels of the extracted amounts shown in ppb

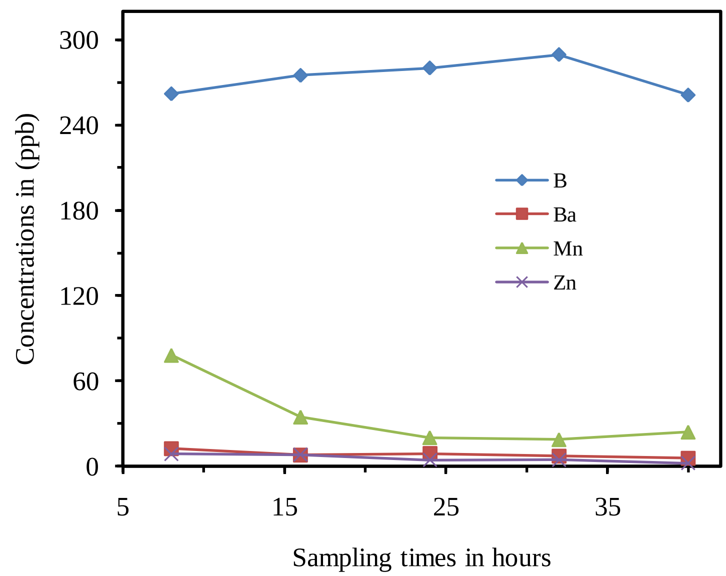

Figure 10: Continuous leaching (sampling point 5, flow rate 6.33 ml/min)

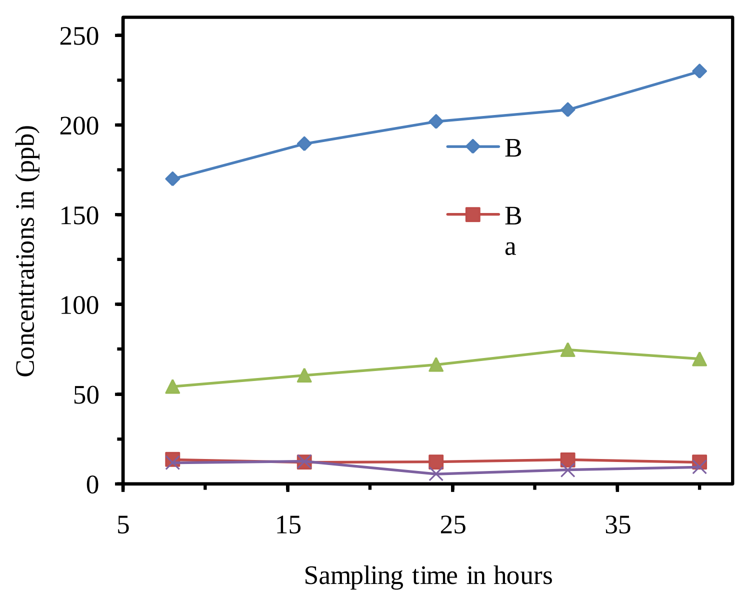

Figure 11: Batch leaching (sampling point 5, total volume 1900ml)

concentrations. The concentrations are plotted against collection sampling time periods of 8, 16, 24, 32 and 40 hours. Experiments were conducted at a constant temperature of 21^{o}C and a pH of 6. A water flow rate of 6.33ml/min was used in the continuous leaching. In the case of batch leaching, a quantity of water (about 1900ml) was added from the top of the column sufficient to immerse the 5kg of sandstone particles at the beginning of the process. Samplings were taken periodically every 8 hours. Only four metals (B, Ba, Mn and Zn) appeared to have any mobility in either leaching process. The amounts of Ba and Zn leached were comparable regardless of the leaching process. Steady water contact with the particle surfaces in batch leaching did not cause any noticeable desorption enhancement of the leached metals, rendering extracted metal concentration levels similar to those of the continuous process. However, B was an exception to this finding, evincing a slightly higher mobility in the continuous process compared to the batch process. The reason for this might be due to the flow of water moving downward through the particles, causing the greater mobility of B. By contrast, the behavior of Zn was opposite that of B, due perhaps to the physical interaction or bonding of Zn to the particle surface. Finally, water contact and flow rate were not shown to have any significant effect on leaching of the remaining elements present in the studied rock material.

5. Significance

On one hand, Wyoming is broadly considered to be in a semi-arid hydroclimatic region. As such, surface water distributions are bi-modal. The vast majority of the time, rivers and streams in the state have little flow although, occasionally during rare events, rivers and streams can swell to almost unbelievable levels. In general, WY has limited sustainable surface water available for use. Moreover, natural disasters such as droughts and tornadoes may unpredictably plague some regions of Wyoming by undermining agricultural, industrial productivity and the well-being and social fabric of communities. Manmade disasters caused by point and nonpoint pollution have been a long-standing concern that may further undermine Wyoming's ability to meet its water needs. It is imperative that Wyoming will not be threatened forever due to the lack of water supply.

In response to the water crisis, Wyoming statute Title 35, Chapter 11, Article 3 (35-11-309) declares that "water is one of the Wyoming's most important natural resources, and the protection, development and management of Wyoming's water resources is essential for the long-term public health, safety, general welfare and economic security of Wyoming and its citizens."

The people are increasingly interested in resorting to aquifer storage and recovery (ASR) to solve the water shortage issue in Wyoming. For instance, the City of Laramie utilizes both surface and groundwater to meet their municipal water needs. The Spur well field is located North of Laramie off of North 9th Street. Water levels have been declining at the Spur Well Field. As a result, the City is investigating the potential for an Aquifer Storage and Recovery (ASR) project to mitigate declining water levels.

ASR would serve to conserve waters that would ultimately go unused. However, the groundwater expansion efforts have met some resistances due to the concerns about aquifer contamination and human health. Acceptance of this potentially important source of drinking water in Wyoming requires solutions to various technical, economic, and regulatory issues, e.g., 1) is contaminant leaching an issue in the application of ASR? 2) do we need to treat the water before it is injected? 3) what monitoring measures should we take to avoid the potential problems? 4) what are the energy costs related to ASR? Obviously many questions need to be answered before ASR technology can be implemented in Wyoming. This project is focused on studying the 1st issue mentioned above. Therefore, the project is important to the successful application of ASR.

OTHERS

One graduate student, Abdulwahab M. Ali Tuwati, has been supported by the project. With the support of the project, he successfully finished his MS study in the Department of Chemical and Petroleum Engineering in Spring/2011, and will continue his PhD study in the Department of Chemistry. The progress of the project was presented to Wyoming Water Research Program on Thursday, December 2, 2010, in the WWDC conference room, 6920 Yellowtail Rd, Cheyenne, and to the Department of Chemistry at University of Wyoming on December 8, 2010.

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Development of GIS-Based Tools and High-Resolution Mapping for Consumptive Water Use for the State of Wyoming

Basic Information

Title:	Development of GIS-Based Tools and High-Resolution Mapping for Consumptive Water Use for the State of Wyoming
Project Number:	2010WY58B
Start Date:	3/1/2010
End Date:	2/29/2012
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Irrigation, Water Use, Water Supply
Descriptors:	Crop consumptive water use, Evapotranspiration, Crop irrigation requirements, Spatial interpolation of weather data
Principal Investigators:	Gi-Hyeon Park, Mohan Reddy Junna

Publications

There are no publications.

Development of GIS-based Tools and High-Resolution Mapping for Consumptive Water Use for the State of Wyoming

1st year Annual Report, Year 1 of 2

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April 30, 2011

Executive Summary

Accurate estimation of consumptive irrigation requirement is one of the key components for making decisions in irrigation scheduling and management, water rights allocation, administration of water rights, and hydrologic studies. State water resources managers rely on consumptive water use data to monitor and guide farmers and make sustainable future plan and decision. Traditionally, consumptive irrigation requirement (CIR) has been computed based on the estimated reference evapotranspiration (reference ET) by multiplying crop coefficient and subtracting effective precipitation. However, the estimation of reference ET has been calculated using single weather station data near the area of interest due to the limited number of stations. This project provides spatially distributed daily and monthly reference ET in 0.01 x 0.01 degree resolution using data available in the State of Wyoming from 1960 to current.

Gridded daily and monthly weather data and reference ET were processed for the period of 1960-2009. Monthly climate normals (1971-2000) of weather data and reference ET for the state of Wyoming were calculated by averaging daily gridded data. Gridded weather data and reference ET will be served to the public through the data server at the Wyoming State Engineer's Office.

Three reference ET methods – ASCE standard reference ET method, Hargreaves-Samani, and FAO Blaney-Criddle methods – were used to estimate reference ET for the area. GIS-based ET calculation tools (ArcInfo reference ET tool and ArcGIS ET calculation tool) are being developed to help water resources managers as local water users make operation decisions. ArcGIS ET tool are being developed using C# and .NET, which will allow water resources managers to calculate consumptive water use by providing crop types, crop coefficients, and water supply condition. The default parameters (growing season, crop types, and crop coefficient) for ET tool were developed based on Pochop et al. (1992). A dynamic ET web will be developed during the 2nd year of the project to provide high resolution gridded weather data and reference ET.

Objectives: The main objectives of this study are to:

1) Generate spatially interpolated high resolution (0.01° by 0.01°) weather data for the State of Wyoming;
2) Produce high-resolution (0.01° by 0.01°) reference ET maps for the state of Wyoming using ASCE standard ET method, Blaney-Criddle method, and Hargreaves-Samani equation;
3) Develop an ArcInfo tool for reference ET calculation; and,
4) Develop an ArcGIS ET calculation tool for the three major river basins in southern Wyoming to enhance the Spreadsheet ET calculator that has been used by the Wyoming State Engineer's Office (SEO).
5) Develop a Web-based mapping tool for public to access gridded weather data and reference ET with dynamic user-interface.

Study Area

The study area includes the three major basins in southern Wyoming: the North Platte River Basin, the Green River Basin, and the Bear River Basin. These basins, along with the digital elevation model (DEM), are shown in Figure 1. The DEM has a resolution of 0.01° by 0.01° (approximately 1 km by 1 km).

Methodology

GIS-based ET calculation tool use the ASCE standard ET, FAO Blaney-Criddle and Hargreaves-Samani methods to calculate the spatially distributed high resolution reference ET for the three river basins in Wyoming and mean areal crop ET, CIR, and CU. Schematic flow diagram of the project is shown in Figure 2. Data needed for the ASCE standard reference equation include maximum and minimum temperature, wind speed, dew point, and solar radiation. Precipitation was also acquired to calculate consumptive irrigation requirement (CIR). Weather data were obtained from various sources in a daily timescale from 1960 to 2009 (a total of 18,263 days). In addition, real-time weather data are being obtained from the Applied Climate Information System (ACIS) and will be implemented for real-time reference ET calculation during the summer of 2011.

Precipitation, maximum and minimum temperature

Precipitation and maximum and minimum temperature data were obtained from the National Climatic Data Center (NCDC) from January 1960 to December 2009. To get a better interpolation, weather data was not limited to Wyoming. Figure 2 shows the 825 weather stations in Wyoming and in parts of Colorado, Utah, Idaho, and Nebraska that were used. Inverse distance weighting method (IDW) was used to spatially interpolate temperature into 0.01° (1 km by 1 km) grids that are in the same resolution as the DEM, while lapsed according to elevation.

Examples of the interpolation for maximum and minimum temperature are shown in Figure 4 and Figure 5, respectively. Precipitation was also interpolated to a 0.01°, but it was instead rescaled using monthly PRISM data. Two precipitation maps, one before and one after rescaling, are shown in Figure 6. Climate normal of monthly precipitation and maximum and minimum temperatures were also calculated (Figure 7, Figure 8, and Figure 9)

Dew point temperature

Daily dew point temperature data were downloaded from Quality Controlled Local Climatological Data (QCLCD) from July 1996 to December 2009. The QCLCD does not have records before July 1996 and only has data for Weather-Bureau-Army-Navy (WBAN) stations (mostly airports). These 43 stations are shown in Figure 10. This daily dew point was subtracted from daily minimum temperature to get a daily dew point adjustment, as shown in Figure 11. The monthly average dew point adjustment was then calculated for each station, resulting in 12 monthly dew point adjustments for each station. These monthly point values were then interpolated using IDW over the DEM to get monthly grids of dew point adjustment, as seen in Figure 12. The actual dew point grids were then calculated by subtracting the appropriate monthly dew point adjustment grid from the daily minimum temperature grids, as shown in Figure 13.

Wind speed

Wind speed Reanalysis I and Reanalysis II data were obtained from National Centers for Environmental Prediction (NCEP). Since both data sets have a resolution of 2°, it was necessary to downscale them into 0.01° (Figure 14). When reanalysis I and II were compared, it was found that both have a similar pattern but reanalysis II generally has higher values. To help determine which dataset to use, actual measured wind data was downloaded from the NCDC (from January 1984 to June 1996) and from the QCLCD (from July 1996 to December 2009) for the same 43 stations that had dew point data. There is no measured wind data before 1984. When the measured wind speeds were compared to both reanalysis sets, it was found that the measured wind speeds rarely matched the NCEP values. Therefore, biases at the stations were calculated and spatially interpolated to adjust wind speed grid. Since Reanalysis I data go back to 1948 but Reanalysis II data start in 1979, Reanalysis I data were used for the bias calculation, as shown in Figure 15.

The daily bias point values were then interpolated using IDW to get daily bias grids, as shown in Figure 16. Then, the final daily wind speed grids for 1984 to 2009 were calculated by subtracting the daily bias grids from the daily NCEP grids, as seen in Figure 17. Since there are no measured wind speeds before 1984, daily bias cannot be calculated. Instead, average monthly wind bias was calculated by averaging all of the daily bias grids for each month to get 12 monthly bias grids. Finally, the final wind speed grids for 1960 to 1983 were calculated by subtracting the appropriate monthly bias grids from each daily NCEP grid. All wind speeds are at a height of 10 meters.

Incoming Solar Radiation

Incoming solar radiation was estimated from Hargreaves radiation formula (FAO56, eq. 50) using minimum and maximum temperature:

$$R_s = k_{RS} * \sqrt{T_{max} - T_{min}} * R_a$$

where

R_s = predicted incoming solar radiation
k_{RS} = adjustment coefficient (0.16 for inland locations)
T_{max} = maximum temperature
T_{min} = minimum temperature
R_a = extraterrestrial radiation (depends only on location and time of year)

Reference ET

With gridded maximum temperature, minimum temperature, dew point temperature, and wind speed data, reference ET was calculated. An Arc Macro Language (AML) script was developed for the ASCE Standardized Reference Evapotranspiration Equation.

$$ET_{ref} = \frac{0.048 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{C_n}{T + 273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + C_d \cdot u_2)}$$

where

ET_{ref} = standardized reference ET
Δ = slope of saturation vapor pressure-temperature curve
R_n = net radiation
G = soil heat flux density
γ = psychrometric constant
C_n = numerator constant (900 for short reference, 1600 for tall reference)
T = mean temperature
u_2 = wind speed at 2 m height
e_s = saturation vapor pressure
e_a = actual vapor pressure
C_d = denominator constant (0.34 for short reference, 0.38 for tall reference)

The Hargreaves-Samani and FAO Blaney-Criddle equations will be implemented during the 2nd year of the project. An example of the ASCE standard reference ET maps is in Figure 18. As with the weather data, the reference ET maps are in daily from 1960 to 2009. Monthly climate normal reference ET was also calculated (Figure 19)

Crop Coefficient (K_c)

After the reference ET maps were completed, the next step was to obtain default crop coefficients (K_c) to use in the ArcGIS ET calculation tool. The 1992 National Land Cover Data (NLCD) map, seen in Figure 20, was chosen to be the default crop type map. Pochop et al. (1992) reported K_c for 67 stations in Wyoming. Pochop classified these stations into 5 groups (see Table 1) based on elevation and on the length of the growing season.

Table 1: Groups (Pochop et al., 1992)

Group #1 4/1-10/15		Group #2 4/15-10/15	Group #3 4/15-9/30	Group #4 4/15-9/15	Group #5 5/1-9/15
Albin	Lusk	Double 4 Rch	Centennial	Afton	Big Piney
Arvada	Midwest	Ft Washakie	Encampment	Alta	L Yellowston
Basin	Morrisey	Green River	Evanston	Bedford	Moran
BoysenDam	Newcastle	Laramie	MedicineBow	Border	Pinedale
Buffalo	Pathfinder	Moorcroft	Rawlins	Dubois	South Pass
Casper	Pine Bluffs	Muddy Gap	Saratoga	Farson	
Cheyenne	Powell	Riverton	Seminoe Dam	Jackson	
Chugwater	Redbird	Rock Springs	Wamsutter	Kemmerer	
Cody	Sheridan	Sundance		Sage	
Douglas	Ten Sleep	Sunshine		Tower Falls	
Gillette	Thermopolis				
Glenrock	Torrington				
Kaycee	Upton				
LaGrange	Weston				
Midwest	Whalen Dam				
Lander	Wheatland				
Lovell	Worland				

Since each group has different K_c values, a "land ID map" (based on the NLCD map and the group number) will be used as a default crop type map for the ArcGIS ET calculator instead of the NLCD map alone. Because the group numbers are at stations, they were interpolated using the Thiessen polygon method within each basin boundary. The resulting Thiessen polygons are shown in Figure 21 and the group map is shown in Figure 22.

By multiplying the group map times 100 and adding the NLCD value, the land ID map, as seen in Figure 23, was created. For example, Yellowstone Lake is in group 5. The NLCD value of open water is 11. Therefore, the land ID for Yellowstone Lake is 511.

Effective Precipitation Fraction

Effective precipitation will be set as unity as default. However, user can change it in ArcGIS ET tool.

Potential Evapotranspiration

Potential Evapotranspiration will be calculated within the ArcGIS ET tool by multiplying crop coefficients to the reference ET. The values are highly dependent on the type of crop that exists in the area of interest. Default crop types are defined based on 1992 NLCD land type, but users will be able to define actual crop type and further adjust crop coefficients.

Consumptive Irrigation Requirement (CIR)

Consumptive Irrigation Requirement will be calculated within the ArcGIS ET tool. CIR is calculated by subtracting effective precipitation from reference ET in daily scale, and they will be aggregated into monthly and growing season totals.

ArcGIS ET Tool

An ArcGIS ET tool is being designed and tested as part of the 2nd year project. During the 1st year, we identified that C# and .NET under visual studio environment will provide the longer life time of the tool, since ESRI will not provide any more support on Visual Basic from the next release of ArcGIS. We have begun working on design and implementation of the interface under this environment.

Dynamic ET Web Development

Development of dynamic ET web has not developed yet, which will be part of the 2nd year project. User will be able to navigate to any area in Wyoming, define area of interest, and obtain high resolution weather data and reference ET. User interface will be developed via MapServer in the 2nd year.

Progress during the first year

We have completed all tasks planned for the 1st year of the project and continue working on the tasks for the 2nd year. All weather data (1960 to 2009) were obtained and interpolated into 0.01 degree resolution, and preprocessing tools were written in several programming languages. Daily, monthly, and climate normal gridded reference ET for the State of Wyoming were calculated using gridded daily weather data. ArcInfo reference ET tool was developed and used to calculate daily reference ET using the ASCE standard reference ET equation, which will be implemented into realtime reference ET processing at the State Engineer's Office. During the 2nd year, the project team will be working on the development of ArcGIS tool and dynamic web interface.

Table 2: Progress during the first year (3/1/2010-2/28/2011). The solid arrows represent the task completed and the dotted arrows are ongoing tasks for the 2nd year.

Activities	3/1/10 to 8/31/10	9/1/10 to 2/28/11	3/1/11 to 8/31/11	9/1/11 to 2/29/12
1. Data Collection and Processing				
2. Development of Preprocessing Tools				
3. Development of Gridded reference ET Data				
4. Evaluation and modification of ET calculation scheme				
5. Development of the GIS-based ET tool for Wyoming				
6. Development of ET Website				
7. Deliver ET tool to SEO for evaluation / Conference Presentation				

Principal Findings

Weather data gridded from available data captures spatial weather pattern of Wyoming, and they are reliable for estimating reference ET in southern Wyoming. Spatial variability of weather pattern was captured very well in gridded high resolution data and they are expected to provide enhanced information for estimating consumptive water use and other related works.

Estimated potential ET was compared to remotely sensed ET (METRIC) for July 9, 2009. For the wet pixels, potential ET agrees well with METRIC ET with less than 10 % errors (Figure 25).

Significance

This project provides the enhanced weather data in high spatial (0.01 x 0.01 degree) and variable temporal (daily, monthly, seasonal, and climate normal) resolutions. This project enhances the current ET spreadsheet model by using daily weather data instead of monthly data and aggregating them into monthly, seasonal, and climate normal. Water resources managers will be able to estimate spatially mapped consumptive irrigation requirements using either real-time weather data or climate normal (1971-2000). High resolution gridded weather and reference ET data will be provide through data server at the State Engineer's Office and benefit other works that requires distributed weather information.

Presentations

Ryan Rasmussen and Gi-Hyeon Park, High-resolution mapping of reference ET for the state of Wyoming – AGU meeting December 13-17, 2010, San Francisco, California.

Student supported

Two graduate students were supported by this grant:

Ryan Rasmussen (MSc student) has been fully supported by this grant since summer 2010. He is a graduate from the University of Wyoming, and he is expected to continue working on this project and graduate in May 2012.

TaeJung Song (PhD student) was partially supported by this grant in Fall 2011. He helped processing historical weather data. He is currently working on climate change impact study of Green River Basin.

References

ASCE (American Society of Civil Engineers). 2005. The ASCE Standardized Reference Evapotranspiration Equation. Edited by Allen, R.G., Walter, I.A., Elliott, R.L., Howell, T.A., Itenfisu, D., Jensen, M.E., and Snyder, R.L., Reston, VA. 59 pp.

Pochop, L.O., Teegarden, T., Kerr, G.L., Delaney, R. 1992. Consumptive Use and Consumptive Irrigation Requirements in Wyoming. Report Submitted to the Wyoming Water Resources Center. 59 pp.

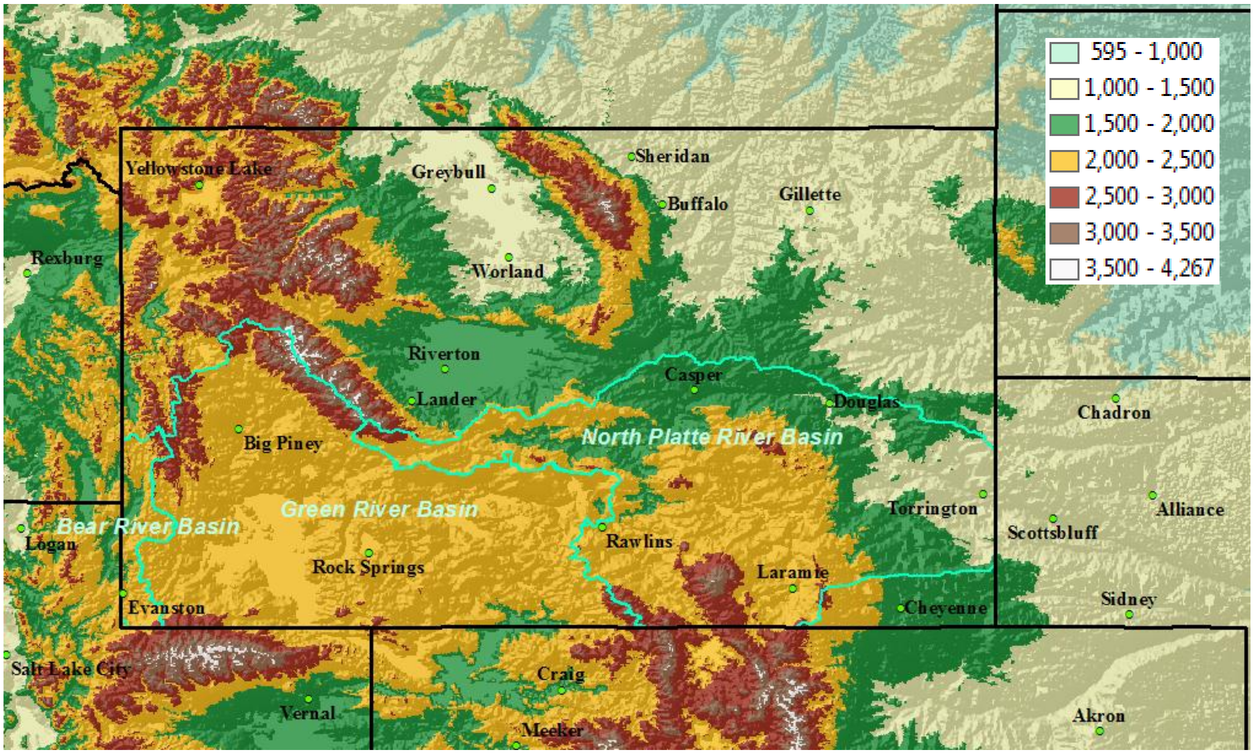

Figure 1: Three study basins shown with 1km DEM. The three basins are Green River Basin, North Platte River Basin, and Bear River Basin.

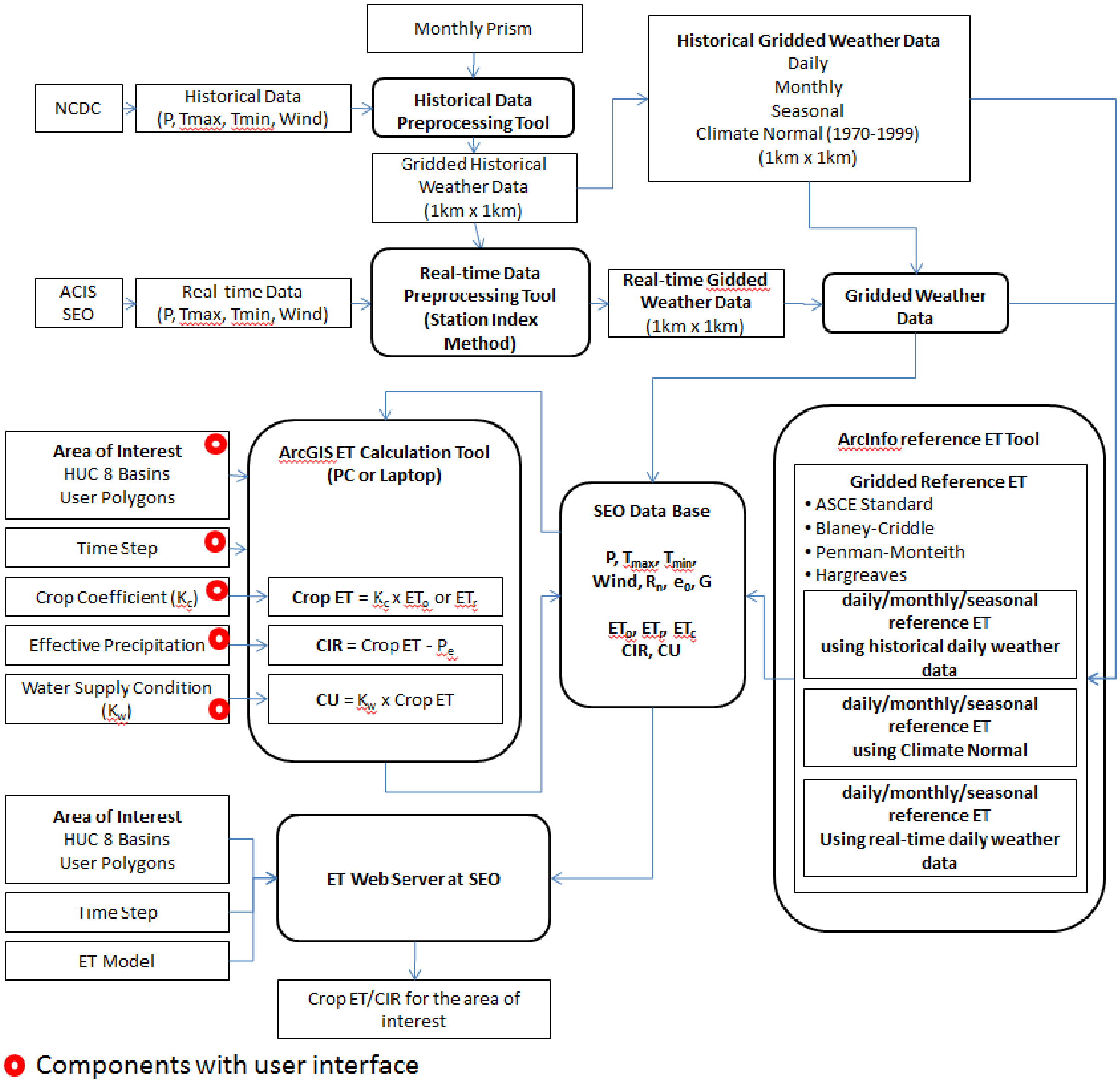

Figure 2: Schematic diagram for the GIS-based ET Tool Development

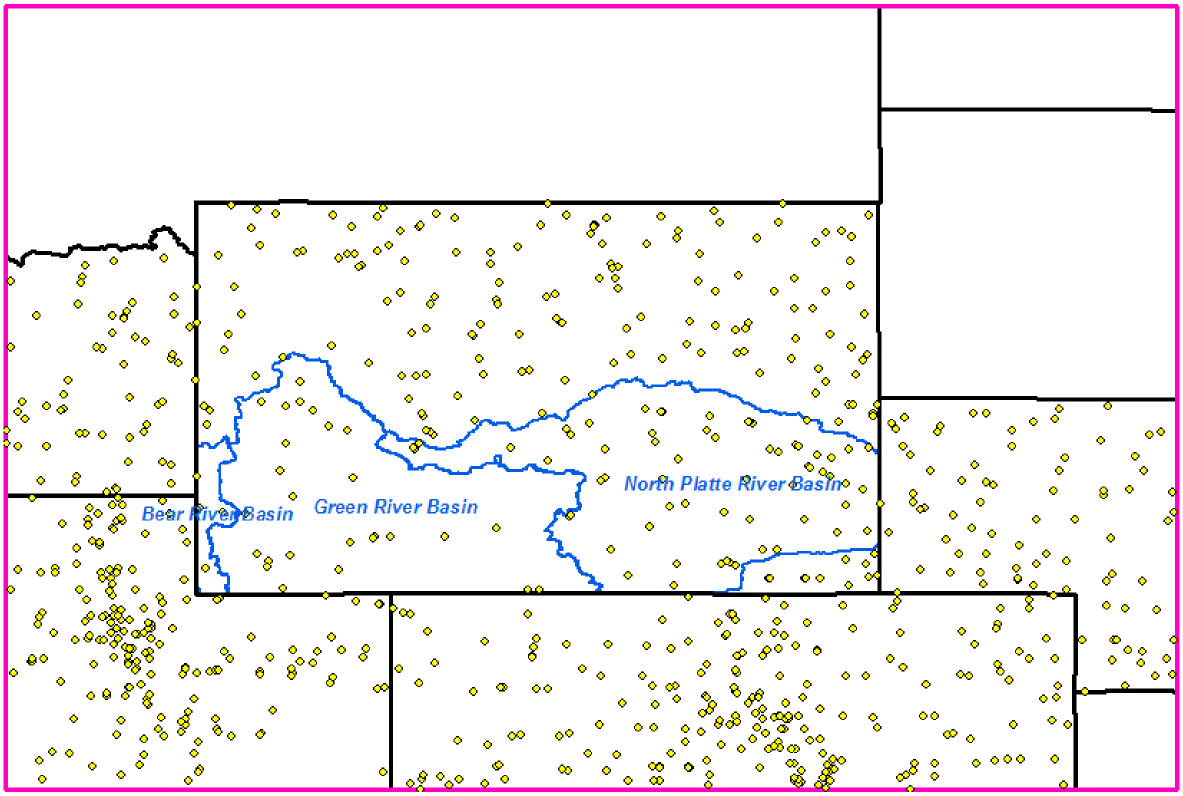

Figure 3: Weather stations for maximum temperature, minimum temperature, and precipitation.

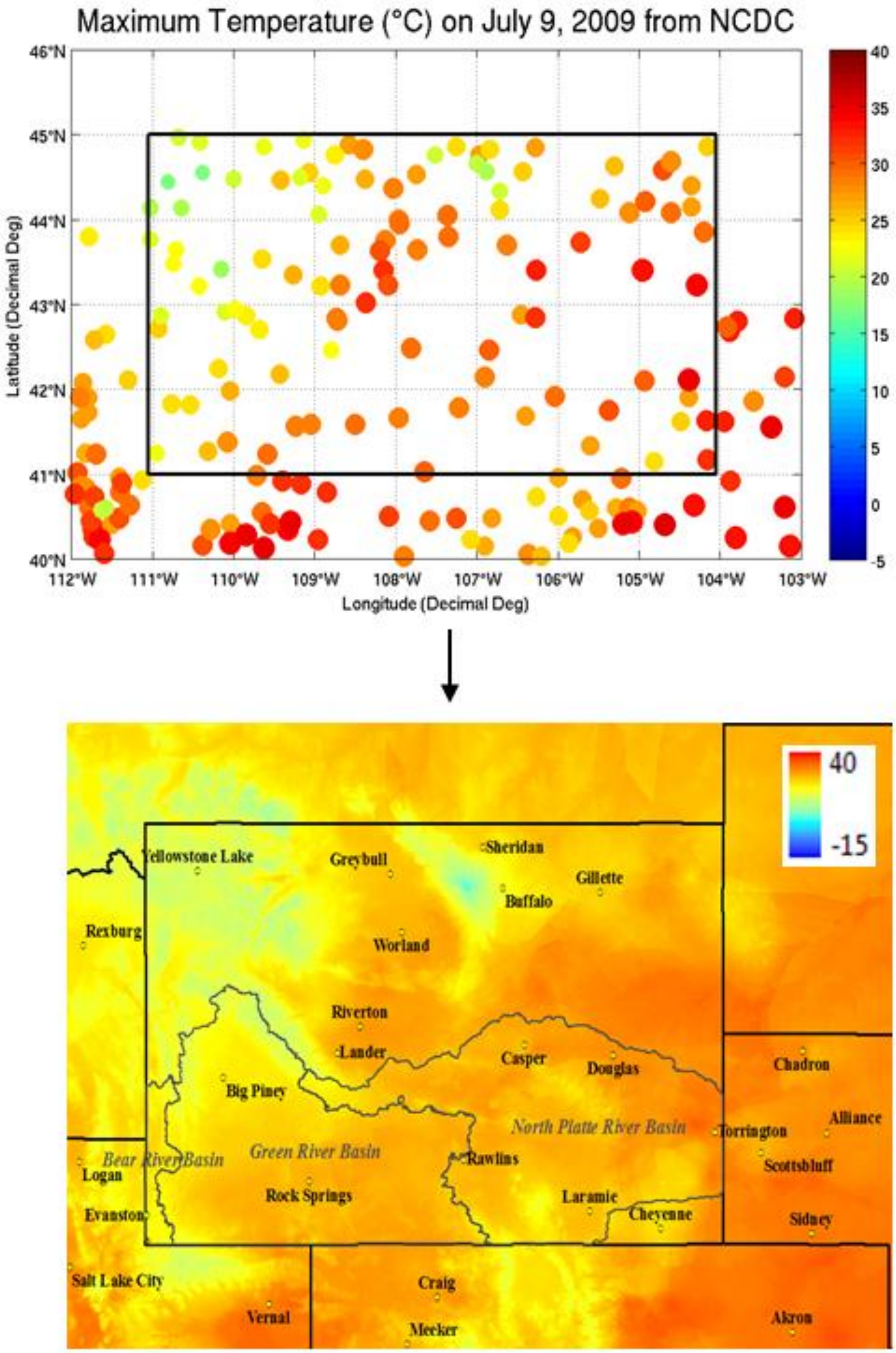

Figure 4: Interpolation of maximum temperature (July 9, 2009)

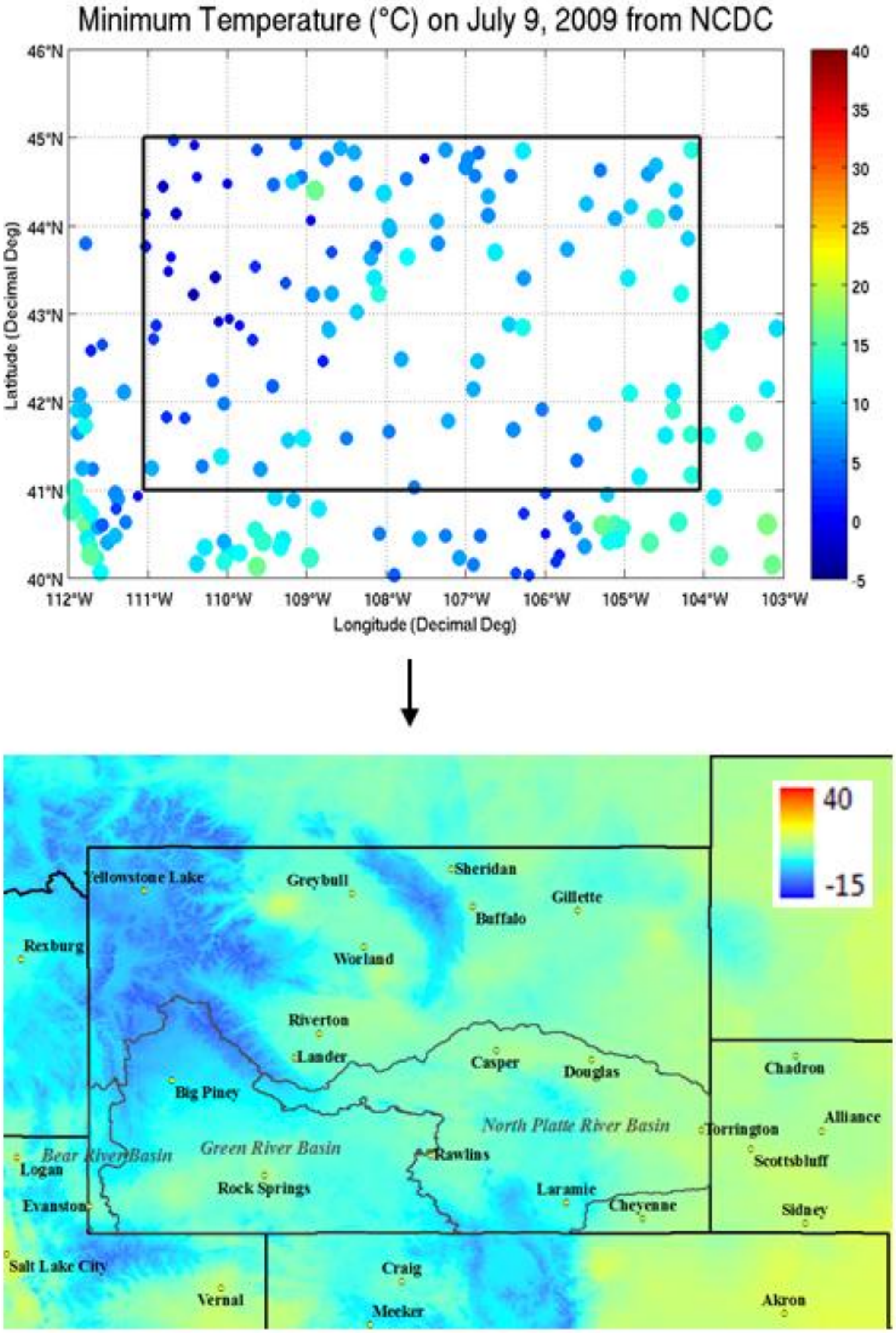

Figure 5: Interpolation of minimum temperature (July 9, 2009)

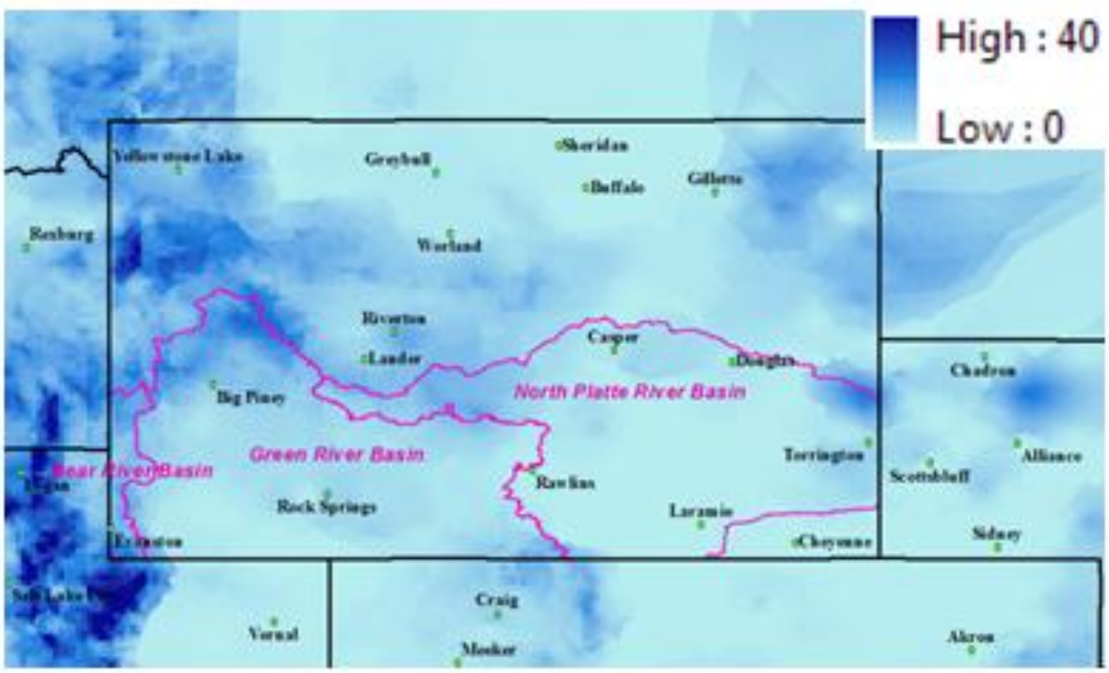

Figure 6: Interpolated precipitation (top) and PRSIM adjusted precipitation (bottom) of April 15, 2009.

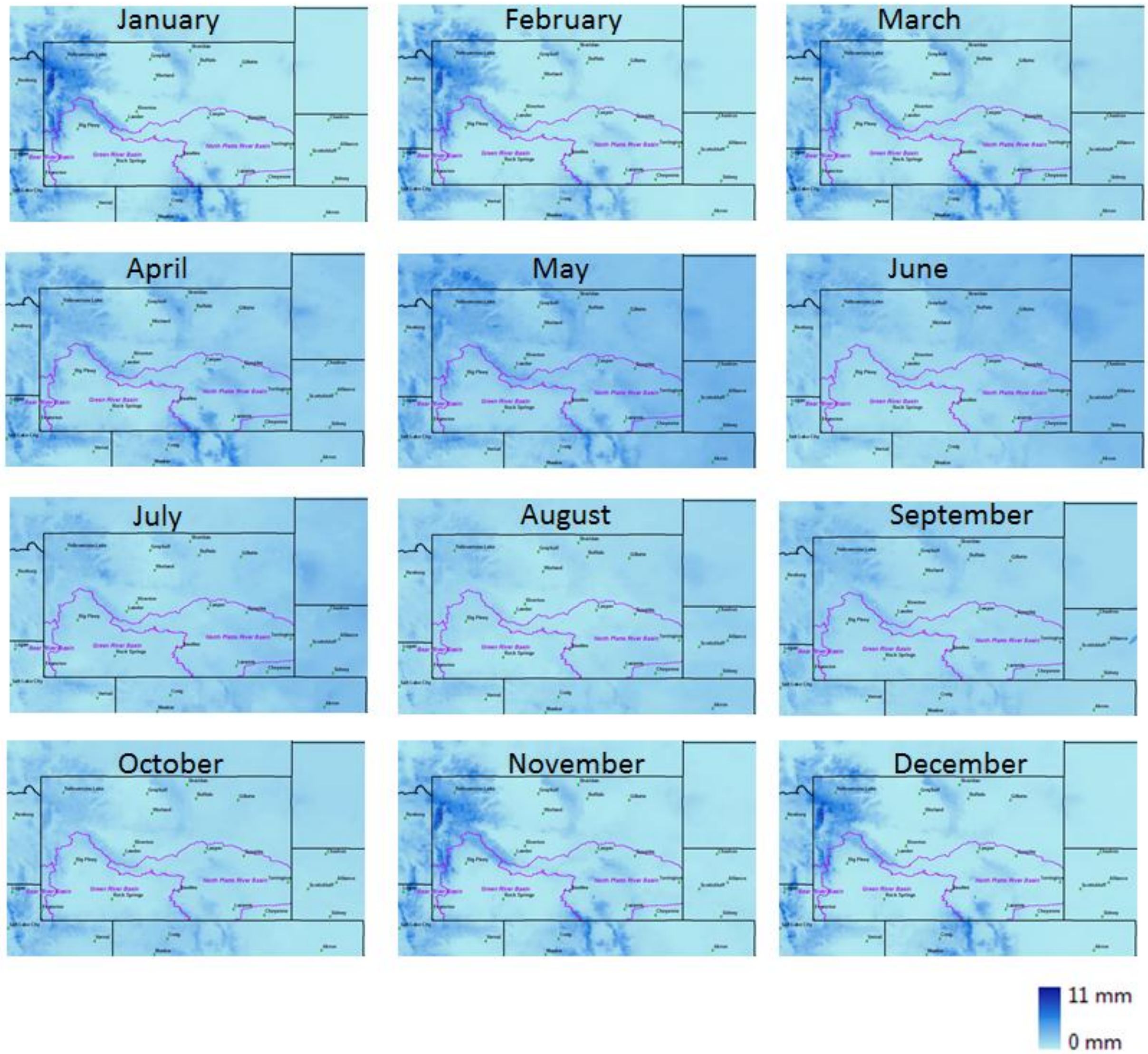

Figure 7: Monthly climate normal (1971-2000) of Precipitation (mm)

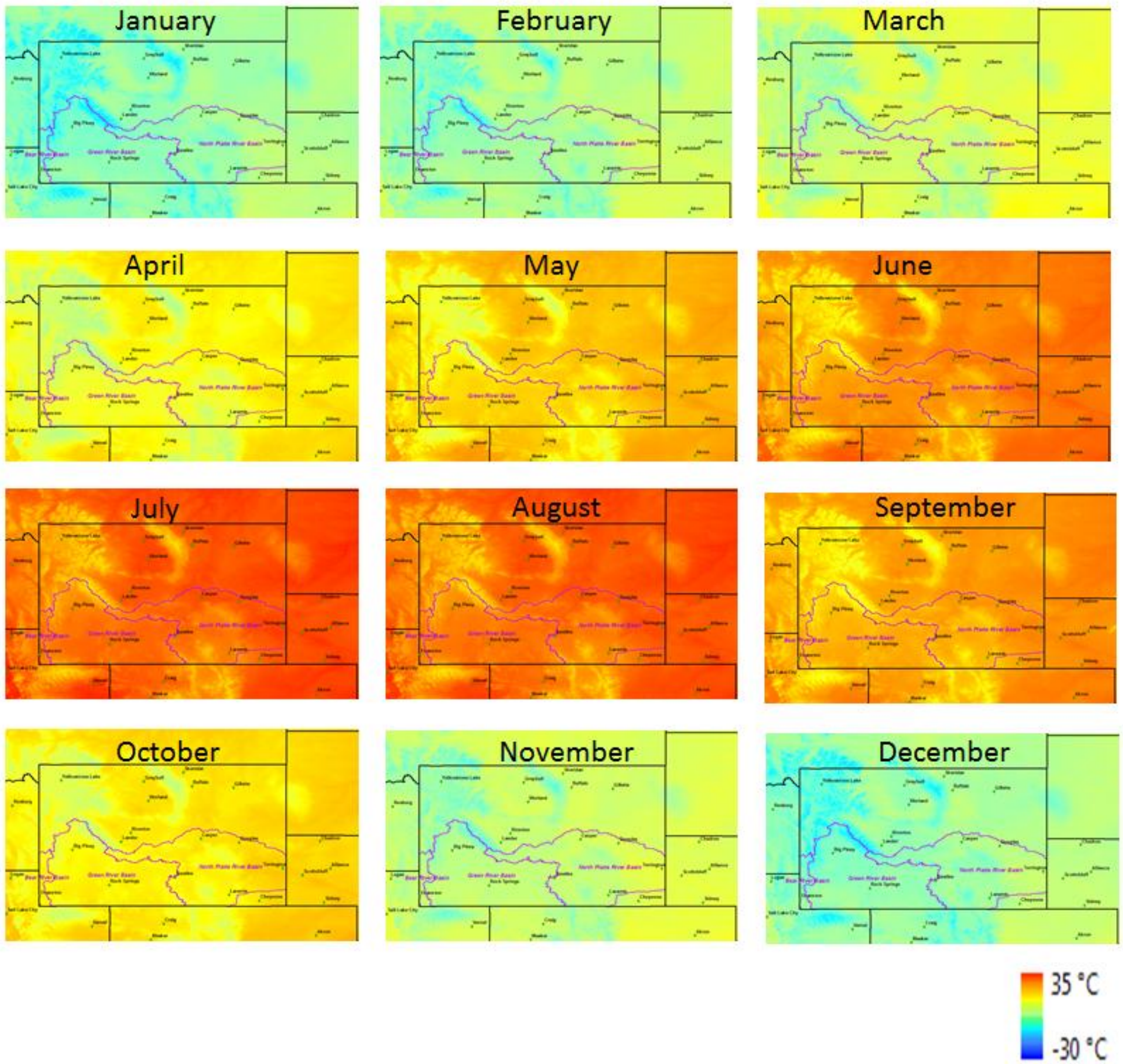

Figure 8: Monthly climate normal (1971-2000) of maximum temperature

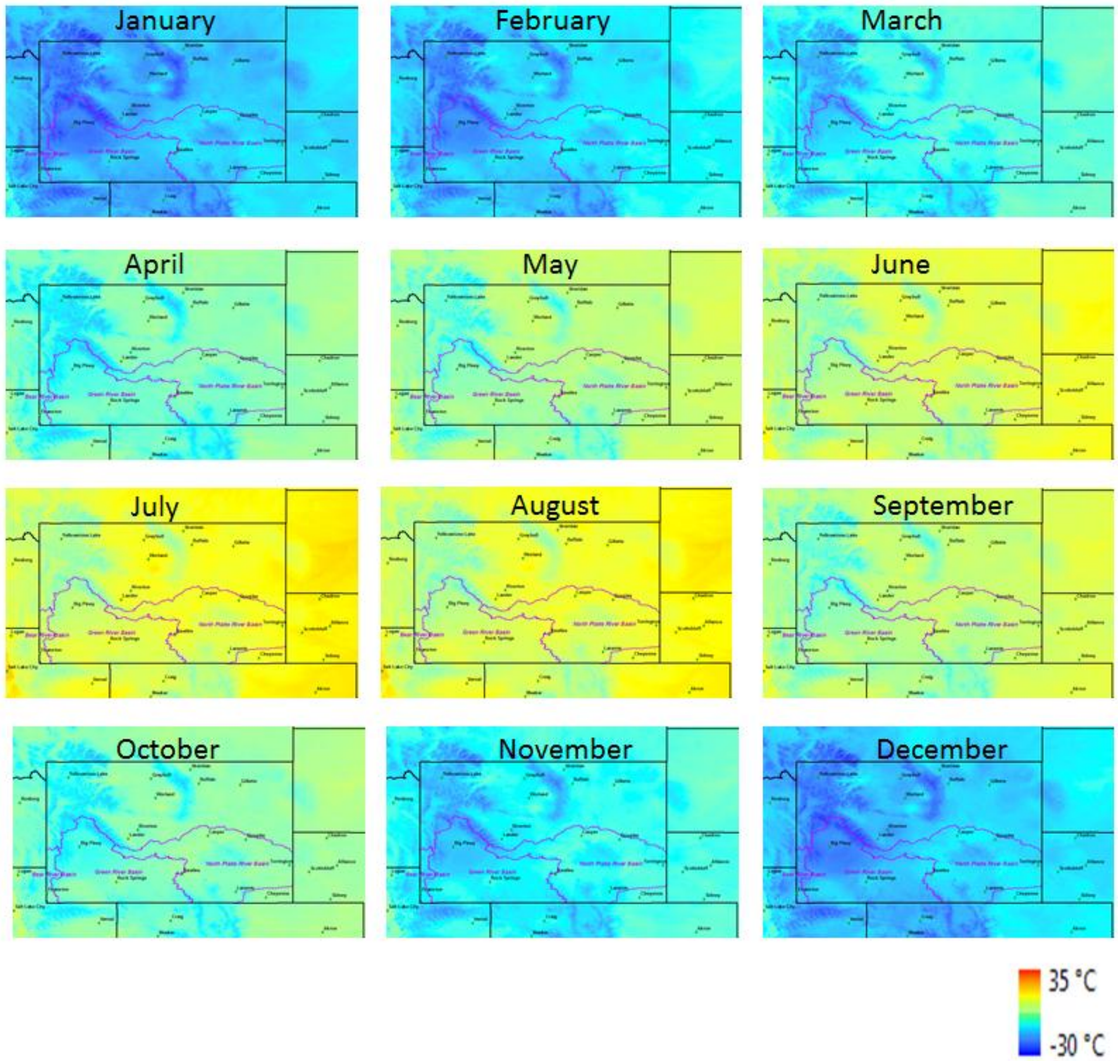

Figure 9: Monthly climate normal (1971-2000) of minimum temperature

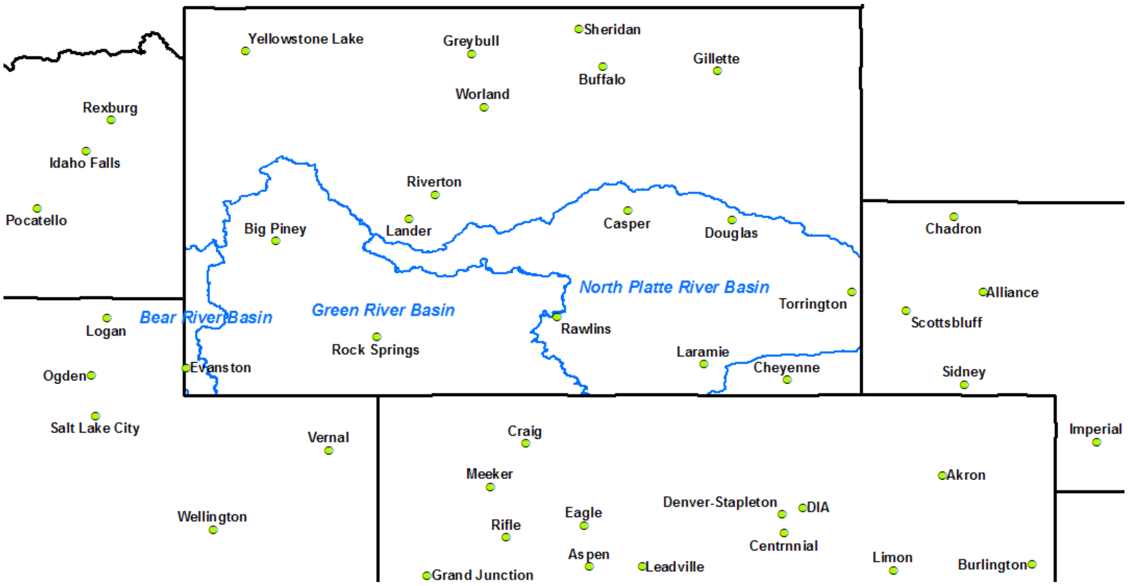

Figure 10: Weather stations used for dew point temperature and wind speed

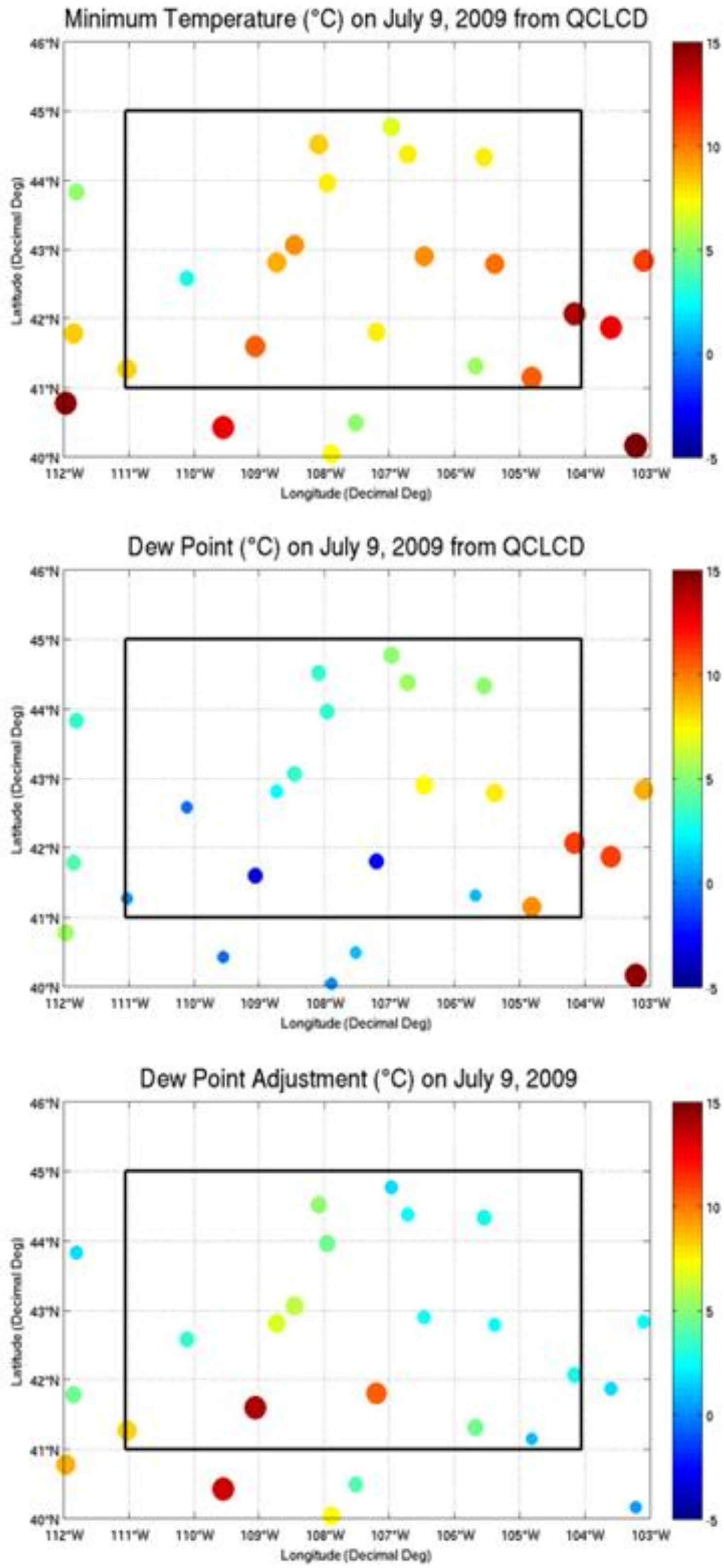

Figure 11: Calculation of dew point adjustment factor

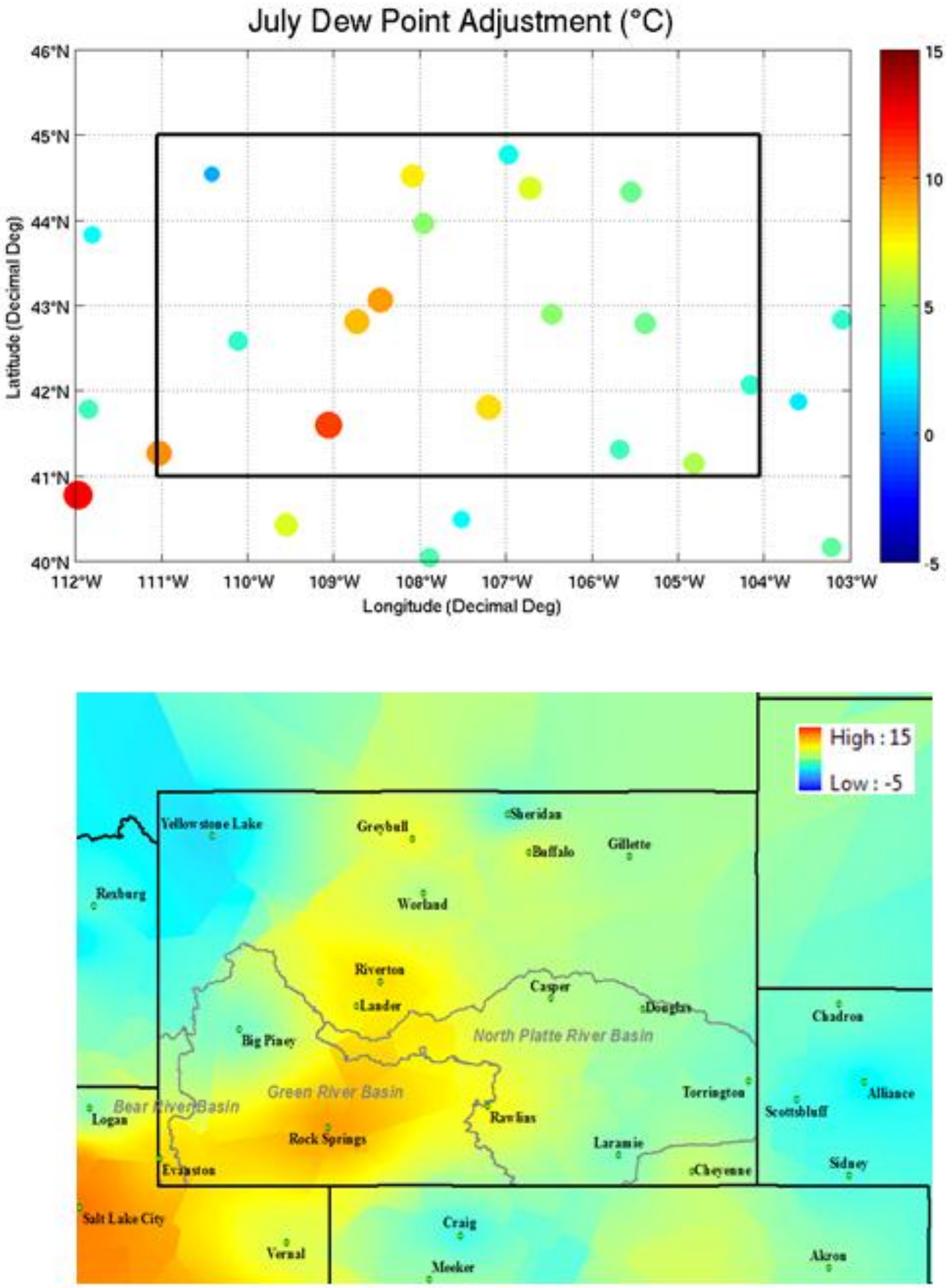

Figure 12: Interpolation of dew point temperature adjustment factor (July as an example)

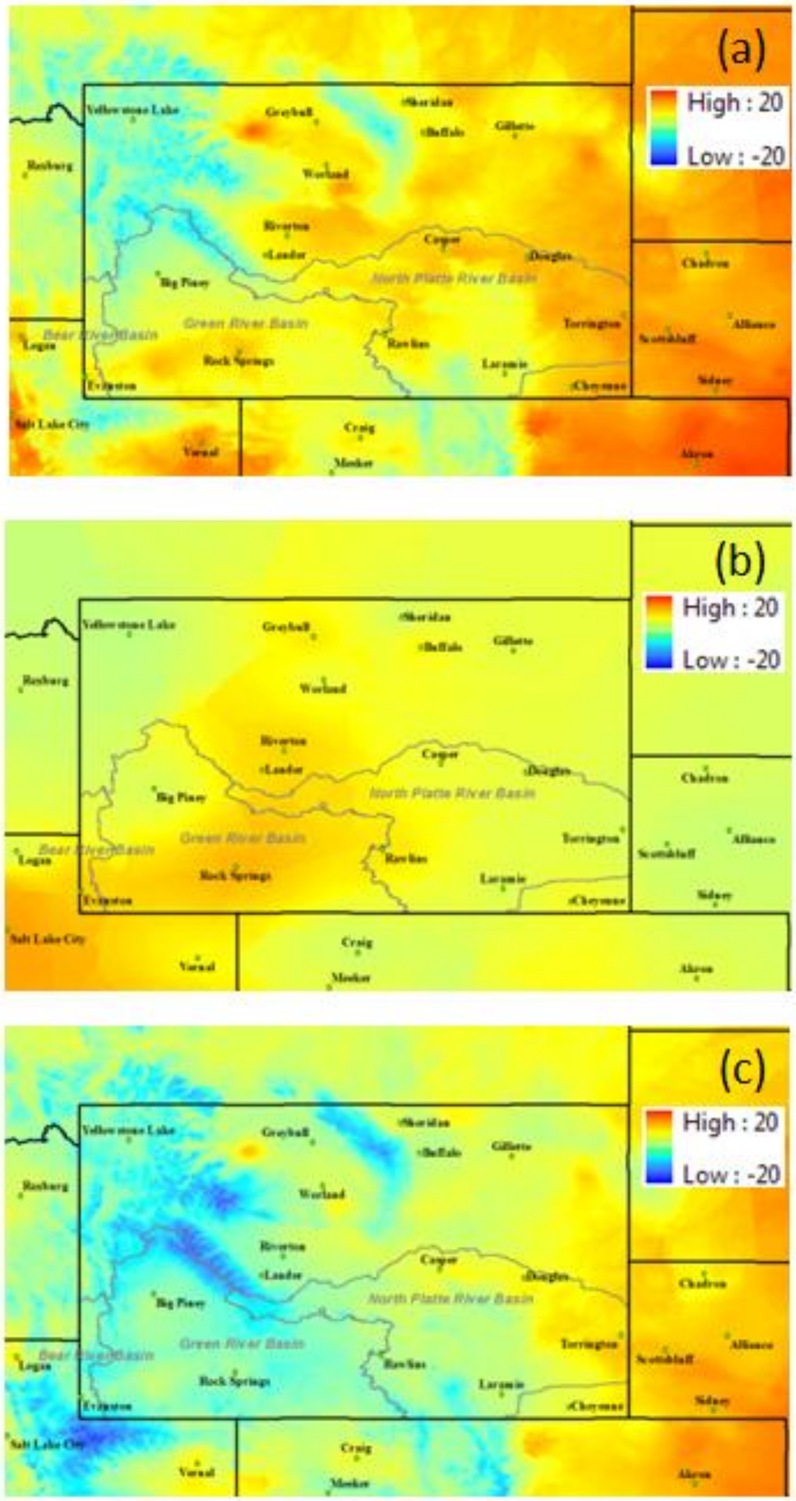

Figure 13: Estimation of dew point temperature using the dew point temperature adjustment factor. Dew point temperature (c) = Minimum Temperature (a) - Dew Point Adjustment factor (b)

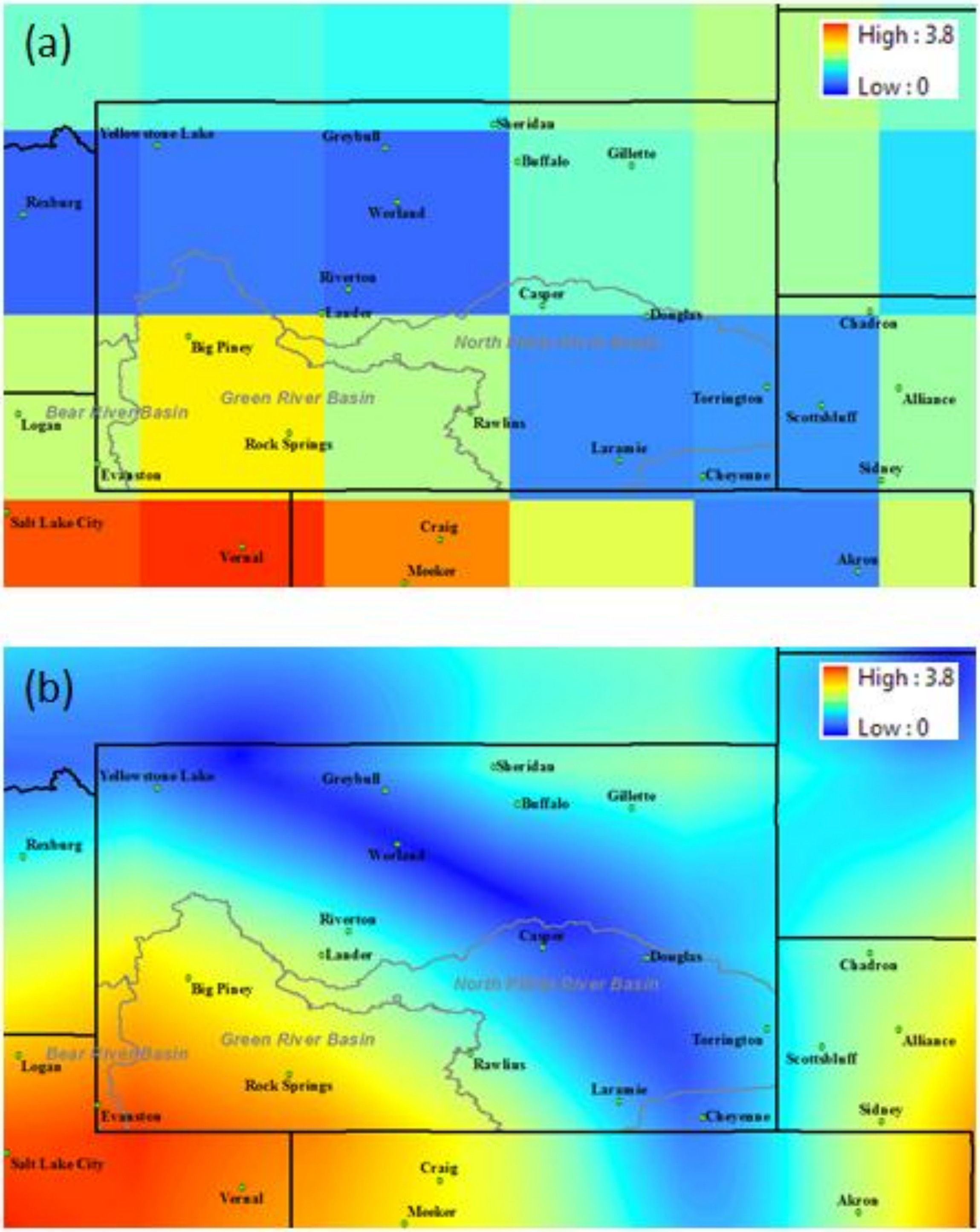

Figure 14: Wind speed Interpolation. (a) NCEP Reanalysis II Wind Speed (2 x 2 degree resolution) and (b) spatially interpolated wind speed into 0.01 degree resolution.

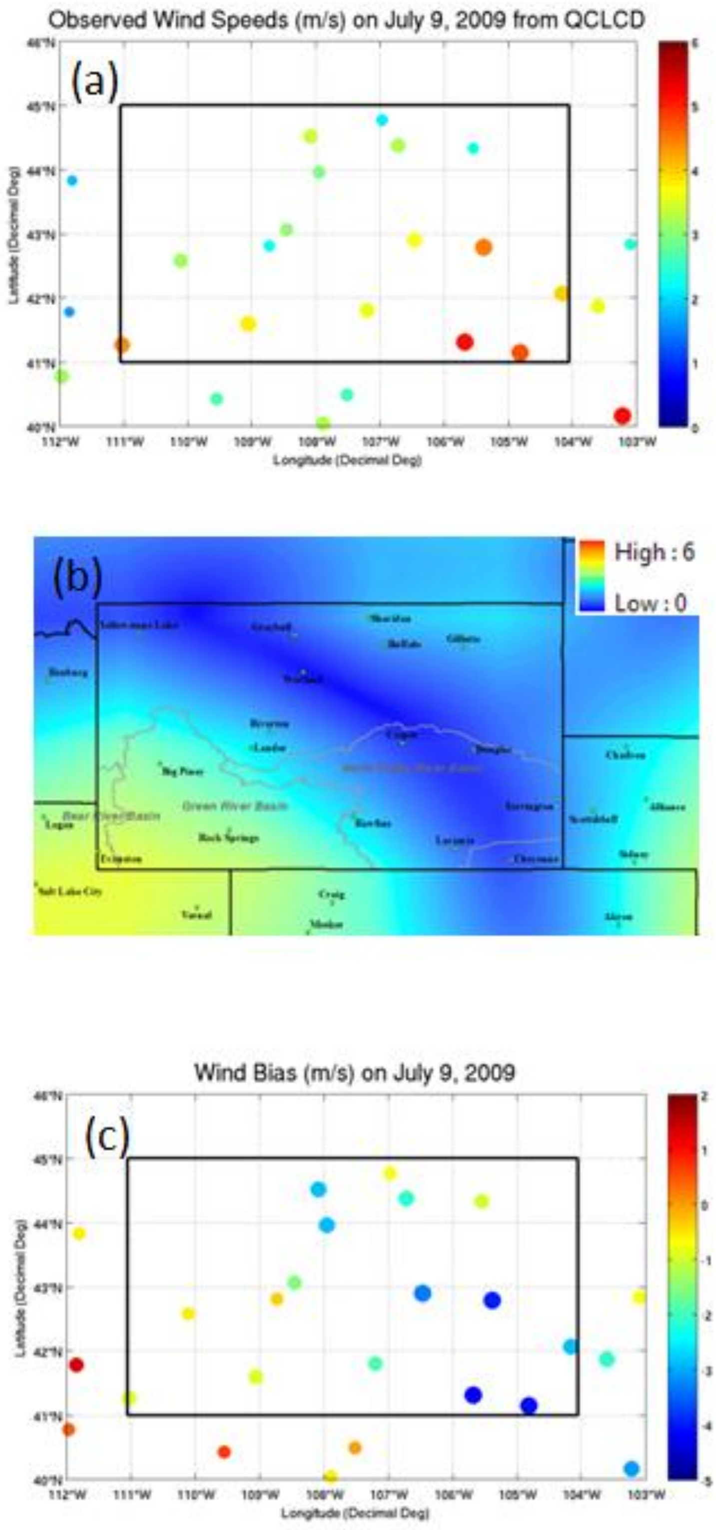

Figure 15: Daily wind bias (c) between observed wind speed (a) and NCEP Reanalysis wind speed (b) (July 9, 2009)

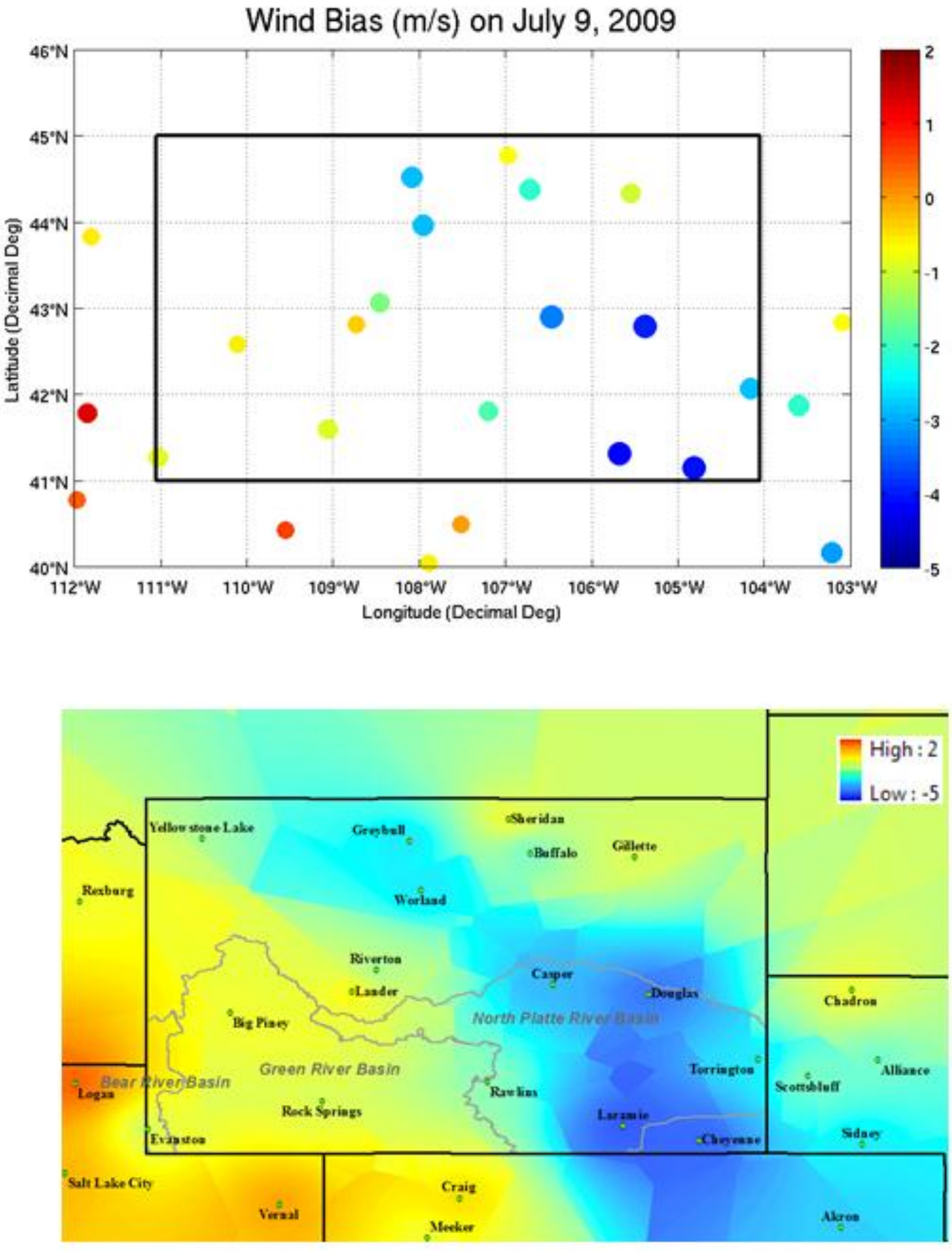

Figure 16: Spatial interpolation wind bias into 0.01 x 0.01 degree (July 9, 2009 as an example)

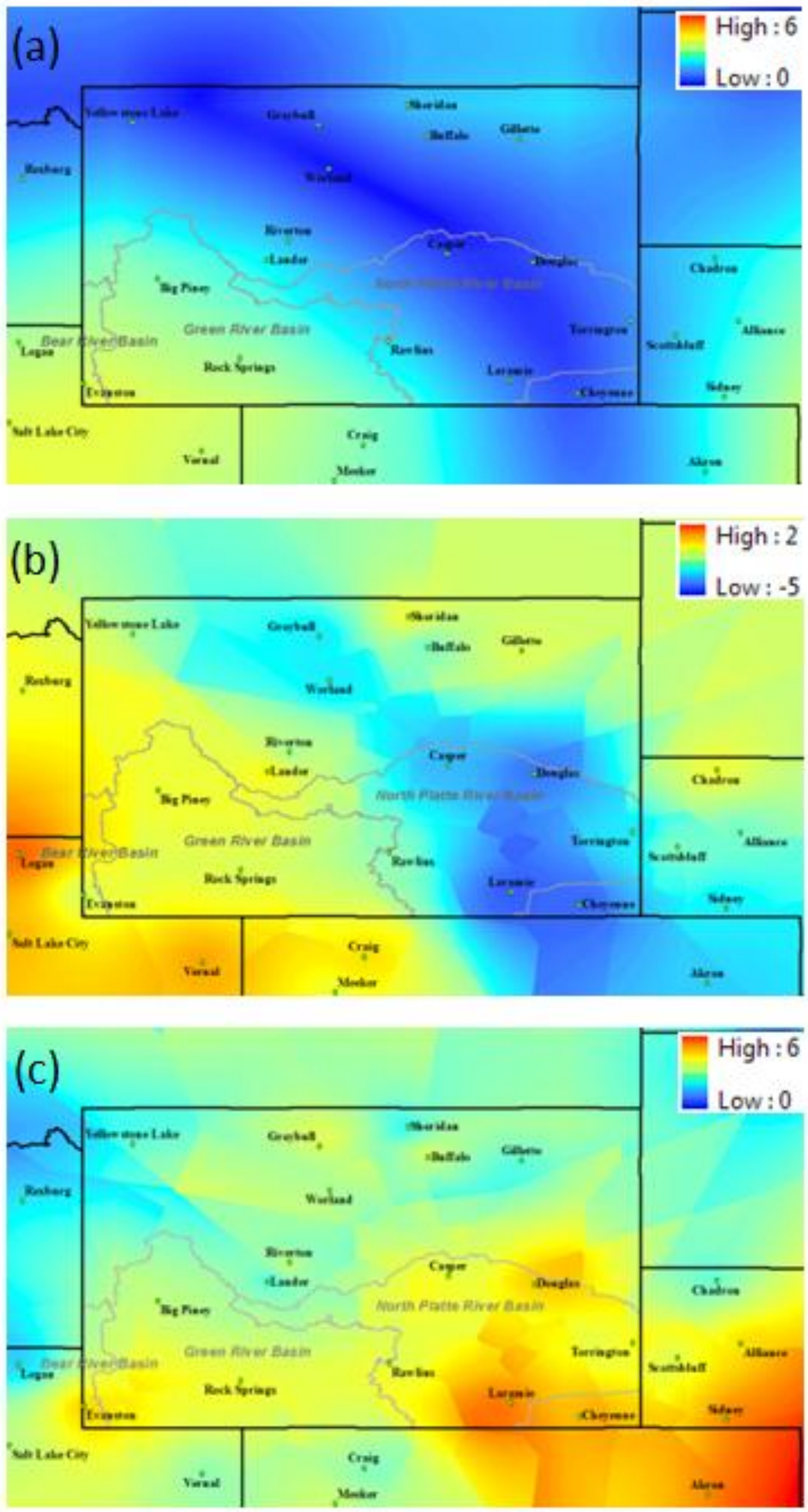

Figure 17: Wind bias adjustment using spatially interpolated wind bias (July 9, 2009). (a) NCEP Reanalysis wind speed, (b) wind bias, and (c) final wind speed.

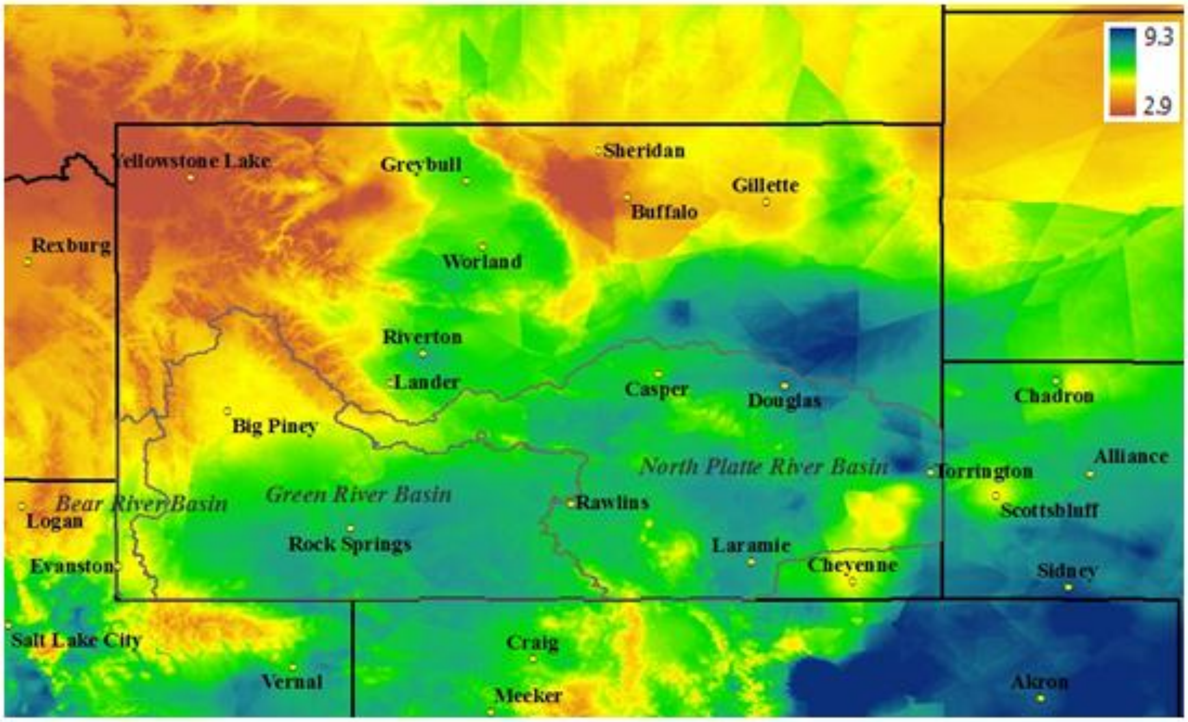

Figure 18: Reference ET for July 9, 2009 (ASCE Standard ET method)

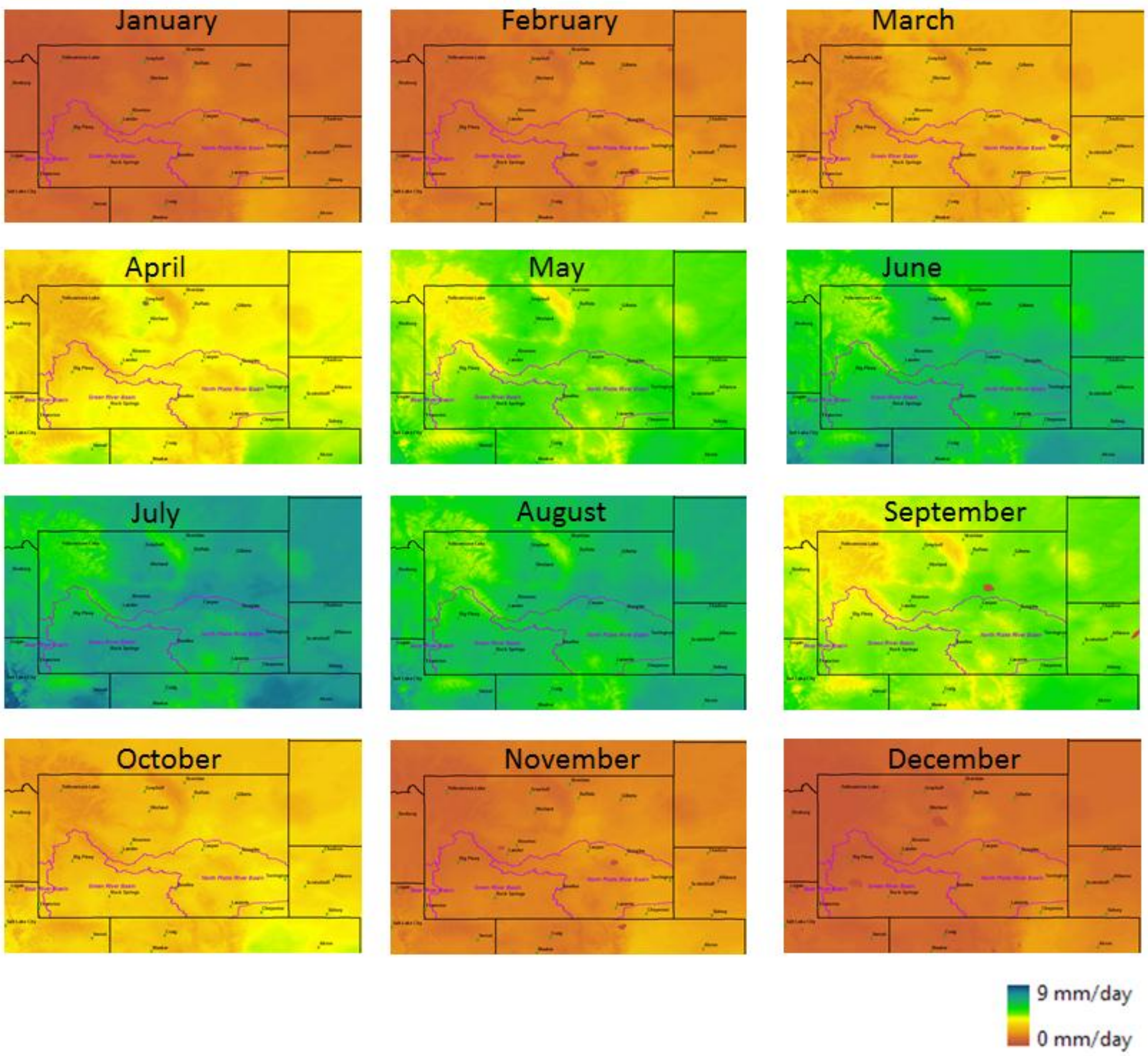

Figure 19: Monthly climate normal (1971-2000) of reference ET (mm/day)

Figure 20: 1992 National Land Cover Database (NLCD) Map

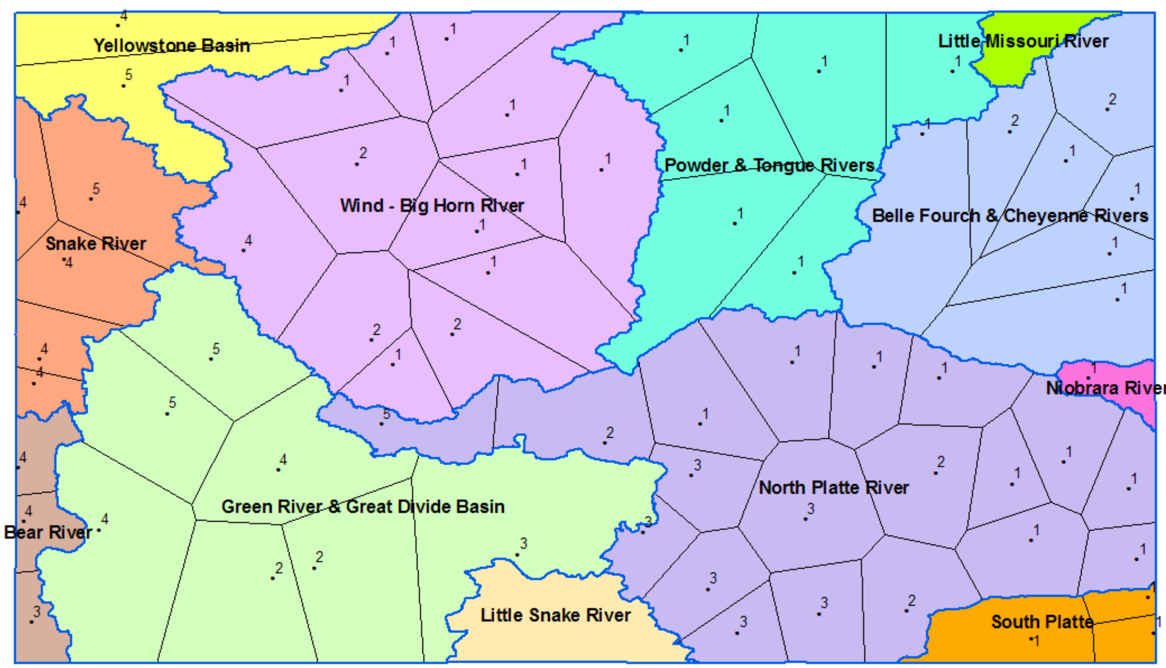

Figure 21: Thiessen Group ID Map based on the group of Pochop et al. (1992)

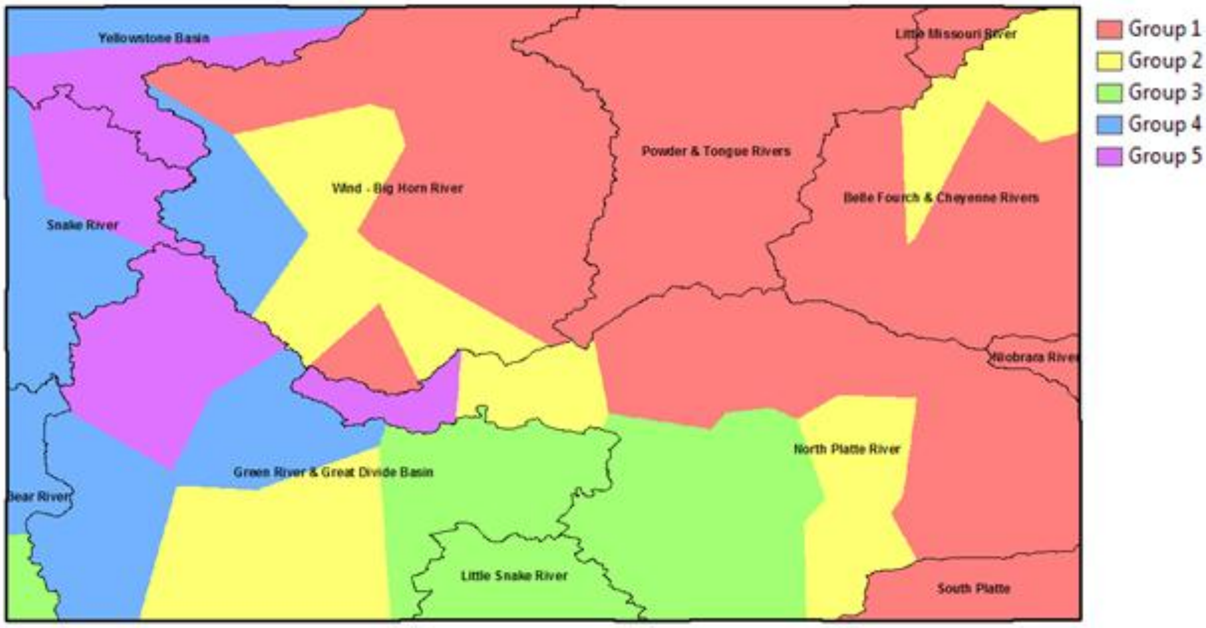

Figure 22: Group Polygon using the groups from Pochop et al. (1992)

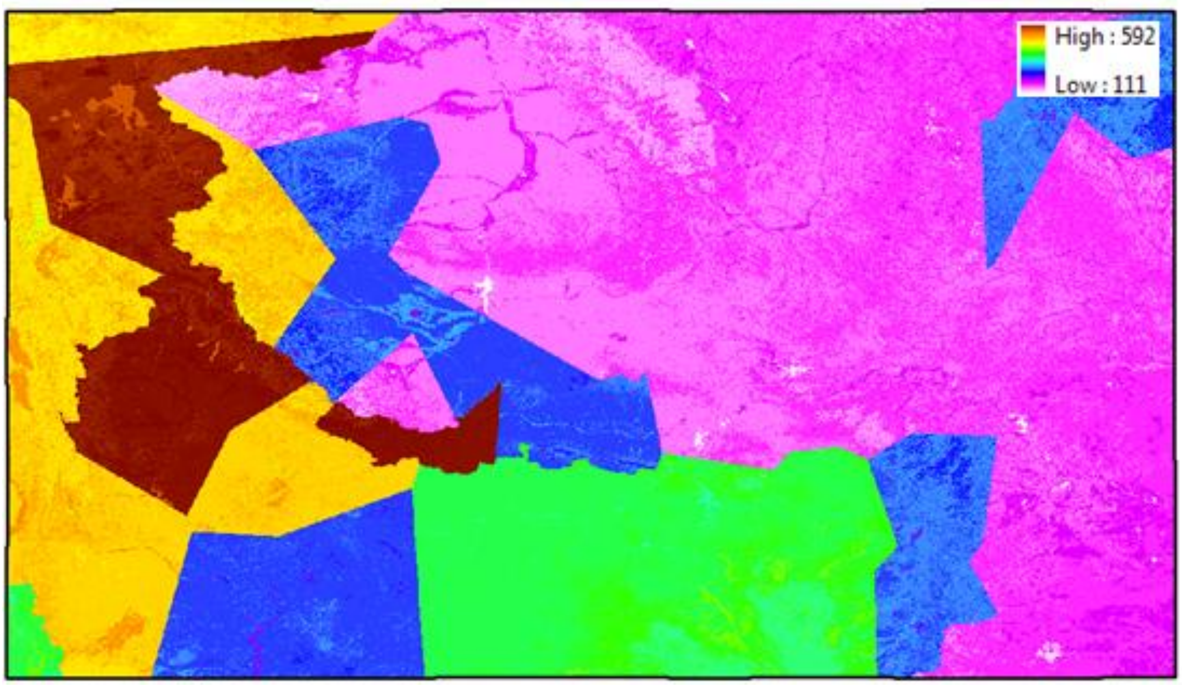

Figure 23: Composite ID Map (Group ID x 100 + NLCD ID)

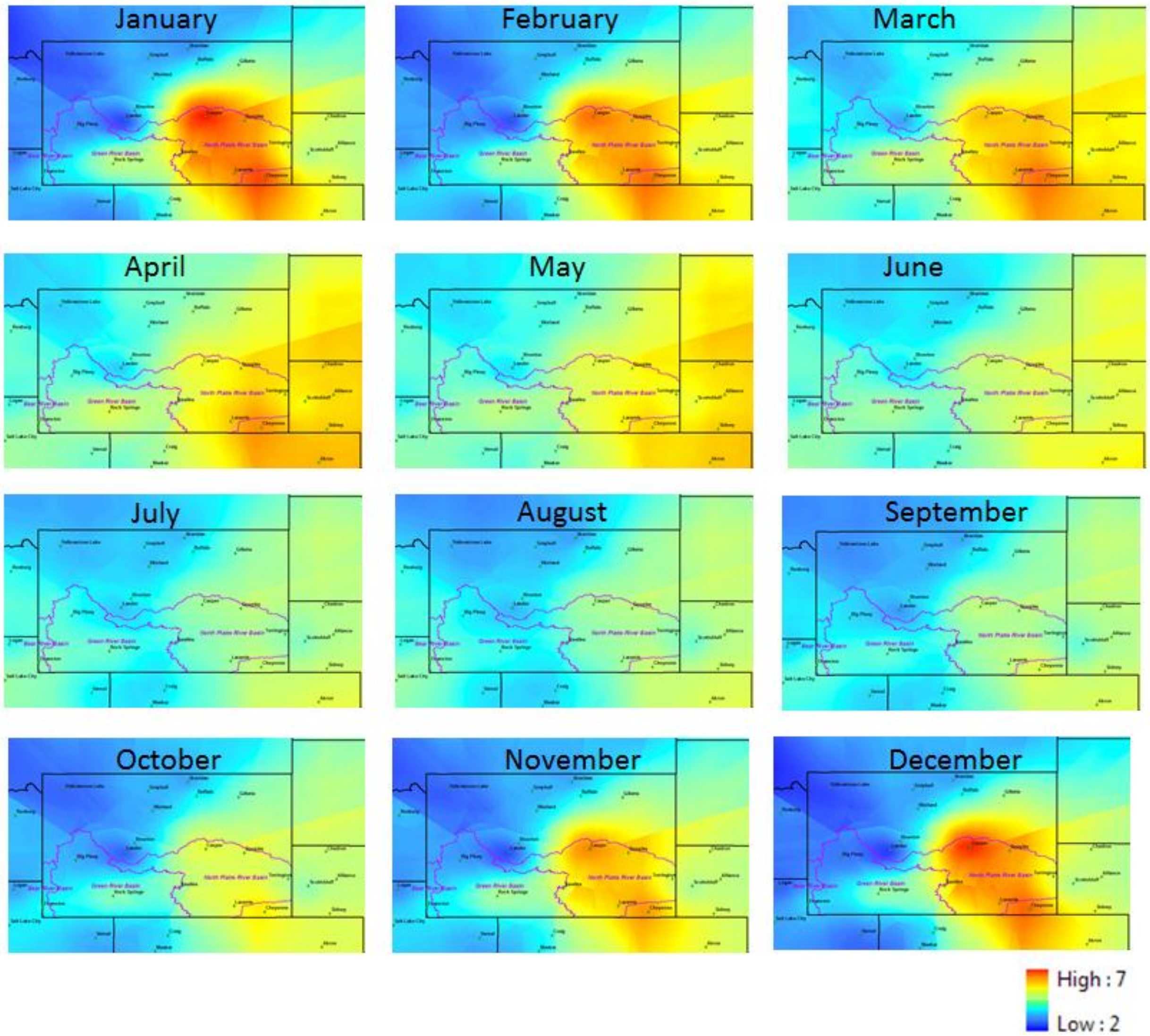

Figure 24: Monthly climate normal (1971-2000) of dew point temperature

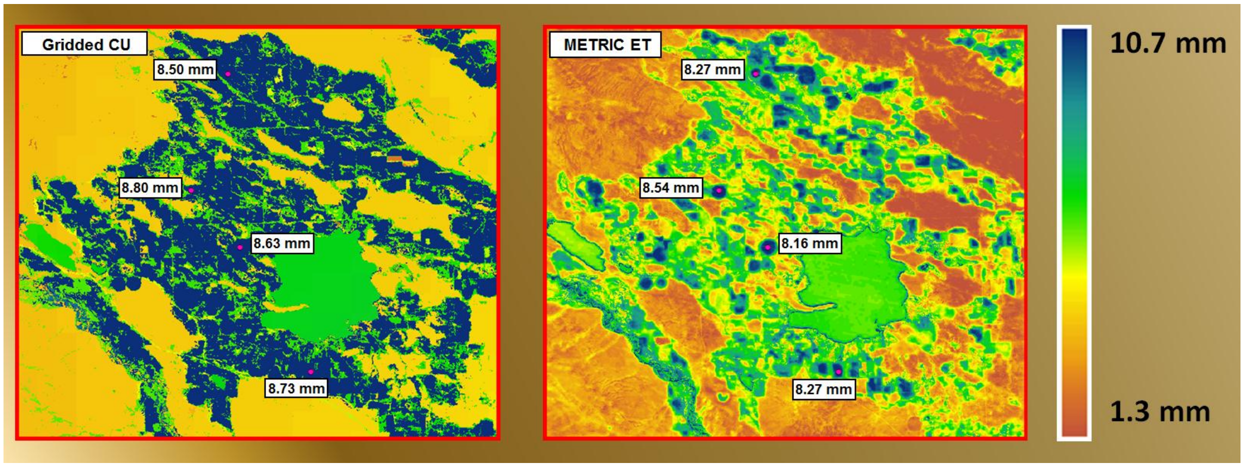

Figure 25: Comparison of potential ET with METRIC ET for wet pixels in Wind River Area. Differences are within 10 percent.

Treatment of High-Sulfate Water Used for Livestock Production Systems

Basic Information

Title:	Treatment of High-Sulfate Water Used for Livestock Production Systems
Project Number:	2010WY59B
Start Date:	3/1/2010
End Date:	2/29/2012
Funding Source:	104B
Congressional District:	1
Research Category:	Water Quality
Focus Category:	Agriculture, Treatment, Water Quality
Descriptors:	Sulfate, Water treatment, Livestock health
Principal Investigators:	Kristi Cammack, Kathy Austin, Ken C Olson, Cody L Wright

Publications

There are no publications.

Treatment of High-Sulfate Water Used for Livestock Production Systems
Annual Report, Year 1 of 2
04/26/2011

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Abstract: Reliable drinking water sources that meet minimum quality standards are essential for successful livestock production. Recent surveys have shown that water sources throughout the semi-arid rangelands of the U.S. are not of sufficient quality to support optimum herd/flock health and performance. Water sources high in sulfur (S) concentrations, usually in the form of sulfate (SO_4^{2-}), are problematic in many western regions. High SO_4^{2-} concentrations in water sources can arise from several factors. First, water sources can be naturally high in SO_4^{2-}. Second, drought conditions can cause SO_4^{2-} to be concentrated within the water source. Third, conventional oil and gas production can also increase SO_4^{2-} content within the water source. Many of these water sources are used for livestock production systems, especially throughout the western states. High-SO_4^{2-} water has been shown to reduce performance and cause secondary health and immunity complications in exposed livestock. Additionally, high SO_4^{2-} levels in drinking water are a primary cause of polioencephalomalacia (PEM) in ruminant livestock. Sulfur-induced PEM (sPEM) is a disease state in ruminant animals that can cause 25% morbidity and 25-50% mortality in affected populations, resulting in substantial economic losses to the livestock producer. Currently, there are no available treatments for affected livestock, and frequent and stringent testing of drinking water sources for levels of SO_4^{2-} and other S compounds, a costly and time-consuming process, is the best prevention strategy. In addition, methods for SO_4^{2-} removal from the water source are neither cost-effective nor practical. Ferrous carbonate ($FeCO_3$) is a soluble iron salt that is routinely used in water treatment plants to bind S. We hypothesize that treatment of high-SO_4^{2-} water with $FeCO_3$ will bind excess S, enabling such sources to be used for livestock production. Our objectives are to 1) determine the effectiveness of $FeCO_3$ treatment in binding S in high-SO_4^{2-} water, and 2) determine if treatment of high-SO_4^{2-} water with $FeCO_3$ prevents the reduced performance and poor health normally observed in livestock consuming high-SO_4^{2-} water.

Statement of Critical Regional or State Water Problem: ***Need for Project.*** Reliable drinking water sources that meet minimum quality standards are essential for successful livestock production. However, recent surveys have shown many water sources, especially throughout the semi-arid rangelands of the U.S. and Wyoming, are not of sufficient quality to support optimum herd/flock health and performance [1]. Many of these low quality sources are dangerously high in S and S compounds, especially SO_4^{2-}, due to underlying soil conditions, drought conditions, and(or) manmade contaminants (e.g. conventional gas and oil water; CBM water). However, because of limited water resources throughout the western regions, many of these high-SO_4^{2-} water sources are still used in livestock production systems. Ruminant livestock consuming high-SO_4^{2-} water are prone to poor growth and performance and health complications, including polioencephalomalacia (sPEM), a neurological disorder typically terminating in death. Outbreaks of sPEM can cause 25% morbidity and 25-50% mortality in affected populations. This in combination with the losses in growth and performance results in significant economic losses to producers. Currently, there are no available treatments for livestock affected by high-SO_4^{2-} water consumption (including sPEM), and frequent and stringent testing of drinking water sources for levels of SO_4^{2-} and other S-compounds, a costly and time-consuming process, is the best prevention strategy. Methods for removal of SO_4^{2-} from the water source include reverse osmosis, distillation, and ion exchange, none of which are cost-effective or practical for livestock producers.

Who Would Benefit and Why. Many water sources high in SO_4^{2-} are still used for livestock production due to lack of alternative available sources. Additionally, in many of these areas it is neither feasible nor practical to haul in water low in SO_4^{2-}. Therefore, identification of an effective treatment for high-SO_4^{2-} water sources would 1) prevent the health and performance problems associated with livestock consuming high-SO_4^{2-} water, and 2) allow producers to use available water resources despite high SO_4^{2-} concentrations.

Statement of Results or Benefits: ***Information to be Gained.*** Ferrous carbonate ($FeCO_3$) is a soluble iron salt with potential to bind S. We had previously stated that $FeCl_2$ would be used. However, upon further investigation, we found that $FeCO_3$ is more easily obtained by producers, and more affordable. Because it has the same properties as $FeCl_2$, we decided that $FeCO_3$ would be a more feasible, and reasonable, option. We hypothesized that treatment of high-SO_4^{2-} water with $FeCO_3$ will bind excess S and ultimately prevent the poor performance and health (i.e. sPEM) of livestock consuming high-SO_4^{2-} water. We expect to determine 1) if $FeCO_3$ treatment of high-SO_4^{2-} water sufficiently binds S and reduces it to levels within the recommendations for livestock production, and 2) if $FeCO_3$ treatment of high-SO_4^{2-} water prevents the decreased performance and poor health that livestock typically experience when administered high-SO_4^{2-} water. Identification of a practical, water-applied treatment for high-SO_4^{2-} water would offer livestock producers a means by which such sources could be used for livestock production without compromising herd/flock health and performance.

How Information will be Used. The information garnered from this research will be used to 1) determine if treatment of high-SO_4^{2-} water with $FeCO_3$ lowers S concentrations to within the recommended levels for livestock production, and 2) determine if the $FeCl_2$ water treatment prevents the reduced performance and poor health normally observed in livestock consuming high-SO_4^{2-} water. Further studies will be needed to 1) confirm the effectiveness of

$FeCO_3$ water treatment, 2) determine the most effective rate of $FeCO_3$ treatment, and 3) develop protocols for $FeCl_2$ application. In addition, all potential effects of $FeCO_3$ water treatment on animal health must be investigated, which will require additional studies. Therefore, data from the present study will be used to seek further funding for each of the aforementioned needs. *The long-term potential of this research is the development of a practical, water-applied treatment for high-SO_4^{2-} water sources that will bind S and reduce it to levels acceptable for livestock consumption, enabling such sources to be used in livestock production systems.*

Nature, Scope, and Objectives of the Project: The basic nature of the proposed research is to identify a water-applied treatment for high-SO_4^{2-} water that producers can affordably and practically apply to those high-SO_4^{2-} water sources used for livestock production. This research is especially important for livestock producers in the western regions of the U.S., including Wyoming, where high-SO_4^{2-} water sources are prevalent. The objectives of this project were to 1) determine if $FeCO_3$ treatment of high-SO_4^{2-} water reduces S to levels within the accepted recommendations for livestock production, and 2) determine if treatment of high-SO_4^{2-} water with $FeCO_3$ prevents the reduced performance and poor health normally observed in livestock consuming high-SO_4^{2-} water. Health was assessed by incidence of sPEM and changes in hepatic gene regulation; performance was assessed by measures of feed intake, feed efficiency, and gain. This project will be completed over a two year period (Table 1), and was designed to be the thesis project for a M.S. student (Amanda Jons).

Table 1. Timeline of research activities.

Year	Activity
1	Completion of animal trial. ***Completed.***
	Completion of mineral analyses (hepatic and serum). ***Completion of analysis expected Summer, 2011.***
	Completion of production data summarization and analyses. ***Completed.***
2	Completion of RNA extractions. ***Completed.***
	Completion of real-time RT-PCR. ***Completed.***
	Completion of manuscript preparation and submission. ***Completion expected Fall, 2011.***
	Completion of M.S. program. ***Defense expected August, 2011.***

Methods, Procedures, and Facilities: Cattle and sheep are both ruminant livestock affected by high-SO_4^{2-} water. Sheep are commonly used as a model species, as they are the most economical ruminant farm animal available. This study will use ram lambs (n = 80; 6 months of age) maintained at the University of Wyoming's Stock Farm. The Stock Farm houses a GrowSafe Feed Intake and Behavior Monitoring system, the only system to-date specifically designed to collect feed intake and behavior data of individual sheep in group settings.

Accomplished to Date: Rams were allowed a 10 d adjustment period to become accustomed to the GrowSafe system. Prior to treatment, drinking water was analyzed for concentrations of total dissolved solids, S, and S compounds. Ram lambs were randomly assigned to one of four treatments for the 60 d trial period: low-SO_4^{2-} water (< 400 mg SO_4^{2-}/L water; n = 20); high-SO_4^{2-} water (2,500 mg SO_4^{2-}/L water; n = 20); high-SO_4^{2-} water + low $FeCO_3$ (2,500 mg SO_4^{2-}/L + 250 mg $FeCO_3$/L; n = 20); or high-SO_4^{2-} water + high $FeCO_3$ (2,500 mg SO_4^{2-}/L + 500 mg $FeCO_3$/L; n = 20). This level of SO_4^{2-} administration has been shown to cause performance and health deficiencies in previous studies conducted by the PI and co-PIs. All lambs were administered the same diet throughout the experimental period. Lambs were allowed *ad libitum* access to feed and water. Weights were recorded on d -2 and -1, d 29 and 30, and d 60 and 61, and averaged for more precise estimates of initial, mid, and final BW, respectively. Blood samples were collected in conjunction with BW on d -2, d 29, and d 60 for serum Fe, copper (Cu^{2+}), and molybdenum (Mo) analyses. High SO_4^{2-} acts as a Cu^{2+} antagonist in ruminants, irreversibly binding Cu^{2+} and rendering it unavailable for utilization. Additionally, Mo is involved in the binding of Cu^{2+} through the formation of thiomolybdates in high-S environments. Because excess H_2S gas production is causal to sPEM, rumino-centesis was performed on d -2 and d 60 to obtain measures of, and changes in, ruminal H_2S gas production. Ruminal gas was collected via the rumen gas caps and aspirated through H_2S detector tubes.

Traits measured for each individual ram using the GrowSafe system included daily feed intake, residual feed intake (a measure of feed efficiency), daily feeding time, and rate of feed intake. In addition, average daily gain was estimated for each lamb. Lambs were closely monitored for clinical signs of sPEM. No lambs exhibited severe signs of sPEM and had to be removed from the trial. All lambs were euthanized at the end of the trial period for liver collection; muscle samples were also collected to determine S accumulation in muscle tissues. Multiple subsamples of each liver were collected for mineral and gene expression analyses.

Results to date indicate that there were no differences in ADG (P = 0.668), daily water intake (P = 0.795), or daily feed intake (P = 0.659) between treatments. Trace mineral analysis showed no treatment differences in serum concentrations of Cu (P = 0.199), Fe (P = 0.590), Mo (P = 0.119), Mn (P = 0.549), or Zn (P = 0.422). Hepatic concentrations of these minerals have been determined, and analysis of these concentrations is currently underway. Production of H_2S gas was less ($P \leq 0.001$) in low-S control lambs compared to lambs in the high-S treatment groups; no differences in H_2S gas production were detected between high-S treatment groups. These production results to date indicate that Fe is not effective in countering the effects of high dietary S (through the drinking water in this instance) in lambs.

Gene Expression Analyses. The liver plays a key role in sulfide (S_2) detoxification. Previous studies in our laboratory have shown chronic exposure to high-SO_4^{2-} water induces changes in hepatic gene regulation (Table 2). Many of these genes are integral to immune function, indicating that liver health is affected by high-S water. Assessment of those genes in the present study may determine any changes in health due to the $FeCO_3$ treatment at a molecular level. Assessment at the molecular level is essential to determine if the $FeCO_3$ treatment causes any changes not readily detectable at the phenotypic level. Real-time RT-PCR has been performed to determine if treating high-SO_4^{2-} water with $FeCO_3$ causes molecular changes and alters liver function. Briefly, RNA was extracted from liver subsamples from each animal, reverse transcribed into cDNA, and quantified relative to a standard housekeeping gene. To date, differences in expression have been observed in the APEX nuclease 1 (*APEX1*), erythrocyte membrane protein band 4.1 (*EPB41*), glycine N-methyltransferase (*GNMT*), and integrin beta 2 (*ITGB2*) genes. The *APEX1* gene, which is involved in repairing oxidative DNA damage, had greater (P = 0.0241) expression in high-S lambs administered 500 mg $FeCO_3$/L compared to control lambs. Up-regulation of this gene in the Fe supplemented lambs may indicate repair of damage, at the molecular level, caused by the high S water. Expression of the *EPB41* gene, which plays a key role in regulating membrane physical properties of mechanical stability and deformability, was greater (P < 0.0001) in high-S lambs administered 500 mg $FeCO_3$/L compared to all other treatment groups. Similar to *APEX1*, the up-regulation of this gene may suggest repair at the molecular level in Fe supplement high S lambs. Finally, the *GNMT* (*P* = 0.0318) and *ITGB2* (*P* = 0.0295) genes had greater expression in the high-S lambs administered 500 mg $FeCO_3$/L compared to the high-S lambs with no Fe supplement. The *GNMT* gene is involved in glycine methylation and methionine metabolism. The *ITGB2* gene participates in the cell adhesion process and cell-surface mediated signaling. The role of these two genes in response to Fe supplementation warrants further investigation. No other changes in gene expression were detected. In general, it appears that administration of a Fe supplement (500 mg $FeCO_3$/L) does have an effect at the molecular level, perhaps in repairing molecular damage caused by high dietary S.

Table 2. Genes identified as differentially regulated in response to high-S water.

Gene(s)	Function
MHC Class I Heavy Chain	Immune system
MHC Class II, DQ alpha 5, DQ beta, and DRB3, TGF beta 1	Immune system; Stimulus response
Regakine 1 and Integrin, beta 2	Immune system; Stimulus response; Binding
Inhibin, Beta A	Immune system; Binding
Interleukin 8 Receptor, Beta	Response to stimulus
ZFP 385A, Interleukin 1 Rc, HOP Homeobox, Pyrroline-5 CR 1, Cys-rich EGF-like 2	Binding
Tubulin beta 4, Protein Kinase (cAMP-dependent, catalytic, alpha)	Cytoplasmic function; Binding
Transglutaminase 2	Cation binding
Lysosomal-associated Protein Transmembrane 4 Alpha	Cytoplasmic function
Glycine N-Methyltransferase	Hepatic S-adenosylmethionine function
Aldo-keto Reductase Family 1, Member B10	Oxidoreductase activity
Pyruvate Carboxylase, Uncoupling Protein 2	Cell/membrane function

Statistical Analyses. M.S. student Jons has analyzed the performance data using the MIXED procedure of SAS (SAS Inst., Inc., Cary NC) to test for treatment differences. Real-time RT-PCR expression levels were estimated by the $2^{-\Delta\Delta CT}$ method, and analyzed using the MIXED procedure.

Future Plans. Amanda Jons, the M.S. student, will defend her thesis based on this work in August of 2011. She will continue to work under PI Cammack's direction to complete publications and final laboratory work associated with this project. In particular, we would like to determine the S content in muscle samples collected at slaughter from high-S lambs. Also, we will complete further histological and gene expression work on liver samples. Amanda will present her research this summer at the American Society of Animal Science national meeting, and again at the Colorado Ruminant Nutrition Roundtable. We anticipate submitting a manuscript for publication in the Small Ruminant Research journal in the fall of 2011.

Related Research. The current NRC recommendation for dietary S is < 0.3% dry matter (DM), with the maximum tolerable concentration estimated at 0.4% DM [2]. Sulfur content in water, however, is typically reported in parts per million (ppm), and the most common form of S in water is SO_4^{2-}. Polioencephalmalacia is associated with water SO_4^{2-} concentrations of $\geq$ 2,000 mg/L, which when combined with a typical 0.2% DM S feedstuff results in 0.53% DM total dietary S [3]. Therefore, when S or SO_4^{2-} content of water is included in the estimation of dietary S, the total dietary S is often much higher than anticipated. *Mechanism:* Sulfate and S_2 together form a recycling system, as absorbed S_2 is oxidized into SO_4^{2-} in the liver. Levels of H_2S gas increase with greater dietary S. The excess production of H_2S inhibits cytochrome oxidase in the electron transport system, reduces ATP production, and ultimately causes necrosis in the brain [4]. The S_2 ion is also capable of binding to hemoglobin and forming sulfhemoglobin, reducing the ability of the blood to deliver oxygen to the body [5].

Sources of High-S Water: Survey and field data have consistently shown surface and subsurface water can be high in SO_4^{2-}, particularly throughout the western regions of the U.S. The Water Quality for Wyoming Livestock & Wildlife review [6] reported that of > 450 forage and water collection sites located throughout the U.S., 11.5% exceeded the dietary S concentrations considered safe for livestock. Of those sites, 37% were located in the western U.S., including Wyoming. Drought further exacerbates the high SO_4^{2-} problem, as SO_4^{2-} is concentrated in the water due to greater evaporation and reduced moisture recharge [7]. In addition, conventional gas and oil produced water discharge can be high in SO_4^{2-}, particularly in arid regions such as the Big Horn Basin (John Wagner, personal communication). Of five water discharge sites sampled in the Big Horn Basin, two exceeded 2,000 mg SO_4^{2-}/L [8], well above the limit considered safe for livestock consumption. Although many CBM water sources are low in SO_4^{2-}, including those in the Powder River Basin, there have been reports of high and variable SO_4^{2-} concentrations (hundreds to thousands of mg/L) in CBM waters from the Fort Union Formation in Campbell County [9]. Because of the limited availability of water resources in those regions, many of those sources high in SO_4^{2-} are still used for livestock production.

***High-S Water and Performance*:** Poor performance of animals exposed to drinking water sources with high levels of SO_4^{2-} is common. Declines in average daily gain in cattle consuming high- SO_4^{2-} water have been reported in both grazing and confined environments [1,10]. Also, decreases in feed consumption and body weight gain in ruminant livestock exposed to high-SO_4^{2-} drinking water are consistently reported. *High-S Water and PEM:* Polioencephalomalacia is characterized by necrosis of the cerebral cortex and remains one of the most prevalent central nervous system diseases in cattle and sheep [2,11]. Clinical signs of PEM may include head pressing, blindness, incoordination, and recumbency accompanied by seizures [2], with young ruminants the most commonly affected [12]. The limited amount and availability of quality water is problematic for producers, especially when livestock consuming SO_4^{2-} contaminated water are also exposed to forages with moderately elevated S levels [3].

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Training Potential. Graduate student training is a priority in the Department of Animal Science. Research endeavors are overseen by faculty and staff, but carried out by graduate students. This project serves as the thesis project of a M.S. student in the Department of Animal Science. PI Cammack is serving as the advisor for the student. The student, Amanada Jons, is currently being trained in the areas of animal production, toxicity, genomics, and water quality. She has been responsible for carrying out all aspects of this research project, including both the animal and laboratory components. Together with the PIs, the student will prepare manuscripts and bulletins for submission upon final data analyses.

To date, the M.S. student has prepared one Annual Report for the Department of Animal Science describing her experiment and presenting preliminary results. She has successfully submitted one abstract to present her data at the American Society of Animal Science national meeting in summer of 2011 in New Orleans; the abstracted has been accepted for presentation and publication. Amanda will also prepare a poster for the Colorado Ruminant Nutrition Roundtable. Amanda's research has progressed quickly, and she presented her results to date at the Animal Science Department's spring seminar series. We anticipate that Amanda will defend her thesis work in August of 2011. She will continue to work under PI Cammack's direction during the fall to finish up her manuscripts and other remaining laboratory work for this project.

This research is also an opportunity for undergraduate training. PI Cammack regularly employs 2-3 undergraduate students (Becky Vraspir; Alicia Komloski) in her laboratory, who assist with a variety of projects. This project has provided those undergraduate students the opportunity to gain hands-on animal care, and for laboratory experience through tissue processing to date. Additional laboratory experience is anticipated.

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

Basic Information

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

Publications

1. Shinker, J.J., B.N. Shuman, T.A. Minckley, and A.K. Henderson, 2010. Climatic Shifts in the Availability of Contested Waters: A Long-term Perspective from the Headwaters of the North Platte River, Annals of the Association of American Geographers (Special Issue on Climate Change), 100 (4), 866-879.
2. Shuman, B., P. Pribyl, T.A. Minckley, and J.J. Shinker, 2010. Rapid hydrologic shifts and prolonged droughts in Rocky Mountain headwaters during the Holocene, Geophysical Research Letters, DOI:10.1029/2009GL042196.

Multi-Century Droughts in Wyoming's Headwaters: Evidence from Lake Sediments
Annual Report, Year 1 of 3
Bryan Shuman, J. J. Shinker, and Thomas Minckley

Abstract

Wyoming has historically experienced extended periods of drought, which have had significant economic and social impacts. Tree-ring records and archeological evidence indicate that past centuries have contained multi-decadal "megadroughts" far more severe than any drought of the past 150 years. This project has been studying past dry periods, which likely exceeded even the severity of multi-decadal "megadroughts" in Wyoming watersheds. In doing so, we are building upon funding from a previous Wyoming Water Research Program grant, and have found evidence of consistent moisture histories across the water-producing regions of the state. Evidence derives from prehistoric shoreline elevations in lakes in the Medicine Bow, Wind River, and Bighorn Mountains, and shows that climatic shifts can rapidly generate new hydrologic regimes that persist for centuries to millennia. Aridity at least as severe and extensive as during the AD 1930s Dust Bowl prevailed from >8000-5500, 4500-3000, and 2800-2000 years before AD 1950). The lake-shoreline elevations as well as watershed moisture budget calculations indicate that at least portions of the North Platte and Bighorn River systems were probably ephemeral for several millennia when dune activity was common across parts of Wyoming, Colorado, and Nebraska. These centennial-to-millennial variations in the availability of water are important because they occurred when the world's climate was similar to today, and represent part of the natural climate variability that preceded historic time. The reconstructed moisture histories show correlations with reconstructed histories of ocean temperatures and processes such as El Nino, which point to the underlying causes and indicate that some regional hydrologic variability may be predictable based on ocean conditions. Such persistent drought may, for this reason, represent an analogy for periods in Wyoming's future. Work in 2010 included 1) an extensive survey of lakes in the Bighorn drainage basins, using sub-surface radar, to determine the extensiveness of past periods of low lake levels, 2) sediment core analysis, including radiocarbon dating and fossil analyses, of a few representative lakes to date and quantify past climate conditions, and 3) hydroclimatic analysis, comparing paleoclimate estimates with modern climatic data and climate model output, to examine the factors that contributed to the periods of prolonged drought. This work involved several graduate students, undergraduates, and high school interns in different activities from field work to data analysis and presentation.

Progress

Objectives

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

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

To reach our goal, the project incorporates four activities:

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

Methods

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

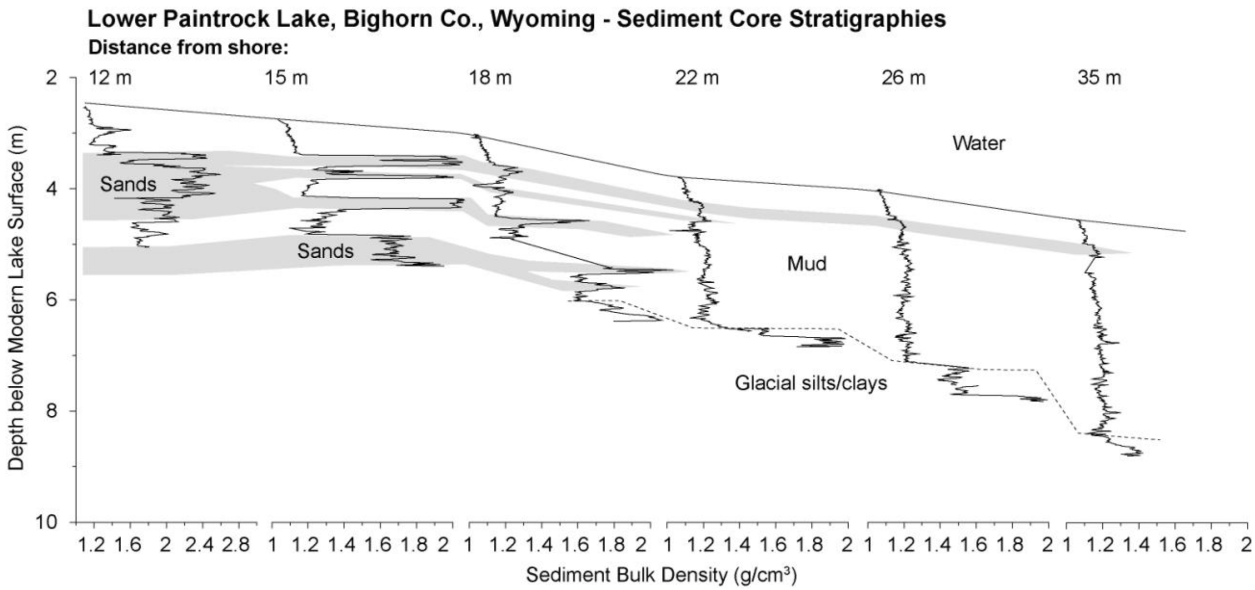

Figure 1. Sediment characteristics (such as sediment density above) in a transect of sediment cores collected perpendicular to shore can be used to track shifts in a lake's shoreline over time. Here, cores collected in July 2010 from Lower Paintrock Lake show layers of sand associated with periods of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

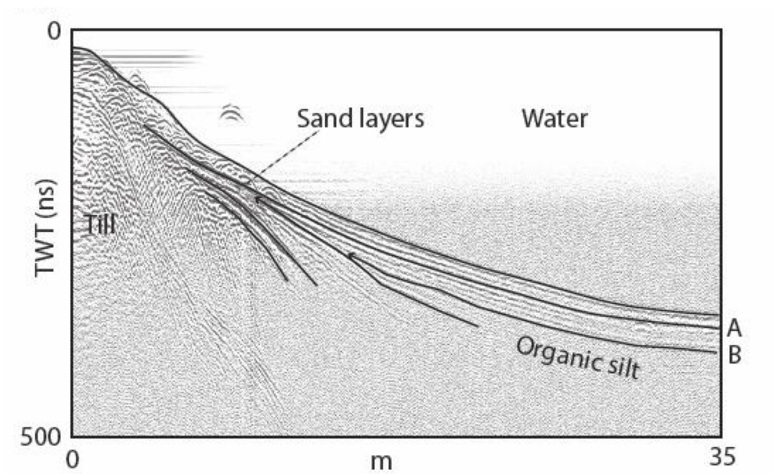

Figure 2. Ground-penetrating radar profiles show submerged paleoshorelines (sand layers marked by the convergence of stratigraphic layers and large amplitude radar reflections) in Lower Paintrock Lake. This profile spans the area of core locations (see Fig. 1), and confirms that the sand layers in the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

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

Targeted sediment coring at representative lakes, Upper Medicine Lodge and Lower Paintrock Lake in the west-central Bighorn Mountains (Fig. 1), enabled us to date past shoreline deposits

(Fig. 3). Shifts in sediment composition and grain size have been assessed using loss on ignition, magnetic susceptibility, grain-size analysis, and other core logging techniques that can be conducted in the UW Geology and Geophysics Department, using equipment in Shuman's lab. To date the sedimentary changes, one-cm wide slices were removed from sediment cores and sieved to find plant macrofossil material for AMS radiocarbon dating. Future work will use standard pollen analysis techniques to reconstruct vegetation composition during periods of long-term drought, and to infer regional temperature trends.

We have focused our coring on lakes with well-defined watersheds, with limited additional groundwater inputs, because such lakes can be used to estimate long-term moisture-balance changes. To calculate long-term ΔP-E (e.g., Fig. 3), we have developed a new method for systematically estimating elevational shifts in each lake's shoreline from the maximum depths of the paleoshoreline sediments compared to the water depths of similar sediment today . We then calculate changes in lake volume by accounting for lake size and bathymetry, and divide by the watershed area and 365 days to obtain a ΔP-E value for the watershed in mm/day as we did previously for only certain snap-shots of the past (Shuman et al., 2010; Shinker et al., 2010). Additional analyses will include comparisons of maps of our lake-level data with maps of historic climate data and ENSO phases to examine the potential influences on spatial patterns of change as we have done in other studies.

<u>2010 Activities</u>

- <u>Fieldwork:</u> GPR profiles collected from five and two lakes in Bighorn and Beartooth Ranges respectively; collected sediment cores from two lakes and four small ponds in the Bighorn Mountains. Also, collected cores from Long Lake, Medicine Bow Mountains, as a training exercise for undergraduates and SRAP (Summer Research Apprenticeship Program) high-school interns.
- <u>Lab work:</u> Core analyses of Long Lake (Carbon Co.) and Lower Paintrock Lake (Bighorn Co.), including loss-on-ignition, grain-size, sediment density, sedimentary charcoal, macrofossils and radiocarbon analyses.
- <u>Analyses:</u> Developed methodology to quantify the lake-level reconstructions and calculate associated changes in watershed moisture balance. We also incorporated results from Wyoming lakes into a continental-scale database of similar data, and conducted analyses of historic droughts in Wyoming to examine climatic processes that might have contributed to past aridity.
- <u>Paper writing:</u> See list of publications and manuscripts below.
- <u>Outreach:</u> The 2010 meeting of the American Quaternary Association (AMQUA) was held in Laramie in August 2010, and the PIs organized related field trips for >60 people to several of our study sites in the Platte River watershed. The field trips provided an opportunity to present results to the scientific community at the locations of our work. Presentations were also given to Wyoming Farm Bureau and State Engineer's Office Water Forum.

Principal Findings

Findings to date parallel our primary questions:

1. **The extent and magnitude of past droughts**: Our new methodology (Shuman et al., in prep b) enabled us to systemically produce time series of water-level changes from our sediment core data, and then calculate watershed hydrologic balance based on these data. In this way, we have produced reconstructions of the balance of precipitation and evaporation for two different watersheds: one on the northern side of the Medicine Bow Mountains (around Little Windy Hill Pond) and one at the northern end of the Wind River Range (at Lake of the Woods). The two reconstructions agree well in terms of both magnitude and timing of past dry episodes (Fig. 3, blue lines).

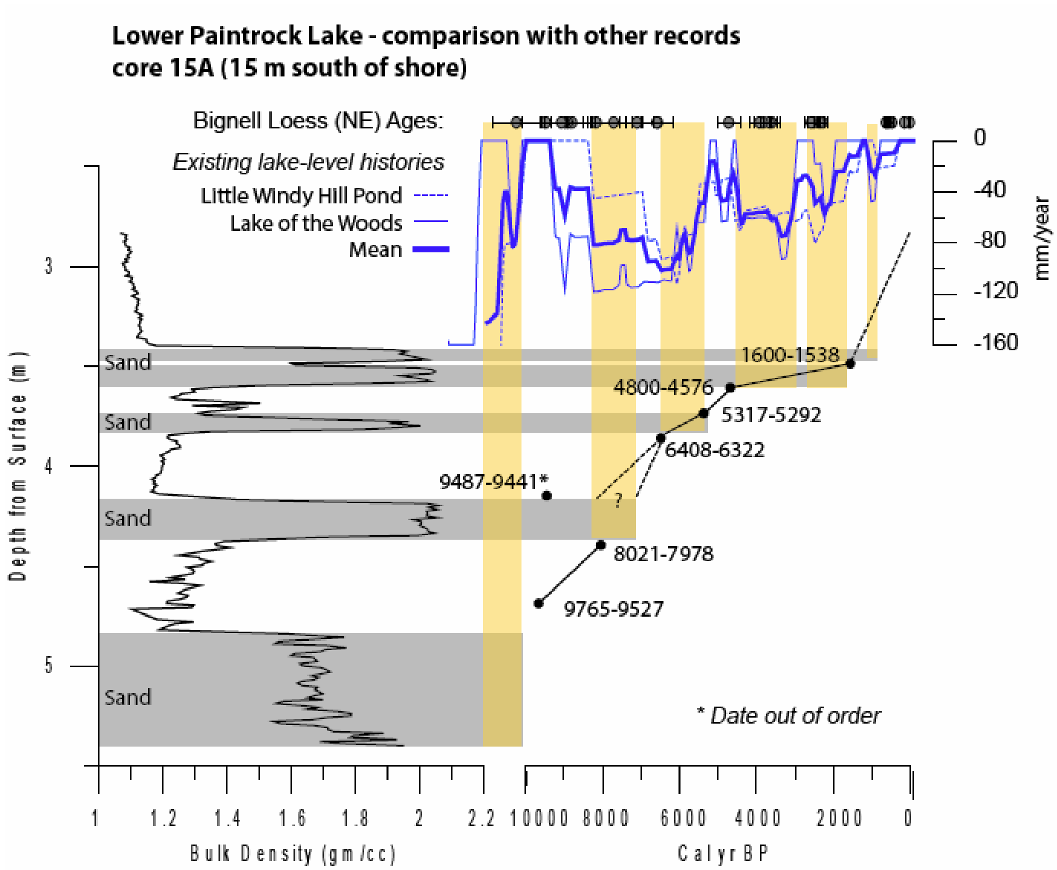

Figure 3. Sediment core density data (left) from 15-m south of shore at Paintrock Lake, Bighorn Co., show intervals of low density deep-water sediment interrupted by dense, sand layers typical of ancient shoreline (low water) deposits. Black dots (plotted versus time on the right) mark the stratigraphic position of radiocarbon ages (1-sigma uncertainty listed) that provide constraints on the timing of low water intervals at the lake. The timing of sand deposition appears to agree well with that of dry periods reconstructed at Little Windy Hill Pond (Medicine Bow Range; blue dashed line plotted as reconstructed precipitation minus evaporation over time) and Lake of the Woods (Wind River Range, thin blue line), as well as with episodes of loess deposition (dune activity) in Nebraska.

Preliminary data from Lower Paintrock Lake in the Bighorn Mountains appear to show episodes of severe aridity at similar times as the other sites (Fig. 3), which indicates that much of the high-elevation snow-dominated areas of the state had similar moisture histories. The results show prolonged periods of >50 mm/yr reductions in annual moisture balance from ca. 8000-5500, 4500-3000, and 2800-2000 years before AD 1950; these episodes overlap in time with other evidence of aridity, such as periods of dune activity recorded by loess deposition in Nebraska's Sand Hills (Fig. 3, symbols in upper right).

The consistency of the timing of events is well represented by the similarities of radiocarbon dates bracketing the paleoshorelines (sand layers) formed in each lake during arid periods. For example, at Lower Paintrock Lake (Bighorn Co.), the uppermost pair of sand layers in core 15A began to form at 4800-4576 years before AD 1950 (Fig. 3); similar sand layers formed at Lake of the Woods (Fremont Co.), Little Windy Hill Pond (Carbon Co.), and Upper Big Creek Lake (Jackson Co., Colorado) above respective radiocarbon ages of 4812-4625, 4806-4529, 4808-4584 years before AD 1950. Likewise, a synchronous interval of loess deposition in western Nebraska buried a soil formed during the previous wet period, which radiocarbon dates to 4810-4550 years before AD 1950 (Miao et al., 2007).

2. **The predictability of drought**: The timing of past drought in Wyoming appears to be linked to the histories of Pacific and Atlantic sea-surface temperatures (Fig. 4).

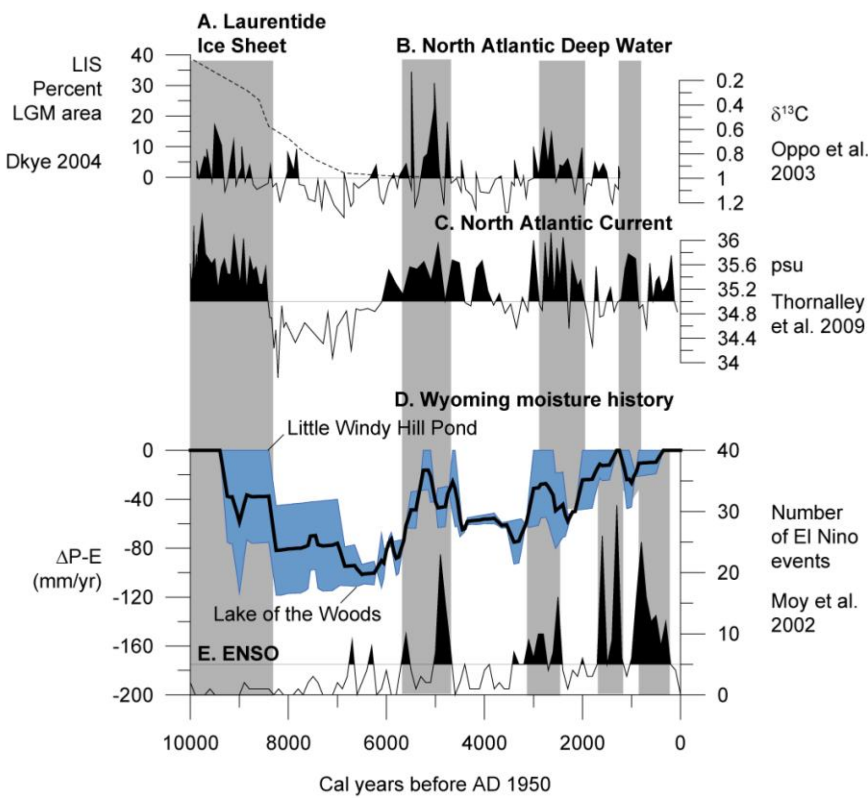

Figure 4. Wyoming moisture reconstructions (plotted in blue as change in precipitaiton minus evaporation, ΔP-E, versus time) have variations consistent with documented oceanic variability. Before ca. 8000 years before AD 1950, the presence of the Laurentide Ice Sheet in central Canada (A, dashed line) likely contributed to wet conditions in Wyoming. Since then, wet phases have coincided with periods of frequent El Nino events (E), and may have also been influenced by variability in the North Atlantic (B, C).

Additional work by Shinker and students has examined the atmospheric dynamics and circulation associated with dry episodes in Wyoming to help explore the mechanistic linkages that may have been the underpinning to the events of the past 10000 years.

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

Significance

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

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

Publications and Presentations (* Student Author)**:**

Published in 2010

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

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

Submitted publications

Minckley, T.A., R.K. Shriver*, and B. Shuman. Resilience and regime change in a southern Rocky Mountain ecosystem during the past 17000 years. *Ecological Monographs.* Peer Reviewed.

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

Publications in preparation

Pribyl, P.*, and B. Shuman. Changes in moisture availability during the Holocene at the Colorado-Columbia-Missouri River headwaters, central Wyoming. Plan to submit to *Bulletin of the Geological Society of America*. Peer Reviewed.

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

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

Shuman, B., J. Marsicek*, P. C. Newby*, G. Carter*, D. D. Hougardy*, P. Pribyl*, S. Brewer, J. P. Donnelly, D. Foster, and W. Wyatt Oswald (B). From Causes to Impacts of Holocene Moisture Variation in Mid-Latitude North America. Plan to submit to *Nature Geosciences*. Peer Reviewed.

Kelly, R., T. Surovell, and B. Shuman. Strong climatic influence on human populations in the central Rocky Mountains over the past 13,000 years. Plan to submit to *Science*. Peer Reviewed.

Presentations

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

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

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

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

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

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

Student Involvement

Marc Serravezza, a Ph.D. student in Geology & Geophysics, was supported by this grant and took the lead on analyses of the new sediment cores from Lower Paintrock Lake, Bighorn Co. Marc was supported in this work by recent UW undergraduate, Devin Hougardy, and another Geology Ph.D. student, John Calder. Both contributed to field work in the Bighorn Mountains, and have been developing supplementary datasets from field sites in the Platte River drainage (e.g., Long Lake, Carbon Co.) for comparison with data generated in northern Wyoming. Likewise, Grace Carter and Jeremiah Marsicek, Ph.D. students in Geology & Geophysics contributed to field work in summer 2010, and have generated complementary datasets from other regions (via support from the National Science Foundation), which is providing a broader-scale perspective on the events documented in Wyoming (such as the shift in moisture availability at ca. 5500 years before AD 1950).

Joshua Fredrickson, a Geography/Water Resource master’s student was supported through a one-year fellowship from the Geography Department. Fredrickson will be analyzing climate data associated with recent low stream flow events in the Platte and Colorado River drainages. During the last year Fredrickson has focused on completing 90% of his required coursework. He is also partially funded through the McNair Scholars program to mentor undergraduate Joshua Heyer.

Joshua Heyer, an undergraduate in Geography is supported through the McNair Scholars program, which supports first-generation undergraduate student research in preparation for a graduate school. Mr. Heyer’s contribution to our research project includes training in climate analysis related to understanding drought and low stream flow years. Mr. Heyer presented his preliminary research, “An Investigation of Climatic Controls in the Upper Laramie River Watershed During Low Stream Flow Years”, at UW Undergraduate Research Day, April, 2011.

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

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

Basic Information

Title:	Impact of Bark Beetle Outbreaks on Forest Water Yield in Southern Wyoming
Project Number:	2010WY61B
Start Date:	3/1/2010
End Date:	2/28/2013
Funding Source:	104B
Congressional District:	1
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Surface Water, Water Quantity
Descriptors:	Bark beetles, Water budget, Water yield
Principal Investigators:	Brent E. Ewers, Elise Pendall, David Williams

Publications

There are no publications.

Impact of Bark Beetle Outbreaks on Forest Water Yield in Southern Wyoming
Annual Report, Year 1 of 3

PIs: Brent E Ewers, Elise Pendall and David G Williams

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

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

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

Methodology
All components of forest stand water budgets are being measured at the lodgepole pine bark beetle sites with a select group of major components at the higher elevation spruce and fir bark beetle site. Some of the following measurements are being partially or fully funded by ongoing National Science Foundation project and a nearly completed UW Agriculture Experiment Station grant. **Precipitation** is being measured with multiple approaches to obtain incoming liquid and frozen preciptiation as well as throughfall and

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

Progress

We now have data from all the major measurements outlined in the methods except liquid throughfall precipitation. This data will be collected as soon as liquid precipitation begins falling at these elevations. Stable isotope data was just received from the UW SIF lab; quantitative analyses of these findings will occur over the next few months. Tree physiology mechanisms from leaf gas exchange and hydraulic conductance are now being tested. Full drafts of manuscripts are now in revision on the energy balance changes from bark beetle mortality and a conceptual overview of the impact of bark beetle mortality on carbon, water and nutrient cycles from these forests. Manuscript sare in the initial stages for tree transpiration and nutrient budgets from bark beetle impacts forests.

Principal Findings

Our significant results to date are 1) transpiration and evapotranspiration decline measurably in the first year and precipitously in the second year of an outbreak, 2) water fluxes from the stands decline faster than carbon uptake, 3) soil moisture increases with the decline in transpiration and evapotranspiration strongly suggesting increased streamflow, 4) soil N increases after the outbreak due to reduced vegetation activity and 5) energy balance closure is on the low end for forests indicating that there is a high degree of uncertainty in evapotranspiration measurements from these extremely heterogeneous (due to spatial patterns of mortality) forests.

Significance

This work is providing measurements and analysis of stand-level water balance that are critical to developing forecasting tools for determining the impact of bark beetles on streamflows from primary streams to major river systems. We are testing mechanisms of bark beetle impacts on water yield by conducting investigations at the stand and ecosystem level. Our work shows that predictive tools should be based on mechanistic understanding of first-order beetle impacts which can then be scaled appropriately and tested by comparison against streamflow data as part of future research efforts beyond the scope of this project.

Our proposed research will apply the stand water balance approach to sites that cover the major land and management cover types in the Medicine Bow Mountains, maximizing applicability to both forest and water managers (see multiple presentations to forums with managers below), while improving basic knowledge of disturbance effects on water cycling and providing quantitative, hands-on training to graduate and undergraduate students. Finally, our research data is now being sought by many investigators from multiple science fields further illustrating the high impact nature of the work.

Students Supported
Bujidma Borkhuu-PhD student, main responsibilities are soil measurements and assistance with atmospheric measurements.

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

David Reed-PhD Student, main responsibilities are the atmospheric and streamflow measurements

Faith Whitehouse-MS Student, main responsiblities are the tree physiology measurements

Claire Hudson-Undergraduate Student, main responsiblities are assisting with soil trace gas measurements and lab processing and vegetation measurements

Margo Hamann-Undergraduate Student, main responsbilities are assisting with tree physiology field measurements and lab processing

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

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

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

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

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

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

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

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

Ewers, B.E. et al. The Rocky Mountain epidemic of bark beetles and blue-stain fungi cause first order effects on ET and second order effects on other greenhouse gases. Ecological Society of America Meeting, Pittsburgh, PA, August, 2010.

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

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

Information Transfer Program Introduction

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

Publications and other information dissemination efforts were reported by the PIs of the projects funded under this program. The project PIs report to the Institute Advisory Committee on an annual basis. Presentations discussing final results are made by PIs of projects which were completed during the year at the July committee meeting. Presentations discussing interim results are made by PIs of continuing projects at the fall/winter committee meeting. PIs are encouraged to publish in peer reviewed journals as well as participate in state-wide water related meetings and conferences. Publications are listed in the individual research reports.

Director information dissemination 2010 activities are listed in the following two paragraphs:

Director 2010 Service: (1) Wyoming Water Development Commission Workshop. Cheyenne, WY., January 5, 2010. (2) Wyoming Representative to the Colorado River Authority Tour, Nevada to California. January 11-16, 2010. (3) Wyoming Water Association Board Meeting (Advisor), Cheyenne, WY., January 21, 2010. (4) Wyoming Engineering Society, 90th Annual Convention, Laramie, WY., February 4-5, 2010. (5) Wyoming Water Association Board Meeting (Advisor), Cheyenne, WY., February 11, 2010. (6) The National Institutes for Water Resources (NIWR) annual meetings. Washington, DC., March 1-3, 2010. (7) Weather Modification Association (WMA) annual meetings. Santa Fe, NM., April 20-23, 2010. (8) Sponsor UW Water Instructors for the 8th Annual Conference Wyoming Water Law, with CLE International. Cheyenne, WY., April 29-30, 2010. (9) Wyoming Water Development Commission program selection criteria. Cheyenne, WY., May 7, 2010. (10) Energy Resources and Produced Waters Conference. Laramie, WY., May 25-26, 2010. (11) Wyoming Water Association Board Meeting (Advisor), Cheyenne, WY., May 1, 2010. (12) Wyoming Water Development Commission Workshop. Cheyenne, WY., June 2, 2010. (13) Wyoming Water Development Commission/Select Water Committee Meeting. Cheyenne, WY., June 3, 2010. (14) Wyoming Weather Modification NCAR Planning Meeting. Laramie, WY., June 22, 2010. (15) Wyoming Water Association Board Meeting/Summer Tour, (Advisor). Casper, WY., July 14-15, 2010. (16) Wyoming Weather Modification Technical Advisory Team Meeting. Lander, WY., July 20, 2010. (17) UW Water Research Program. WRP Priority and Selection Committee meeting to select research priorities. Cheyenne, WY., July 29, 2010. (18) Wyoming Water Development Commission/Select Water Committee joint workshop. Cody, WY., August 18, 2010. (19) Wyoming Water Development Commission/Select Water Committee joint meeting/summer tour. Cody, WY., August 19 - 20, 2010. (20) Wyoming Water Association Committee meeting (Advisor), Cheyenne, WY., August 24, 2010. (21) Wyoming Water Association Committee meeting (Advisor), Cheyenne, WY., September 22, 2010. (22) State of Wyoming/Univ. of Wyoming Science and Technology Meeting, Cheyenne, WY., September, 24, 2010. (23) Wyoming Water Association Committee meeting (Advisor), Cheyenne, WY., October 4, 2010. (24) Wyoming Water Association Board meeting (Advisor), Laramie, WY., October 26, 2010. (25) Co-Sponsor Wyoming Water Association Annual Meeting & Educational Seminar, University of Wyoming Water Initiatives. Laramie, WY., October 27-29, 2010. (26) Wyoming Weather Modification 2010-2011 Pre-project Ground School. Laramie, WY., November 10-11, 2010. (27) Wyoming Association of Conservation Districts (WACD) Annual Conference. Worland, WY., November 17-18, 2010. (28) UW Water Research Program Meeting. WRP Priority and Selection Committee to select research projects. Cheyenne, WY., December 2, 2010.

Director 2010 Presentations: (1) Wyoming Water Forum, Presentation on Office of Water Programs and Water Research Program projects. Cheyenne, WY., January 4, 2010. (2) Wyoming Water Development Commission Meeting, Presentation on recommendation for FY2011 WRP Annual funding and OWP Biennium funding. Cheyenne, WY., January 6, 2010. (3) Wyoming Legislative Select Water Committee, Presentation on WRP projects and recommendation for FY2011 WRP Annual funding and OWP Biennium funding. State Capital, Cheyenne, WY., January 7, 2010. (4) Green River Basin Advisory Group meeting, Presentation on UW Office of Water Programs. Rock Springs, WY. January 28, 2010. (5) Wyoming Water Forum, Presentation on UW Office of Water Programs/Water Research Program funded projects. Cheyenne, WY., February 2, 2010. (6) Farm and Ranch Days 2010, Presentation on Wind River Glacier Study . Riverton, WY., February 12, 2010. (7) AWRA Spring Specialty Conference (GIS) and Water Resources VI, Presentation on Remote Sensing of Wind River Glaciers, WY . Orlando, FL., March 30-April 1, 2010. (8) Wyoming Water Forum, Presentation on UW Office of Water Programs/Water Research Program. Cheyenne, WY., April 6, 2010. (9) Wyoming Water Forum, Presentation on UW Office of Water Programs/Water Research Program. Cheyenne, WY., May 4, 2010. (10) 12th Annual Summit on the Snake, Presentation on Wyoming Glaciers: Trends and Impacts . Teton Science School, Jackson Hole, WY., May 5, 2010. (11) Wyoming Water Forum, Presentation on Water Research Program RFP and Project Selection. Cheyenne, WY., November 2, 2010. (12) Wyoming Water Development Commission/Select Water Committee joint workshop. Presentation on the UW Office of Water Programs and Water Research Program. Casper, WY., November 3-5, 2010. (13) Wyoming Water Forum, Presentation on Water Research Program Project Selection. Cheyenne, WY., December 7, 2010. (14) Wyoming Water Development Commission/Select Water Committee joint workshop. Presentation on Wyoming Water Research Program. Cheyenne, WY., December 13, 2010. (15) Wyoming Water Development Commission. Presentation on Wyoming Water Research Program. Cheyenne, WY., December 14, 2010. (16) Legislative Select Water Committee. Presentation on Wyoming Water Research Program. State Capital Bld., Cheyenne, WY., December 15, 2010.

FY10 Information dissemination activities reported by research project PIs are listed in the following six paragraphs:

Project 2008WY44B: Water Quality Criteria for Wyoming Livestock and Wildlife. (1) B. Wise and M. F. Raisbeck: Water quality for Wyoming Livestock and Wildlife. Soc Toxicol annual meeting, Salt Lake City, 3/9/10. (2) B. Wise and M. F. Raisbeck: Water quality for Wyoming Livestock and Wildlife. RMSETAC, Denver, CO, 4/15/10.

Project 2009WY46B: Detecting the signature of glaciogenic cloud seeding in orographic snowstorms in Wyoming II: Further airborne cloud radar and lidar measurements. (1) Cloud seeding: Dr. Geerts gave an oral presentation at the 2010 Annual Meeting of the Weather Modification Association and the North American Interstate Weather Modification Council (Santa Fe, NM, April 2010). We also continue to give regular research updates at the WWMPP Technical Advisory Team (TAT) meetings, in Lander (typically in July) and in Cheyenne (typically in January), at the WWMPP Ground School (typically in November), and in 2011 also at the WWMPP seasonal debriefing meeting in mid-April. And we have provided the WWMPP team with material for use in their presentations at meetings of the Select Water Committee, a group of Wyoming state senators and representatives, in the context of updates and further funding requests. (2) PBL turbulence and orographic precipitation: Dr. Geerts gave talks on the importance of PBL turbulence on the growth of snow particles over mountains at the 19th AMS Conf. on Boundary Layer Processes and Turbulence, Keystone CO (2-6 August 2010), the 10th Annual Meeting of the European Meteorological Society, Zurich, Switzerland (13-17 Sept), and the UW Department of Atmospheric Science seminar on 11/23/2010.

Project 2009WY47B: Effects of Warm CBM Product Water Discharge on Winter Fluvial and Ice Processes in the Powder River Basin. (1) Stiver, Jared, March 5, 2010. Effects of CBM waters in the Powder River Basin, invited presentation to RNEW 5710 class taught by KJ Reddy. (2) Stiver, J.J., April 7, 2010, Presentation to Class: Watershed H20 Quality, REWM 5710, Instructor: KJ Reddy. (3) Kempema, E.W., Ettema, R, and

Stiver, J. May 25, 2010. Effects of Coalbed Methane Product Water on Winter Flow in the Powder River; Energy Resources and Produced Waters Conference: Laramie, WY. (4) Stiver, J.J April 20 2011, Presentation to Class: Spatial Analysis, RNEW 5200, Instructor: Scott Miller. (5) Stiver, J.J., April 7 2011, Presentation to Class: Water Resources Seminar, REWM 5250, Instructor: KJ Reddy. (6) Kempema, E.W., Stiver, J.J. and Ettema, R., September, 2011, Effects of CBM water discharge on fluvial and ice processes in Powder River Basin, Wyoming Streams; at: CRIPE 2011 Workshop on River Ice, Winnipeg, Canada, September 2011.

Project 2009WY48B: Characterization of Algal Blooms Affecting Wyoming Irrigation Infrastructure: Microbiological Groundwork for Effective Management. (1) Steven, B., and N. Ward. Deep sequencing of ribosomal RNA genes during an algal bloom in a eutrophic lake: a primer for metagenomic sequencing. DOE Joint Genome Institute 5th Annual User Meeting: Genomics of Energy & Environment. Walnut Creek, CA. March 24-26, 2010. (2) Steven, B., S. McCann, K. H. Schulmeyer, and N. L. Ward. Characterization of the microbial diversity associated with algal blooms in a eutrophic freshwater lake. 13th International Symposium on Microbial Ecology. Seattle, WA. August 22-27, 2010.

Project 2010WY58B: Development of GIS-based Tools and High-Resolution Mapping for Consumptive Water Use for the State of Wyoming. (1) Ryan Rasmussen and Gi-Hyeon Park, High-resolution mapping of reference ET for the state of Wyoming AGU meeting December 13-17, 2010, San Francisco, California.

Project 2010WY60B: Multi-Century Droughts in Wyomings Headwaters: Evidence from Lake Sediments. (1) Shuman, B. N., J.J. Shinker and T. A. Minckley. 2010. Millennial-scale hydroclimatic variation and prolonged episodes of ephemeral river flow in the Rocky Mountains during the Later-Quaternary, Geological Society of America, Denver, CO. (2) Shinker, J. J., B. N. Shuman, T. A. Minckley, and A. K. Henderson. 2010. Climatic shifts in the availability of contested waters: A long-term perspective from the headwaters of the North Platte River, Poster presenter, American Quaternary Association, Laramie, WY. (3) Shinker, J. J., B. N. Shuman, T. A. Minckley, and A. K. Henderson. 2010. Climatic shifts in the availability of contested waters: A long-term perspective from the headwaters of the North Platte River, Association of American Geographers, Washington, DC. (4) Shinker, JJ. 2010, Women in Science Conference, Career Panelist, University of Wyoming. (5) Shinker, J. J., 2011, Spatial Heterogeneity of Western U.S. Climate Variability. Association of American Geographers, Seattle, Washington. (6) Heyer, J. and Shinker, J.J., 2011. An Investigation of Climatic Controls in the Upper Laramie River Watershed During Low Stream Flow Years, at UW Undergraduate Research Day, April, 2011.

USGS Summer Intern Program

None.

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	12	0	0	0	12
Masters	11	0	0	0	11
Ph.D.	10	0	0	0	10
Post-Doc.	1	0	0	0	1
Total	34	0	0	0	34

Notable Awards and Achievements

Project 2009WY46B: Detecting the Signature of Glaciogenic Cloud Seeding in Orographic Snowstorms in Wyoming II: Further Airborne Cloud Radar and Lidar Measurements, Bart Geerts, Dept of Atmospheric Science, UW, Mar 2009 thru Feb 2012. Project findings are believed to be very significant. Geerts was an invited keynote speaker at the Annual Weather Modification Association meeting in Santa Fe NM in April 2010. At that meeting, Arlen Huggins, a veteran researcher in weather modification, mentioned project work as one of the most significant achievements in glaciogenic seeding efficacy research in the past decade. Second, Dr. Geerts is the PI in a proposal, known as ASCII (AgI Seeding of Cloud Impact Investigation), funded by the National Science Foundation. This grant is a collaboration with NCAR (Rasmussen, Breed, Xue). The USGS/WWDC-funded field work and data analysis were instrumental in the success of this grant of $493,320 entitled The cloud microphysical effects of ground-based glaciogenic seeding of orographic clouds: new observational and modeling tools to study an old problem (Aug 2011 Jul 2014; reference: AGS-1058426). ACII will be conducted in the Sierra Madre between 4 Jan and 4 March 2012, in the context of the WWMPP, which will be in its last year. The emphasis here is on the cloud microphysical effects of glaciogenic seeding in cold orographic clouds.

Project 2009WY48B: Characterization of Algal Blooms Affecting Wyoming Irrigation Infrastructure: Microbiological Groundwork for Effective Management, Naomi Ward, and Blaire Steven, Dept of Molecular Biology, UW, Mar 2009 thru Feb 2011. The PIs submitted a proposal (Metatranscriptomic analysis of bacterial-algal interactions: an ecological foundation for enhancing algal biofuel and geoengineering initiatives) that was selected for funding support in 2010 by the US Department of Energys Community Sequencing Program (CSP), This is not a traditional award mechanism in which funds are distributed to the University, but rather a peer-reviewed program that allows researchers to compete for access to the high-throughput sequencing resources of the DOEs Joint Genome Institute. The proposal leveraged the support provided by USGS/WRP to obtain this funding, which will help to establish a program that uses both bioinformatic and experimental approaches to characterize algal-bacterial interactions.

Publications from Prior Years

1. 2007WY37B ("Tracing Glacial Ice and Snow Meltwater with Isotopes") - Articles in Refereed Scientific Journals - Cable, J., K. Ogle, and D.G. Williams, 2011. Contribution of glacier meltwater to streamflow in the Wind River Range, Wyoming inferred via a Bayesian mixing model applied to isotopic measurements. Hydrological Processes, DOI: 10.1002/hyp.7982.