Montana Water Center
Annual Technical Report
FY 2013

Introduction

The Montana University System Water Center (MWC), located at Montana State University in Bozeman, was established by the Water Resources Research Act of 1964. Each year, the Center's Director at Montana State University works with the Associate Directors from the University of Montana - Missoula and Montana Tech of the University of Montana. Butte, to coordinate statewide water research and information transfer activities. This is all in keeping with the Center's mission to investigate and resolve Montana's water problems by sponsoring research, fostering education of future water professionals and providing outreach to water professionals, water users and communities.

To help guide its water research and information transfer programs and to help develop research priorities and assess research proposals the Montana Water Center depends on advice from members of its advisory council. During the 2013 research year, the Montana Water Research Advisory Council members were:

Duncan Patten, MWC Director; Stephanie McGinnis, MWC Assistant Director; John LaFave, MWC Associate Director, Montana Tech of the University of Montana, Montana Bureau of Mines; William Woessner, MWC Associate Director ,University of Montana; John Kilpatrick, Director - Montana Water Science Center, U.S. Geological Survey; Bonnie Lovelace, Water Protection Bureau Chief Montana Department of Environmental Quality; Tom Pick, Natural Resource and Conservation Service (now retired); Jeff Tiberi, Montana Association of Conservation Districts, Executive Director; Kathleen Williams, Montana Legislature (Water Specialist); and Laura Ziemer, Trout Unlimited.

Research Program Introduction

Through its USGS funding which was limited for 2013, the Montana Water Center partially funded only one new water research project in 2013 and completed funding for three other projects for faculty at three of Montana's state university campuses.

Those projects funded in 2011 for two years submitted final reports in spring 2013 and were included in the 2012 Annual Report. The Montana Water Center requires that each faculty research project directly involve students in the field and/or with data analysis and presentations.

This USGS 104b funding also provided research fellowships to four students involved with water resource studies.

Here is a brief statement of the researcher's and students' work, with the one faculty research project initiated in 2013 listed first.

Drs. Katie Hailer and Stephen Parker of Montana Tech of the University of Montana initiated work titled "Do Sediments in the Warm Springs Ponds Operable Unit Act as a Sink for Organic Wastewater Compounds?." They received $13,835 for this study. An interim report from this project is presented later in this annual report.

Student Fellowships funded in 2013 were:

Heidi Clark at Montana State University Department. "Rephotography as a tool to Understand the Effects of Resource Use on Rivers of the Greater Yellowstone Region". She received $1,000.

David Dockery at Montana State University. "Maintaining Migratory Pathways of Imperiled Large River and Small Stream Prairie Fishes in the Face of Climate Change". He received $1,000.

Thomas Matthews at Montana State University. "Understanding Trends in Snow Accumulation, Water Availability and Climate Changes Using Snow Telemetry Observations in the Missouri River Headwaters". He received $1,000.

Robert Livesay, an undergraduate at University of Montana. "Investigating Upstream Channel Response to Dam Removal, Black Foot River MT". He received $500.

Final reports from these students are presented later in this research report.

During 2013 two MUS faculty researchers were selected for grants that the Montana Water Center administers under the USGS 104(b) research program, one from Montana State University and one from Rocky Mountain College. These grants and fellowships will be funded with 2013 USGS 104(b) funds. The faculty grants are:

Dr. Paul Stoy of Montana State University received an award of $4,080 to study " Improving accessibility to satellite soil moisture measurements: Linking SMOS data retrievals to ground measurements in Montana".

Kayan Ostovar of Rocky Mountain College received an award of $11,475 to study " Contaminants monitoring and natal dispersal of ospreys along the Yellowstone River".

The student fellowships to be awarded with 2013 USGS 104(b) funds went to six graduate students each receiving $2,000.

Douglas Brugger, a PhD student at the University of Montana will study "The Impact of Irrigation on the Hydrologic Cycle under Low Water Availability".

Emily Clark, Montana State University will study " Thresholds of Hydrologic Connectivity: Shallow Water Table Development at the Hillslope Scale".

Elizabeth Harris, Montana State University will study " Seasonal Timing of Evapotranspiration and the Effect on Soil Moisture and Water Availability for Groundwater Recharge with Different Crop Rotation Practices".

Aiden Johnson, Ph.D. student in the Ecology & Environmental Sciences program at Montana State University will study " Estimating Evapotranspiration at the Regional Scale: An Energy Balance Approach".

Justin Martin, Montana State University will study " Precipitation and topographic controls over montane forest transpiration".

April Sawyer, University of Montana will study " Conditions necessary to maintain chute-cutoff morphology in meandering gravel-bed rivers".

Assessing Hydrologic, Hyporheic, and Surface Water Temperature Responses to Stream Restoration

Basic Information

Title:	Assessing Hydrologic, Hyporheic, and Surface Water Temperature Responses to Stream Restoration
Project Number:	2012MT263B
Start Date:	3/1/2012
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	MT01
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Groundwater, Surface Water
Descriptors:	None
Principal Investigators:	Geoffrey Poole

Publications

There are no publications.

Project Title: Assessing Hydrologic, Hyporheic, and Surface Water Temperature Responses to Stream Restoration.

Principal investigator: Geoffrey Poole, Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT, ph: (406) 994-5564, fax: (406) 994-3933 gpoole@montana.edu

Student: Byron Amerson, Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT, (415) 912-8792, byron.amerson@gmail.com

Groundwater and Surface Water Hydrologic and Temperature Monitoring

This research project combines a variety of field and numeric modeling techniques to create a complete picture of the residence time distribution for hyporheic water at the restoration site for both pre- and post- restoration conditions and will document the effects of channel re-alignment on hyporheic exchange (rates, magnitude, and volume), hyporheic flow path lengths, residence time, and ultimately, channel temperature. This research was designed to meet the following three objectives:

1. Quantify ground the rate and magnitude of surface water - groundwater exchange and groundwater residence time both prior to and after restoration actions to assess changes in recharge and discharge between Meacham Creek and its alluvial aquifer (hyporheic exchange).
2. Establish a monitoring network of stream temperature loggers and water level loggers to measure changes in the surface and subsurface water elevation and temperature due to restoration actions.
3. Pilot a new method of stream restoration monitoring that will have broad utility to other restoration efforts in the region.

Actions to meet these objectives to date are presented below.

Actions and Methods to Date

Groundwater Modeling Methods and Preliminary Model Analysis

In late 2010 and early 2011, groundwater hydrology of the baseline and restored channel alluvial aquifers was modeled using the USGS groundwater modeling software MODFLOW (Harbaugh, 2005), where the main input into the aquifer was the water surface elevation of the creek plan form. Surface water elevation was derived from first-return LiDAR for the baseline condition, and under the restored condition it was based on "filling" the design channel pools and the riffle ground elevations. In either case, aquifer thickness was assumed to be 5 m in the valley center, tapering to .5 m at the valley wall using the LiDAR terrain model as the surface. Once the potentiometric flow surface was developed, subsurface flow path lines through the potentiometric flow field were generated by releasing "particles" along the creek using the USGS solute modeling software MODPATH (Pollock, 1994).

Based on the groundwater modeling, we predicted that there would be a substantial shift in groundwater surface elevation, as well as in the pattern and magnitude of exchange between groundwater and surface water in the project reach. Based on these initial hydrologic simulations of the site (Figure 1), we predicted that the residence time distribution of hyporheic water will shift to include a higher number of intermediate duration hyporheic flow paths, but that the magnitude of gross hyporheic exchange may either increase or decrease, depending on the change in hydraulic conductivity (Figure 2).

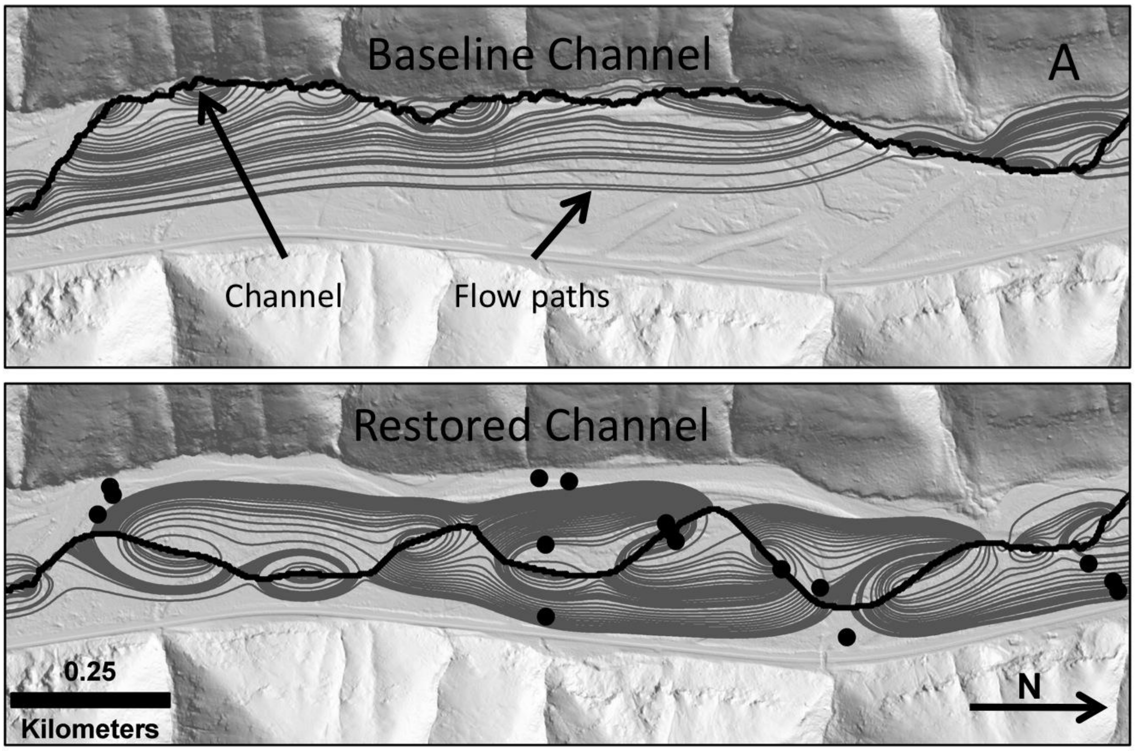

Figure 1. Results from MODFLOW simulation showing expected influence of restoration on hyporheic flow paths (grey lines) on the Meacham Cr. restoration site. Dots show locations of installed monitoring wells in the project site area (This figure is reproduced from the 2011 Seed Grant Proposal).

Groundwater Elevation and Temperature Monitoring

During the spring and summer of 2011 and 2012, a series of 32 monitoring wells were established prior to and during stream restoration activities. In each well a water temperature and level data logger was deployed (Onset HOBO U20 Water Level Data Logger model U20-001-01 [pressure accurate to 0.05% and temperature to 0.1 °C] or Solinst Model 3001 Levelogger Junior Edge [pressure accurate to 0.1% and temperature to 0.1 °C]). Twenty of the well loggers were deployed six weeks before the restoration project began, and another twelve were deployed just prior to diversion of flow to the new channel, and two were install in July 2012. Twenty-one wells remain active, while the remainder were either accidentally broken, destroyed by high flows, or were removed during construction or prior to the onset of seasonal high flows.

Results from the initial MODFLOW simulations with the restored channel planform (Figure 2) were used to select well locations that captured the expected range of hyporheic residence times across the alluvial aquifer. Because daily and seasonal temperature signals are useful tracers of groundwater movement as well as indicators of systematic changes in the temperature status of water as it moves through the hyporheic zone(Arrigoni et al., 2008; Hoehn and Cirpka, 2006; Stonestrom and Constantz, 2003), it is expected changes in the patterns of water temperature across this well network that reflect the restructuring of hyporheic hydrology within the alluvial aquifer.

Since 2011, temperature and water level data from the well loggers was periodically downloaded. In January 2014, the final download of temperature & pressure data from each operable well logger, 21 in total, was completed. Temperature & pressure data from surface water stage gages at two locations was also downloaded. All operable loggers were redeployed after they were downloaded to facilitate an ongoing long-term monitoring program.

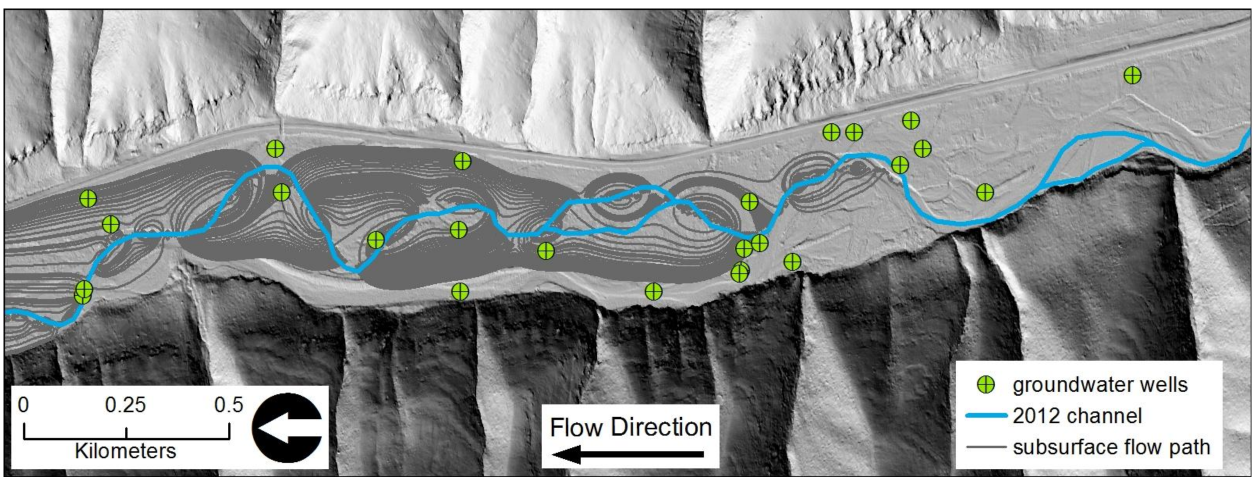

Figure 2. The location of groundwater monitoring wells in juxtaposition to modeled groundwater flow paths of the restored channel at the Meacham Creek Restoration site in 2012.

Surface Water Temperature Monitoring

In 2011 thirty temperature loggers were deployed in surface water features along the restored stream channel prior to diversion of flow into it (Onset HOBO Pendant Temperature/Light Data Logger model 64K - UA-002-64 (accurate to 0.53 °C), or Maxim Dallas iButton model DS1922L (accurate to 0.5 °C) encased in waterproof resin (sold as iBcod by Alpha Mach, Inc.). In addition to those loggers deployed along the restored channel reach, approximately 20 more temperature loggers were deployed in the main channel above and below the project reach as well as in groundwater upwelling features near the channel and in the floodplain. The groundwater upwelling features include springs, flowing backwater areas, and spring brooks far-removed from the channel. In 2012, 54 surface water temperature loggers were deployed (Figure 3). Twenty-eight of those were placed in the main flow of Meacham Creek along the restored reach at hydrologic breaks roughly corresponding to typically-defined aquatic habitat features (e.g. pool, riffle, etc.). The remaining temperature loggers were deployed in groundwater upwelling features similar to 2011. In September 2012, all of the surface water loggers in the main channel were removed to protect them from being lost in high winter flows. However, all of the loggers in off-channel springs off from the main channel were re-deployed after being downloaded. In addition, a temperature logger was placed in the open channel flow bolted to a bedrock outcrop. Theses latter deployments were to record over-winter temperatures and capture the full seasonal cycle of surface water temperature variation at the restoration site. In October 2013, 28 of 31 Hobo Pendant temperature loggers that were deployed in June of that year were recovered from throughout the restoration reach and in select "old channel" and off-channel spring locations. Most were repeat deployments in locations selected in 2012, though several were new locations as the channel position has shifted since 2012.

Radon-222 activity and geochemistry

Radon-222 concentration was measured to verify simulated and observed groundwater residence times across the post-restoration site. Radon-222 concentration is a reliable indicator of subsurface water residence time up to ~20 days (Hoehn and Cirpka, 2006; Lamontagne and Cook, 2007). In October 2011, we measured Radon-222 activity and collected geochemistry samples at twenty wells, five open channel locations, and four spring brook source waters using methods described by Schubert et al., (2006). In March and October 2013 repeat sampling for radon-222 and geochemistry was repeated at all wells and in several open channel locations. Geochemistry data will be used to determine the magnitude of mixing between hyporheic and deep groundwater (Freeze and Cherry, 1977; Hoehn and Cirpka, 2006; Jones et al., 2008), a prerequisite for estimating hyporheic residence time from Radon-222. An additional value that is required to determine residence time using radon-222 is the equilibrium concentration of the dissolved radon-222 gas in the aquifer of interest. This value is related to radon-222 production by the aquifer material, and is generally idiosyncratic to the system in question; hence literature values do not serve well. Therefore, 8 250 ml pickling jars have been filled up completely with aquifer material from the study material and degassed tap water. After six weeks, samples from the middle of the volume of sediment will collected and the concentration of radon will be measure by scintillation counter. This method has proved reliable in similar studies (Sebastian LaMontange, personal communication, March 2013).

Aquifer thermal modeling

To model thermal energy dynamics of the Meacham Creek aquifer, numerical solutions of the canonical advection-diffusion equation for temperature were applied. Simplified 1D heat flux simulations were run with the groundwater solute and energy flux model MT3DMS (Zheng and Wang, 1999). MT3DMS couples groundwater flow solutions from MODFLOW with the advection-dispersion solute and energy transport solutions (Zheng and Wang, 1999). The one-dimensional advection-dispersion equation is:

$$\frac{\delta T}{\delta t} = (\kappa_e + D)\frac{\partial^2 T}{\partial x^2} - v_t\frac{\partial T}{\partial x}\ , \qquad (1)$$

where T is temperature, t is time, κ_e is thermal diffusivity (m^2s^{-1}) D is thermomechanical dispersion (m^2s^{-1}), v_t is area-averaged rate of heat movement induced by movement of water through the bed (ms^{-1}), and x is distance along the subsurface flow path (m) (Bear and Cheng, 2010; Luce et al., 2012).

In the last decade, there has been a steady increase in research on the use of shallow groundwater temperature signals to estimate the seepage velocity of water across the stream channel boundary into or out of the hyporheic zone (Briggs et al., 2012; Constantz et al., 2003; Hatch et al., 2006; Lautz and Siegel, 2006; Luce et al., 2012). The pioneering work of Stallman (1965) and Suzuki (1960) form the basis of the method (Anderson, 2005; Stonestrom and Constantz, 2003). In particular, Stallman (1965) and Suzuki (1960) showed that when the boundary condition is a periodic function of temperature (e.g. diurnally or seasonally varying) then a solution to the one-dimensional advection-dispersion equation is:

$$T(x,t) = T_\mu + Ae^{-ax}\cos(\varpi t - bx), \qquad (2)$$

where T_μ is the mean temperature, A is the amplitude, ω is the frequency, a is a damping function, and b is a phase-shifting function (Luce et al., 2012). Hatch et al. (2006) propelled a rapid increase in related research by developing an iterative approach to solve for values of a and b using the temperature signal from measured at two depths separated by a known distance. Recent work by Luce et al. (2012) shows that the need for the iterative approach for solving for a and b can be dispensed with, and the use of temperature signals alone can be used to find values for a and b.

A hallmark of the last 10 years of research on groundwater temperature methods in the use of diurnal signals and length scales of the order of a few meters to determine the properties of interest. Application of the methods at the river reach scale (tens of meters) using annual temperatures signals has not been explored. The Meacham Creek research requires the use of annual temperature signals at the river reach scale.

To apply the advection-dispersion equation using annual temperature signals at the river reach scale, an understanding of effective thermal diffusivity is required. The sum ⍰$_e$ + D in the first term of the right hand side of equation 1 is termed effective thermal diffusivity. The first term in the summation, ⍰$_e$, thermal diffusivity, is determined by the bulk thermal properties and bulk density of the aquifer material (sediment and water together) and therefore is determined by material properties of the system; the values of these properties are relatively easy to measure and reasonable estimates are published in many places (e.g. www.engineeringtoolbox.com). The second term, *D*, thermomechanical dispersion, is determined by multiplying longitudinal dispersivity by water velocity. Longitudinal dispersivity is a non-linear process, the scale of which is bounded at some characteristic length set by a poorly-understood combination particle size distribution and discontinuities in the flow system of interest (e.g. impermeable layers such a pervasive silt deposit, or highly transmissive feature such as relict channels, etc.) (Gelhar et al., 1992). Hence, longitudinal dispersivity is an emergent *system* property, and it is challenging to measure (Anderson, 2005).

In all of the studies mentioned above that employ time-varying temperature signals to model systems of interest, thermomechanical dispersion is ignored. At the spatial and time scales of the problems they are working on (meters, diurnal), this is a reasonable simplification (see discussion in Anderson [2005] and Luce et al. [2012]). It turns out that when using annual temperature signals at the river reach scale, reasonable estimates of thermomechanical dispersion are required. And in fact, the opposite simplification can be made: thermal diffusivity can be ignored. The scale-and-velocity-dependent trade-off between the dominance of diffusivity and thermomechanical dispersion is well known from contaminant transport modeling (Bear and Cheng, 2010; Fetter, 2008), but as far as we know, this is the first application of this distinction in temperature modeling. In our modeling we incorporate estimates of thermomechanical dispersion to generate hypothetical temperature signals that closely match patterns observed in our empirical data; using thermal diffusivity alone fails to do so.

Results to Date and Discussion

Work on the Groundwater and Surface Water Hydrologic and Temperature Monitoring is complete, the 1D thermal modeling is in progress with some preliminary results available, and preliminary analysis of the radon data is complete. Once the 1D thermal modeling and radon data analysis are completed, an updated 3D groundwater model will be generated. Coupled to this model will be a 3D thermal model. The radon data will be used to corroborate groundwater velocity estimates.

1D Modeling

Plots of annual groundwater temperature measured in the wells at the study exhibit a typical buffered and lagged (Arrigoni et al., 2008) appearance when plotted alongside annual surface water temperature measured in the open channel (Figure 1). As a test of our revision of the analytical methods of Luce et al. (2012), plots of groundwater temperature solutions that do not include and do include thermomechanical dispersion are compared (Figure 2). It is readily apparent that when no thermomechanical dispersion is included, the groundwater temperature solution is lagged but not damped. When thermomechanical dispersion is included, the groundwater temperature solution is both lagged and damped. With this confirmation, we moved forward with numerical modeling using MT3DMS, incorporating thermomechanical dispersion.

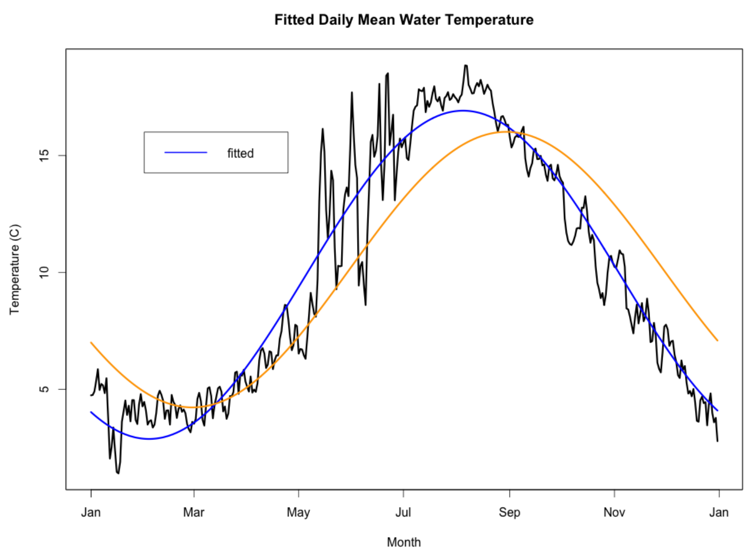

Figure 1. A plot of mean daily temperature in the open channel (black line measured, blue

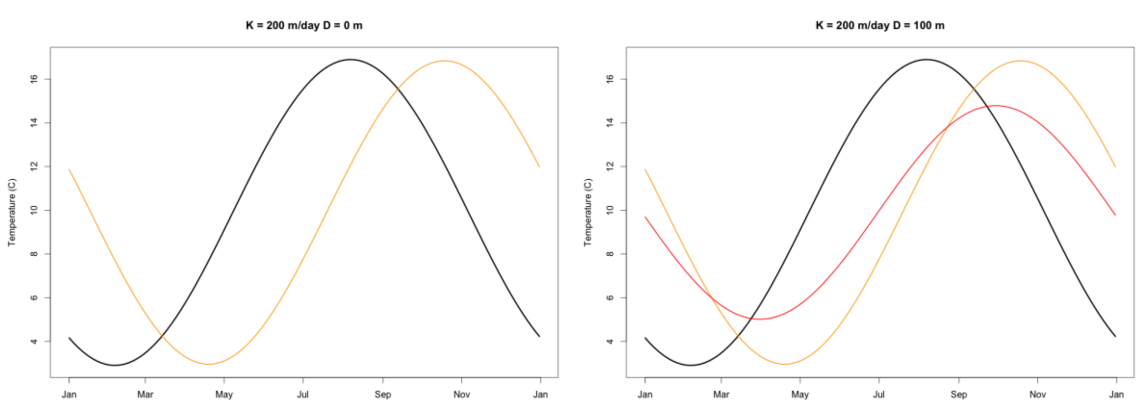

Figure 2. Plots of analytical temperature solutions of mean daily temperature. In the both panels the black line represents the annual temperature in the open channel flow. In the right and left panels, the orange line depicts the analytical temperature solution in a well 100m downstream where thermomechanical dispersion is 0 m. In the left panel, the red line shows the temperature solution when thermomechanical dispersion is set 100 m.)

line fitted) and in a groundwater well (orange).

A particularly useful consequence of the methods presented in Luce et al. (2012) is that if system properties are known, then the distance between points of temperature measurement can be estimated (e.g. equation 57 from Luce et al. [2012]). Utilizing this approach allows comparison of analytical solutions and modeled solutions derived from the 1D model. For instance, using the analytical formulas from Luce et al. (2012), values for a and b for temperature sensors that are 100 meters apart can be derived (this was an arbitrarily chosen distance). Then applying these values to a temperature signal generated by the 1D model using the same inputs as the analytical solution can be used to check that incorporating dispersion does indeed reproduce results similar to those measured in the field. Since this same modeling approach will be used for the 3D model, testing a simplified 1D model allows evaluating whether incorporating thermomechanical dispersion is effective. Using this approach, we determined that the numerical model (MT3DMS) perfectly predicted the distance between points of temperature measurement, accounting for unavoidable numerical modeling error. This satisfying result gives us confidence in using this approach in future 3D modeling efforts.

Radon

Preliminary results of analysis of the radon data support using these data to help corroborate estimates of groundwater residence time. Theory suggests that radon should accumulate proportional to residence time. Theory also suggests that the amplitude of groundwater temperature signals will dampen proportional to residence time, and that phase lag will increase with residence time. As a simple check that groundwater temperature and radon measurements at a given well behave as predicted, scatter plots of these data from each well were made. First to check for internal consistency in the temperature data, a plot of phase verses amplitude was made which behaved as expected: as phase lag increases the amplitude is dampened (Figure 3). Second sequential plots of phases verses estimated radon residence time and amplitude verses estimated radon residence time were made. These too exhibited the predicted patterns, with a positive relationship between phase lagging and radon residence time (Figure 4) and a negative relationship between amplitude and radon residence time (Figure 5).

These preliminary results give us confidence that the radon data will be a useful independent estimate of groundwater residence time that will help corroborate the estimates that we generate using the 3D groundwater model that is presently under development.

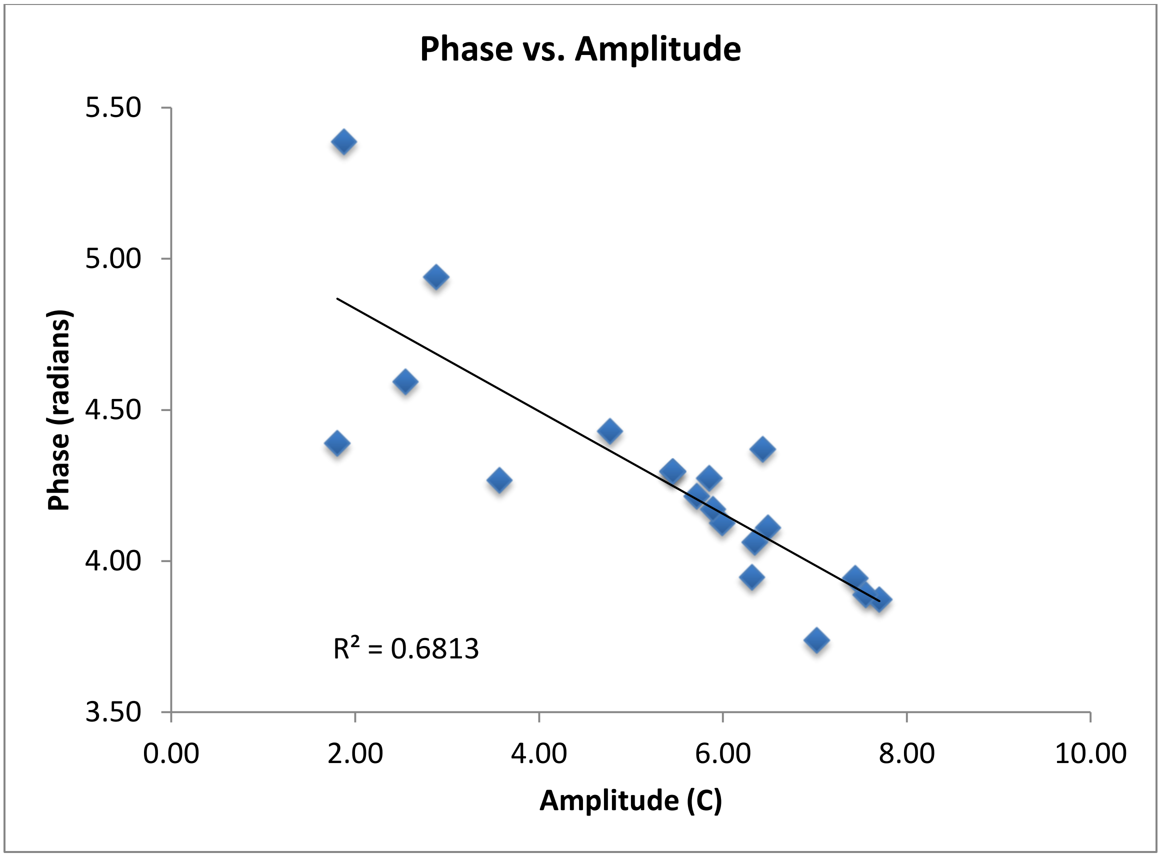

Figure 3. A plot of groundwater temperature phase verses amplitude in each well at the Meacham Creek restoration site.

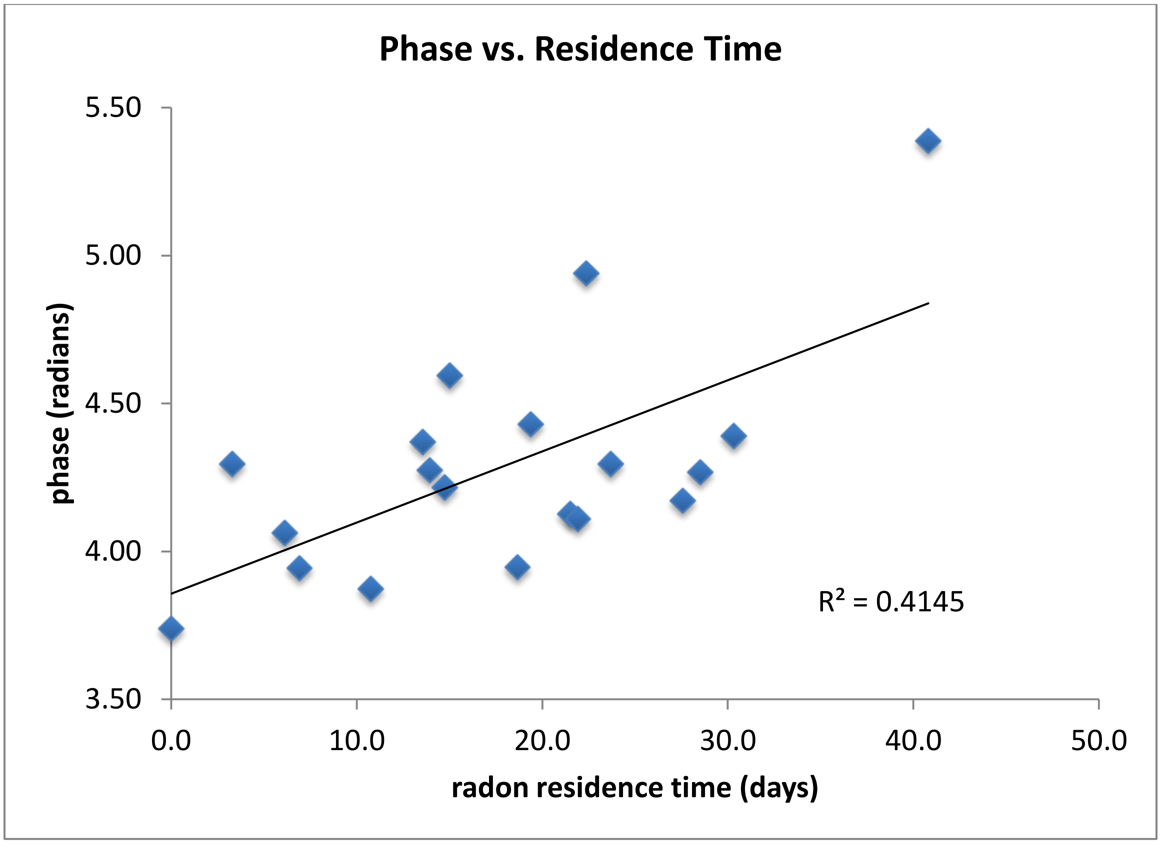

Figure 4. A plot of groundwater temperature phase verses radon residence in each well at the Meacham Creek restoration site.

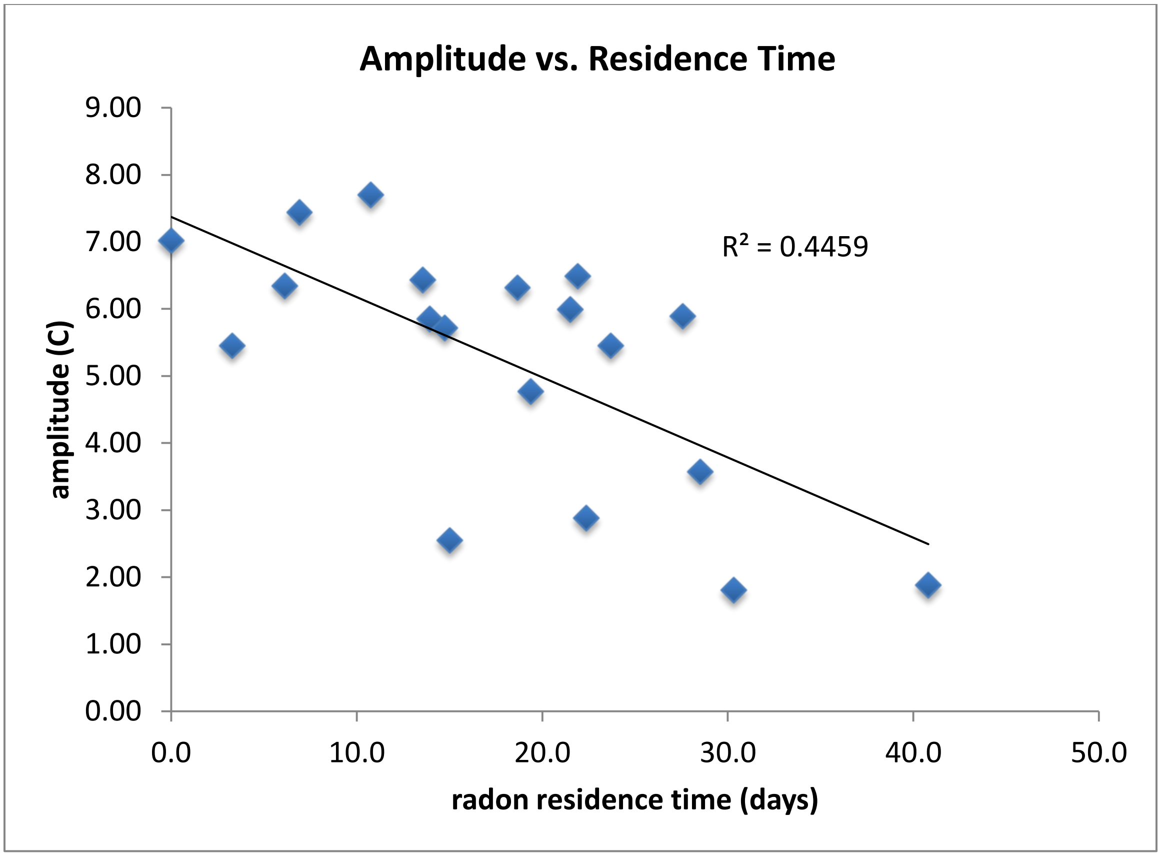

Figure 5. A plot of groundwater temperature amplitude verses radon residence in each well at the Meacham Creek restoration site.

Hydrologic observations

Observation of over 25 groundwater upwelling features along the restored channel in 2012 (Figures 6 & 7) demonstrate that there has been a shift in groundwater hydrology at the restoration site. These features include a range of types from strongly flowing springs to seeps along the downstream margin of point bars marked by filamentous algae growing in these nutrient-enriched outflows. In addition, observations of groundwater flow into the exposed portions of the baseline channel and in other areas throughout the floodplain suggest substantial changes in groundwater hydrology. It is expected that there has been concomitant changes in the thermal processes of the aquifer as well. Cursory exploration of level logger data confirms these observations.

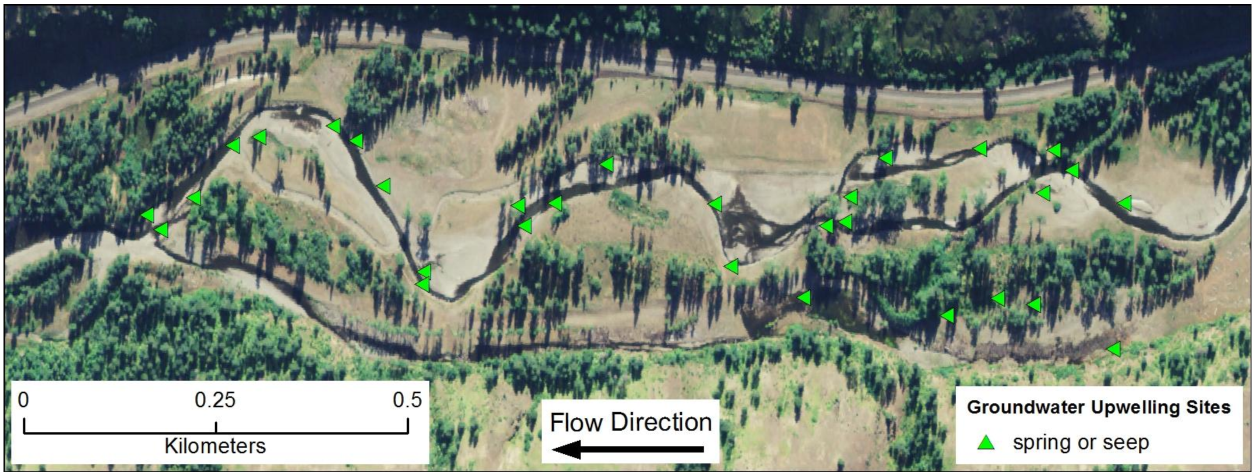

Figure 6. The location of easily-observed groundwater upwelling features along the restored reach of Meacham Creek observed in summer 2012.

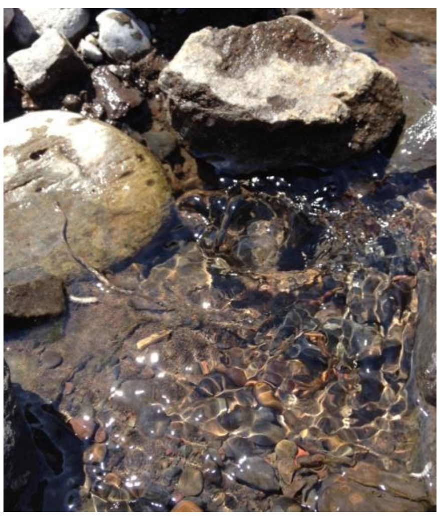

Figure 7. An actively flowing groundwater spring and seep (note filimentaous algae growing in nutrient-rich outflow) along the restored reach of Meacham Creek in summer 2012.

Database

Surface water temperature, groundwater temperature, and water level data from all instrument deployments been added to a PostgreSQL database (http://www.postgresql.org). Subsequent to data upload, any irregularities and errors revealed via QA/QC were corrected. An optional for a geospatial field for each measurement point has been added to the database, though not yet fully implemented. The addition of the spatial field allows straightforward extraction of spatially-referenced measurements for use in a GIS. To date there are 2.3 million temperature and water level records in the database; these data are the sum of continuous hourly measurements in 22 wells, and about 30 surface water locations each summer since 2011.

Future Actions and Methods

In 2014 an updated groundwater hydrology model, a groundwater thermal model, and an energy balance for the restored reach of Meacham Creek will be developed. Temperature and water level data collected to date and in the future will be used to develop, corroborate, and check the models and energy balance.

Hydrogeologic modeling

Modeling of hyporheic hydrology using updated as-built topographic surveys will allow stream-reach scale comparison of the change in magnitude and residence time of hyporheic flux for pre- vs. post-restoration scenarios. As with the preliminary hyporheic hydrologic models, the updated model will be developed using the USGS groundwater models MODFLOW (Harbaugh, 2005) and MODPATH (Pollock, 1994). The simulations will use updated model parameters for aquifer properties measured from aquifer stress tests to be carried out in spring 2013 (see aquifer properties section below for more detail). Observations of groundwater elevations, hyporheic temperature patterns measured to date will be used to help parameterize the model and verify results.

Thermal modeling

Once the groundwater has been modeled, it will be used input a groundwater temperature model for the pre-and post-restoration scenarios. The groundwater temperature model will be developed using the University of Alabama solute transport model MT3DMS **(Zheng and Wang, 1999)**. Water temperature data from the wells and the surface water loggers will be used as boundary conditions and calibrate the temperature model.

Aquifer properties (model parameter estimation)

Field efforts in 2013 to make quality aquifer property measurements were problematic and the data were inconclusive and unsatisfying. Hence, a renewed effort to collect key aquifer properties will be made in 2014. These data used to refine the input parameters to the hydrogeologic (Figure 2) and temperature models. Key parameters include hydraulic conductivity, porosity, thermal conductivity, bulk heat capacity, thermal conductivity at saturation, thermal conductivity at residual moisture content and volumetric heat capacity. These latter thermal properties are difficult to measure in the field. We are planning to use a heavily insulated water cooler in the lab as a calorimeter to measure thermal properties of the sediments, following good results using this approach for a similar purpose in unrelated research.

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Thresholds in fluvial systems: Flood-induced channel change on Montana rivers

Basic Information

Title:	Thresholds in fluvial systems: Flood-induced channel change on Montana rivers
Project Number:	2012MT264B
Start Date:	3/1/2012
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	MT01
Research Category:	Climate and Hydrologic Processes
Focus Category:	Floods, Geomorphological Processes, Climatological Processes
Descriptors:	None
Principal Investigators:	Andrew Wilcox

Publications

There are no publications.

Montana Water Center / USGS Final report

Project title: "Thresholds in fluvial systems: Flood-induced channel changes on Montana rivers "
Start Date: March 1, 2012
End Date: February 28, 2014
Report Date: May 9, 2014
Principal Investigator: Andrew Wilcox, Assistant Professor
Department of Geosciences, University of Montana
andrew.wilcox@umontana.edu; 406-243-4761

Overview

Our research investigated geomorphic changes associated with floods in western Montana rivers. We have focused on the Blackfoot, Clark Fork, and Bitterroot Rivers, and we have considered several elements of floods and channel change in these systems. Funding from the USGS / Montana Water Center seed grant program has supported field data collection and analysis of aerial photography and Lidar of our study systems. Our studies have included three main components:

(1) Investigation of channel change along the lower Blackfoot River to document changes associated with 2011 and 2012 floods and how such changes fit into the context of channel adjustment following the removal of Milltown Dam.

(2) Analysis of flood effects on chute cutoffs in gravel-bed rivers, including modeling of chute cutoffs that occurred in the newly constructed reach of the Clark Fork River upstream of the Milltown Dam sits during the 2011 floods.

(3) Evaluation of threshold forces associated with scour of riparian cottonwood seedlings along the Bitterroot River (this work also included Arizona field sites and other species).

(4) Analysis of geomorphic changes along the Clark Fork River between the former Milltown Dam site and the Bitterroot River confluence to assess changes associated with post-dam removal (e.g., 2011) floods and how such changes fit into the context of channel adjustment following the removal of Milltown Dam.

Outreach activities by participants in this project have included volunteering with Missoula's Watershed Education Network, judging the state high-school Science Fair, teaching about river processes at local elementary schools, and assisting with design of river-science exhibits at the SpectrUM science museum in Missoula. The PI also regularly interacts with local groups such as Clark Fork Coalition and Trout Unlimited. Science outcomes include several presentation on this research (see below), including at the Montana AWRA annual meeting. Several journal manuscripts are in preparation as well. A list of presentations related to this project is included at the end of this report

1. Geomorphic responses of the lower Blackfoot River to dam removal and floods.

One element of our study of flood-induced channel changes has been investigation of the lower Blackfoot River, including effects of the 2011 and 2012 floods and how such changes fit into the context of channel adjustment following the removal of Milltown Dam. Data collection included repeat cross sections and longitudinal profiles to assess topographic changes and pebble counts to assess changes in bed-material size. This work has resulted in a senior honors thesis (by Robert Livesay), and a journal manuscript is in preparation. Figures are used here to convey the key elements of this work. Livesay's thesis is available on request for more information. Figure 1 shows the lower Blackfoot River and Milltown Dam removal study area. One of the unique elements of channel response in the lower Blackfoot River has been exhumation of thousands of logs, which have moved downstream and mediated erosion of former reservoir sediments. To monitor channel change in the lower Blackfoot, we performed repeat topographic and grain size surveys at a series of cross sections, over a time frame from 2008 to 2012, as well as aerial photo analysis (Figure 2). In recent years, the study system has been exposed to a series of above-average flood years (Figure 3), producing changes in topography (Figure 4) and grain size (Figure 5).

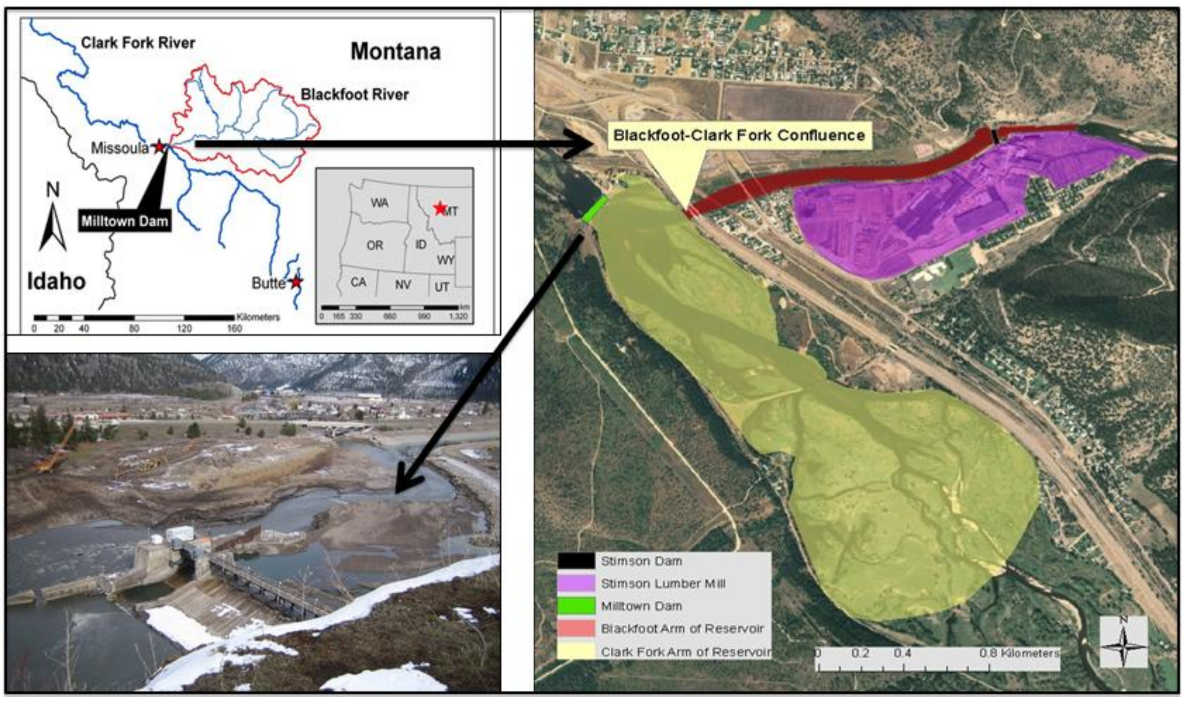


Figure 1. Top left: The Blackfoot watershed is outlined in red and meets the Clark Fork River west of Missoula immediately upstream of the former site of the Milltown Dam (Epstein 2009). Right: Aerial view of field site with the location of Milltown and Stimson Dam indicated. Bottom left: Milltown dam following 2008 breach.

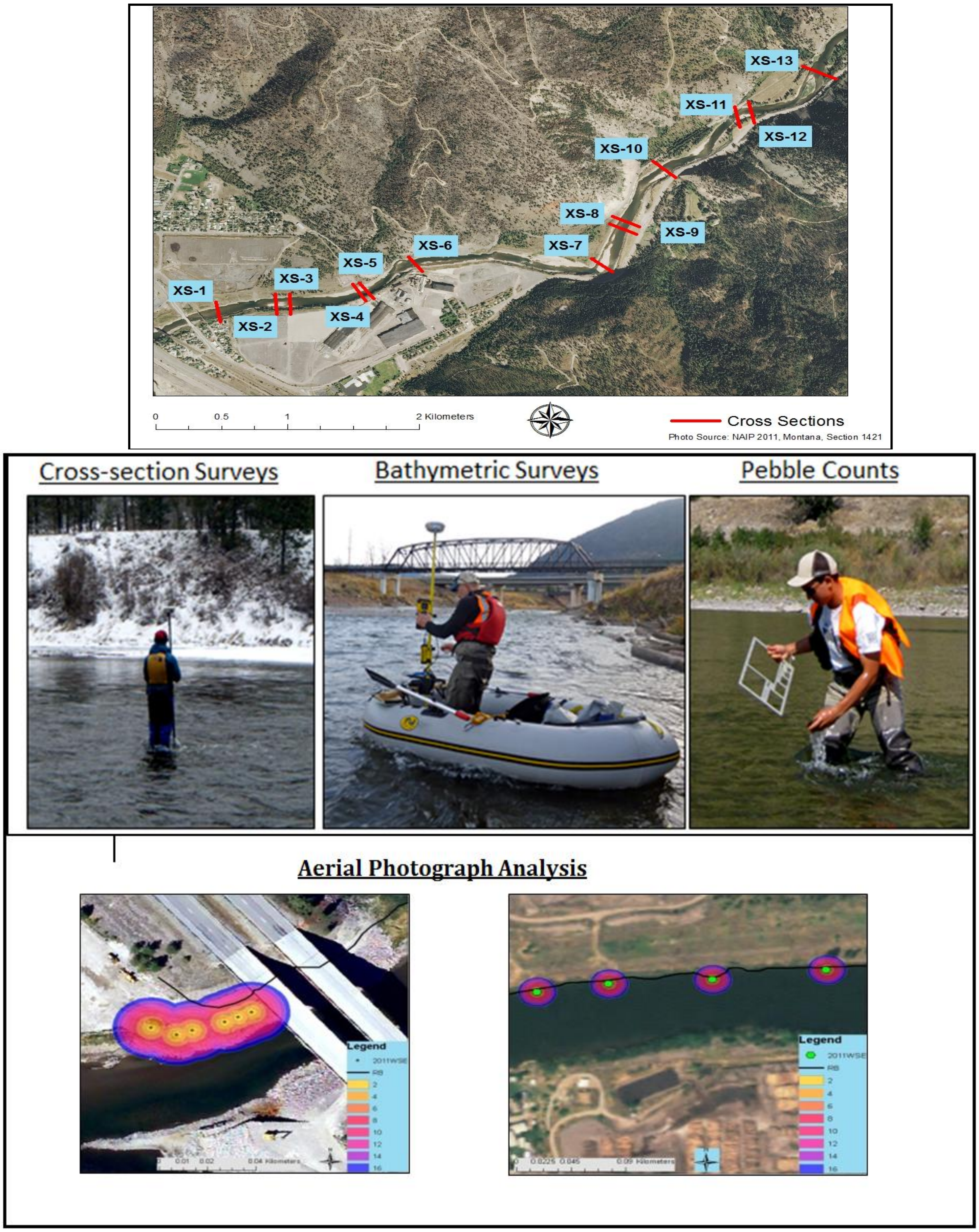


Figure 2. Top: Lower 5 km of Blackfoot River, showing location of survey cross-sections (red lines). Middle row: Field data collection methods included wading surveys with GPS (left), boat-based echosounder surveys (center), and pebble counts using a gravelometer (right). Bottom: Colored buffers represent bank full water surface elevation in 2011. The black line represents the right bank boundary of the downstream reach.

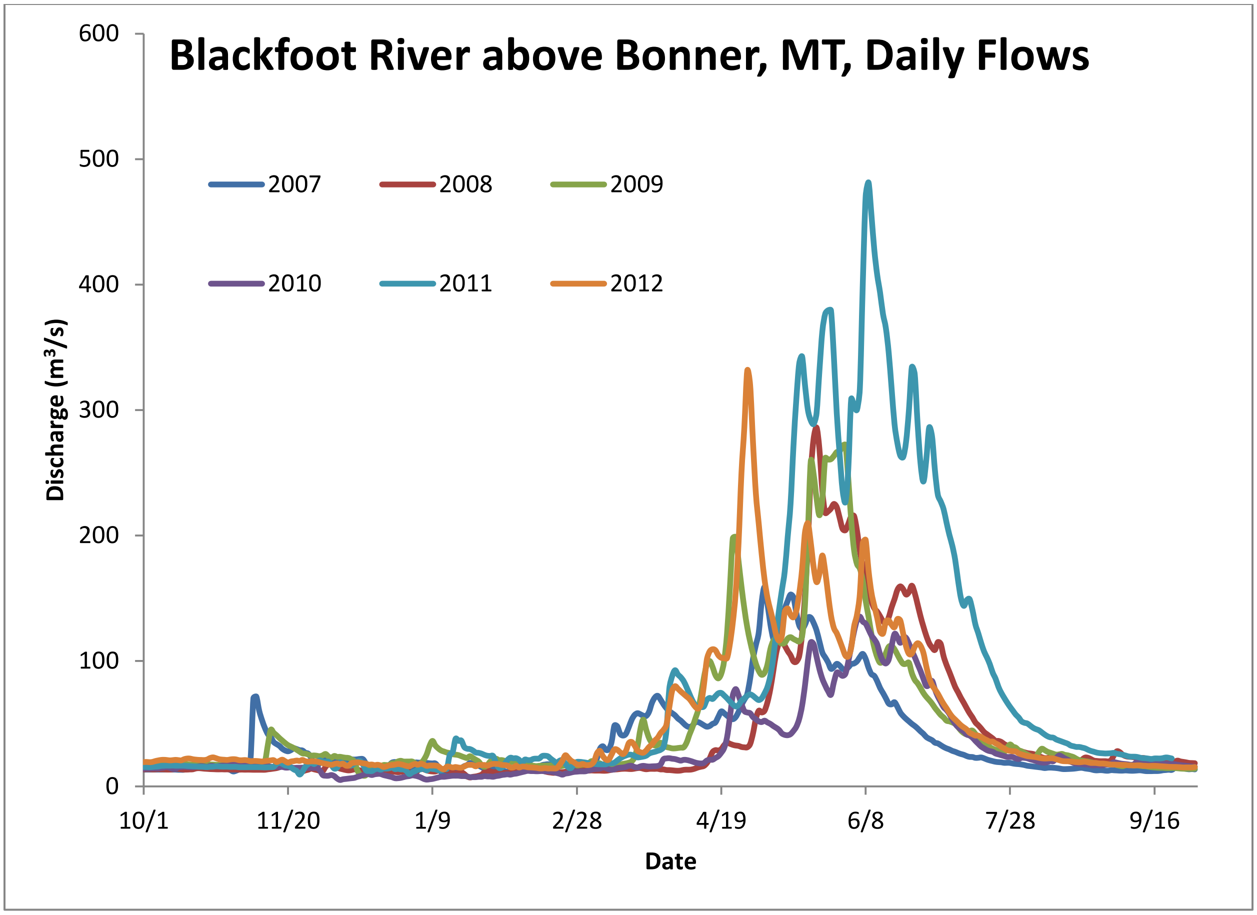
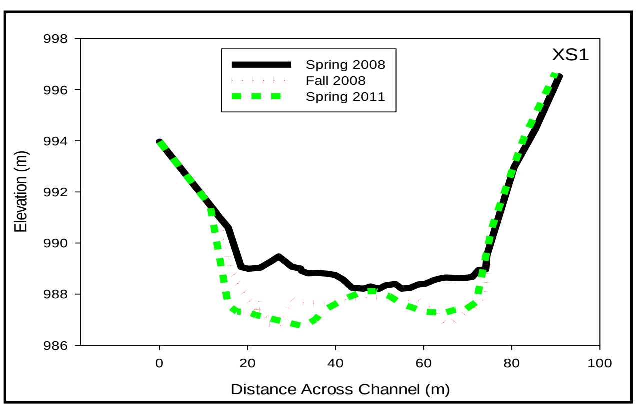


Figure 3. Blackfoot River annual flows for 2007 – 2012 water years (Bonner, MT: #12340000, Lat: 46°53'57.88", Long: 113°45'22.75



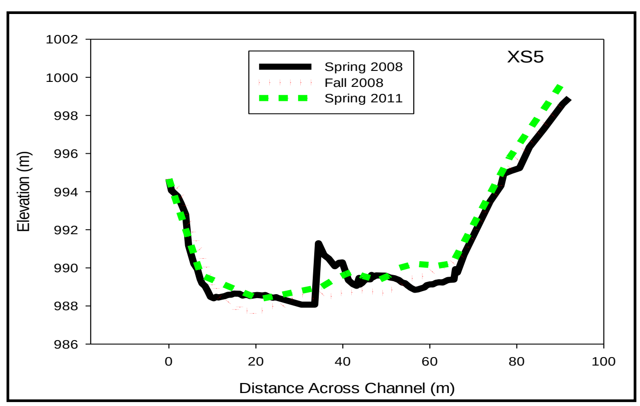


Figure 4. Example cross sections from lower Blackfoot River

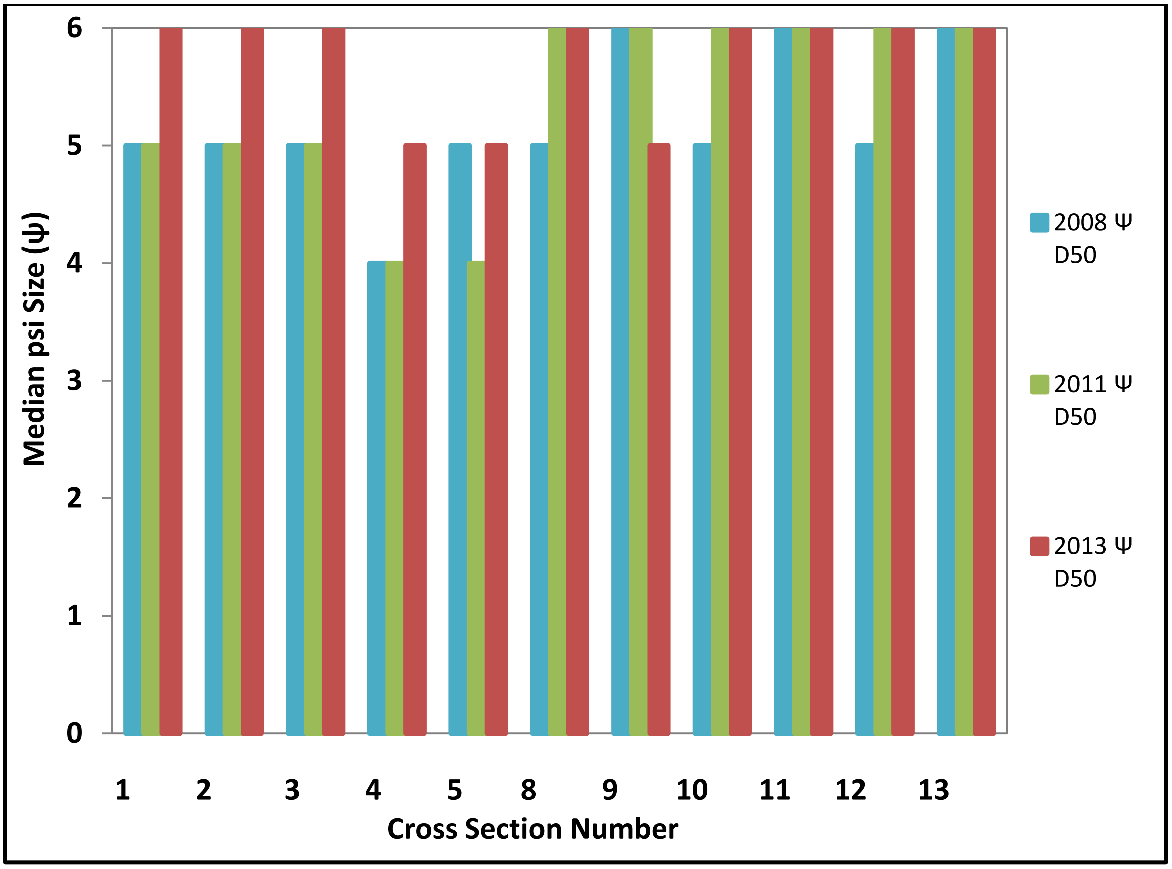
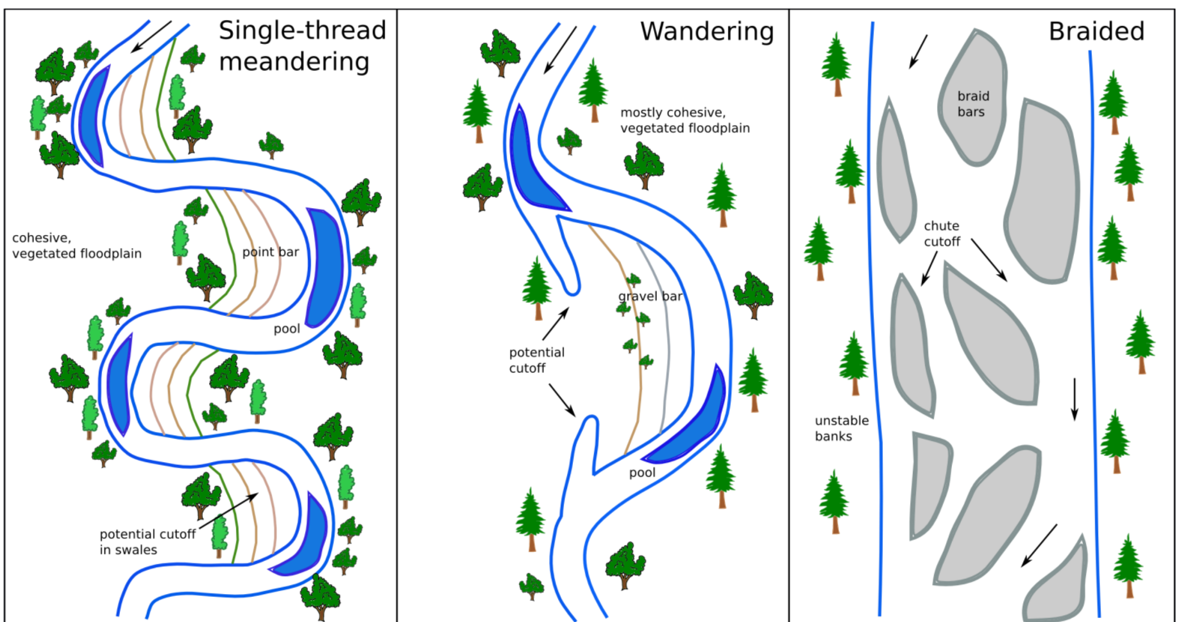


Figure 5. Bar chart represents the median psi size for each cross section recorded during 2008, 2011 and 2013. In general substrate size did not significantly change over the 4-year period represented by this chart.

2. *Investigation of flood effects on chute cutoffs in wandering gravel-bed rivers*

Another element of our research has been investigating the influence of overbank flow duration, and variations in sediment flux on chute cutoff occurrence and formation in wandering gravel-bed rivers (Figure 6). Chute cutoffs occur in rivers when a bypass or “chute” channel incises across a point or braid bar (Figure 7). Cutoffs act as unstable bifurcations that distribute water and bedload and suspended load sediment, regulate sinuosity, and create important off-channel aquatic habitat. Physical controls on cutoffs have been described primarily on high-sinuosity, meandering, lowland rivers (Figure 8). In wandering rivers, at the transition from meandering to braiding, cutoffs are prevalent and maintain channel form (Figure 6), but these processes have not been well documented. This research, which is part of the ongoing M.S. research by April Sawyer, is using a two-dimensional hydrodynamic model to simulate a range of steady flows (variable magnitude, frequency and duration) for the Clark Fork River in order to model cutoffs in the newly restored reach upstream of Milltown Dam during 2011 floods (Figure 9). These simulations are seeking to isolate the specific effects of overbank flow duration on erosional work in chute cutoff channels. Modeling is being used to compute spatially variable hydraulic conditions (e.g. depth, velocity and shear stress) in the Clark Fork River over a long duration flood hydrograph to identify and track zones of steep shear stress gradients (Figure 10). The modeling is being supplemented with historical aerial photograph and USGS bedload and suspended load dataset analyses for several gravel-bed rivers (Figure 11). These analyses are being used to document and describe chute cutoffs across a range of river settings near the meandering to braiding transition (i.e. wandering). This work has implications for river restoration, flow and habitat management, and interpreting alluvial valley stratigraphy.



Sediment Caliber	silt/sand	gravel/sand	gravel or sand
Sediment Supply	moderate	moderate	high
Channel Gradient	low	moderate	moderate/high
Bank Stability	high	moderate/spatially variable	low
Sinuosity	high	low/moderate	low
Width/Depth	low	moderate	high

Figure 6. Alluvial river channel morphology and principal governing factors along the transition from meandering to braiding.

Figure 7. Time series illustrating channel evolution toward, and culminating in, chute cutoff on the Bitterroot River. From 2006 to 2009, meander migration occurs, and initial chute cutoff formation at the upstream bar and a backwater/swale downstream is evident in 2009. In 2011 (post-2011 flood) chute cutoff has developed across both bars and initial deposition of a chute bar plugging the former main channel has occurred. By 2013, deposition of bedload and fine sediment has resulted in abandonment of the former main channel.

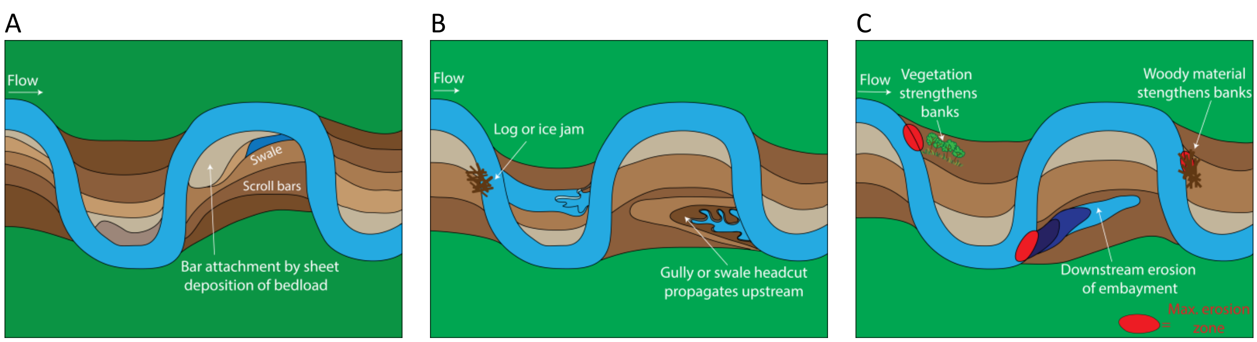


Figure 8. Three mechanisms of chute cutoff: scroll ridge and swale growth (A), headcut (B) and downstream erosion at embayment (C).

Figure 9. Multi-year setup and trigger (May – July 2011 overbank flow, 75 days above Q_{bf}) of the upper chute cutoff on the Clark Fork River above the Milltown Dam restoration.

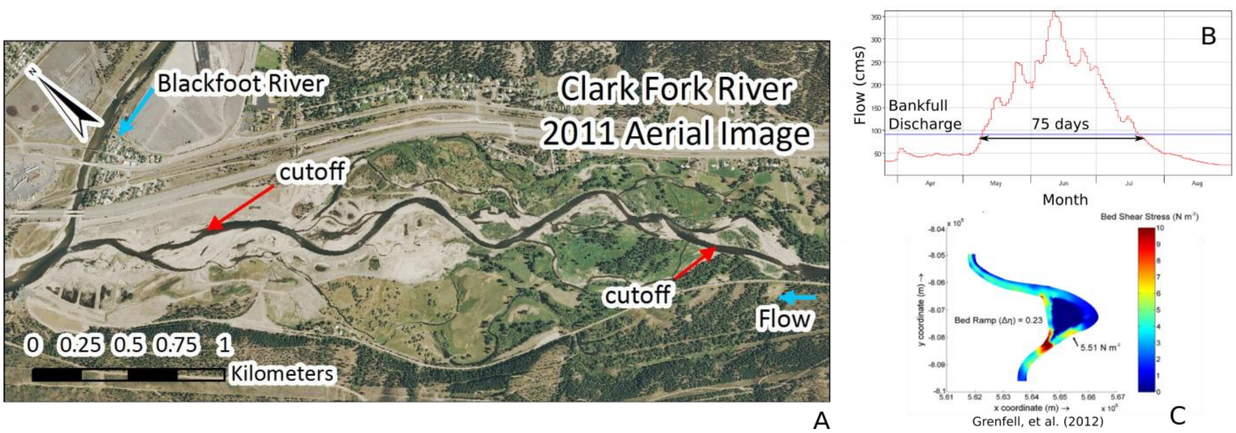


Figure 10. Clark Fork River 2D modeling study area. A) Note two cutoffs, upstream initiated between 2006 and 2009 and downstream initiated during 2011. B) Spring 2011 hydrograph. C) Example of spatially variable shear stress at a meander bend with a cutoff computed using a 2D model.

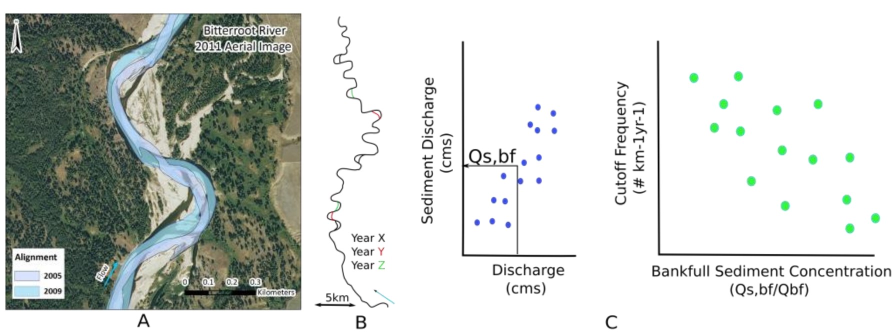


Figure 11. Examples of metrics for analysis of gravel-bed river reaches across the Rockies and Pacific Northwest. A) Description of setup periods and documentation of trigger events using aerial photographs as in Figure 7 on the Bitterroot River. B) Cutoff frequency is being mapped in time and space near USGS gages. C) Bankfull sediment concentration is being computed from sediment rating curves as available. Cutoff frequency will be plotted against bankfull sediment concentration.

3. Uprooting thresholds for pioneer woody riparian trees

A third element of our research has investigated thresholds required to uproot pioneer woody riparian trees, which may be uprooted by river flows if they are subjected to drag forces greater than their anchoring force (Figure 12). We tested species (*Populus*, *Salix*, and *Tamarix*), grain size, and river regulation effects by targeting field sites characterized by different hydrology and substrates, including an unregulated gravel-bed (Bitterroot River, MT; Figure 13), an unregulated sand-bed (Santa Maria River, AZ), and an impounded sand-bed river (Bill Williams River, MT). The effect of scour on decreasing anchoring force was tested by excavated seedlings 10 – 40 cm and repeating uprooting tests. We measured seedlings' anchoring force by uprooting seedlings (1-5 yrs. old) laterally to simulate flood flows (Figure 13). Statistical analyses compared the uprooting force for each species, site, and scour treatment. Although statistically significant ($p < 0.05$) species and site differences in anchoring force were found, scour depth was the dominant factor controlling anchoring force. We set driving forces (drag force) equal to resisting forces (anchoring force) and solved for the threshold velocity at or above which seedlings would uproot. The mean uprooting velocities for all species and sites were greater than modeled flood velocities, indicating drag forces alone are unlikely to uproot seedlings. The 30 and 40 cm scour treatments decreased the mean uprooting velocities to values seedlings may experience during flood events. Our results imply sediment transport in the form of scour must play a major role in dictating seedling uprooting in rivers, and should therefore be incorporated into our understanding of their ecology and management. This work is one part of PhD research by Sharon Bywater-Reyes, and a manuscript is in preparation.

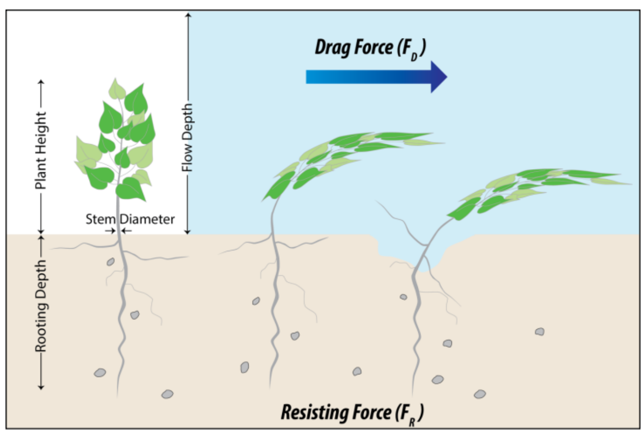


Figure 12. Conceptual model of seedling uprooting, whereby river flow subjects a seedling to a drag force (F_D) which, if it is greater than the resisting force of the roots (F_R), uproots the seedling. Scour may reduce F_R, lowering F_D required to uproot a seedling.

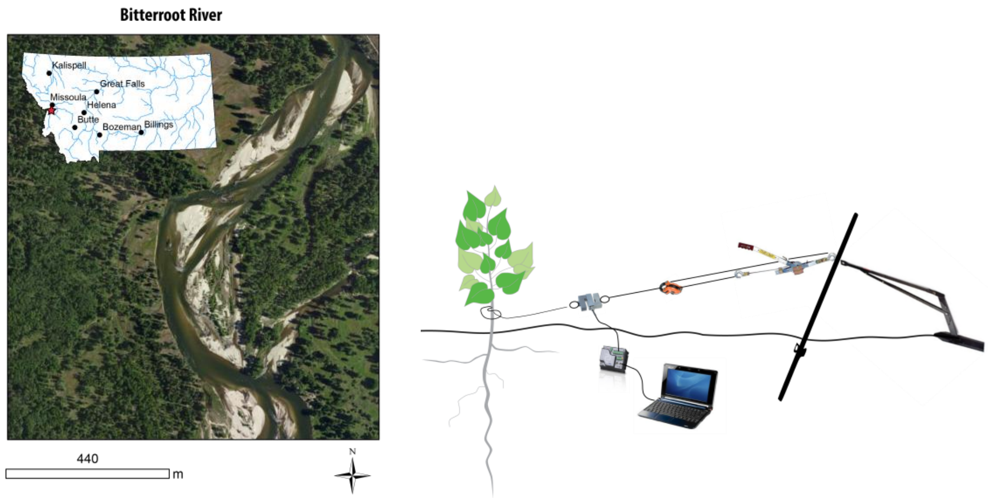


Figure 13. Left: The Bitterroot River (BRR) flows from south to north within its floodplain of Ponderosa and gallery *Populus* forests (Bing Imagery). Right: Pull tests were conducted by uprooting seedlings from manually saturated sediments with a rope tied near the base of the seedling, hand winch, and counterweight. Maximum pullout force (F_R) was recorded using a load cell and datalogger.

4. *Geomorphic changes along the Clark Fork River downstream of the former Milltown Dam site associated with 2011 floods*

Wilcox's research group has been studying the geomorphic effects of the Milltown Dam removal since 2008, when the dam was breached. That work was largely supported by a NSF grant and an earlier Montana Water Center / USGS grant. A continuation of that work was supported by this grant. The continuation work focused on studying the effects of the 2011 floods on the Clark Fork, building on earlier post-Milltown-dam removal studies, and included repeating photographs at photo points along the Clark Fork River to provide visual documentation of channel changes, and repeat surveys of bar topography along the Clark Fork (Figures 14 and 15).

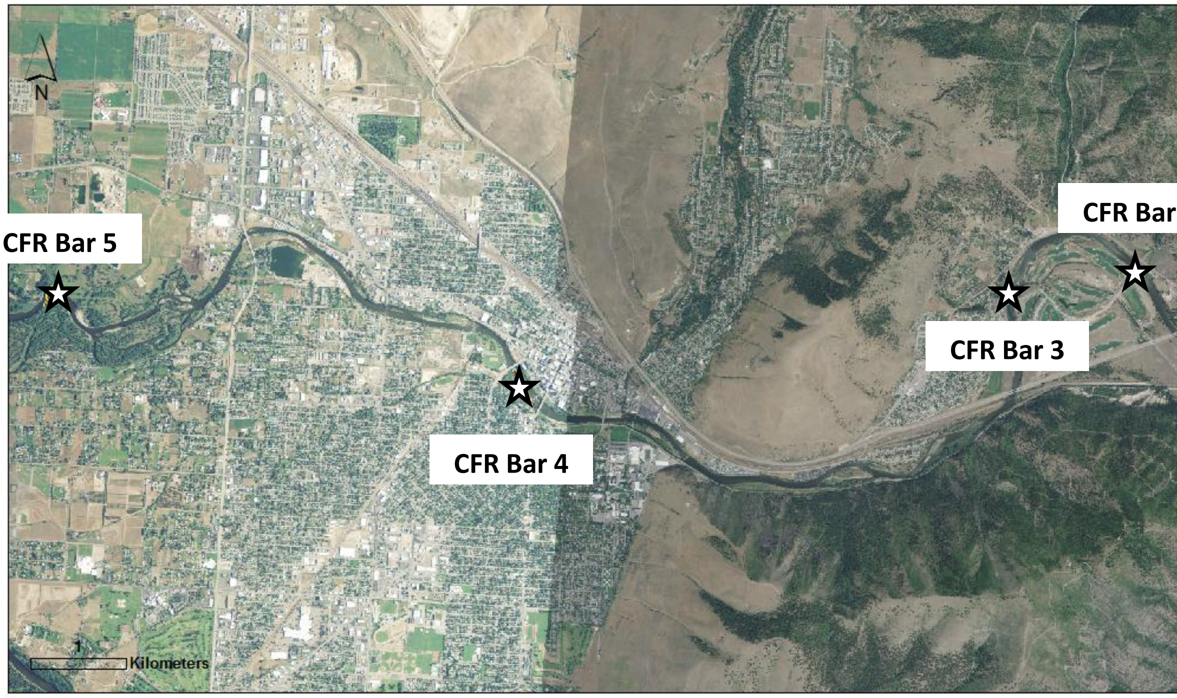


Figure 14. Location map of the Clark Fork River in the vicinity of Missoula, MT indicating the locations of bars surveyed in 2008 and in this study (2011).

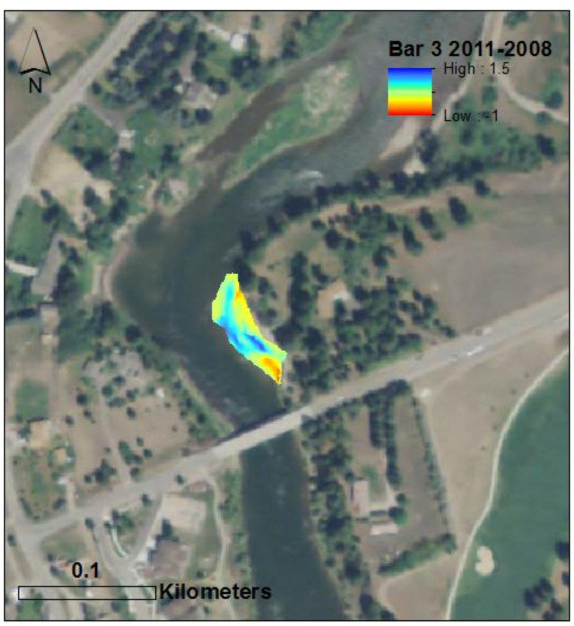


Figure 15. Digitial Elevation Model showing topographic difference between 2008 and Fall 2011, for Bar 3 (left), indicating deposition in the central portion of the bar and erosion on the up-stream and down-stream tails of the bar; and Bar 5 (right), indicating erosion in the side-channel feature and deposition on the river-side of the bar. Note that the dramatic change and deposition that occurred here is not captured well by the DoD. Legend is in meters.

List of presentations related to this research

Bywater-Reyes, S., A. C. Wilcox, A. Lightbody, K. Skorko and J. C. Stella, 2012, Uprooting force balance for pioneer woody plants: A quantification of the relative contribution of above- and below-ground plant architecture to uprooting susceptibility: American Geophysical Union Annual Meeting 2012, EP41A-0768.

Bywater-Reyes, S., A. Wilcox, J. Stella and W. Woessner, 2012, Scour susceptibility of Black Cottonwood on the Bitterroot River, Montana: Insights for successful restoration of riparian areas: American Water Resource Association Montana Section Annual Meeting, 2012.

Colaiacomo, E. and A.C. Wilcox. 2012. "Downstream spatial and temporal response to dam removal: Reach and bedform scale variations in transport capacity, White Salmon River, Washington." Poster, Montana AWRA Annual Meeting, 10-12 October, Fairmont, MT.

Livesay, R. and A. Wilcox. 2013. Investigating upstream channel response to dam removal, Blackfoot River, MT. GSA Rocky Mountain section meeting. Geological Society of America *Abstracts with Programs.* Vol. 45 (5).

Wilcox, A.C., H. Langner, L. Eby and S. Sullivan. 2013. Linkages Between Geomorphology, Geochemistry, and Aquatic Ecology in Mining-Impacted Headwater Streams: Mike Horse Mine Complex, Upper Blackfoot River Basin, Montana. Montana AWRA Annual Meeting, 3-4 October. Bozeman, MT.

Do Sediments in the Warm Springs Ponds Operable Unit Act as A Sink for Organic Wastewater Compounds?

Basic Information

Title:	Do Sediments in the Warm Springs Ponds Operable Unit Act as A Sink for Organic Wastewater Compounds?
Project Number:	2013MT279B
Start Date:	3/1/2013
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	MT01
Research Category:	Water Quality
Focus Category:	Surface Water, None, None
Descriptors:	None
Principal Investigators:	Katie Hailer, Stephen Parker

Publications

There are no publications.

Do Sediments in the Warm Springs Ponds Operable Unit Act as a Sink for Organic Wastewater Compounds?

Principle Investigator: Dr. Katie Hailer, Assistant Professor , Dept. of Chem. & Geochem., Montana Tech, Butte MT 59701; 406-496-4117; 406-496-4135(fax); khailer@mtech.edu
Co-Investigator: Dr. Stephen Parker, Professor , Dept. of Chem. & Geochem., Montana Tech, Butte MT 59701; 406-496-4185; 406-496-4135(fax); sparker@mtech.edu

Interim Report: Project summary/update – May 1, 2014.

Abstract:
This project will identify and quantify a selection of 11 organic wastewater chemicals in Silver Bow Creek and Warm Springs Ponds. These compounds originate from human and animal waste discharges and are potentially bioactive and can have harmful effects on plant and animal species living in the downstream systems. During the period from June 2013 through April 2014 two undergraduate students have participated in project work and developed a methodology for the analysis of the target compounds using liquid chromatography coupled with tandem mass spectrometry. Environmental samples will be processed and analyzed during the summer of 2014. Additionally, a graduate student will begin the gas chromatography-mass spectrometry portion of the project starting in May 2014.

Project rationale:
Organic wastewater chemicals (OWCs) originate from human or animal wastewater discharges to the environment. These compounds represent a broad range of contaminants, including hormones, pharmaceuticals, industrial chemicals, pesticides, and personal care products. Many of these chemicals have been shown to interfere with the endocrine system of both animals and humans at very low concentrations. Surface and groundwater studies have received the most attention by researchers studying OWC occurrences and effects on the environment. Fewer studies have focused on storage and/or movement of these chemicals in lake or pond sediment. This investigation will document the occurrence and concentration of a selected and representative set of pesticides, hormones and pharmaceuticals in the sediment of Warm Springs Ponds Operable Unit (WSPOU), a settling pond for the partially remediated Silver Bow Creek west of Butte, MT.

Project Objectives:

1) Assess sediment cores from WSPOU to determine the occurrence and concentration of a target set of pesticides and endocrine disruptors.

2) Investigate the possible movement of OWC contaminants from the sediment back in to the bulk water column using a series of leaching experiments.

Progress to date:
Summer 2013 - The investigators became familiar with the equipment (liquid chromatography system coupled with an ion trap mass spectrometer; LC-MS) during the spring of 2013 after the project award was made. Sample bottles, analytical standards, solvents and other materials were purchased at the same time. During the summer of 2013 undergraduate student Heidi Reid was recruited to begin work on this project. Ms. Reid was funded through the Summer Undergraduate Research Fellowship (SURF) at Montana Tech. With the help of the investigators she participated in preparing standard solutions;

learning how to run the instrument; and programming and developing the analytical methodology based on EPA Method 1694. Ms. Reid began running the instrument and developing baseline values for the analytes of interest that are being investigated using LC-MS (the antibiotics ciprofloxacin, sulfamethoxazole, and triclosan; the pharmaceuticals carbamazepine, gemfribrozil, and naproxen; the fungicides miconazole and thiabendazole;).

Most of June 2013 was spent learning the intricacies of operating the LC-MS, improving instrument response and developing the MS-MS methodology to be able to confirm the presence of the analytes of interest. During July 2013 Ms. Reid was able to resolve mixtures of the standards and confirm the presence of each compound in the mixture. Next she prepared serial dilutions of the concentrated standard mixtures and was able to identify the target compounds at lower concentration. However, the detection limits we were able to obtain were not in the range recommended by the EPA method. On July 23, 2013 we performed water sampling along Silver Bow Creek in order to obtain field samples in an attempt to test our method development to that point. We collected 2.5 L samples of filtered (0.45 µm) water at 5 sites ranging from the central Butte area above the Municipal Waste Water Treatment outfall to a location just above Warm Springs Ponds. At the same time we collected these water samples we also measured water temperature, pH, specific conductivity, dissolved oxygen and oxidation-reduction potential. Also, samples were collected for determination of dissolved inorganic carbon, dissolved organic carbon and the $\delta^{13}C$ of each of these carbon pools.

Another phase of method development was a concentration step for the water collected in the field. Solid phase extraction (SPE) cartridges were used to remove the target compounds from the sample water and then the SPE cartridges were eluted with a small volume to produce a laboratory sample that should be about 600-fold more concentrated than that collected. Ms. Reid ran these samples using the LC-MS method we had developed. We obtained weak signals for one of the target analytes, carbamazepine. This did prove that the method was working but our inability to reach the necessary low-level detection limits hindered our ability to get a true picture of the contaminants in the water samples we collected. At this time we reached the end of the summer undergraduate research program. Heidi presented a poster detailing her accomplishments. That poster can be found on the Montana Tech Library Digital Commons[1].

In fall of 2013 undergraduate student Brandon Mus started on the project when Heidi Reid ended. His portion of the project was slowed by several instrument problems which delayed progress. He spent Sep and Oct reading the background literature and learning about the instrumentation. During Nov and Dec he began running samples and working with the instrument settings to try to improve the detection limits which was the problem encountered by Ms. Reid. In Jan-2014 Brandon started establishing profiles for each target compound with the improved instrument settings; finishing this in Feb. Finally in April of 2014 Brandon was able to complete the LC-MS method development and obtain good instrument performance for all the target analytes except thiabendazole. Brandon will continue to work on this project through the summer (Jun, Jul, Aug-2014) and analyze field samples from Silver Bow Creek and Warm Springs Ponds.

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[1] http://digitalcommons.mtech.edu/urp_aug_2013/3/

Also, during the summer of 2014 graduate student Delilah Friedlander will begin method development with the GC-MS to analyze for DEET, 17-α-ethynylestradiol and 17-β-estradiol. The method (USGS) will also be able to detect and quantify several of the analytes that we are examining by LC-MS and will give us corroboration of our method success.

Student Fellowship: Rephotography as a tool to Understand the Effects of Resource Use on Rivers of the Greater Yellowstone Region

Basic Information

Title:	Student Fellowship: Rephotography as a tool to Understand the Effects of Resource Use on Rivers of the Greater Yellowstone Region
Project Number:	2013MT280B
Start Date:	3/1/2013
End Date:	2/28/2014
Funding Source:	104B
Congressional District:	MT01
Research Category:	Biological Sciences
Focus Category:	Surface Water, None, None
Descriptors:	None
Principal Investigators:	Heidi Clark

Publications

There are no publications.

Student Fellowship: Rephotography as a tool to Understand the Effects of Resource Use on Rivers of the Greater Yellowstone Region

Heidi Clark, Land Resources and Environmental Sciences, Montana State University

ABSTRACT

Repeat photographs provide a glimpse of the past and thus tell a story of how man and nature have shaped the landscape. With the use of repeat photography based on on-the-ground oblique images, this study investigated how historical natural resource uses (e.g., logging, mining, ranching, and dam building) have affected headwater rivers of the Greater Yellowstone Ecosystem (GYE). These rivers included the Gallatin, Yellowstone, Wind, Gros Ventre, Snake, Madison, and Green Rivers along with several of their tributaries. Oblique photo pairs or series of photos were compared using three types of analyses: quantitative pixel comparisons, rank order statistics, and individual descriptions, in order to identify changes in riparian vegetation cover, sinuosity, bankfull, and flood plain area. Additionally, additional data from a stream reach of the upper Yellowstone River in Paradise Valley, Montana, allowed for aerial comparisons to quantify vegetation cover and sinuosity within photo frame wedges of corresponding oblique photos. The results of the comparisons revealed: (1) increased riparian vegetation where anthropogenic perturbations had ceased, indicating resilience and recovery; (2) decreased riparian vegetation and sinuosity where impacts intensified; and (3) little change in riparian vegetation where human natural resource use continued at a similar intensity. Application of this methodology to more photo points and other regions will provide a better understanding of the extent of previous threats and how river systems have responded or continue to counter ongoing anthropogenic impacts.

SUMMARY

Since the fall of 2011, I have been working with Dr. Duncan Patten on a historical repeat photography project to show how both human and natural forces have affected the headwater rivers of the Greater Yellowstone Ecosystem (GYE) over the last one hundred years. We intend to create two documentary books (one on the Gallatin River and the other on the rivers of the GYE), displaying the repeat photographs and text to describe both natural and human induced changes.

My M.S. thesis research focused on the impacts of historical natural resource use (e.g., logging, mining, ranching, and dam building) on the rivers in the GYE using repeat photography as a tool to examine riverine change over the last century. I utilized 54 photo comparisons to describe changes in rivers over time through photo comparison descriptions, ranks of change, and land cover pixel quantifications. After two field seasons retaking photos and two years of graduate classwork, I completed my thesis in April 2014 and will graduate in May. I will continue to work with Duncan on the repeat photography books.

My thesis photo comparisons indicated how historical timber harvest, agriculture, and domestic grazing influenced rivers in the GYE. Tie drive comparisons revealed recovery, yet still showed signs of former impacts. Even though photo comparisons along with previous research indicated impacts of tie driving, all of the tie drive photo comparisons showed signs of recovery, including: increased vegetation along riverbanks, decreased scouring, and increased instream heterogeneity, especially in former dammed locations (Figure 1 and Figure 2). Comparisons of dam photos indicated how dams have dramatically influenced upstream and downstream riverine regions. Overall these comparisons revealed that dam construction leads to channelization, cottonwood forest maturation along the rivers, reduced sediment aggradation, and decreased cottonwood and willow recruitment and establishment on sediment bars within channels (Figure 3 and Figure 4). Photo comparisons of agriculture suggested three trends: 1) increased vegetation, 2) decreased vegetation, and 4) relatively little change in vegetation (Figure 5, Figure 6, and Figure 7).

Of the many forms of historical data, repeat photography provides a unique and valuable way to analyze change over time. Photographs capture glimpses of ecosystems and thus can convey information on many different variables (e.g., vegetation, geology, and geomorphology). Historical oblique photos offer a wider span of time than historical aerial photos; however, when coupled these two sources provide a more detailed understanding of a site. Additionally, the visual aspect of repeat photography allows this tool to serve as a vector between the scientific community and general public because photographs portray change in a more apparent and understandable than scientific graphs and descriptions. With a better understanding of habitat resilience and riverine processes people can restore degraded rivers, provide guidelines for sustainable resource industries, and supplement conservation studies.

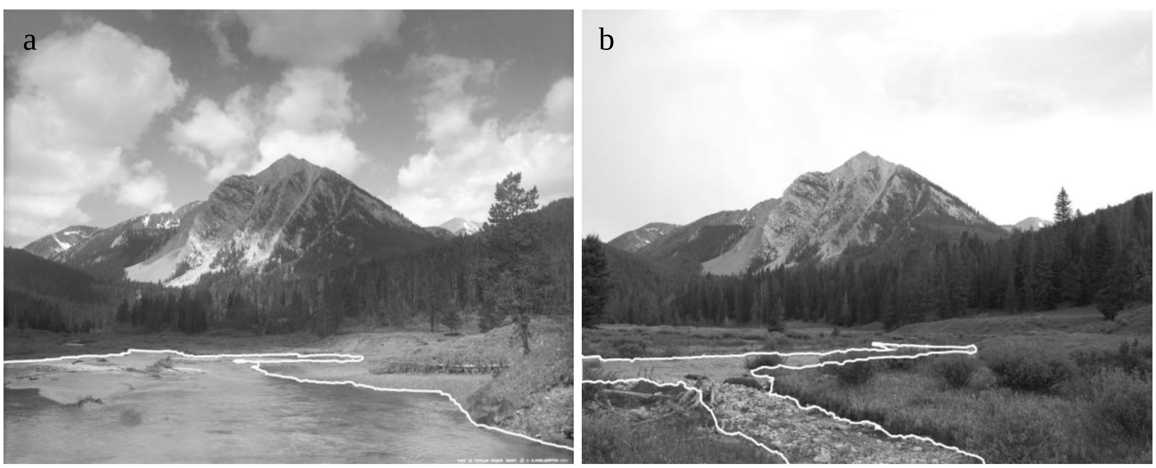

Figure 1. Behind a surge dam, near the base of Koch Peak, Taylor Fork, MT (photo point 181) a. Schlechten, Albert 1911, Courtesy of Museum of the Rockies. b. Clark, H.M 6/29/2013.

Figure 2. Warm River, tributary of the Wind River, WY (photo point 413) a. Unknown ca. 1940, Courtesy of Dubois Museum. Clark, H.M. 6/9/2013.

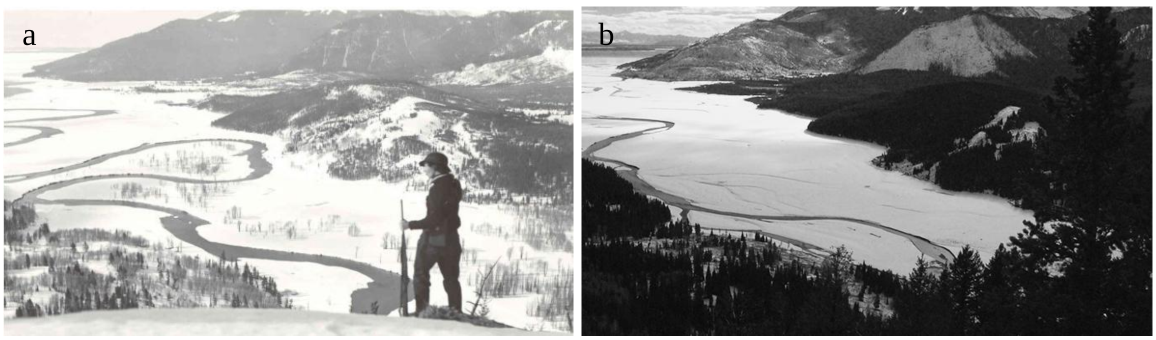

Figure 3. Just upstream of Jackson Lake, Snake River, WY (photo point 279) a. Unknown ca. 1930s, Courtesy of Museum of the Rockies. b. Clark, H.M. 11/9/2013.

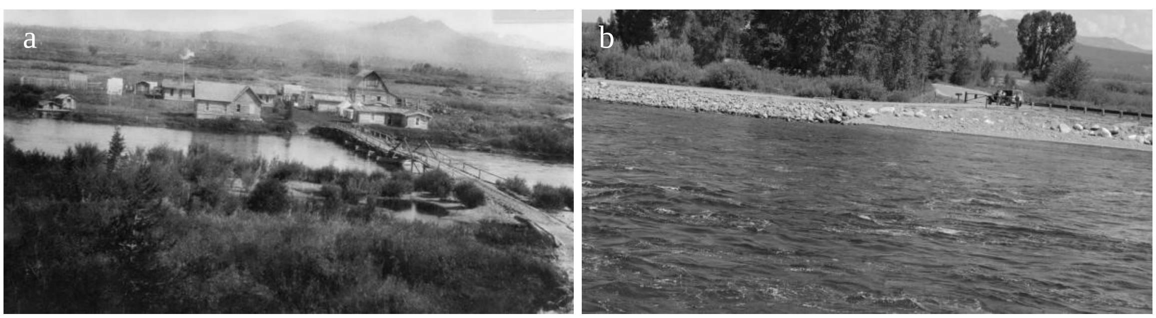

Figure 4. Downstream of Jackson Lake Dam, WY (photo point 388) a. Unknown est. 1900s, Courtesy of Jackson Hole Historical Society. b. Clark, H.M. 7/4/2013.

Figure 5. Downstream of Point of Rocks, Yellowstone River, MT (photo point 304) a. Walcott, C.D. 1898, Courtesy of USGS. b. Clark, H.M. 8/7/2013. Quantified polygons are outlined in white.

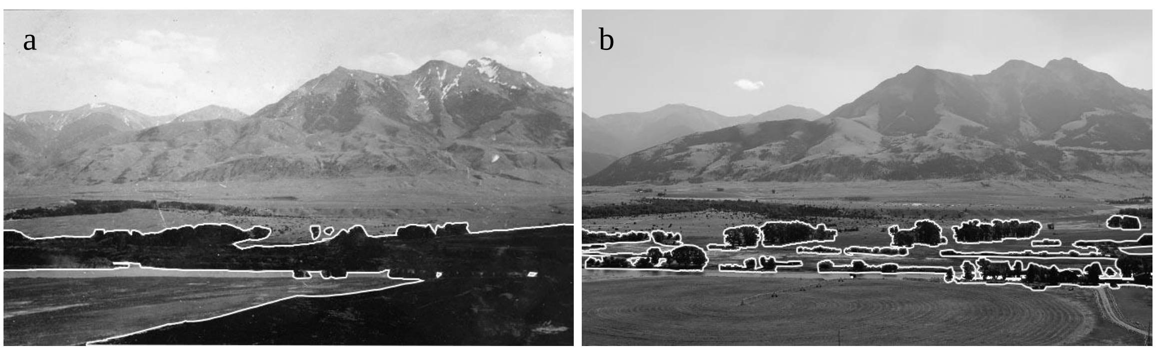

Figure 6. Near historical Bottler's Ranch, Yellowstone River, Emigrant, MT (photo point 325) a. Alden, W.C. 1922, Courtesy of USGS. b. Clark, H.M. 8/25/2013. Quantified polygons are outlined in white.

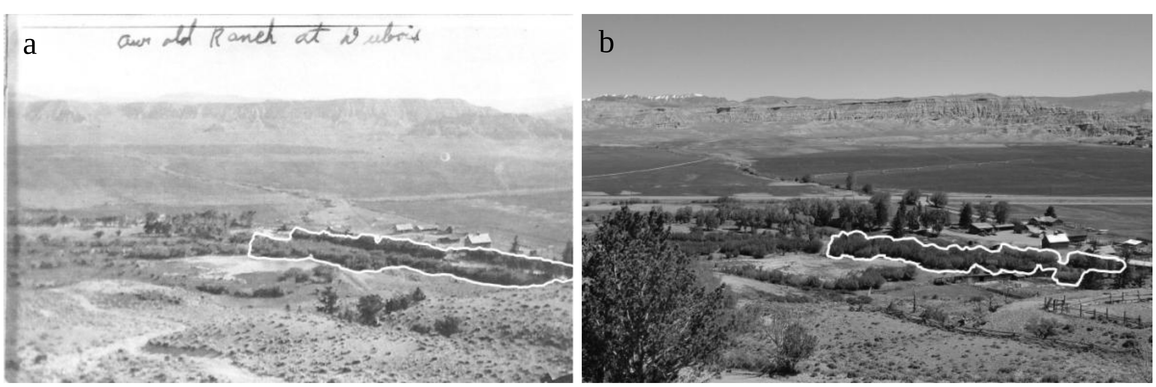

Figure 7. Warm River Ranch, Wind River, WY (photo point 398) a. Unknown ca. 1940, Courtesy of Dubois Museum. b. Clark, H.M. 6/9/2013. Quantified polygons are outlined in white.

Student Fellowship: Maintaining Migratory Pathways of Imperiled Large River and Small Stream Prairie Fishes in the Face of Climate Change

Basic Information

Title:	Student Fellowship: Maintaining Migratory Pathways of Imperiled Large River and Small Stream Prairie Fishes in the Face of Climate Change
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Student Fellowship: Title: Maintaining Migratory Pathways of Imperiled Large River and Small Stream Prairie Fishes in the Face of Climate Change and Energy Development

David Dockery, USFWS Pathways intern, Masters Student, Ecology Department, College of Letters and Science – Montana State University, Bozeman, MT 59717-4250, (406) 599-5649, dockery.david@gmail.com

Dr. Matt Blank., Assistant Research Professor, Western Transportation Institute and Civil Engineering Department, College of Engineering – Montana State University, Bozeman, MT 59717-4250, (406) 994-7120, mblank@coe.montana.edu

Kevin Kappenman, Fisheries Research Biologist, U.S. Fish and Wildlife Service, Bozeman Fish Technology Center, USFWS, 4050 Bridger Canyon Rd, Bozeman, MT 59715, phone (406) 994-9917, fax (406) 586-5942, kevin_kappenman@fws.gov

Dr. Tom McMahon, Professor of Fisheries, Ecology Department, Montana State University, Bozeman, MT 59717-4250, (406) 994-2492, tmcmahon@montana.edu

Summary - This report provides an update for the project period May 1, 2012 to April 15, 2014. The research described is based on a fish passage project aimed at characterizing the swimming abilities and the effects of temperature on swimming abilities for 1) sauger and 2) small-bodied minnows native to the northern plains and prairie potholes ecoregion. The work is being performed by a partnership led by the Western Transportation Institute at Montana State University, the Fish and Wildlife program at Montana State University, and the Bozeman Fish Technology Center (BFTC) of the United States Fish and Wildlife Service.

Abstract – Habitat fragmentation in freshwater systems can threaten the viability of freshwater and anadromous fish populations through direct loss of spawning and rearing habitat, loss of gene flow between isolated populations, and prevention of movements that may be necessary to obtain food or avoid deleterious local conditions. The swimming abilities of longnose dace *Rhinichthys cataractae*, one of the most widely distributed minnow species, were quantified using a 10 meter section of an open-channel flume which approximates the length of many culverts. Maximum distance of ascent was measured at 0.30, 0.45, 0.55, and 0.65 m/s at 10, 15, and 19 C. Performance was volitional, with fish volitionally entering the open-channel from a small holding area. The data will be used to generate models of maximum distance of ascent taking water velocity, body weight, and temperature into account. These models will provide the information necessary to properly design culverts and other fish passageways and identify instream barriers for longnose dace. A coerced sprint test in the open-channel flume was used to characterize the maximum swimming velocity of longnose dace, which can be used to identify barriers and set maximum allowable water velocities of instream structures. Similarly, a sprint test was used to characterize the maximum swimming velocity of sauger *Sander canadensis* and an open-channel flume test was used to assess the ability of sauger to ascend an open-channel over a range of hydraulic conditions. Additionally, an incremental velocity test in a swim chamber, referred to as an 'Usprint' test, was used to determine the length of time sauger could sustain burst swimming.

Introduction

Habitat fragmentation in freshwater ecosystems can threaten the viability of freshwater and anadromous fish populations through the direct loss of spawning and rearing habitat, loss of gene flow between isolated populations, and prevention of migrations that may be necessary to obtain food or avoid deleterious local conditions. Dams on large rivers that block spawning tributaries are suspected to be the primary factor associated with the rapid decline of sauger (*Sander canadensis*) populations throughout the plains and prairie potholes ecoregion (Hesse 1994). On small prairie streams, improperly designed or constructed culverts associated with road crossings are suspected to be a major cause of habitat fragmentation for many species of native minnows (Bouska 2010). Creating fishways around dams for sauger and properly designing road-stream crossings for minnows requires knowledge of each species swimming capabilities. In both cases, little is known about the swimming abilities of these species of concern. Without a better understanding of how these and other fish species swim, efforts to restore connectivity are likely to be less successful or in some cases completely unsuccessful. The purpose of our study is to characterize the swimming abilities of sauger and select minnow species native to the plains and prairie potholes ecoregion so that aquatic barriers can be identified, eliminated or retrofitted, and new instream structures can be properly designed and constructed in order to reconnect vital fish habitat. As climate change is expected to alter regional water temperatures, the effect of temperature on swimming performance will also be examined.

Fish swimming performance is generally described using three categories: sustained, prolonged, and burst swimming. Sustained swimming is the speed that the fish can maintain for an indefinite period of time (analogous to a human walking). Prolonged swimming is a moderate speed that can be maintained for several minutes to a couple of hours (analogous to a human jogging). Burst speed is the maximum speed that a fish can produce, usually maintainable for less than 15 seconds (analogous to a human sprinting) (Beamish 1978). Our research focuses on characterizing burst and prolonged swimming as these are generally believed to be the primary swimming modes used when fish are negotiating fishways and other potential instream barriers such as culverts, or when fish are moving through areas of higher velocities within streams and rivers. Increasing evidence in the literature suggests there is a large amount of intra-species variation in swimming abilities with some individuals being better ‘sprinters’ (i.e. burst swimmers), whereas others are better endurance swimmers (i.e. prolonged swimmers) (Reidy 2000, Kolok 1992, Kolok 1994, Nelson 1992). As different individuals will likely use different swimming modes to negotiate an instream barrier, multiple tests to characterize the different swimming modes are needed to fully assess the swimming abilities of a species and ensure that instream structures are properly designed to pass the majority of individuals in a population (Reidy 2000).

Fish swimming performance tests were conducted at the Bozeman Fish Technology Center utilizing two experimental tools: a large swim tunnel and an experimental open-channel flume (see Appendix C for photos). Swim tunnels have been used to characterize swimming performance for decades. However, recent studies suggest that swimming capabilities estimated from swim tunnels may substantially underestimate species abilities to navigate through fishways (Peake 2004). While swim data from swim tunnels still provides useful information for species comparisons and for estimating fatigue times and critical swimming velocities, swim trials with large, open-channel flumes that more closely mimic conditions fish experience in nature have proven to provide more realistic correlates of fish passage success in natural conditions. One key difference between these two types of experimental apparatus is that swim tunnels force fish to swim at a fixed point against flow, whereas studies in open-channel experimental flumes allow the fish to swim upstream through the flow under their own volition and thus provide more realistic assessment of swimming abilities. Together these tools provide a wide range of options for evaluating swimming abilities of different fish species over a range of flows, velocities, depths and temperatures. However, there are very few facilities for testing fish passage using open-channel flumes. The BFTC is uniquely suited to fish swimming testing, as both swim tunnels and a large test flume are available for characterizing swimming capabilities, with the additional unique capability of conducting swim experiments under different temperature conditions.

Objective 1: Characterize the Swimming Abilities of Sauger

Swimming performance experiments of sauger were completed during the 2012 project year. Video analyses of the data was completed in 2013 and data analysis is expected to be completed by May of 2014.

Sauger Swimming Experiments

During the spring of 2012 sauger (*Sander canadensis*) were collected from the Bighorn River near GreyBull, Wyoming. Sauger were chosen to represent a large-bodied, large river fish that has declined throughout the ecoregion due to habitat fragmentation. Because of the widespread decline of sauger in the Missouri drainage, the number collected was limited to fifteen, of which only twelve survived to the completion of experiments. Due to this small sample size, fish were used multiple times in each of the swimming performance experiments.

Swimming performance experiments to characterize the swimming abilities of sauger were completed during the summer of 2012. Three different experiments were performed: (1) an open-channel flume swimming experiment to assess the ability of a fish to ascend an open-channel over a range of hydraulic conditions, (2) a coerced 'sprint test' used to determine the maximum obtainable burst speed of a fish, and (3) an incremental velocity test, referred to as an "Usprint" test, to determine the length of time a fish could sustain burst swimming (see Appendix A for detailed methods). All experiments were conducted at multiple temperatures to determine the possible effects of temperature on swimming performance.

1) Open-Channel Flume Test

Open-channel flume swimming tests allow fish to volitionally ascend large-scale experimental channels (see Figure 1-3 of Appendix C for photos). These tests currently provide the best controlled testing to approximate natural conditions and allow fish to express normal upstream migratory behavior (Haro 2004).

At 17 meters in length, the open-channel flume approximates the length of a culvert or a fishway. By conducting tests over a range of temperatures and velocities, the results of this test could be used to predict passage in culverts or fishways with hydraulic conditions that lie within the range tested. Swimming tests occurred at all the combinations of three velocities (nominally 0.5 m/s, 0.77 m/s, and 0.92 m/s) and three temperatures (nominally 10 ^{o}C, 14 ^{o}C, and 18 ^{o}C), for a total of 9 tests. A specific combination of water temperature and water velocity was termed a hydraulic challenge (HC). Test water velocities and temperatures were chosen to represent a wide range of water velocities and temperatures. The average hydraulic conditions for the 9 different velocity and temperature combinations (HC1-HC9) are summarized in Table 1. All available fish swam in each hydraulic challenge. Each trial was video recorded and later analyzed to determine if fish successfully ascended the flume and also to measure fish swimming speeds (see methods description in Appendix A).

Progress: All open-channel flume swimming tests were completed during the summer of 2012. Video analysis and data entry were completed during the summer of 2013. Preliminary data analysis has begun and is expected to be finished at the end of May 2014.

Table 1: Summary of test conditions for sauger open-channel flume test

Sauger – Open-Channel Flume Test							
			Average Values of Flume Parameters				
Trial Number	Hydraulic Challenge	Date	Number of Fish Tested	Water Temperature	Flow	Velocity	Depth
				°C	m^3/s	m/s	m
1	1	8/23/2012	9	10.66	0.0616	0.48	0.305
2	2	6/4/2012	3	10.55	0.10024	0.717	0.32025
3	2	6/5/2012	9	9.61	0.10052	0.741	0.3294
4	3	6/11/2012	12	9.1	0.13356	0.891	0.35685
5	4	6/15/2012	11	14.14	0.13104	0.921	0.3294
6	5	6/19/2012	11	14.29	0.10668	0.789	0.2989
7	6	6/21/2012	11	14.46	0.06776	0.516	0.28975
8	7	6/27/2012	11	17.62	0.06944	0.519	0.2989
9	8	6/29/2012	11	18.4	0.10136	0.834	0.305
10	9	7/6/2012	11	18.83	0.14	0.939	0.3294

Note: Test at HC2 occurred over two days

2) Sprint Test

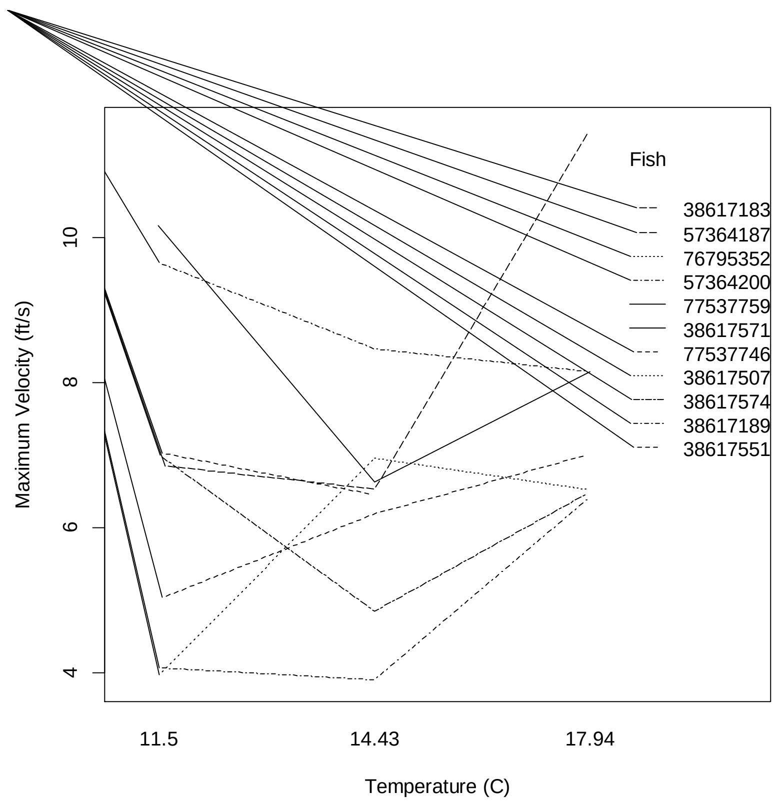
In the sprint test, fish were stimulated by gentle prodding them to initiate a swimming burst upstream through the entire length of the open-channel flume. The flume was set at a relatively low velocity to orient fish into the current but not force them to swim excessively. This test was designed to determine the maximum burst speed that sauger can attain. This information can be used for assessing if a fishway or instream structure is a barrier to sauger and over what range of flows it may serve as a barrier. Sprint tests occurred at three temperatures (11.5 °C, 14.5 °C, and 18 °C) to investigate possible temperature effects on burst swimming. A summary of the test conditions is supplied in Table 2 and the maximum burst speeds of individual sauger for each temperature are presented in Figure 1.

Progress: All sprint tests were completed during the summer of 2012. Video analysis and data entry were completed during the summer of 2013. Preliminary data analysis has begun and analysis is expected to be completed at the end of May 2014.

Table 2: Summary of test conditions for sauger sprint tests

Sauger-Sprint Test						
		Average Values of Flume Parameters				
Trial Number	Date	Number of Fish Tested	Water Temperature	Flow	Velocity	Depth
			˚C	m^3/s	m/s	m
1	7/27/2012	11	17.94	0.053	0.46	0.27
2	8/21/2012	9	11.50	0.053	0.46	0.27
3	9/25/2012	8	14.43	0.53	0.47	0.27

Figure 1: Maximum burst speed vs. temperature for individual sauger identified by PIT tag number.



3) Usprint Test

A 185 liter Loligo model swim tunnel (Loligo Systems, Tjele, Denmark) was used to conduct Usprint tests (see Figure 4 of Appendix C for picture). Swim tunnels allow for finer control of water hydraulics, temperature, and light conditions than large scale flumes; allowing precise control of confounding variables while examining the effects of temperature on swimming ability. Traditionally, swim tunnels have been used in fixed velocity (endurance) tests and incremental velocity (Ucrit) tests. Fixed velocity tests are conducted to determine the maximum time a fish can swim at a fixed velocity before exhaustion, whereas Ucrit tests are believed to be a measure of maximum aerobic swimming capacity. However, there is a growing body of literature that indicates that exhaustion is not reached in fixed velocity tests ('behavioral' exhaustion occurs first) and Ucrit tests underestimate the aerobic swimming abilities of fish (Peake 2004). For these reasons we decided to perform a newly developed method for swimming fish in a swim tunnel: the Usprint test (Starrs 2011). In this method water velocity is increased 0.25 ft/s every 15 seconds until exhaustion is reached. This test is designed to determine the maximum speeds obtainable by a fish and how long a fish can sustain these maximum speeds. The data from the Usprint test will complement the data from the sprint tests and allow for a comparison of the two methods, while also providing endurance information for sprint swimming.

Usprint tests occurred at 7 temperatures (~10 ^{o}C, 12 ^{o}C, 14 ^{o}C, 16 ^{o}C, 18 ^{o}C, 20 ^{o}C, and 22 ^{o}C) to investigate possible temperature effects on sprint swimming. The average hydraulic conditions for the 7 Usprint tests are summarized in Table 3.

Progress: Usprint tests were completed during the summer of 2012. Video analysis and data entry was completed during the summer of 2013. Data analysis is expected to be completed at the end of May 2014.

Table 3: Summary of test conditions for sauger Usprint tests

Sauger-Usprint				
Trial Number	Date	Group number	Number of Fish Tested	Average Water Temperature
				˚C
1	7/23/2012	1	6	22.25
2	7/25/2012	2	5	20.23
3	7/18/2012	1	5	18.11
4	7/30/2012	1	5	16.30
5	8/1/2012	2	6	13.98
6	8/3/2012	1	5	11.96
7	8/6/2012	2	6	10.02

Objective 2: Characterizing Swimming Abilities of Small-Bodied Minnows

Longnose Dace Swimming Experiment

During the spring of 2013, longnose dace (*Rhinichthys cataractae*) were collected from the Gallatin and Madison watersheds near Bozeman, Montana. Longnose dace were chosen due to their local presence and abundance in the surrounding watersheds, and because they have the widest distribution of any cyprinid in North America, with a range reaching as far south as the Rocky Mountains in northern Mexico and as far north as the Mackenzie River near the Arctic Circle, and across the continent from the Pacific to Atlantic coast. Additionally, longnose dace have a fusiform body shape typical of high performance swimmers, and were chosen to represent minnows with this more streamlined body shape.

Swimming experiments to characterize the swimming abilities of longnose dace were completed during the summer of 2013. Two different experiments were performed: (1) an open-channel flume swimming experiment to assess the ability of a fish to ascend an open-channel over a range of hydraulic challenges, and (2) a sprint test, similar to that conducted for sauger, to measure the maximum burst speed of a fish. All experiments were conducted at multiple temperatures to determine the possible effects of temperature on swimming performance.

1) Open-Channel Flume Test

In May and June of 2013 modifications were made to the open-channel flume to better accommodate the small size of the minnows and make the test more volitional. A white liner was added to the bottom of the flume in order to better see fish and distance markers were painted every foot. Cracks that could provide resting or hiding places within the open-channel were eliminated with caulking. Cameras were lowered and an extra camera was added in order to better track the smaller fish. Small holding areas were created at the upstream and downstream ends of the flume to provide fish with resting refugia at the beginning and end of the swim test.

The length of the open-channel between holding areas was 10 m, which was chosen to approximate the length of a typical culvert. Trials were run at 4 velocity challenges (nominally 0.39, 0.69, 0.78, 0.90 m/s) at 3 different temperatures (nominally 10.7, 15.3, 19.3 ^{o}C) with the goal of creating a model that can predict the passage probability for longnose dace at a given hydraulic challenge. The passage performance and average hydraulic challenges for the 12 different velocity and temperature combinations are summarized in Table 3 and Table 4, respectively . Three fish were placed in the downstream holding area in each trial and allowed to ascend the flume of their own volition. Trials lasted for 40 minutes and were recorded by an array of 7 cameras. Video footage was later analyzed to determine the maximum distance of ascent. Fish were randomly assigned to swimming trials and fish were tested only once (see methods description in Appendix B).

Progress: All open-channel flume swimming tests were completed during the summer of 2013. Video analysis and data entry were completed during the Fall of 2013. Data has been summarized in Excel spreadsheets and preliminary data analysis has begun and is expected to be completed at the end of May 2014.

Table 3: Summary of passage performance for the 12 volitional open-channel flume trials (NV=nominal velocity (m/s), T=average temperature (^{o}C), N=sample size, FL=average fork length, Participation=participation rate, Success=success rate, Dmax=average maximum distance of ascent).

NV	T	N	FL (SE)	Participation	Success	Dmax (SE)
0.39	15.07	20	7.0 (0.4)	0.95	1	9.15 (0.00)
0.69	15.43	21	6.8 (0.3)	1	0.95	8.91 (0.26)
0.78	15.35	21	6.9 (0.4)	1	0.8	8.76 (0.21)
0.9	15.41	20	7.1 (0.3)	0.95	0.25	7.45

						(0.31)
0.39	10.58	19	6.8 (0.2)	0.9	0.84	8.77 (0.23)
0.69	10.56	20	6.8 (0.2)	0.95	1	9.15 (0.00)
0.78	10.86	20	6.7 (0.2)	0.95	0.55	8.07 (0.41)
0.9	10.78	21	6.6 (0.2)	1	0.1	7.16 (0.20)
0.39	19.41	20	5.7 (0.2)	0.95	1	9.15 (0.00)
0.69	19.36	21	5.5 (0.1)	1	0.9	8.91 (0.19)

Table 4: Summary of hydraulic conditions for the 12 volitional open-channel flume trials (NV=nominal velocities (m/s), T=temperature (^{o}C), AVB= average bottom velocities (m/s), AV=average velocities at 0.6 x depth (m/s), Q=discharge (m^3/s), Depth=water depth (m), Re=Reynolds number).

NV	T	AVB (SE) (min, max)	AV (SE) (min, max)	Q	Depth (SE) (min, max)	Re (SE)	Fr (SE)
0.39	15.07	0.26 (0.01) (0.16, 0.41)	0.36 (0.05) (0.25, 0.41)	0.02	0.15 (0.004) (0.11, 0.18)	12333.72 (2084.10)	0.23 (0.08)
0.69	15.43	0.45 (0.02) (0.23, 0.61)	0.63 (0.03) (0.38, 0.74)	0.06	0.26 (0.003) (0.22, 0.29)	33131.04 (2805.97)	0.29 (0.05)

0.78	15.35	0.54 (0.02) (0.42, 0.76)	0.75 (0.06) (0.62, 1.05)	0.08	0.25 (0.003) (0.20, 0.29)	38568.40 (3580.95)	0.35 (0.06)
0.9	15.41	0.65 (0.04) (0.40, 1.06)	0.90 (0.15) (0.55, 1.06)	0.06	0.18 (0.006) (0.12, 0.22)	34436.93 (7528.78)	0.53 (0.24)
0.39	10.58	0.33 (0.02) (0.23, 0.52)	0.44 (0.06) (0.29, 0.45)	0.03	0.16 (0.003) (0.13, 0.19)	14942.83 (2376.09)	0.28 (0.09)
0.69	10.56	0.48 (0.01) (0.34, 0.64)	0.64 (0.04) (0.51, 0.67)	0.06	0.26 (0.003) (0.22, 0.30)	30257.69 (2599.97)	0.29 (0.05)
0.78	10.86	0.63 (0.04) (0.40, 1.22)	0.84 (0.07) (0.64, 1.18)	0.08	0.24 (0.003) (0.21, 0.29)	37375.93 (2680.33)	0.35 (0.06)
0.9	10.78	0.64 (0.04) (0.40, 1.22)	0.88 (0.13) (0.53, 1.03)	0.05	0.17 (0.006) (0.10, 0.22)	29133.76 (4008.06)	0.53 (0.24)
0.39	19.41	0.30 (0.02) (0.26, 0.38)	0.36 (0.01) (0.26, 0.39)	0.02	0.16 (0.003) (0.12, 0.18)	16846.89 (1488.54)	0.25 (0.07)
0.69	19.36	0.48 (0.02) (0.36, 0.73)	0.66 (0.05) (0.53, 0.87)	0.06	0.26 (0.003) (0.22, 0.30)	40320.76 (5547.05)	0.31 (0.07)
0.78	19.49	0.56 (0.02) (0.43, 0.79)	0.75 (0.05) (0.63, 0.97)	0.08	0.25 (0.003) (0.22, 0.29)	46278.02 (4000.97)	0.27 (0.06)
0.9	18.86	0.66 (0.05) (0.37, 1.17)	0.92 (0.16) (0.54, 1.09)	0.06	0.17 (0.006) (0.12, 0.23)	39716.00 (6953.20)	0.55 (0.25)

2) Sprint test

In the sprint test fish were stimulated by gently prodding them to burst the entire length of the open-channel flume. The flume was set at a relatively low velocity to orient fish into the current but not force them to swim excessively. This test was designed to determine the maximum burst speed that longnose dace can attain. This information can be used for assessing if instream structures are barriers to longnose dace and over what range of flows it may serve as a barrier. Sprint tests occurred at 3 temperature (~12.4 ^{o}C, 14.5 ^{o}C, and 19.4 ^{o}C) to investigate possible temperature effects on burst swimming (see method description in appendix B). A summary of hydraulic and test conditions is provided in Table 5.

Progress: All sprint tests were completed during the summer of 2013. Video analysis and data entry were completed during the spring of 2013. Preliminary data analysis has begun and analysis is expected to be completed at the end of May 2014.

Table 5: Summary of test conditions for the longnose dace sprint tests

T	AVB (SE)	AV (SE)	Q	Depth (SE)	N	FL	Re (SE)	Fr (SE)

						(SE)		
14.5	0.10 (0.003)	0.17 (0.004)	0.016	0.21 (0.003)	37	7.0 (0.25)	15728.9 (163.7)	0.12 (0.003)
12.27	0.13 (0.005)	0.20 (0.004)	0.014	0.20 (0.003)	32	6.8 (0.14)	15912.9 (289.9)	0.14 (0.005)
19.37	0.10 (0.003)	0.16 (0.003)	0.015	0.18 (0.004)	32	7.2 (0.25)	16442.84 (174.4)	0.12 (0.004)

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Appendix A – Materials and Methods – Sauger Swimming Trials Summer 2012

Fish Collection and Holding

Adult sauger were collected (via electrofishing) from the Bighorn River near Basin, Wyoming on May 11, 2012 and transported in an aerated live well to the Bozeman Fish Technology Center (BFTC) the same day. Prior to transport, fish were given a salt treatment (5 ppm) to alleviate osmotic stress and to facilitate the replacement of their slime coat. Sauger were housed in a 14x4x4 foot rectangular flow through holding tank within the containment building at the BFTC located a short distance from the open-channel flume. The holding tank was covered with plywood and black plastic to reduce light and simulate the preferred environment of sauger (turbid water) and to minimize stress associated with exposure to humans. All fish were individually pit tagged, weighed and measured (fork length and total length) in May prior to initiating the swimming trials. Fish were weighed and measured again after the completion of experiments in August. Water temperature in the holding tanks was adjusted to match the flume or swim chamber testing temperature. After the completion of swimming trials at a given temperature, fish were given a salt treatment (5ppm) and the temperature was gradually changed to the next experimental test temperature at a maximum rate of 1°C every 8 hours. Once the new experimental temperature was reached, fish were allowed to acclimate for a minimum of one day before experimentation resumed. The holding tank was stocked with two- to three-hundred juvenile rainbow trout (~3") approximately every four weeks to provide food for the sauger.

Open-Channel Flume Swimming Tests

Part 1: Hydraulic methods

Before and after each experimental trial water depth, velocity, temperature, and discharge were recorded in a field book and later transferred into an Excel spreadsheet for storage and future analysis. A copy of the field notes were scanned into the Excel spreadsheet as a backup.
The pump that supplies water to the flume was turned on at the beginning of the day and discharge was adjusted to obtain the desired test velocity. Once the desired velocity was obtained the flume was allowed to equilibrate for a minimum of an hour before measurements were taken. Once the flume had established equilibrium the water level and temperature in the headwater and tailwater boxes were recorded and continuously monitored using an AquaRod-TruTrack Digital Crest Gage (GEO Scientific LTD, Vancouver, Canada). These measurements were used to verify that the flow environment was stable during the experiment and that it was within acceptable limits for each trial. Also, by continuously recording water depths during the experiment, we can determine if there were any flow surges that may have influenced the experiment and outcome. Temperature readings were taken before and after the swimming trials with a calibrated digital thermometer in the tailwater box, 20 feet and 42 feet upstream from the tailwater box, and in the headwater box (see figures 1-3 for photos of the flume).

Water depth and velocity measurements in the flume were collected before and after each fish swimming trial using a graduated rod and Marsh-McBirney Flo-Mate (Hach Corporation, Loveland, CO, USA), respectively. Measurements were collected every two feet along the longitudinal axis of the open-channel in the center of the channel. Velocity was measured at 0.6 x the water depth. Discharge was measured with the Marsh-McBirney Flo-Mate 34 feet upstream from the tailwater box before swimming trials began. This location was chosen as it typically had stable flow profiles. Measurements were taken every inch along the cross-section of the open-channel flume; with velocity measurements taken at 0.6 x water depth and used to calculate discharge following USGS protocols (Rantz, 1982). Additionally, a Flexus F601 Flow Recorder (Flexim Aericas Corporation, Edgewood NY, USA) continuously measured and recorded the discharge throughout each swimming experiment and was used to check the manual measurement of discharge. By continuously measuring discharge, we could determine if there were any flow surges that might have affected the experimental outcome.

Part 2: Open-Channel Flume Swimming Test

After the flume hydraulic configuration was recorded the video camera array was activated to record the swimming trials and a shade cloth was lowered to minimize differences in light between trials, reduce glare on the water, and minimize the effects of 'outside' disturbances affecting swimming behavior. Fish were tested individually. A randomly chosen fish was removed from a holding tank and its PIT tag number was recorded. Fish were transported to the flume in a 15 gallon bucket and placed in the open-channel directly above the tailwater box. A screen blocked off access to the tailwater box. The fish was observed for several minutes to determine if the fish could maintain its position in front of the screen. If the fish immediately began resting on the downstream grate the fish was stimulated off the grate by touching the caudal peduncle with a net. The position of the fish was checked again 10 minutes and 20 minutes after the start of the trial and the fish was stimulated if found to be resting on the downstream grate. These attempts to coerce the fish were recorded. Besides stimulations, the fish was allowed to volitionally ascend the flume or hold position. Trials were terminated after 30 minutes and the fish was removed from the flume and placed in a separate compartment of the holding tank. This process was repeated until all fish had been tested. At the end of each test hydraulic measurements were taken throughout the flume. All available fish were swum for each combination of temperature (10 ^{o}C, 14 ^{o}C, and 18 ^{o}C) and water velocity (1.5ft/s, 2.5ft/s, 3.5 ft/s). Video recordings of the trials were analyzed and swimming speeds between distance markers located every two feet in the flume were calculated and entered in an Excel spreadsheet.

Part 3: Sprint Swimming Test

After the flume hydraulic configuration was recorded the video camera array was activated to record swimming trials and a shade cloth was lowered to minimize differences in light between trials, reduce glare on the water, and minimize the effects of 'outside' disturbances affecting swimming behavior. Fish were tested individually. A randomly chosen fish was removed from a holding tank and its PIT tag number was recorded. The fish was placed in a bucket and transported to the flume. The fish was placed in the flume and contained within the downstream 4 feet of the flume during a 5 minute acclimation period with an upstream and downstream screen. At the end of the acclimation period, the upstream containment screen was removed and the fish was stimulated up the entire length of the flume by gently touching the caudal peduncle with a net. This process was repeated a total of 3 times for each fish, with fish being allowed to rest at the downstream end for 30 seconds between ascents. After completion of 3 ascents, the fish was removed from the flume and placed in a separate compartment of the holding tank. All available fish were tested at three temperatures: 11 ^{o}C, 14 ^{o}C, and 18 ^{o}C. Video analysis of the tests will be used to determine maximum obtainable burst speeds of each fish.

Swim Tunnel 'Usprint' Test

Prior to swimming fish in the swim tunnel, the swim tunnel was enclosed with a black plastic curtain to eliminate outside disturbances affecting fish swimming performance. Two video cameras were set up: one to record the trials for later analysis and another that was linked to a computer outside of the curtain to allow real time observation of the trial. A black plastic cover was placed over the front edge of the swim tunnel and a halogen light was directed at the back half of the swim tunnel to encourage fish to swim in the front half of the tunnel and discourage resting on the downstream grate. For the ‘Usprint’ tests, all available fish were split into two groups with each group alternatively swimming at a given temperature. A randomly chosen fish from the group selected for the trial was removed from the holding tank and its PIT tag number was recorded. The fish was transported to the swim tunnel in a bucket and placed in the swim tunnel. Fish were allowed to acclimate for 10 minutes in the swim tunnel at a water velocity of 1.5 ft/s (~1 body length/second). At the end of the acclimation period water velocity was increased 0.25 ft/s every 15 seconds until fish became impinged on the downstream grate. Impingement was defined as no longer being able to orient upstream. When a fish became impinged the motor to the swim tunnel was quickly turned off then back on and the test was continued if fish resumed swimming. If fish remained impinged the trial was ended and the motor was turned off. After completion of the trial the fish was transported back to the holding tank and the process was repeated for all available fish in the group. Trials were conducted at seven temperatures: 10 ^{o}C, 12 ^{o}C, 14 ^{o}C, 16 ^{o}C, 18 ^{o}C, 20 ^{o}C, and 22 ^{o}C. Consequently, one group of fish swam four trials and the other swam three (see Table 3 for reference). Video of the trials was analyzed to determine length of the trial and maximum speeds obtained and this information was entered into an Excel spreadsheet

Appendix B – Materials and Methods – Longnose Dace Swimming Trials Summer 2013

Fish Collection and Holding

Longnose dace were collected (via electrofishing) from the Gallatin River near Belgrade, Montana on June 4, 2013 and July 16, 2013 and from the lower Madison river on May 21, 2013 and June 4, 2013 and transported in an aerated live well to the Bozeman Fish Technology Center (BFTC) the same day. Upon arrival, fish were placed in 3x3 foot circular flow through holding tanks and given a salt treatment (5 ppm) to alleviate osmotic stress and to facilitate the replacement of their slime coat. Water temperatures in the holding tanks were adjusted at a maximum rate of 2 ^{o}C to the testing temperature. Fish were then individually randomly assigned to one of 1x3x0.8 foot rectangular flow through tanks of the same temperature. Each tank was then randomly assigned to one of the four velocity challenges. Fish were allowed to acclimate to the new tanks and the testing temperature for a minimum of three days before testing began.

Open-Channel Flume Swimming Tests

Part 1: Hydraulic methods

Hydraulic methods were the same for the longnose dace open-channel flume swimming tests as for the sauger open-channel flume swimming tests (see Appendix A) with the exception that additional velocity measurements were taken. For the open-channel flume test velocity measurements were taken at 0.6xdepth and at 0.1 feet off the bottom every two feet. The additional velocity measurement on the bottom was taken due to observations of fish swimming mostly along the bottom of the open-channel. For the sprint test velocities measurement were taken at 0.6xdepth and 0.1 feet off the bottom at every foot along the length of the channel.

Part 2: Open-Channel Flume Swimming Test

After the flume hydraulic configuration was recorded the video camera array was activated to record the swimming trials and a shade cloth was lowered to minimize differences in light between trials, reduce glare on the water, and minimize the effects of ‘outside’ disturbances affecting swimming behavior. Fish were tested in groups of three. A large, medium and small fish were netted from the holding tanks, transported to the flume in a 15 gallon bucket, and placed in the bottom holding area directly above the tailwater box. Fish of different sizes were used so that they could be differentiated during video analysis. A screen blocked off access to the tailwater box. Trials lasted for 40 min and the tailwater grate was checked at the 20 min mark to see if any fish were impinged tailwater grate. If fish were impinged, they were stimulated off the grate with a net. Beside this stimulation, the fish were allowed to volitionally ascend the flume or hold position. At the end of the trial, fish were collected and there final position was noted to aid in the video analysis. Fish were weighed and measured before being placed in a separate holding tank. This process was repeated until all fish had been tested. At the end of each test hydraulic measurements were taken throughout the flume. Individual fish swam in only one open-channel flume test. Video recordings of the trials were analyzed and distance of maximum ascent were recorded and entered in an Excel spreadsheet.

Part 3: Sprint Swimming Test

After the flume hydraulic configuration was recorded the video camera array was activated to record swimming trials and a shade cloth was lowered to minimize differences in light between trials, reduce glare on the water, and minimize the effects of 'outside' disturbances affecting swimming behavior. Fish were tested individually. Fish that were tested in the first two velocity trials of open-channel flume test were used for the sprint test. Because the open-channel flume tests were performed before the sprint tests for a given temperature, this allowed the most rested fish to be used in the sprint tests. This methodology allowed the most rested fish to be used in the sprint tests, because the open-channel flume tests were performed before the sprint tests for a given temperature. Individual fish were netted and placed into a five gallon bucket and transported to the flume. The fish was placed in the flume and contained within the downstream 3 feet of the flume during a 5 minute acclimation period with an upstream and downstream screen. At the end of the acclimation period, the upstream containment screen was removed and the fish was stimulated up the entire length of the flume by gently touching the caudal peduncle with a net. Fish were weighed and measured after the completion of the sprint test. Video analysis of the tests was used to determine maximum obtainable burst speeds of each fish over a 1 foot distance.

Appendix C- Fish swimming experimental equipment

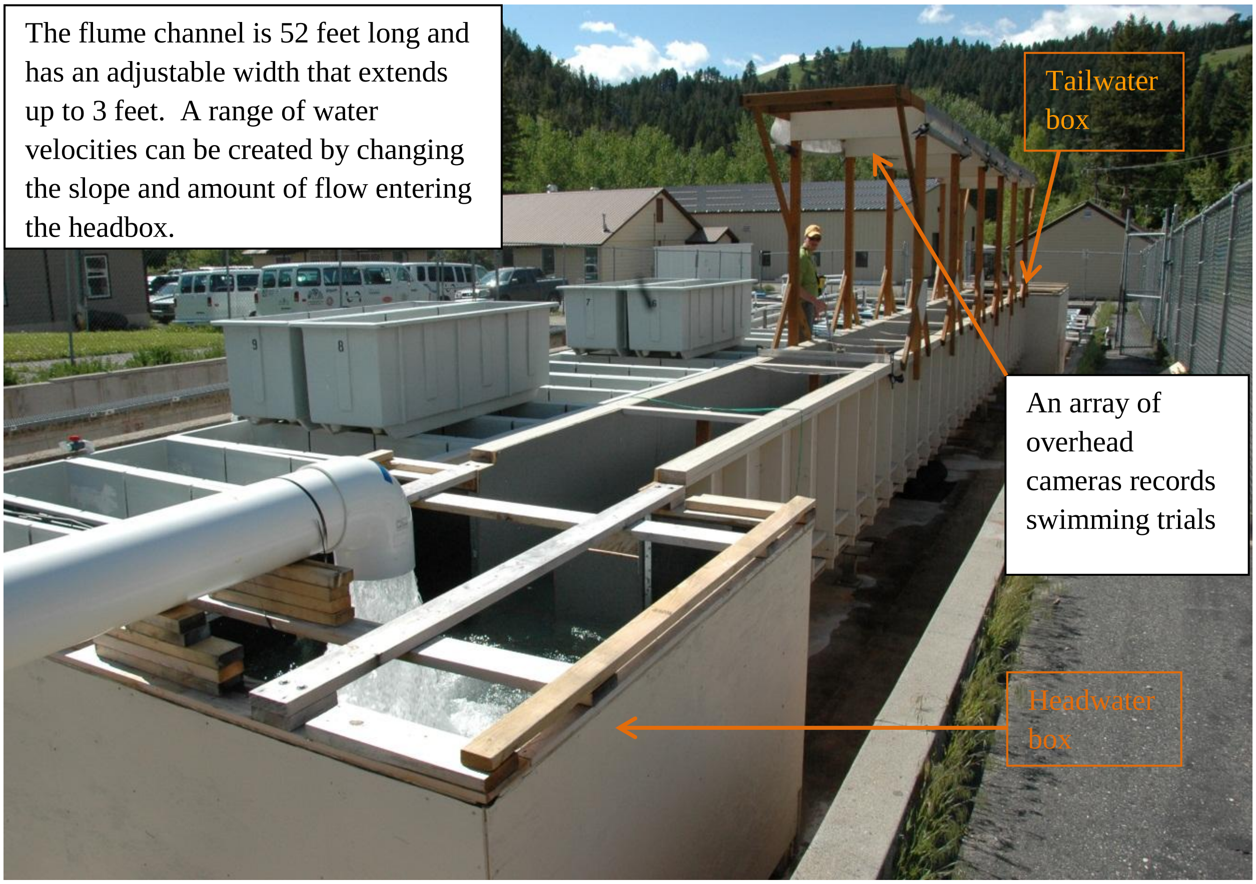

Figure 1: Open-channel flume

Figure 2: Flume set up for experimentation

Figure 3: Sauger ascending flume

Figure 4: Sauger resting during acclimation period of 'Usprint' test

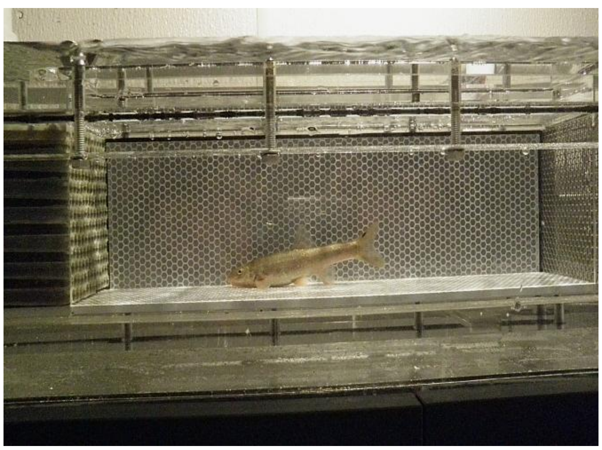

Figure 5: Longnose dace swimming in small swim chamber.

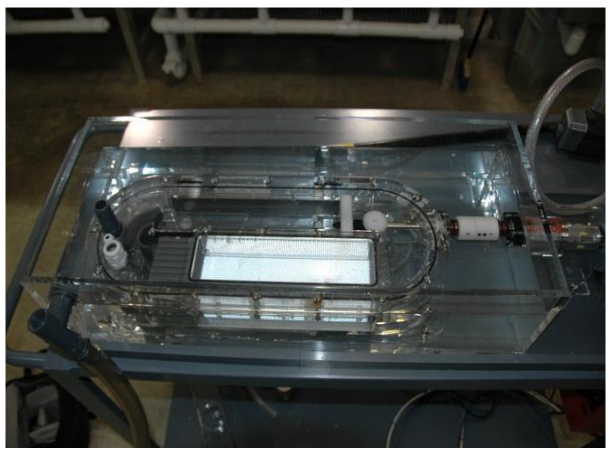

Figure 6: Overhead view of small swim chamber.

Student Fellowship: Understanding Trends in Snow Accumulation, Water Availability and Climate Changes Using Snow Telemetry Observations in the Missouri River Headwaters

Basic Information

Title:	Student Fellowship: Understanding Trends in Snow Accumulation, Water Availability and Climate Changes Using Snow Telemetry Observations in the Missouri River Headwaters
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Principal Investigators:	Thomas Michael Matthews

Publications

There are no publications.

STUDENT FELLOWSHIP: UNDERSTANDING TRENDS IN SNOW ACCUMULATION AND STREAMFLOW USING SNOW TELEMETRY AND STREAMGAGE OBSERVATIONS IN THE MISSOURI RIVER HEADWATERS

Thomas Matthews

Department of Earth Sciences
MONTANA STATE UNIVERSITY
Bozeman, Montana

ABSTRACT

The Missouri River headwaters are located in the mountains of southwestern Montana and drain the eastern side of the continental divide. These headwaters serve as a water source for the Missouri River basin, which covers 10 states with an approximate population of 12 million people. A key component of the annual water budget in the headwaters is from snowfall, accounting for around 70% of the total annual flow in this region. The Western U.S. is generally comprised of semi-arid to arid regions that exhibit a high degree of inter-annual to multi-decadal variability. Changing trends in water availability due to climate change and yearly variations must be understood and quantified for proper allocation and forecasting of water resources. Here we use snow, temperature and precipitation records from the Natural Resource Conservation Service (NRCS) and streamflow records from the U.S. Geological Survey (USGS) in a coupled analysis designed to assess recent changes in these temperature sensitive high alpine headwaters over the last 40 years of record. Snow water equivalence, streamflow and temperature are key metrics that are indicative of changes in these headwater regions and are useful in determining the amount, timing and duration of hydrologically important snow-driven events. These data are being examined to determine what role inter annual and decadal drivers such as the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Pacific/North American Pattern (PNA) play in controlling the amount and timing of water availability in this catchment. Metadata from the weather stations used in this study are being analyzed to determine how changes in station characteristics, such as vegetation growth or equipment updates, can help explain variances in trends or relationships seen in the data beyond large-scale climate variations.

INTRODUCTION

In the Western United States the winter snowpack is a major water resource. Depending on location snowfall accounts for as much as 50 – 70% of total annual precipitation (*Serreze et al.,* 2001) and the melting and runoff of snow in the spring season regulates water availability in summer months. Water is a valuable resource for the interior west, which is characterized in many parts by an arid to semi arid climate and by high annual variability in precipitation (Serreze et al., 1999). Currently the Western US uses a large portion of existing water (*Regonda et al.,* 2005) and continued development is limited by water availability. The establishment and quantification of a relationship between water and climate is a crucial step in a water-sustainable west. To meet the needs of human development understanding water and snowfall trends is imperative for allocating water resources.

The major waterways in the Missouri River headwaters are the Jefferson, Madison, Gallatin and Upper Yellowstone Rivers. Here results focus on the Gallatin and Madison River basins. The headwaters feed the Missouri River basin, which encompasses 10 states with a population of approximately 12 million people. Landmass in the Missouri River basin is predominantly used for agriculture, accounting for roughly 40% of wheat, 20% of corn and 30% of cattle produced in the US (*Mehta et al.,* 2012). As one of the only mountainous catchment basins feeding to the Mississippi, the Missouri relies heavily on snowfall as a water source. Drought in the Missouri River basin can have serious economic impacts. It has been estimated that variability in water availability can reduce corn and wheat yields by up to 30% of average (*Mehta et al.*, 2012). In the 20th century drought has affected between 20 and 60% of landmass in the Missouri River basin (*Mehta et al.*, 2012).

The Snow telemetry (SNOTEL) network, which is operated by the Natural Resources Conservation Service (NRCS) and streamgage sites operated by the U.S. Geological Survey (USGS) provide a record for tracking our water resources. The SNOTEL records help monitor important parameters of snow accumulation over the winter and ablation in the spring. SNOTEL has allowed for observations of snow water equivalence (SWE), snow depth, precipitation, and temperature to occur on a daily basis. 39 out of the 49 sites in the Missouri headwaters have a record greater than or equal to 30 years. The average record for all sites in the headwaters is 33 years. Streamgage sites are operated by the United States Geologic Survey (USGS). These stations track daily stream stage, streamflow, discharge and temperature. All streamgage sites used in this study have been operating since 1891, covering the entire history of the SNOTEL record. The distribution of SNOTEL and streamgage sites in the Missouri River headwaters is dense, making this an excellent area for water monitoring. Most watersheds in the Missouri Headwaters contain multiple SNOTEL sites representing high and low elevations and a single streamgage station near the outlet of the basin. This design and the dense frequency of sites allows for analysis of water conditions on a localized scale. Often times water conditions in individual basins may vary from the regional or statewide conditions. The localized design of SNOTEL and streamgage stations allows users access to water conditions in their immediate area. This research generally uses basin-wide and headwaters-wide statistics. Basin-wide statistics would not be available if it weren't for this localized design and dense distribution of SNOTEL and streamgage sites.

Using the historical record provided by the SNOTEL and streamgage network, temporal relationships between snow, water and temperature metrics have been established. These metrics are used to measure and summarize SWE, snow depth, precipitation, stream discharge and temperature. Key metrics used throughout this report are snowfall represented by annual maximum SWE, temperature represented by annual average temperature and runoff represented by total annual discharge. The temporal patterns in the approximately 35 year history of the SNOTEL network in southwest Montana show overall trends for the area, which gives crucial insight into long term climate trends and how they may effect future snow accumulation and runoff regimes. These records also help identify climate-based changes in the snowpack in the mountains of the Missouri headwaters. The snowpack effects the duration of winter water storage and the timing and magnitude of spring and summer snow melt and water runoff. The SNOTEL record also shows inter annual and decadal patterns in precipitation. The relationship between these decadal patterns and large scale climate patterns has implications for water forecasting. Examining temporal relationships in the snowpack and stream flows of the Missouri headwaters and their connection to large scale weather patterns gives insight into the highly variable nature of precipitation in the west. This variability in precipitation currently makes forecasting water resources difficult (*Barnett et al.*, 2005). Water supply forecasts are unreliable and can only be issued for relatively short time periods (*Barnett et al.*, 2005). Understanding how local water supplies relate to large-scale global weather patterns would potentially increase confidence in, and extend time frames for forecasts.

The representativeness of using SNOTEL stations in determining changing trends in snowfall and water availability is studied. Growth of vegetation around the SNOTEL site, changes in the location of the site sensors and mechanical changes in sensors can all affect accurate measurement of snowfall and temperatures. These changes have been documented in the metadata for SNOTEL stations and have been analyzed to determine how changes to the station could explain any trends or relationships seen in the data. This should differentiate between what may be a change in snowfall trends and what may be a change in the overall state of the recording device. While numerous studies have used historical SNOTEL records to investigate trends in water resources they have generally not addressed potential complications that could arise from changes documented in the metadata.

The purpose of this research is to explore trends in snow accumulation and streamflow and their relationship with climatic patterns by addressing the following questions.

1. Is there a relationship between snowfall, runoff and climatic trends in the SNOTEL records in the Upper Missouri River basin? What are the larger implications for areas whose water supply relies on the upper Missouri River basin?

2. Are there any patterns (i.e. inter annual or decadal) that could be taken account of and planned for into the future?

3. How does the use of metadata from SNOTEL sites improve our understanding and quantification of these observed trends?

For each of these primary research questions secondary questions have been established and statistical models have been developed that directly address the secondary question. Methods and results sections outline how metrics have been collected and statistical models developed. Findings are interpreted in the results and discussion sections.

METHODS

Study Area

This study concentrates on the Missouri River headwaters in Southwestern Montana.

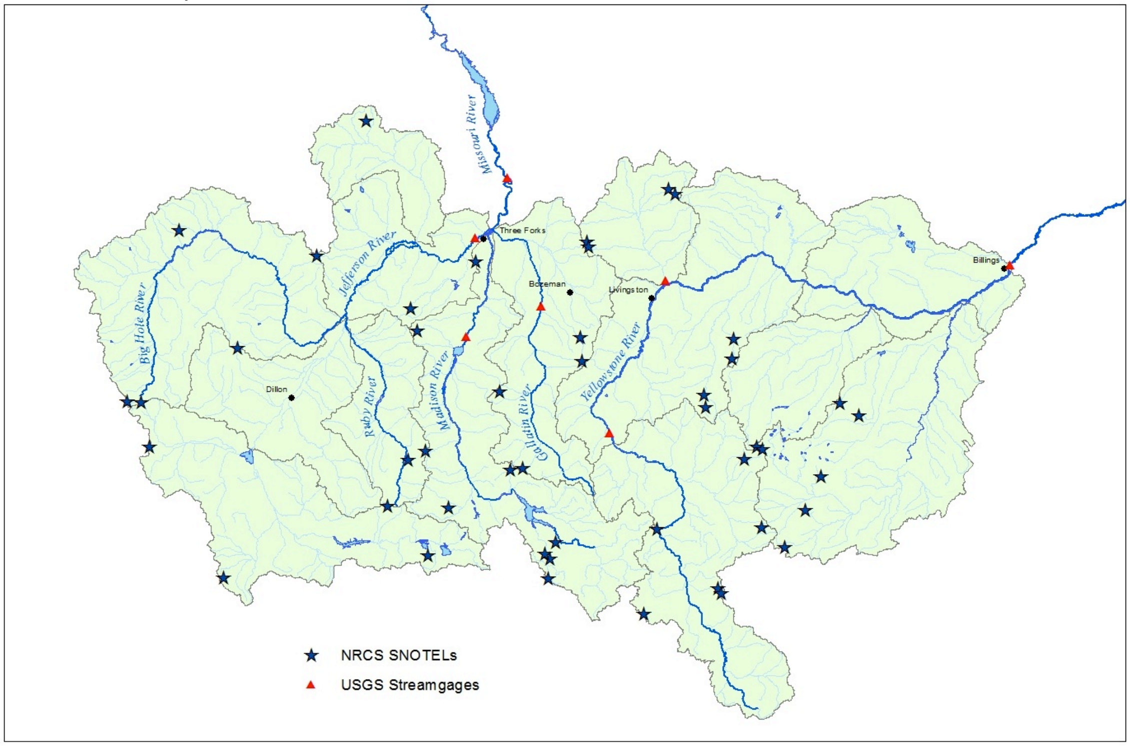

Fig. 1. The 14 sub basins, 4 major rivers, NRCS SNOTEL sites, USGS Streamgage sites and major towns of the Missouri River headwaters.

The Missouri River headwaters in southwestern Montana are made up of large mountain ranges and wide river valleys. The headwaters cover 21,722 km^2 with elevations ranging from 1,200 to 3,900 meters. The major waterways of the Missouri River headwaters are (from east to west) the Upper Yellowstone, Gallatin, Madison and Jefferson Rivers. These river's headwaters are located in the mountainous terrain of Southwest Montana. The Missouri River forms at the confluence of the Gallatin, Madison and Jefferson near Three Forks, MT. The Yellowstone River flows north then northeast and eventually joins the Missouri River across the Montana border in North Dakota. The Missouri Headwaters can be broken down into specific basins represented by these main rivers and their tributaries. Using only the primary rivers gives 4 major basins that make up the headwaters area. Using the main tributaries for these rivers the area can be broken into 14 watersheds. Major mountain ranges from east to west include the Beartooth, Absorka, Crazy, Bridger, Gallatin, Madison, Tobacco Root, Gravelly, Centennial, Ruby, Pioneer, Tendoy and Beaverhead Mountains. The continental divide forms the southern and western extent of the Missouri headwaters.

Data Collection

The statistical program, R, was used to collect and summarize historical data from SNOTEL and streamgage sites. This historical data is available from the NRCS and USGS websites. SNOTEL data stores daily observations of SWE, cumulative precipitation, maximum temperature, minimum temperature, average temperature and snow depth. Length of records vary between sites and between measurements, for example, snow depth was added to most sites in 2003 whereas SWE has been measured since each site was installed. Streamgage sites collect daily observations on discharge. Using these daily summary statistics, metrics that help summarize the quantity and timing of annual accumulation, ablation and runoff of snow, are calculated. Comparing these metrics from year to year for the history of the record would then give an understanding of the temporal changes of snow accumulation and runoff. A list of metrics was developed and R code was written to analyze the raw data, calculate and return each specific metric for each year. Each year for each SNOTEL and streamgage station was run through the R code and a data file of metrics for the history of the station was developed. This resulted in a table for each station's record with annual values for each metric. This allows for a year-to-year comparison of each metric.

Decadal Weather Patterns

Decadal weather patterns used in this analysis are the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the Pacific/North American Pattern (PNA). The National Climatic Data Center (NCDC), part of the US National Oceanic and Atmospheric Administration keeps records on indices measuring the state of decadal weather patterns. The NCDC is a federal agency responsible for managing weather and climate data. Historical, monthly records are available from the NCDC for the SOI and ENSO3.4 indices representing ENSO conditions and the indices representing PDO and PNA conditions. All data are analyzed using standard deviations from the mean. Standardized data is reported because it makes it comparable to data from different scales and forms of measurement.

Point Changes in Data

Changes that happen at once rather than gradually over time can complicate data records causing discrepancies between data output and the reality on the ground. A number of changes have been documented. The most significant change to the SNOTEL stations is the change in location for temperature sensors. In 1997 and 1998 temperature sensors were moved from outside of the shed, which houses equipment, to the tower that holds the sonic sensor (A tower and arm hold the sensor over the snow pillow). This could have a number of different effects. Commonly temperatures are higher next to dark structures and moving the temperature sensor away from this and onto a thin tower suspended in the air results in the sensor reporting colder temperatures. However, if this location change moves the temperature sensor from a shaded area into direct sunlight temperatures would rise.

Canopy Images

To study the effects of vegetation growth around the SNOTEL site canopy images are used. Canopy images capture vegetation growth and open sky by pointing a camera directly upward on top of the snow pillow. This is intended to capture the percentage of open and closed canopy over the SNOTEL station. To assess changes in the canopy at SNOTEL sites the growth affecting the site needs to be quantified. Canopy images were taken from 1965 to 1975 at 13 of the SNOTEL stations in the headwaters. These images were taken near the snow pillow facing directly upward with a fisheye lens capturing 90°. Five of the sites, which were easily accessible from Bozeman, were revisited and canopy images were retaken in 2013. These images were taken directly adjacent to the snow pillow directly opposite the sonic sensor facing directly upward. A fisheye lens was used to replicate the old images. The sets of old and new images will be analyzed to record changes in the percentage of open canopy above the snow pillow. Open canopy is defined as the portion of the canopy that shows no interference from trees or structures. Gap Light Analyzer, a computer program, analyzes the images and gives percentages for open and closed canopy. For proper comparison old and new images must be cropped until they both show the same proportion of the canopy overhead at the snow pillow.

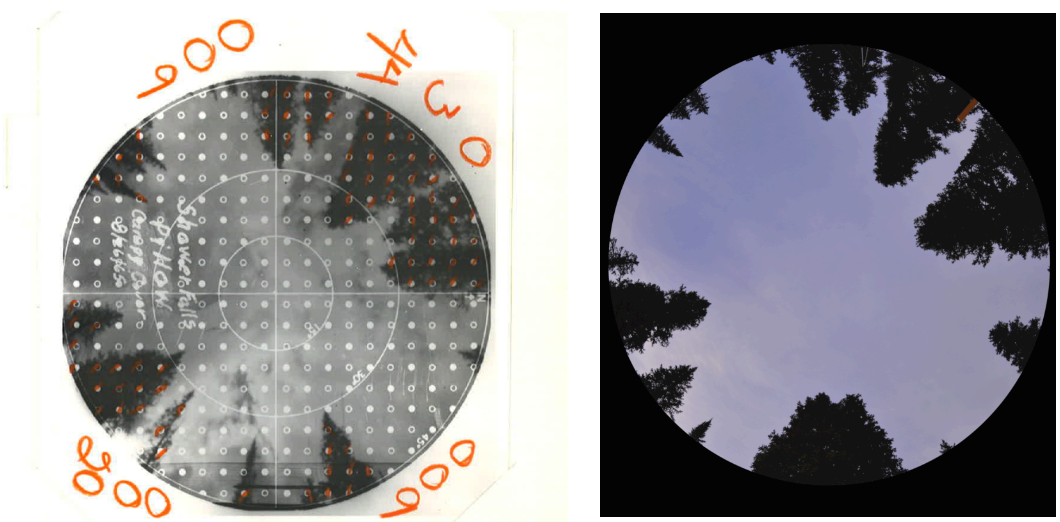

Fig. 2. 'Old' and 'new' canopy images from the Shower Falls SNOTEL site.

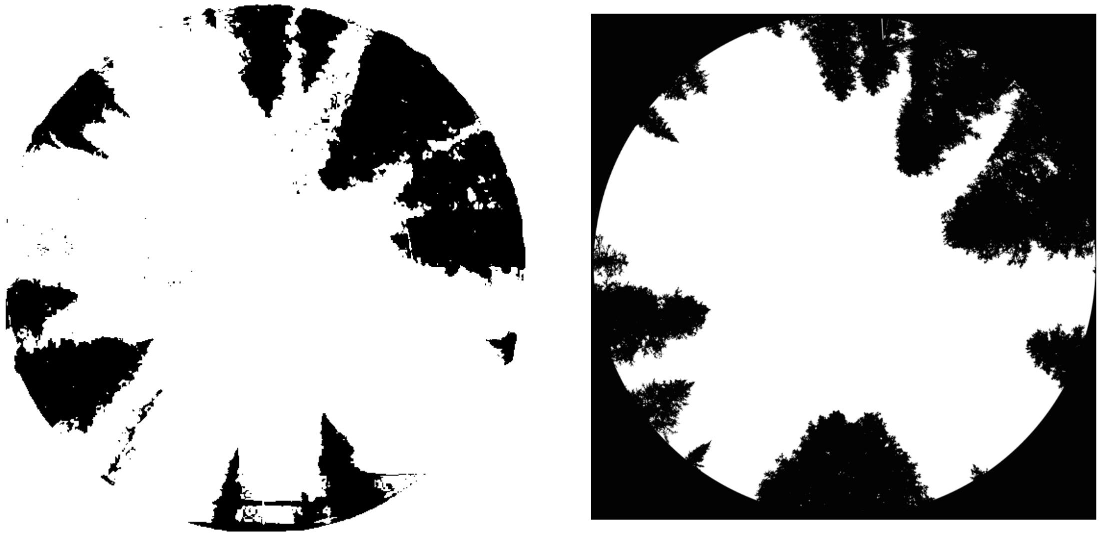

Fig. 3. Threshold images showing open and closed canopy for the 'old' and 'new' canopy images at Shower Falls.

RESULTS AND DISCUSSION

Relationships between metrics and trends over time for metrics are reported. Decadal weather patterns are analyzed to see how they help explain these trends and relationships. Finally metadata from the SNOTEL stations is examined and its role in those trends and relationships is summarized. These research questions are explored through the use of statistical tools and models. Results for each relationship are reported for both the Gallatin and Madison River basins.

What are the Relationships between snowfall, runoff and climatic trends in the SNOTEL records of the Missouri River headwaters?

To look at the primary question involving relationships between snowfall, water availability and climatic trends secondary questions were presented and models to answer these questions were developed. The secondary questions are as follows:

1) How do annual max SWE, total annual precipitation and average annual temperature help explain annual stream discharge?

2) What is the relationship between annual average temperatures, freeze days (the number of days with an average temperature below 0°C) and max SWE after accounting for annual precipitation?

3) How does the timing of max SWE and annual maximum, minimum and average temperatures help explain the timing of snow-melt runoff.

4) What are the overall trends in annual max SWE, annual total discharge and annual average temperatures over the history of the SNOTEL record?

A few of the relationships will be discussed and other results will be summarized in following tables.

1) How do annual maximum SWE, total annual Precipitation and average annual temperature help explain total annual stream discharge?

A major theme of this research is that snow is a valuable water resource. How well does water stored in the snowpack relate to runoff? What role do precipitation and temperature play in these processes? The following multiple linear regression will be used to analyze the data.

{Total Runoff | Max SWE, total annual Precipitation, avg annual Temp }

Relationship Between Max SWE and Total Runoff

Gallatin River Basin

There is very strong evidence for a relationship between max SWE and total runoff (p-value = 0.0016, from a t-stat of 3.58 on 23 d.f.) in the Gallatin River basin. It is estimated that a change from the mean of one standard deviation in maximum SWE would result in a variation in the same direction of 0.55 standard deviations from the mean in total annual runoff, with an associated 95% confidence interval from 0.23 to 0.86 standard deviations.

Gallatin Basin- Runoff & Max SWE

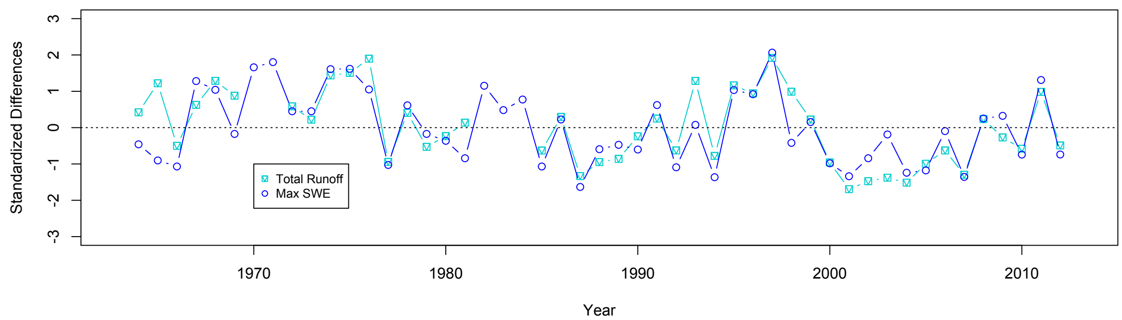

Fig. 4. An analysis of total runoff and maximum SWE shows evidence of a strong positive relationship, this can be seen in this time series where metrics closely follow each other.

Madison River Basin

Unlike the Gallatin Basin there is no evidence for a relationship between max SWE and total runoff (p-value = 0.6527, from a t-stat of 0.455 on 27 d.f.) in the Madison River basin. It is estimated that a change from the mean of one standard deviation in maximum SWE would result in a variation in the same direction of 0.14 standard deviations from the mean in total annual runoff, with an associated 95% confidence interval from -0.50 to 0.79 standard deviations. It is possible that the presence of 2 dams on the Madison river has made this relationship difficult to quantify.

Madison Basin- Runoff & Max SWE

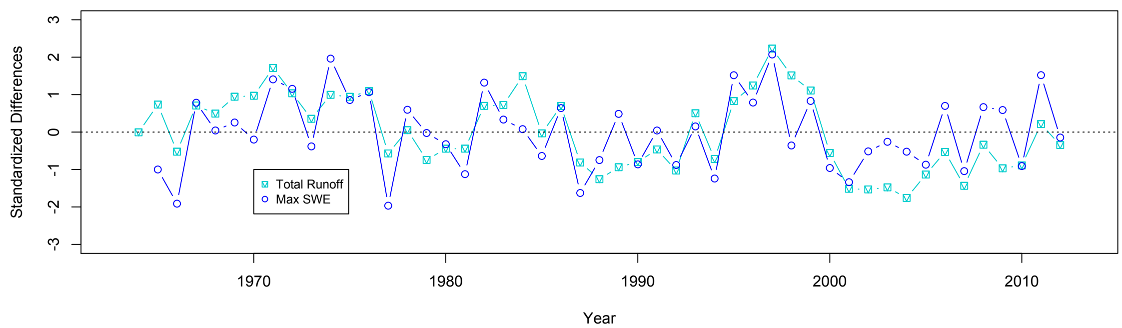

Fig. 5. Time series of total runoff and maximum SWE for the Madison River basin. Despite the time series appearing to show a good relationship between the two metrics statistically evidence was weak for a relationship.

Relationship Between Average Annual Temperatures and Total Runoff

Gallatin River Basin

Evidence of an inverse relationship also exists between average annual temperatures and total runoff (p-value = 0.0233, from a t-stat of -2.43 on 23 d.f.) in the Gallatin River basin. It is estimated that a change from the mean of one standard deviation in average temperature would result in a variation in the opposite direction of 0.22 standard deviations from the mean in total annual runoff, with an associated 95% confidence interval from -0.03 to -0.41 standard deviations.

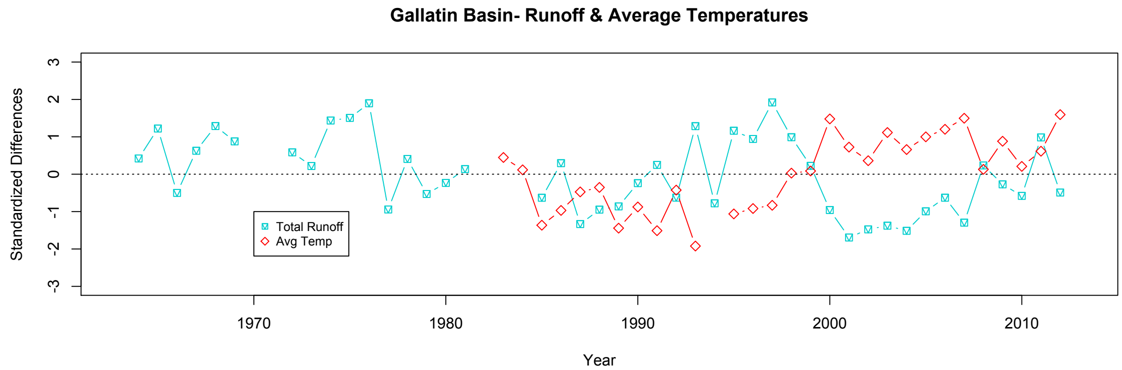

Fig. 6. Analysis on total annual runoff and average temperatures suggests a negative relationship.

Madison River Basin

There is some evidence of an inverse relationship between average annual temperatures and total runoff (p-value = 0.0554, from a t-stat of -2.00 on 27 d.f.) in the Madison River basin. It is estimated that a change from the mean of one standard deviation in average temperature would result in a variation in the opposite direction of 0.28 standard deviations from the mean in total annual runoff, with an associated 95% confidence interval from 0.01 to -0.56 standard deviations.

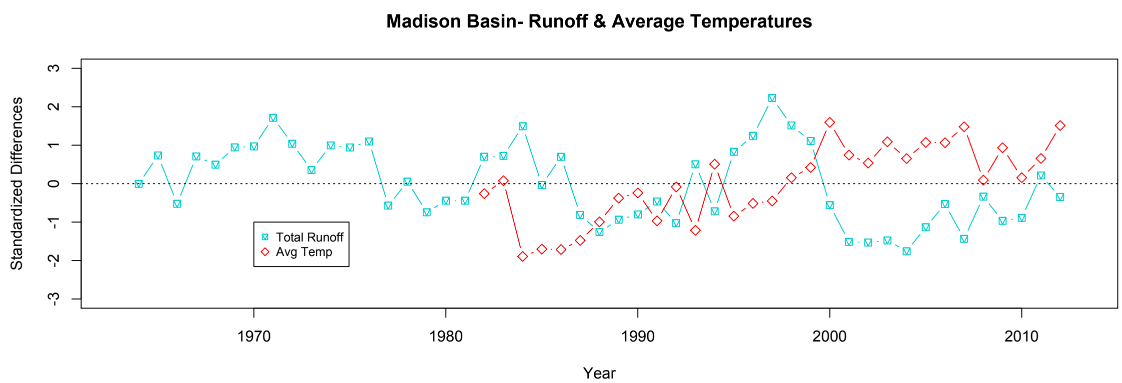

Fig. 7. Analysis on total annual runoff and average temperatures suggests a negative relationship.

2) What is the relationship between annual Average Temperatures, freeze days (the number of days with an average temperature below 0°C) and Max SWE after accounting for annual precipitation?

With a strong consensus on increasing temperature, it is important to study the effects of temperature on annual maximum SWE. Annual maximum SWE, annual average temperature, the number of days with an average temperature below 0°C (freeze days) and annual total precipitation are averaged over all the SNOTELs in each basin. The number of freeze days is useful for explaining the length of the snow season and the time available for the accumulation of SWE. These data were fitted to a model using max SWE as the response and average temperature, freeze days and total precipitation as explanatory variables. It is expected that total precipitation has a good correlation with max SWE so the question of interest focuses on the temperature metrics. Precipitation was included so temperatures can be examined without confounding the data with varying precipitation amounts. Interest focuses on the effects of temperature on SWE for years with similar precipitation. The model used is a follows.

{Max SWE | annual Avg Temp, freeze days, total annual Precipitation}

Evidence for a relationship was found between max SWE and freeze days in the Gallatin Basin. No evidence for a relationship was found between max SWE and average temperatures. As expected, evidence for the relationship between max SWE and precipitation was very strong.

Table 1. Results from secondary questions 1 and 2 not explicitly discussed are summarized. P-values indicating strong evidence for a relationship are presented in red.

Relationship	Gallatin p-value	Gallatin Estimate	Madison p-value	Madison Estimate
Runoff ~ Precip	0.02	1 Δ Precip / 0.35 Δ Runoff	0.06	1 Δ Precip / 0.69 Δ Runoff
Max SWE ~ Avg Temp	0.21	1 Δ Temp / 0.35 Δ SWE	0.47	1 Δ Temp / 0.13 Δ SWE
Max SWE ~ Freeze Days	0.08	1 Δ Freeze / 0.49 Δ SWE	0.88	1 Δ Freeze / 0.03 Δ SWE
Max SWE ~ Precip	< 0.0001	1 Δ Precip / 0.72 Δ SWE	< 0.0001	1 Δ Precip / 1.01 Δ SWE

3) How does the timing of max SWE and annual maximum, minimum and average temperatures help explain the timing of snow-melt runoff.

Previous research has shown evidence for shifts in the snow melt and runoff period to earlier in the spring and summer. This could potentially cause late summer droughts, which could have adverse effects on agriculture and general water use. The model used here examines the timing of the runoff in the Missouri headwaters. Is there evidence of a shift towards earlier melts and runoffs as seen elsewhere?

{Median of Dates defining the Runoff period | Date of Max SWE, annual Max Temp, annual Min Temp, annual Avg Temp}

The response here is the median or center date of the runoff period. The runoff is defined as the period containing all flows greater than 99% of average flow. The runoff period is the starting and finishing date of those flows and is generally from April/May to July/August. This metric uses the date in the center of this period, or the median date. Date of maximum SWE is the day where maximum SWE was reached. To easily compare between years the number of days passed between January 1st and the median runoff and maximum SWE dates are used. The maximum, minimum and average temperatures for each year are used as explanatory variables. Median runoff date comes from the streamgages on the Gallatin and Madison Rivers.

Relationship Between Timing of Runoff and Timing of Maximum SWE

Gallatin River Basin

In the Gallatin River basin there is good evidence for a relationship between the timing of maximum SWE and the timing of the runoff period (p-value = 0.0131, from a t-stat of 2.70 on 22d.f.). It is estimated that 1 standard deviation difference in timing of max SWE is related to a 0.36 standard deviation difference in the same direction for the runoff period, with an associated 95% confidence interval from 0.08 to 0.63 standard deviations.

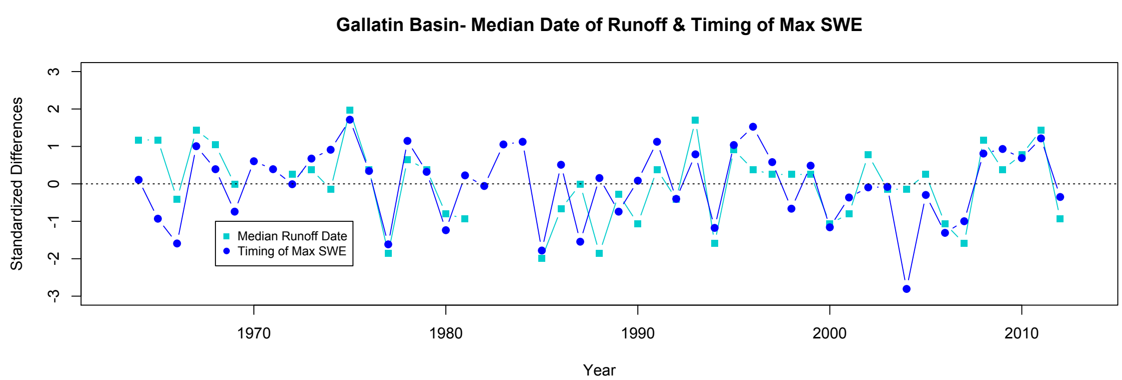

Fig. 8. Time series of median runoff date and timing of max SWE in the Gallatin River basin.

Madison River Basin

There is strong evidence for a relationship between the timing of snow melt runoff and the timing of maximum SWE (p-value = 0.0053, from a t-stat of 3.20 on 17d.f.). It is estimated that 1 standard deviation difference in timing of max SWE is related to a 0.46 standard deviation difference in the same direction for the runoff period, with an associated 95% confidence interval from 0.16 to 0.77 standard deviations.

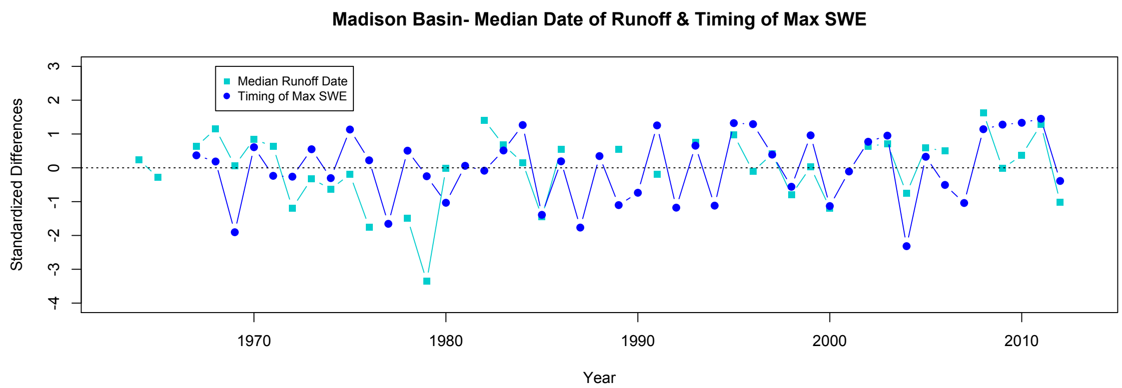

Fig. 9. Time series of median runoff date and timing of max SWE in the Madison River basin.

Table 2. Results from secondary question 3 are summarized. P-values indicating strong evidence for a relationship are presented in red. Relationship column is the relationship between timing of runoff and each listed metric.

Relationship: Timing of Runoff ~	**Gallatin p-value**	**Gallatin Estimate**	**Madison p-value**	**Madison Estimate**
~ Timing of Max SWE	0.01	1 Δ SWE Timing / 0.36 Δ Runoff Timing	0.01	1 Δ SWE Timing / 0.46 Δ Runoff Timing
~ Max Temp	0.0003	1 Δ Max Temp / -0.87 Δ Runoff Timing	0.99	1 Δ Max Temp / 0.00 Δ Runoff Timing
~ Min Temp	0.64	1 Δ Min Temp / -0.08 Δ Runoff Timing	0.91	1 Δ Min Temp / -0.02 Δ Runoff Timing
~ Avg Temp	0.77	1 Δ Avg Temp / 0.04 Δ Runoff Timing	0.74	1 Δ Avg Temp / 0.08 Δ Runoff Timing

4) What are the trends over time in annual max SWE, total annual discharge and annual average temperature over the history of the SNOTEL record?

Annual Maximum SWE

Gallatin River Basin

There is evidence for decreasing SWE over time (p-value = 0.0455, from a t-stat of -2.05 on 47d.f.). It is estimated that each year max SWE decreases by 0.2762cm (1cm decrease every 3.62 years), with an associated 95% confidence interval from -0.005 to -5.74 centimeters. This is an annual loss of 0.4% of the mean each year.

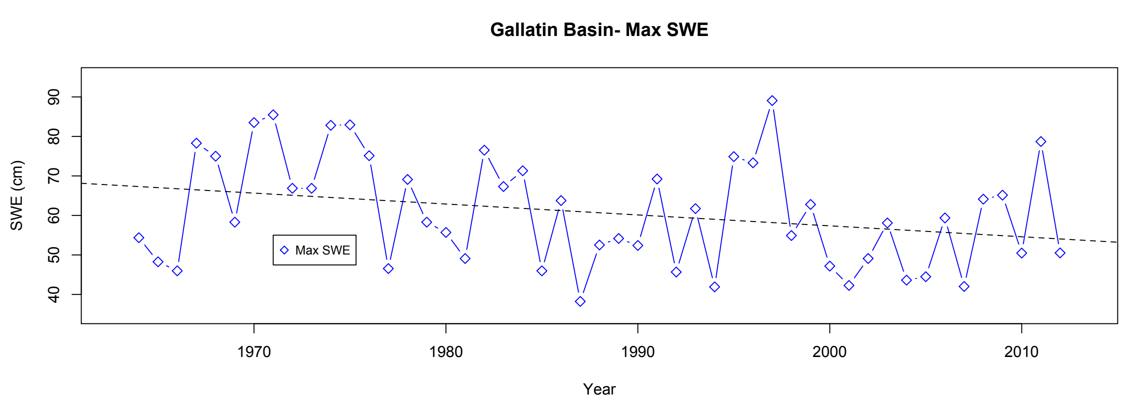

Fig. 10. Time series of annual maximum SWE for the Gallatin basin.

Madison River Basin

There is no evidence for a change in max SWE over time in the Madison River Basin (p-value = 0.7875, from a t-stat of -0.27 on 46d.f.).

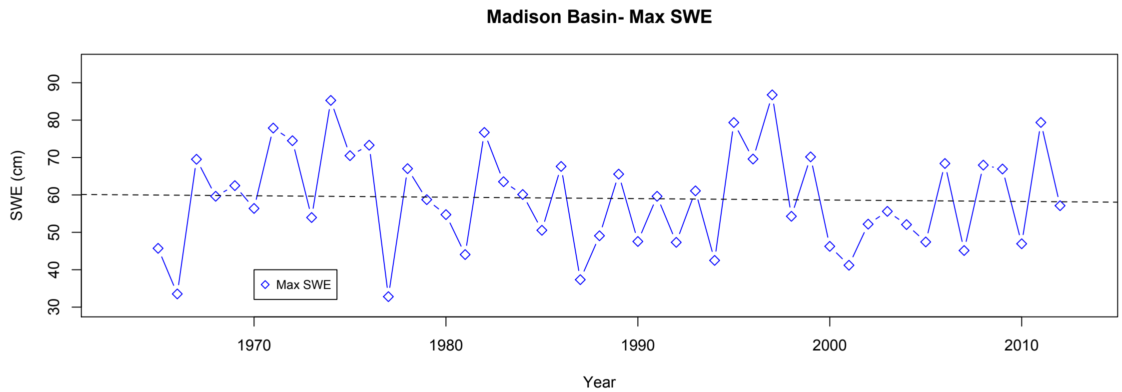

Fig. 11. Time series of annual maximum SWE for the Madison basin.

Total Annual Runoff

Gallatin River Basin

There is evidence for decreasing total annual discharge over time (p-value = 0.0061, from a t-stat of -2.89 on 42d.f.). It is estimated that each year max SWE decreases by 4,663,000 cubic meters, with an associated 95% confidence interval from 1,406,764 to 7,918,755 cubic meters. This is an annual loss of 0.6% of the mean each year.

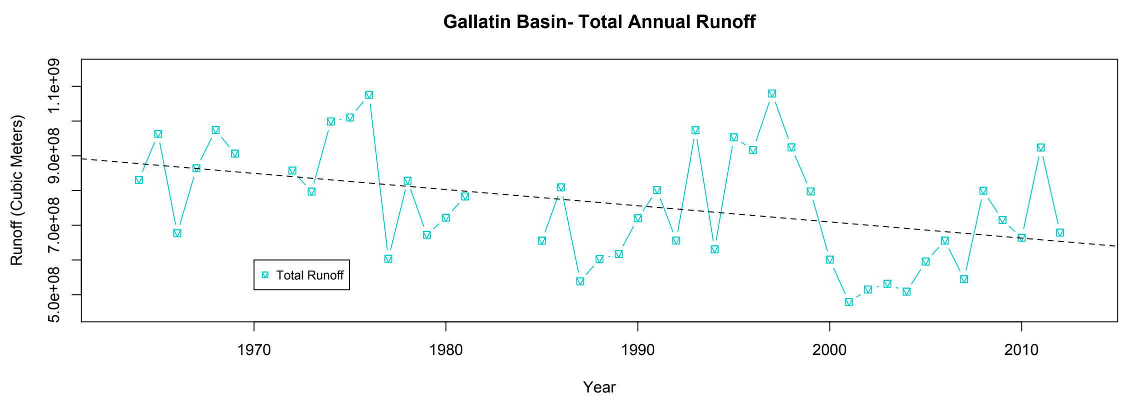

Fig. 12. Time series of total annual discharge (in cubic meters) for the Gallatin basin.

Madison River Basin

There is evidence for decreasing total annual discharge over time (p-value = 0.0016, from a t-stat of -3.36 on 47d.f.). It is estimated that each year max SWE decreases by 9,785,000 cubic meters, with an associated 95% confidence interval from 3,926,168 to 15,644,768 cubic meters. This is an annual loss of 0.6% of the mean each year.

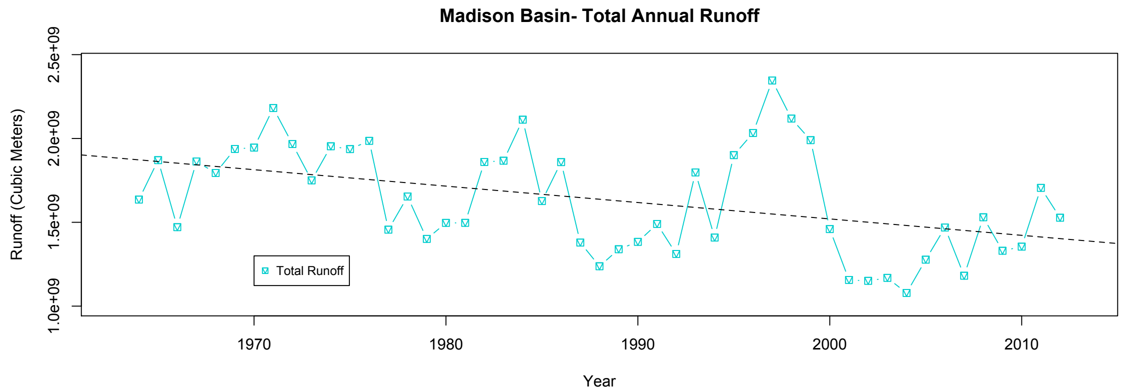

Fig. 13. Time series of total annual discharge (in cubic meters) for the Madison basin.

Annual Average Temperature

Gallatin River Basin

There is strong evidence for increasing temperatures over time (p-value < 0.0001, from a t-stat of 4.73 on 27d.f.) in the Gallatin River basin. It is estimated that the temperature rises 0.0980 degrees Celsius every year, or 1°C every 10.2 years. An associated 95% confidence interval runs from 0.0555 to 0.1406 degrees Celsius per year.

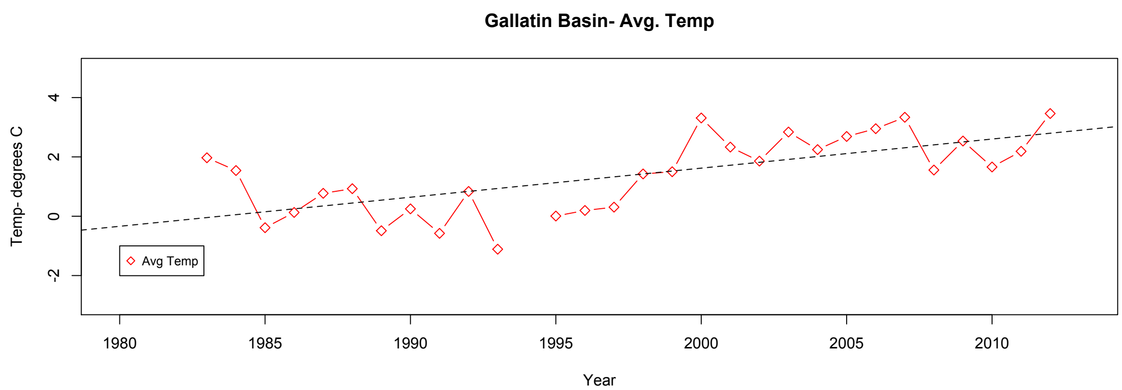

Fig. 14. Time series of annual average temperatures for the Gallatin basin.

Madison River Basin

There is strong evidence for increasing temperatures over time (p-value < 0.0001, from a t-stat of 6.78 on 28d.f.) in the Madison River basin. It is estimated that the temperature rises 0.1134 degrees Celsius every year, or 1°C every 8.8 years. An associated 95% confidence interval runs from 0.0791 to 0.1476 degrees Celsius per year.

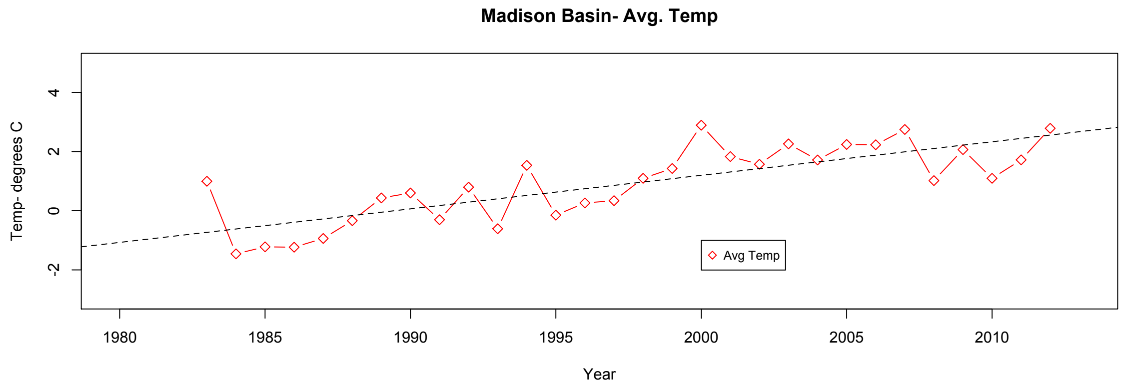

Fig. 15. Time series of annual average temperatures for the Madison basin.

<u>How do inter annual or decadal weather patterns account for the trends seen in the SNOTEL and streamgage data?</u>

A primary goal of this research is to examine the effect that decadal weather patterns have on water resources. Data that summarizes the states of decadal weather patterns are compared to maximum annual SWE, total annual discharge and annual average temperatures.

Annual maximum SWE and annual average temperatures from SNOTELs across each basin and total annual discharge from streamgages have, again, been averaged and standardized; and are used as the response variable in each model. Data representing decadal weather patterns are standardized and used as the explanatory variables. The following model is used to evaluate the extent to which decadal weather patterns can help explain annual variability.

{Metric (Annual Max SWE, Total Annual Discharge, Average Annual Temperature) | Decadal Weather Pattern Data (SOI, ENSO3.4, PDO, PNA}

<u>Max SWE</u>

All 4 indices showed evidence of a strong relationship with max SWE. Table 3. summarizes annual variability explained by each pattern index in each basin.

Table 3. Explained variability of annual maximum SWE for the Gallatin and Madison River basins

Decadal Weather Pattern	Gallatin River basin % Variability Explained	Madison River basin % Variability Explained
SOI	9%	19%
ENSO 3.4	10%	20%
PDO	9%	18%
PNA	11%	21%
Total (ENSO, PDO, PNA)	30%	59%

<u>Total Annual Runoff</u>

The Gallatin basin showed evidence of a relationship between runoff and the PDO and PNA, as well as, weak evidence between runoff and the SOI and ENSO 3.4. In the Madison basin there was weak evidence for a relationship between runoff and the PNA and no evidence between any other weather indices and runoff.

Table 4. Explained variability of total annual discharge for the Gallatin and Madison River basins

Decadal Weather Pattern	Gallatin River basin % Variability Explained	Madison River basin % Variability Explained
SOI	7%	3%
ENSO 3.4	7%	5%
PDO	12%	2%
PNA	12%	7%
Total (ENSO, PDO, PNA)	31%	14%

Annual Average Temperature

The Gallatin River basin shows evidence of a relationship between avg. temperatures and the PDO. The Madison River basin shows evidence of a relationship between avg. temps and the PNA. There is no evidence for a relationship between avg. temps and the SOI and ENSO 3.4 data.

Table 5. Explained variability of annual average temperatures for the Gallatin and Madison River basins

Decadal Weather Pattern	Gallatin River basin % Variability Explained	Madison River basin % Variability Explained
SOI	1%	2%
ENSO 3.4	0%	0%
PDO	3%	19%
PNA	14%	1%
Total (ENSO, PDO, PNA)	18%	22%

Decadal weather patterns do help to explain some of the values for max SWE, runoff and average temperatures. Max SWE showed the strongest relationships while average temperatures showed the weakest. Evidence for the strongest relationship, found between max SWE and decadal weather patterns in the Madison basin is also the metric that saw the smallest change over time. This might indicate that although these decadal weather patterns help to explain some of the normal variability seen in the data, they do not fit as well when confronted with data showing a larger 40 year trend.

How does the use of metadata from SNOTEL sites improve our understanding and quantification of these observed trends?

Closer examination of metadata for the SNOTEL stations reveal that examining both one time changes to the stations and the growth of canopy help explain trends in data and additional variability. Incorporating all available pieces of information generates robust results that help to more effectively construct the truth on the ground. A brief summary of the metadata analysis is given here.

The most notable one time change to the station is the repositioning of temperature sensors from the side of the shed to suspended in the air above the snow pillow. These types of changes to the station are important to consider when analyzing the output data from stations. To analyze the effect of this change temperature data was broken into pre and post sensor change datasets. In this case, looking at this one time change helped explain the alarming temporal trend of 1°C rise every 10 years and ultimately a much more reasonable result was established.

Canopy growth may also be worth considering when looking at data output from weather stations. For this study data on canopy growth was limited to 2 or 3 canopy images per site. However, when modeled canopy growth was compared with annual maximum SWE evidence for relationships existed in some of the stations and not in others. The potential impacts of canopy growth have been argued qualitatively for some time. Although small, the quantitative analysis done here provides some numbers to back the idea of canopy growth effecting data output. The qualitative and quantitative assessment on canopy images is strong enough that it should be considered in future studies where data is available.

SUMMARY

In the Missouri River headwaters, as in a large portion of the Western US, there is evidence for a relationship between snowfall and runoff, a relationship between the timing of snowfall and the timing of the runoff, slight decreases in snowfall, decreases in runoff and increases in temperatures. Decadal weather patterns do seem to play a role in the variability of snowfall, runoff and temperature, although they seem to help explain more of the short term variability than the long term (30-40 year) trends. Analyzing the sources of the data used to produce these results helped to create a more accurate and robust analysis. In some cases the original analysis was proven to be flawed once the metadata from these stations was taken into account. The NRCS SNOTELs and USGS streamgages provide the best datasets on water resources in the west but no station is perfect and the data must be thoroughly analyzed to ensure accurate results.

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Student Fellowship: Investigating Upstream Channel Response to Dam Removal, Black Foot River MT

Basic Information

Title:	Student Fellowship: Investigating Upstream Channel Response to Dam Removal, Black Foot River MT
Project Number:	2013MT283B
Start Date:	3/1/2013
End Date:	2/28/2014
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Focus Category:	Geomorphological Processes, Hydrology, None
Descriptors:	None
Principal Investigators:	Robert Livesay

Publications

There are no publications.

Student Fellowship: Investigating Upstream Channel Response to Dam Removal, Blackfoot River, MT

Robert M. Livesay, Geoscience Department, University of Montana

The following report is taken from an honors thesis by the student.

Abstract:
Dam removal is becoming more accepted as an effective approach to river restoration. Understanding the upstream geomorphic response following dam removal is vital in assessing the potential change to a fluvial system associated with an artificial drop in base level. In this study, I examined the upstream channel evolution of the Blackfoot River (BFR) in response to an 8 m drop in base level due to the 2008 removal of the Milltown Dam. Cross section elevation and grain size data from 13 BFR sites were collected: 5 sites within the area previously inundated by Milltown Reservoir and 8 sites upstream. To quantify the geomorphic response, I compared change in grain size, average bed elevation and bank boundary dimensions from 2008 to 2013. Results indicate spring runoff events in 2008 (Q_{max}: 286 m^3/s) evacuated reservoir sediments out of the Blackfoot arm of the reservoir in the form of bed load and suspended sediment. From Fall 2008 to Fall 2012 average bed elevation at any XS location did not deviate more than 1m and median substrate increased 1 psi size from Fall 2008 to Fall 2012. I claim the channel morphology has reached a new equilibrium, where change to topography and sediment profile no longer reflects the 2008 removal of the Milltown dam. To conceptualize channel evolution I developed 2 channel evolution models (CEM) to document the change in channel morphology from 2008 to 2012. My results indicate the main driver of channel response is spring run-off magnitude. Long-term studies of upstream channel response to dam removals are rare. Results from this study increase the spatial and temporal understanding of dam removals and can be applied to future dam remediation and river restoration projects.

Introduction

Dams impact the hydrology, sedimentology, and ecology of river systems (Evans 2001) and play a dynamic role in managing almost all of America's rivers. The number of dams located throughout America's waterscape totals 85,000 (National Dam Inventory 2010); these facilities provide irrigation, recreation, hydroelectric power and/or protection from flooding (Graff 1999). However, along with the many benefits dams provide, there are also many negative effects of dams such as disruption of natural flow regimes and degradation of ecosystems (Cech 2009).

By the year 2020, 85% of America's dams will be a half century old and in need of replacement, repair or removal (Grant 2001). Lawmakers have recognized this issue and have put forth legislation targeted at fixing this problem such as the Dam and Rehabilitation Act of 2007 and the National Dam Safety Act of 1996 which funded research on America's aging dams (Association of State Dam Safety 2012).

Instead of replacing or repairing a dam, removal is an increasingly common way of dealing with aging or uneconomical dams (Stanley and Doyle 2003). Studying dam removals provides scientists a rare opportunity to conduct real time experiments on the geomorphic response of river system to a disturbance (Grant 2001). Despite dam removal being practiced for several decades (Doyle et al. 2003), there is no centralized method of collecting and archiving dam specific data on the ecologic, hydrologic and geomorphologic change after removals. As of 2002, less than 5% of dam removals are accompanied by published scientific research (Sawaske and Freyberg 2012). Likewise the quality of post removal monitoring data for large dam removals is considered sparse at best (Major et al. 2011). These limited data pose challenges to policy makers and resource managers to make informed decisions regarding the fate of America's aging dams (Hienz Center 2002).

Unfortunately, the uncertainty surrounding dam removals cannot be avoided and although current numerical models are useful they lack robust data sets that test their validity (Pizzuto 2002). By mounting comprehensive post dam monitoring projects geomorphologists aim to develop reliable quantitative parameters that describe post dam channel evolution. For example, researchers monitored erosion, transport and deposition of sediment in the hours, days, months and years following the removal of the Marmot Dam, OR (Major et al. 2011). These types of comprehensive monitoring study are not easily conducted and require large financial and personnel support (Major et al. 2011).

My study aims to quantitatively monitor the geomorphic channel change in response to the largest dam removal project ever conducted in the state of Montana. This study documented the upstream geomorphic response of the Blackfoot River, MT to the 2008 removal of the Milltown Dam. We measured the geomorphic response by 1) repeating topographic surveys of bed elevation 2) characterizing substrate size 3) analyzing channel dimension via multiple year aerial photographs. Using these data, we established reliable parameters capable of describing the geomorphic response of a confined gravel bed river to dam removal.

The objective of my study was to document the change in channel form and bed-material sizes in the lower Blackfoot River, MT, since the 2008 removal of the Milltown Dam, including: 1) determining if the channel has reached a new topographic steady state, and 2) determining if river sediments have reached a new grain-size steady state.

Results

My key results are as follows:

1. Median sediment size increased 1psi size from Fall 2008 to Fall 2012.

2. Average bed elevation at any cross section location did not deviate more than 1m from Fall 2008 to Fall 2012 (figure 1).

3. The bank boundary of the downstream reach decreased by an average of 8 m and wetted channel area reduced .21 km^2 since the dam removal (figure 2).

4. The bank boundary of the upstream reach increased by an average of 11 m and the wetted channel area increased by an average of .005 km^2 since the dam removal (figure 3).

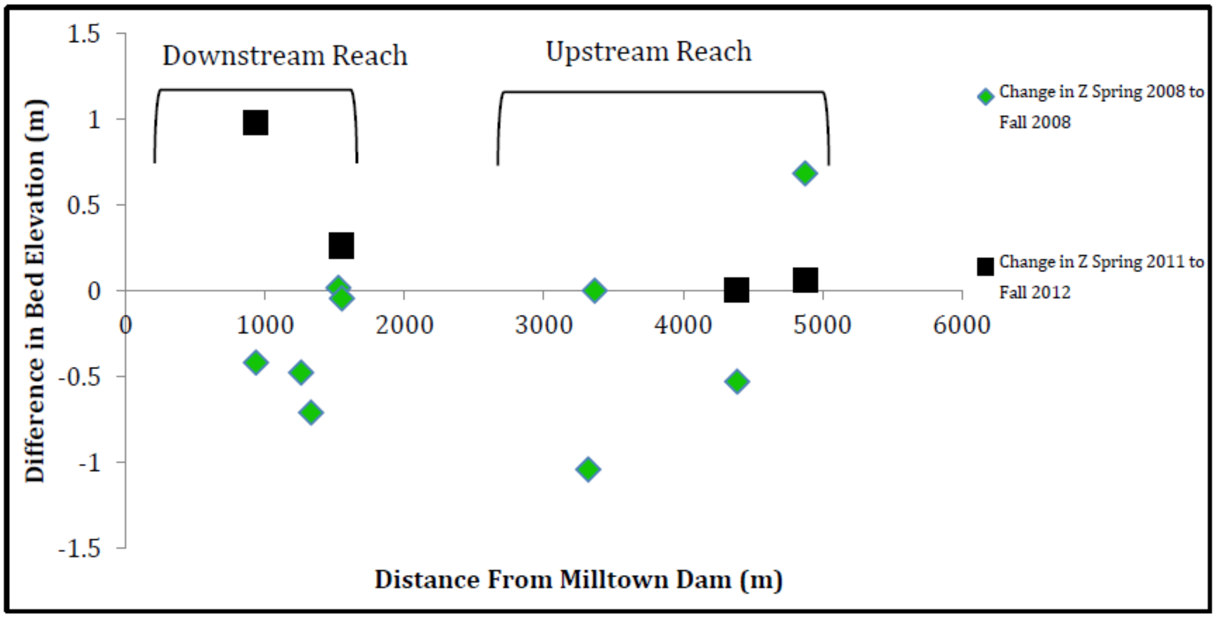


Figure 1. Between Spring 2008 and Fall 2008 average bed elevation difference was calculated at XS 1, 2,3,4,5,8,9,12 and 13. Bed elevation lowered at all XS except for Xs 4 and 13. The same approach was used for cross section surveys conducted in Spring 2011 and Fall 2012 all of which gained bed elevation.

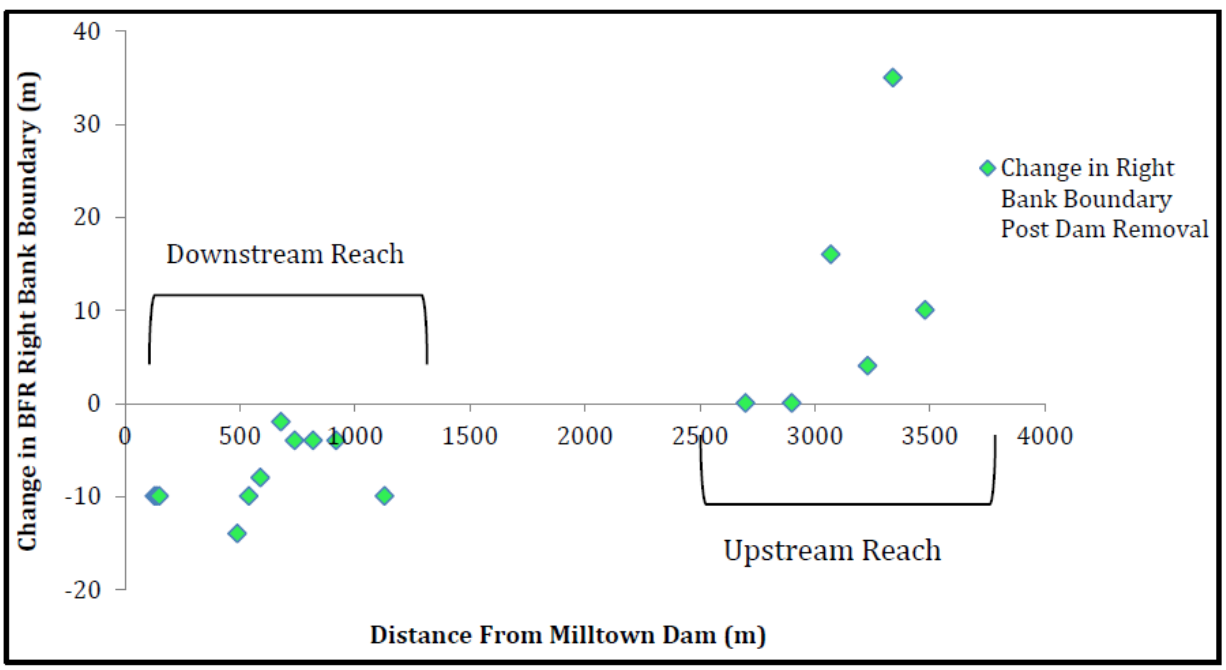
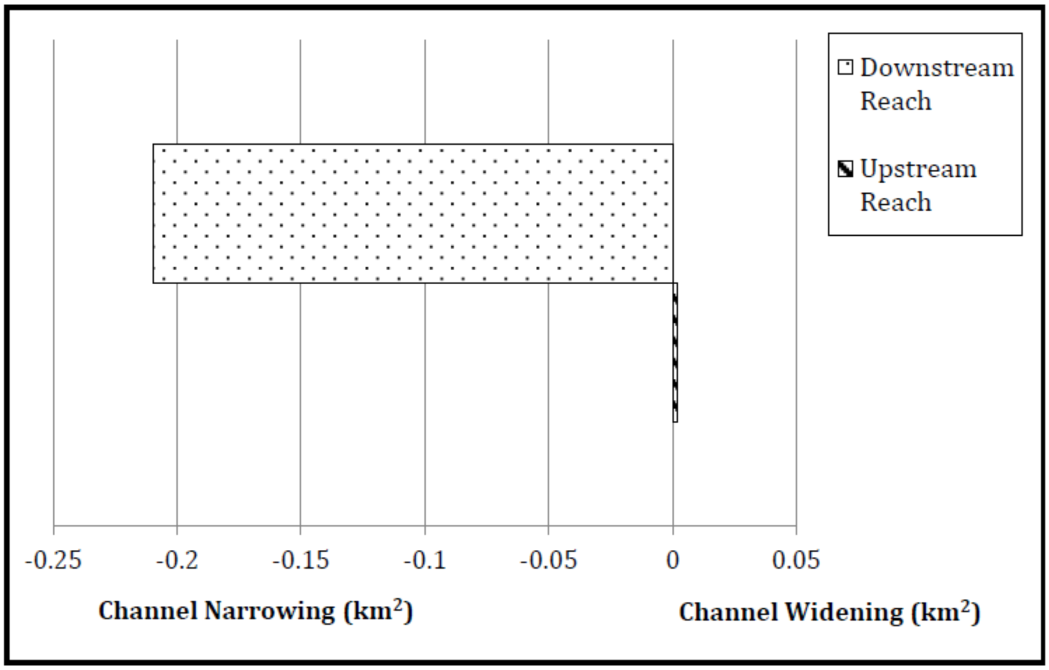


Figure2. I calculated the change in the right bank boundary as the water surface elevation responded to the drop of base level caused by the dam removal. The downstream reach right bank boundary narrowed and the upstream reach bank boundary widened.



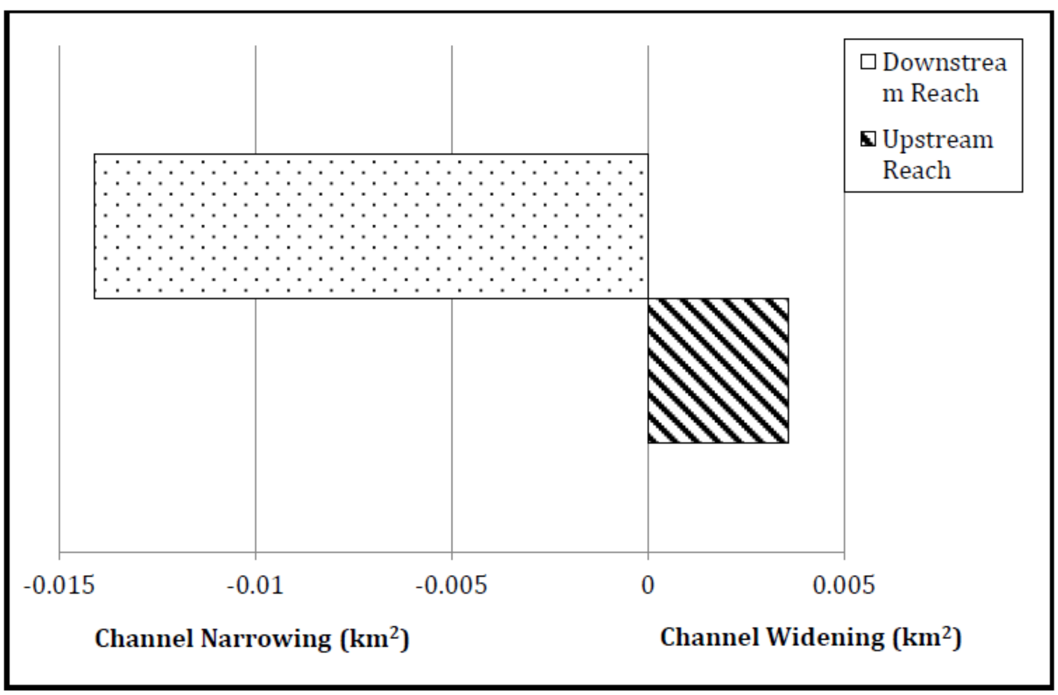


Figure 3. The upper chart is change in wetted channel area between Spring 2008 and Fall 2008 and the lower chart is change in channel area from Spring 2011 to Fall 2012. I observed channel narrowing in the downstream reach during both time intervals. The upstream reach widened instead of narrowing. The upstream reach widened more as time after the dam removal increased.

Conclusions

These findings may be applicable to other dam removal projects.

1. The majority of erosion occurs in the first runoff event following a dam removal.

2. Manmade structures and large wood impact the timescale of erosion and need to be evaluated prior to dam removal.

3. Significant channel narrowing and widening should be incorporated into dam removal plans.

4. The duration of erosion and sediment transport following dam removal may have adverse impacts on downstream areas. This should be fully considered in planning dam removals. Of particular concern is the chemical property of eroded sediments and how downstream deposition could influence ecological habitats.

Based on these findings it is important that submerged channel conditions are fully considered prior to dam removal such as the presence of large wood in the reservoir sediment matrix. This includes understanding potential site-specific obstructions that may increase the channel roughness after a dam is removed. It is also crucial that the hydrology of the drainage is fully understood before a dam is removed. Ideally this means working with watershed hydrologists who have a better understanding of snow pack and how it will influence the magnitude of spring run-off. The mechanics of channel evolution are well documented but events such as site-specific hydrology including high flow magnitude limit my ability to predict a timeline of events following a dam removal.

Application of geomorphology to the evaluation of social issues such as restoring degrading river systems is essential. Findings from this study will help bolster a general understanding of future river restoration projects. The objective of this study was accomplished and outcomes establish a timescale of sediment dispersion following dam removal and steady-state channel parameters for the lower five kilometers of the Blackfoot River.

I acknowledge I have a general understanding of what these data reflect about river morphology and applied basic geomorphic principles throughout the interpretation these data. I would like to expand my research by not only looking at the influence of dam removal on channel morphology but also the influence of other man made objects on river morphology such as bridge piers.

Political obstacles can limit the success of a dam removal or restoration project Therefore, restoration efforts must be well planned and follow a processed based set of concepts. Designation of the Milltown as a Superfund site prompted the involvement of many agencies (EPA, DEQ, FWP). This high profile involvement allowed the restoration team to effectively follow these three principles of river restoration 1) restoration actions addressed the root causes of habitat degradation, 2) efforts did exceed the physical and biological potential of the site, 3) scale of the project matched the extent of the problem (Beechie et al. 2010). These three principles of river restoration were exemplified by this restoration effort and as this project can be used a model for future dam removal projects.

Information Transfer Program Introduction

Supporting students to become water science professionals is a core mission of the Montana Water Center. The center continued to work closely with faculty researchers to engage students in water-related research including producing reports and publishing papers. Faculty researchers who received research funding from the Water Center are required to actively mentor students in the research projects. The Center encouraged students from a wide array of disciplines that are water related to apply for student fellowships. The Water Center also encouraged students engaged in water resource studies to present at regional and national conferences. The presentations and publications of faculty and students reported in their annual reports attests to the support given to students to both take on research and also present it at local and national meetings as well as follow through to publication in national journals.

In addition to working with faculty and students, Water Center programs reached thousands of others interested in water issues in Montana, including water resource professionals, teachers, farmers, ranchers, engineers, drinking water and wastewater system operators.

Education and outreach on various water topics was delivered to Montana citizens through the Montana Watercourse (MTWC), which is part of the Montana Water Center. MTWC provides hands-on, dynamic, water education through a series of diverse programs that target all levels of water users, youth through adults. Using practical, unbiased, legal, and scientific information, MTWC educates Montanans on basic water facts, water problems, and their solutions (mtwatercourse.org).

Specific information transfer activities include the following:

* Published six Montana Water e-newsletters (due to budgetary constraints cut back to every other month part way through the year) and distributed them to almost 2,000 professionals, students and decision makers concerned with water resource management. Newsletter archives are posted at http://water.montana.edu/newsletter/archives/default.asp.

* Continued the web information network MONTANA WATER, at http://water.montana.edu. Known as Montana's clearinghouse for water information, this website includes an events calendar, news and announcement updates, an online library, water-resource forums and water source links, an expertise directory, water facts and more.

* The Montana Water Center continues to distribute training CDs funded by the EPA, for small drinking water systems titled Arsenic and Radionuclides: Small Water System Treatment Experiences.

*Helped organize and execute a state water meeting with the Montana Section of the American Water Resources Association in Bozeman, MT on October 3-4, 2013. The theme of this conference was "Water and Energy". A pre-conference field trip visited Hyalite Reservoir and the Bozeman drinking water treatment plant. Approximately 150 people attended the conference with 38 speakers and 29 poster presentations. Oral and poster presentations highlighted much of the current water research being conducted throughout Montana by university, federal, state, county and non-profit researchers and resource managers. Director Duncan Patten gave a welcoming address at the conference and Assistant Director Stephanie McGinnis presented on her previous research at the conference. The conference also had the usual good turnout of student presenters, representing the University of Montana, Montana Tech and Montana State University. The web-based archive of this meeting is found at http://www.montanaawra.org/conference/conference-archives/2013-meeting/.

* Responded to numerous information requests on water topics ranging from invasive water rights to importance of snowpack to Montanan's, to streamside setbacks to contaminants in Montana's surface and

ground water, and ways to better manage these water sources.

*Sponsored the 80th Annual School for Water & Wastewater Operators & Managers held in October 2013 at Montana State University. This training was attended by staff members of water and wastewater utilities with the purpose of preparing new system operators to pass the certification exam, and familiarize participants with other resources they may find helpful in the future.

*Offered a Wetland Training course supported by an EPA grant through Montana DEQ titled: “Monitoring and Assessment of Wetland and Riparian Ecosystems”. This was offered as a three-day, in-person course on monitoring and assessment of wetland and riparian ecosystems and was based on an adaptive management foundation. Resource managers and educators joined the class, providing a multi-disciplinary perspective. Topic selection and planning of the 2014 Wetland Training course is already in progress.

* Grant funded water education programs were delivered by MTWC that focused on the following areas: water rights trainings, dam owner workshops, riparian best management practices, Project WET curriculum training, lake ecology graduate course, volunteer water monitoring training, careers in water, and the Montanan Water supply Initiative material. Funding for these programs is provided through various grants including significant funding from Montana Department of Natural Resources and Conservation, Montana Department of Environmental Quality, and the Environmental Protection Agency.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	2	0	0	0	2
Masters	2	0	0	0	2
Ph.D.	2	0	0	0	2
Post-Doc.	0	0	0	0	0
Total	6	0	0	0	6

Notable Awards and Achievements

Montana Watercourse received an Administrator’s Award from the Department of Natural Resources and Conservation for excellent performance in providing water resources education and outreach to the citizens of Montana.

Publications from Prior Years

1. 2011MT241B ("Using 222Rn and Isotopic Tracers to Trace Groundwater-Lake Interactions") - Articles in Refereed Scientific Journals - Shaw, G., E. White, and C. Gammons, 2013, Characterizing groundwater-lake interactions and its impact on lake water quality, Journal of Hydrology, 492, 69-78.
2. 2010MT216B ("Ecohydrologic Model Development for the Assessment of Climate Change Impacts on Water Resources in the Bitterroot Valley") - Articles in Refereed Scientific Journals - Lozano-Parra, FJ, M. Maneta, and S. Schnabel, 2014, Response of pasture production to climate variability in a semiarid Mediterranean watershed with scattered tree cover, Hydrology and Earth System Sciences, 18, 1439-1456
3. 2010MT216B ("Ecohydrologic Model Development for the Assessment of Climate Change Impacts on Water Resources in the Bitterroot Valley") - Articles in Refereed Scientific Journals - Maneta, M and N. Silverman, 2013, A spatially-distributed model to simulate water, energy and vegetation dynamics using information from regional climate models, Earth Interactions, 17, 1-44
4. 2010MT216B ("Ecohydrologic Model Development for the Assessment of Climate Change Impacts on Water Resources in the Bitterroot Valley") - Articles in Refereed Scientific Journals - Maneta, M. and R. Howitt, 2014, Stochastic calibration and data assimilation in non-stationary hydro-economic models, Water Resources Research http://dx.doi.org/10.1002/2013WR015196